Effects of Overvoltage on Power Consumption

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by
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'Oh Lord! Illuminate my darkness.'

[Saint Gregory Palamas]

Abstract

In the recent years there is an increasing need of electrical and electronic units for household, commercial and industrial use. These loads require a proper electrical power supply to convey optimal energy, i.e. kinetic, mechanical, heat, or electrical with different form. As it is known, any electrical or electronic unit in order to operate safely and satisfactory, requires that the nominal voltages provided to the power supply are kept within strict boundary values defined by the electrical standards and certainly there is no unit that can be supplied with voltage values above or below these specifications; consequently, for their correct and safe operation, priority has been given to the appropriate electrical power supply. Moreover, modern electrical and electronic equipment, in order to satisfy these demands in efficiency, reliability, with high speed and accuracy in operation, employ modern semiconductor devices in their circuitries or items. Nevertheless, these modern semiconductor devices or items appear non-linear transfer characteristics in switching mode, which create harmonic currents and finally distort the sinusoidal ac wave shape of the current and voltage supply.

This dissertation proposes an analysis and synthesis of a framework specifically on what happens on power consumption in different types of loads or equipment when the nominal voltage supply increases over the permissibly limits of operation. A variety of loads have been selected from those used in everyday life, for household needs, office needs, as well as trade and industry. They were classified in two main categories, the passive loads and the non-linear loads. The classification was made on the event that the passive loads do not create harmonic currents but the non-linear loads create harmonic currents. For the above purpose was made practical experimental testings on several loads – equipment of both the categories in the laboratories, summarising the effects of the supplying voltages in power consumption, at higher values[1] gradually, from the nominal values up to the overvoltages. Also in some cases, for more accurate observation, was used the PSpice simulating program.

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[1] For a better understanding of the events, some experimental testings was made at lower supplying voltages – undervoltages across the loads.

Finally, the results from the experimental testings confirmed that the effects of the overvoltages are:

- the increased consumption of power,
- the decrease of the lifespan of electronic components due to overheating,
- they are different with respect to the nature of the loads,
- the increased amplitude of the current harmonics in the non-linear loads.

For harmonic current reduction, an easy to use Pulse Width Modulation (PWM) method is proposed through booster topology, using a minimum number of components. This electronic circuit (harmonic current reducer) is cheap and easy to use, and can be easily connected between the mains supply and the non-linear load. It reduces, or keeps in low level the amplitudes of the current harmonics of the supplying current (distorted) of a non-linear load, in order to offer an extra protection or relief to the load when the supplying voltage or mains increases from its nominal value to undesired overvoltage values.

Also, in order to avoid the undesirable effects on power consumption, due to overvoltages, design of a prototyping electronic circuit is proposed. This circuit (stabiliser), like the above harmonic current reducer, can be easily connected between the mains supply and a load or equipment; despite the mains supply variations, it keeps constant the desired or nominal voltage supply (voltage amplitude, $V_{\text{peak to peak}}$) across the load or equipment.

Dedication

To my Respectful Parents

Athanasios

and

Fotini

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Author's Declaration

I, Panagiotis Dimitriadis, declare that the ideas, research work, analyses, findings and conclusions reported in my PhD thesis: "*Effects of overvoltage on power consumption*", are entirely my effort, except where otherwise acknowledged. Also, I certify that this thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

Publications from this research work

Conference Papers:

1. Panagiotis A. Dimitriadis M. K. Darwish, “Harmonic Correction in Power Supplies Feeding Non-linear Loads”, presented in *49th International Universities Power Engineering Conference (UPEC 2014),* Technical University of Cluj-Napoca, Cluj Napoca, ROMANIA. 2 - 5 September 2014.

2. C.C. Marouchos, Andria Neroupou, M. Darwish, Panagiotis Dimitriadis, “Investigation on Line Current Compensation Techniques for Rectifier Circuits”, Proceedings of the *50th International Universities Power Engineering Conference (UPEC 2015)*, September 2015.

3. P. A. Dimitriadis, M. K. Darwish, “Effects of over-voltage on power consumption”, submitted to International Review of Electrical Engineering (I.R.E.E.), submitted on October 2015.

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List of Symbols

Symbol	**Meaning**
>	Greater than
≥	Greater or equal to
>>	Much greater than
<	Less than
≤	Less or equal to
<<	Much less than
≈	Approximately equal to
≠	Not equal to
→	Therefore
Σ	Sum of
$\lvert \; \rvert$	Absolute magnitude of
a	Delay angle or fire angle
η	Power transfer efficiency
AC , ac	Alternative Current
Avg , AVG	Average
D	Duty Cycle
DC	Direct current
DF	Distortion Factor
HV	High Voltage
Hz	Hertz
µs	Micro Second

kHz	Kilohertz
kV	Kilo voltage
kWh	Kilowatt Hour
kW	Kilowatt
LV	Low Voltage
MHz	Megahertz
Min	Minute
ms	Millisecond
ns	Nano Second
PF	Power Factor
PFC	Power Factor Correction
pu	Per Unit
S	Second
Sq	Square
θ	Displacement Power Factor
U_c	Declared supply voltage
U_n	Nominal voltage of the system
V	Voltage
VA	Volt Ampere
VAR	Volt Ampere Reactive
W	Watt
Wh	Watt Hour

List of Abbreviations

ANSI	American National Standards Institute
CBEMA	Computer Business Equipment Manufacturers Association
CENELEC	Comité Européen de Normalisation Electrotechnique European Committee for Electrotechnical Standardization
CEC	Commission of the European Communities
DER	Distributed Energy Resources[2]
EC	European Comities
EEC	Electromagnetic of the European Communities
EDN	Eastern distribution network
EHV	Extra High Voltage refers to 230 kV < Un [TR 61000-3-6 © IEC:2008(E)]
EMC	Electromagnetic Compatibility
HV	High Voltage refers to 35 kV < Un ≤ 230 kV [30] [TR 61000-3-6 © IEC:2008(E)]
IEC	International Electrotechnical Commission; Geneva, Switzerland; http://www.iec.ch
IEEE	Institution of Electrical and Electronic Engineering
INSPEC	Information Services for the Physics and Engineering Communities
IT	Information Technology

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[2] "Distributed energy resources (DER) refers to electric power generation resources that are directly connected to medium voltage (MV) or low voltage (LV) distribution systems, rather than to the bulk power transmission systems.

ITIC	Information Technology Industry Council
KEMA	Verification of Electrical Materials
LV	Low Voltage. Refers to Un ≤ 1 kV [30] [TR 61000-3-6 © IEC:2008(E)]
MV	Medium Voltage. Refers to 1 kV < Un ≤ 35 kV [TR 61000-3-6 © IEC:2008(E)]
PCC	Point of Common Coupling[3]
PQ	Power Quality
PSRC	Power System Relaying Committee [4]
SARFI_x	System Average Rms (variation) Frequency $\text{Index}_{\text{Voltage}}$[5]
MTL	Measurement Technology Limited[6]
MV	Medium Voltage, above 1 kV to 36 kV included [30]
RMS, R.M.S, rms	Root Mean Square
THD	Total Harmonic Distortion
VIF	Variance inflation Factor

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[3] Is defined as a point of metering or any point where both the Company and the Customer can access the point for direct measurement [98].

[4] The Power System Relaying Committee is a Treatment of all matters in which the dominant factors are the application, design, construction, and operation of protective, regulating, monitoring, synchronism-check, synchronizing, reclosing, and auxiliary relays, including all matters necessary to the function of such relays and relaying systems employed in the generation, transmission, distribution, and utilization of electrical energy and including the effects of such relays on system operation. Treatment of techniques and requirements for communications within, between, and among protective relays to the extent that these communications affect protection functions or performance. Maintenance of liaison and collaboration as required with other committees of the Power & Energy Society and associated Groups and Societies of the IEEE. [http://www.pes-psrc.org/].

[5] x = rms voltage threshold; possible values are 140, 120, 110, 90, 80, 70, 50, and 10 [32].

[6] It is synonymous with technical innovation in the field of intrinsic safety interface modules, overvoltage protection and field bus solutions [87].

Chapter 1: Introduction

1.1 Background and Motivation of the Project

The amount of the power consumed by a load depends not only on the size and nature of the load, but also on the voltage applied to the load. Technically, in engineering terms, power is the rate of energy delivery and is proportional to the product of the voltage and current.

$$p(t) = v(t) \cdot i(t) \qquad (1.1)$$

The effects on power consumption that are generated by the overvoltages, today, are a key problem for study and resolution [1]. Basically, their unwanted effects include a variety of negative consequences, mainly to the economy and the life span of the loads or equipment [24] [79] [83].

Today, the needs through electric power in survival (cooking, health etc.), education, information, communication, industry, agriculture, livestock, poultry, craft, art, comfort, defence and so forth, are increasing rapidly; this means that the use of the proper equipment to transform the electric power to the relatively demanded useful work, increases straight proportionally [101].

Voltage stability is an important factor of the power system that its importance arises since 1920 [86]. Under normal conditions, the expected useful work comes from standard power consumption and standard power consumption comes from standard power supply [3] [13]. Consequently, every electric load or equipment is supplied by the factory with a tablet, where its electrical specifications are written about the power supply (mainly, voltage (V) with frequency (Hz)), the power consumption (W) for useful work etc. This means that electric loads, devices or equipment are designed to work safely, under specific values (the nominal prices) of voltage across them [16] [21]. Also, Kundur and his all that refer to “transient instability being the dominant stability problem on most systems and the focus of much of the industry’s attention concerning system stability" [57]. What could happen on power consumption, if there was a disturbance of the power supply, e.g. an increase of the voltage supply across such load or equipment more than the nominal? The answer should be given by the relative calculations or by practical experiments [67].

Recently, as the electric devices have evolved through continuing growth of the electric and electronic technology globally, use of standard limits has been developed and proposed internationally, in order to be commonly known about the permissible power supply limits for the safe functioning of the equipment [90] [22] [23]. For instance, the term *overvoltage* has been set to characterize the voltage supply value when it is above a standard higher limit for a time interval longer than specific time [9] [15] [31] [32] [106]. Therefore, the question "what could happen on power consumption, if there was an *overvoltage* supply across a load or equipment", is commonly valid and more specific [43] [46] [47] [66] [67] [83], in evaluation of the relative effects on power consumption, leading to more specific actions in order to eliminate these undesired effects [48] [87].

Undervoltages, in general, compared to overvoltages are no so much often phenomena and dangerous for the safe operation of the equipment – load [67] [113]. Also, the effects of the overvoltages must be taken to account seriously, to the wider area of the equipment – loads in relation to undervoltages [46] [67]. Increasing the voltage applied across a component, the power consumed increases and heat is generated by that component [67] [70]. This can lead to overheating and even damage to circuitry. It is widely documented that overvoltage decreases the lifespan of a component, and the higher the voltage applied, the shorter the component's life will be [83]. This is due to a combination of various factors, notably increased heat production and internal damage to the conductors from electromigration [46] [57] [70].

In power consumption there are electric loads, the linear or passive loads, where the amount of power consumption is directly proportional to the voltage supply across them [143] [101]. Also, in this case, in ac circuits where the waveform of the voltage supply is sinusoidal, the current is proportional to voltage and therefore it remains sinusoidal, even if there is phase difference between voltage and current [100] [142]. This means that the impedance of these loads is fixed [32].

Of course, there are the non-linear loads, like electronic equipment or equipment with switch mode power supplies, where the drawn current is non proportional to the supplied voltage, as the power consumption is being according to the load's requirements [124]. Their impedance is not fixed; it changes with the voltage, and consequently the current depends on the impedance of the load [32]. This concludes to the generation of harmonic currents, higher than fundamental frequency, causing the distortion of the current waveform [109] [114] [122].

1.2 Research Aim and Objectives

The aim of this research is to highlight and evaluate the effects of the overvoltages on power consumption in different types of loads or equipment. Also, as the overvoltages increase the amplitude of the harmonics of the non-linear loads with undesired results, there is a trial to reduce current harmonics, as much as possible, with simple and low cost circuitry. Besides, in order to protect the loads from the undesired overvoltage effects there is a trial for a voltage stabiliser circuitry between mains supply and the load.

In order to achieve the research aim, the following objectives have been accomplished:

- Through experiments (software and laboratory), to test different types of loads or equipment under overvoltages.
- For the non-linear loads, a simple and low cost circuitry for current harmonic reduction is proposed.
- For the voltage supply stabilisation across a load, a relative circuitry is proposed, in order to avoid the undesired effects in power consumption because of the overvoltages.

1.3 Structure and Contribution of the Thesis

The present thesis consists of seven (7) main chapters where each chapter has its own contribution.

Chapter one presents the contents of the thesis. It describes the importance of the voltage supply in relation to the power consumption in the loads. It explains the need for voltage stability in power supply in order to avoid undesired effects on power consumption when the voltage supply increases. It highlights the determinant factor and term of *overvoltage* in relation to the effects on power consumption. It also points out some remarkable specifics of different types of loads that play important role during overvoltages. Finally defines the thesis structure.

Chapter two presents the relative literature review, which first of all outlines the need that the voltage supply must be put in to specific standard basis and the relation of the power quality (PQ) with the related electrical standards, which play significant role for the safe operation of the loads. It refers to the related electrical standards of the supply voltage to the loads. Subsequently it traces the history, in deep, of the overvoltage phenomenon, with the related effects – problems and solutions, definitions of overvoltage concepts by researchers and experts worldwide through the relative literature. Finally, there is also a need, to refer in deep to, as event of the harmonic distortion in power supplies in case of feeding non-linear loads, with the related effects and the proper solutions through filtering.

Chapter three includes trial, in deep, of the overvoltage effects on passive loads. As passive loads have been selected resistive and electromagnetic loads. First, experimental testing through PSpice simulating program is being on resistive loads, and then practical experimental testing on resistive and electromagnetic loads, with the relative results and comments.

Chapter four includes a deep trial of analysis of overvoltage effects on non-linear loads, through practical experimental testing, with the relative results and comments. As non-linear loads have been selected fluorescent lamps and active loads.

Chapter five, deals with the harmonic current reduction by proposing relative circuitry. Since overvoltages may affect to the harmonic currents, increasing the total harmonic distortion caused by a non-linear load, a trial for an easy and simple cost active reducer has been made. A relative circuitry has been proposed, designed and tested through PSpice program and practically evaluated.

Chapter six, deals with the voltage stabilization across a load by proposing relative circuitry. Regarding the need, the voltage supply across a load to remain invariable, an effort for a voltage stabilizer has been made by designing and testing a relative prototyping circuitry through PSpice program.

Chapter seven contains some general conclusions and there, a general assessment of the work is given. Also, similar objects for future research are presented.

The contribution of this work is identified in the following points:
The classification of the loads is presented in principle. The classification has been made on the basis of the relation between the voltage supply and power consumption and more specifically, how the consumed power in a load is affected of the overvoltage across a load. Therefore, two main categories of loads are proposed, the passive loads and the non-linear loads. In the case of passive loads, the amount of power consumed (for a constant value of load) is directly proportional to v^2, a fact that is roughly true in the cases where the resistance varies (not due to the applied voltage) or the loads are partially inductive or capacitive. The other type of the loads are the non-linear loads, where the amount of power consumed (for a constant value of load) is not directly proportional to v^2, as the current source depends on the impedance variations of the load. Despite its importance, this classification does not exist in literature. Thus, a solution has been proposed to a research “gap” of recent years, in classifying the loads for the present research. Based on these types of loads, systematic methods for the evaluation of the effects of the overvoltages on power consumption have been realised. PSpice simulation program was used for experimental testing of some fundamental and important circuitries. Also, practical experimental tastings have been realised for these loads. The results have been recorded in a way that the evaluation of the overvoltages and their effects on power consumption is better understandable or descriptive through tables and analogies.

Consequently, we can analyse and interprete the particular nature of different types of loads and their properties. The importance of current harmonic distortion on non-linear loads has been presented through the research and experimental testing, and the need for a co-existing of a current harmonic reducer was considered and proved. The proposed circuitry performed satisfactory on practical testing, of a simple and cost effective current harmonic reducer. Also, through this research the presence of a voltage stabilizer circuit proved necessary in order, the undesired effects of the overvoltages, to be avoided. The proposed circuitry, tested through PSpice program, performed quite satisfactory for low power loads.

1.4 Summary

The present chapter presents the thesis contents of the study conducted on the effects of the overvoltages related on the power consumption in two main different types of loads, the passive and the non-linear loads. It presents a circuitry proposed for the harmonic current reduction by non-linear load and a circuitry proposed for the stabilization of the voltage supply across a load. It also provides the significance, the motivation of the study, and the contribution achieved. It explains, in brief, the research methodology and approaches followed in this study. Finally, it presents the structure of the thesis.

Chapter 2: Literature Review

2.1 Introduction

This chapter reviews and discusses, focused on the relevant literature, regarding the overvoltage effects on power consumption in different types of loads or equipment, the proposed solutions in order to eliminate this phenomenon, the harmonic distortion in power supplies feeding non-linear loads and then relative proposed solutions for harmonic reduction. It starts from the importance in depth of the correct voltage supply of the equipment or loads from the electric power public distribution system related to the power quality (PQ), the international standards, the overvoltages, ending to the effects of the overvoltages. Moreover, this chapter starts from the harmonics in deep, the event that they cause distortion to the waveshape of the voltage and current supply as products of the non-linearity of some equipment, the harmonic limits according to the international standards, the related indices, ending to harmonic reduction – correction through filtering.

The literature examined in this study aims to identify relevant problems and answers through the following sections:

Section 2.2 presents the need of the voltage supply to be put in to specific standard basis.

Section 2.3 discuses the definition and relation of the power quality (PQ) with the related electrical standards, which play significant role for the correct operation of the equipment, devices or in general the loads.

Section 2.4 illustrates the related electrical standards of the supply voltage to the loads.

Section 2.5 refers to the overvoltage phenomenon, with the related effects – problems and solutions.

Section 2.6 refers to the harmonics, and discusses the event of the harmonic distortion in power supplies through feeding non-linear loads, with the related consequences and the proper solutions of this problem through filtering.

2.2 The Correct Voltage Supply for the Electrical Equipment or Devices

As the electrical and electronic loads – equipment evolve and become more sophisticated, supported by new technologies, with the event that new improved electronic semiconductors are used in their circuits, several different results and effects are observed related to the power consumed on them.

The use of electricity for the common welfare purposes requires voltage standardization, so that the electrical power feeding is coordinated with electrical specifications of the utilised equipments – devices [1] [3] [13] [20], given that the amount of the power consumed by a load depends not only on the size and the nature of the load but also on the voltage applied to the load. A correct operation of electrical equipment – device requires electrical energy to be supplied at a voltage that is compatible to its electrical specifications [3] [13] [15] [16] [21]. The non-proper supply or voltage disturbances on the power distribution system, causes malfunctioning of the loads – equipment, especially to those, containing modern (up-to-date) sophisticated electronic circuits, like the avionics, computers, controllers, adjustable speed drives, contactors and relays [16] [21] in order to increase their efficiency and productivity. Therefore, to avoid malfunctioning and reliable operation, of the loads – equipment, some power characteristics, like voltage supply, current, harmonics and other parameters that regulate the normal operating conditions of the loads – equipment, should be taken into account and follow specific standard basis, [22] [25].

2.3 The Definition and Relation of the Power Quality (PQ) with the Related Electrical Standards

According to Schaffner's comp. "many electricity supply utilities are now mandated to provide a mains supply with controlled quality parameters such as harmonic distortion and voltage limits" [99]. The specific standard basis, that they regulate the normal operating conditions of the loads – equipments is consisted by a list, which determines the "level of quality", or, in other words, the power quality [22] of an electric power system. As, also, the electrical energy is a product, there are these proper power quality requirements (the standards) that must be satisfied [13] [40]. In 1968 Kajihara announced the Power Quality (PQ) term, declaring the seriousness of the relative concept [34]. Bollen also, confirms the critical role of PQ in the design of power systems [35]. During the period of 1969 and 1984 the term of power quality is issued also as "voltage quality" by some publications in the INSPEC database [36]. Some authors use the "quality of supply" term [21]. Finally, the "power quality" (PQ) term has prevailed today [37]. Recently PQ has exponential increasing importance to the public electricity networks [19], as it became a critical factor for the normal electrical and electronic engineering applications and "one of the most expensive and wasteful parameter in the supply network" [13].

There are plenty of definitions of PQ who vary with respect to the standard needs as a reflection of the expected satisfaction from the programmed demands of the customers [38]. Also, it can be defined according to electrical utilities of a system for reliability, showing statistically that the system is 99.98% reliable [32]. Professor Dash notes that "a utility may define power quality as reliability and show statistics demonstrating that its system is 99.98 percent reliable" [106]. PQ can be defined as the "set of limits or conditions that allows electrical devices to function in their planned manner without loss of performance" [171]. As the PQ is depended from "the voltage, current, or frequency deviations that results in failure or disoperation of customer equipment" [32] and it can be defined in general as:
"*a term that refers to maintaining the near sinusoidal waveform of power system bus voltages and currents at rated magnitude and frequency*"[30]
or (IEEE Std 1159.3, 2003) as follows also as:
the "*set of parameters defining the properties of the power supply as delivered to the user in normal operating conditions in terms of continuity of supply and characteristics of voltage (symmetry, frequency, magnitude and waveform)*".

This set of parameters can be defined by the European EN 50160, the IEC 61000 or the IEEE 1159 series of standards [22] [23] [26] [29]. Also, according to IEEE Power System Relaying Committee (PSRC), the "*nature of the standard is to give limits for measured indices during a long period like one week*" [31].

For the normal operation of an electrical equipment – device, it is necessary the power quality (PQ) to be undisturbed, with respect to any change in voltage, current or frequency [4] [16] [17]. The disturbance of the PQ can cause malfunction to sensitive electronic devices – equipments, like avionics, computerised devices, PCs, etc; high costs, such as production losses, resulting in the future to the problem on the choice of locations of industries as well [1] [16] [21]. Also, the supply voltage of the public distribution system has to maintain a constant frequency, has a constant magnitude and has a perfect sine wave [5], an important factor which is included to the disturbance of the power quality (PQ) is the variations of the RMS voltage supply [18]. So, the adopted nominal – rated value of voltage supply to each equipment – device, it is necessary to be maintained within reasonable limits, as the power quality (PQ) remains undisturbed, otherwise there is disturbance to its normal operation.

Poor PQ costs to EU's industry and commerce about € 10 billion per year [26]. Application disturbances of power quality lead to losses of $4 billion to $10 billion in the USA alone [24] [96] and David Brender [40] reports that "the real cost of poor power quality in lost productivity (downtime) is estimated at $15 – 30 billion per year in US and exceeds $1 million/yr. By 2030 on the trial of improvement power grids world wide, PQ is included as a part of "Key Areas of IEEE Standards, IEEE 1159 Recommended Practice for Monitoring Electric Power Quality", where about $13 trillion will be spent, and an amount of them (hundreds of billions), will be absorbed to smart grid projects [20].

2.4 Related Electrical Standards to the Supply Voltage

The EN 50160 standards

The CENELEC (European Committee for Electrotechnical Standardization) in November 1994 has issued the European Norm (EN) EN 50160 standards, in order to promote a common understanding and interpretation among the electricity distributors [7] [9] [10]. The EN 50160 standard includes the description, the specification and the definition of the Low Voltage and Medium voltage main characteristics of electricity distributed by the public electricity networks at the user's terminals under normal operating conditions [10] [22] [26] [31]. Table 2.1 illustrates the requirements regarding power quality in supply voltage variation according to EN 50160 standards.

Table 2.1: Requirements regarding power quality in supply voltage variations [11].

	For systems with synchronous connection to an interconnected system	**Duration**	**For systems with no synchronous connection to an interconnected system (e.g. supply system on certain islands)**	**Duration**
Supply voltage	Under normal operating conditions (excluding interruptions) U_n ± 10 %	95 % of the 10 min mean r.m.s. values over each one week period All 10 min mean r.m.s. values shall be within the range of U_n +10% / -15%	Incl. special remote users U_n + 10% / -15%. Network users should be informed of the conditions. Network user equipment typically designed to tolerate supply voltages of ±10% of U_n.	95 % of the 10 min mean r.m.s. values over each one week period should be within ±10% of U_n All 10 min mean r.m.s. values shall be within the range of U_n +10% / -15%

According to Table 2.1, under normal operation conditions, the voltage magnitude variations must be limited in ± 10 % of the nominal voltage supply (U_n). When transmission systems are not interconnected to electricity supplies in networks, or for special remote network equipment, the voltage magnitude variations must not exceed + 10 % / - 15 % of Un. At least 95% of the time interval of 10 min, the average rms values of the supply voltage must be above the lower limit of 90% of U_n. So, during the time interval of 10 min the average rms values of the supply voltage must not be higher than +10% or lower than -15 % of U_n. Also “the actual power consumption required by individual network users is not fully predictable, in terms of amount and of contemporaneity.” [8].

IEC 61000 series of standards

Except to EN 50160, the IEC 61000 standard series have been developed on Electromagnetic Compatibility (EMC) issues by the International Electrotechnical Commission (IEC) and contain “generic and basic” EMC standards that they deal with the problems on equipment, caused by: the harmonics (considered as low frequency emissions), voltage fluctuations, unbalance of voltages or currents and high frequency emissions [27]. These problems are been created by the supply, or other equipment or by itself influencing the supply [26]. Also, most of IEC standards have been adopted by European countries as IEC/EN [23]. Table 2.2 illustrates a summary of Applicable IEC 61000 Standards. And here (Table 2.2), voltage variation, like EN 50160, is limited to the amount of ± 10%, for the normal operation of the equipment – loads.

Table 2.2: Summary of Applicable IEC 61000 Standards [23].

Parameter	**IEC 61000-x-y**
Voltage Variations	± 10% applied for 15 minutes
Rapid Voltage Changes (Voltage Fluctuations)	IEC 61000-2-2 (Compatibility levels): 3% normally, 8% infrequently IEC 61000-3-3: 3% normal, 4% max. IEC 61000-2-12: 3% IEC 61000-3-7: Planning levels IEC 61000-3-11: Emission limits IEC61000-4-14, 4-15 (Immunity levels and measurements)
Unbalance	IEC 61000-2-2 (Compatibility levels): 2% IEC 61000-2-12 (Compatibility levels): 2%, IEC 61000-4-27 (Immunity requirements and measurements)
Voltage Dips (Sags)	IEC 61000-6-1, 6-2 (Immunity levels): up to 30% for 10 ms, up to 60% for 100 ms IEC 61000-6-2 (Immunity levels): up to 60% for 1000 ms
Transient Overvoltages	IEC 61000-6-1, 6-2: ±2 kV, line-to-earth, ±1 kV, line-to-line, 1.2/50(8/20) Tr/Th μs

APPENDIX A contains an example illustrating a voltage dip and short supply interruption, classified according to EN 50160 (Fig. A.1). Table A.1 shows values of individual harmonic voltages at the supply terminals for orders up to 25 (given in percent of U_n), and Table A.2 shows a comparison on supply voltage requirements according to EN 50160 and the EMC standards EN 61000.

The IEEE 1159 standards

The Institute of Electrical and Electronics Engineers (IEEE) in 1995 also, has approved the IEEE 1159 standard for the evaluation of the power quality and Recommended Practice for Monitoring Electric Power Quality [14]. As it has been mentioned above, The European Standard EN 50160 includes the description, the specification and the definition of the Low Voltage and Medium Voltage main characteristics of electricity distributed by the public electricity networks at the user's terminals under normal operating conditions. The IEEE 1159 standard *"gives the limits or values within which any customer can expect the voltage characteristics to remain under normal operating conditions"* and it is applied in case of proper customer installations or equipment [31]. Also, it classifies the power quality phenomena according to "principal spectral content, duration and magnitude of disturbance" [15]. Table 2.3 illustrates the requirements regarding power quality in voltage supply variations.

Table 2.3: Requirements regarding power quality in voltage supply variations [31].

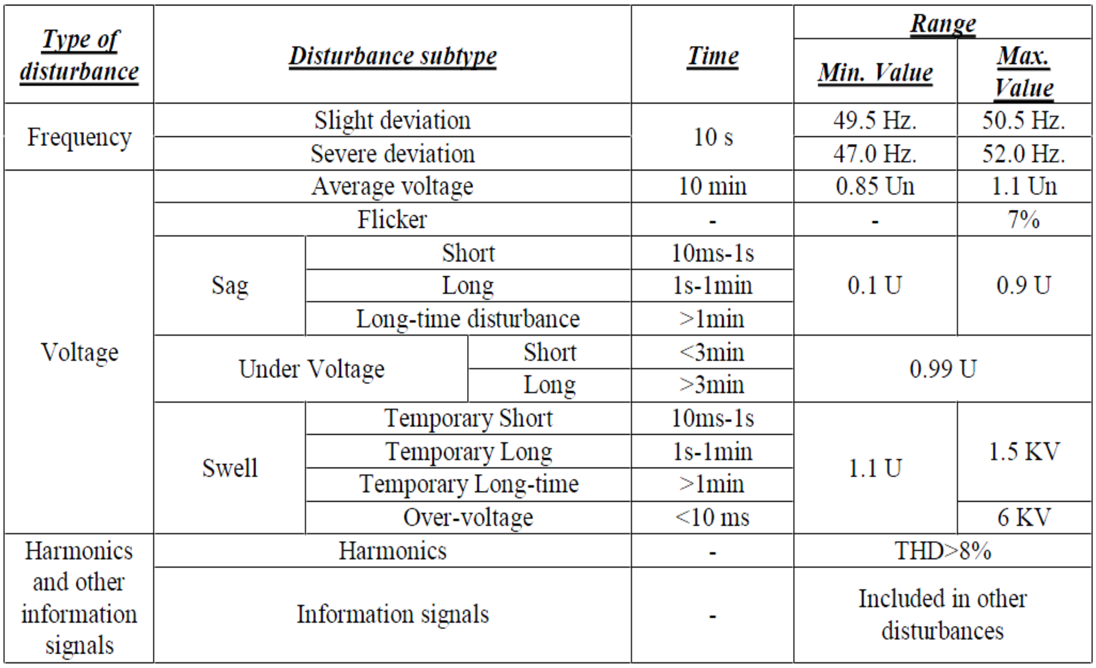
	Duration for a week period	**Duration** for every 10 min period
Voltage variations	95% of rms values (averaged in 10 min intervals) in the interval U_n ±10%	Average rms values must be in the interval U_n + 10% - 15% (only in LV networks).

As the power quality broadly includes the evaluation of deviations of the current and voltage waveforms from ideal sinewaves and voltage amplitude variations in an ac system [12] [13], the voltage characteristics of electricity supplied by the public distribution systems for normal and safe operation of the equipment – loads, have to satisfy the standard constraints about the power quality provided to the users [6].

From Table 2.1, 2.2 and 2.3 can be seen that in the area of voltage variations there is the case where the voltage supply exceeds up to +10% the level of the nominal voltage (U_n) supply. This denotes the importance of this divergence in power systems. Also, the importance for investigation starts when the voltage supply is higher than +10% the level of the U_n.

Monedero [42] in Table 2.4 illustrates the PQ disturbances according to voltage amplitude and frequency, based on the UNE standard in Spain.

Table 2.4: Types of disturbances [42].



Type of disturbance	***Disturbance subtype***		***Time***	***Range***	
				Min. Value	***Max. Value***
Frequency	Slight deviation		10 s	49.5 Hz.	50.5 Hz.
	Severe deviation			47.0 Hz.	52.0 Hz.
Voltage	Average voltage		10 min	0.85 Un	1.1 Un
	Flicker		-	-	7%
	Sag	Short	10ms-1s	0.1 U	0.9 U
		Long	1s-1min		
		Long-time disturbance	>1min		
	Under Voltage	Short	<3min	0.99 U	
		Long	>3min		
	Swell	Temporary Short	10ms-1s	1.1 U	1.5 KV
		Temporary Long	1s-1min		
		Temporary Long-time	>1min		
		Over-voltage	<10 ms		6 KV
Harmonics and other information signals	Harmonics		-	THD>8%	
	Information signals		-	Included in other disturbances	

Note: The UNE standards are documents elaborated by AENOR (Spanish Association for Standardisation and Certification). They include technical specifications for an activity or product and have been agreed upon by all the parties involved. [http://www.uji.es/UK/cd/une.html])

Fig. 2.1 illustrates a general summarisation of the variety of phenomena and aspects that affect PQ.

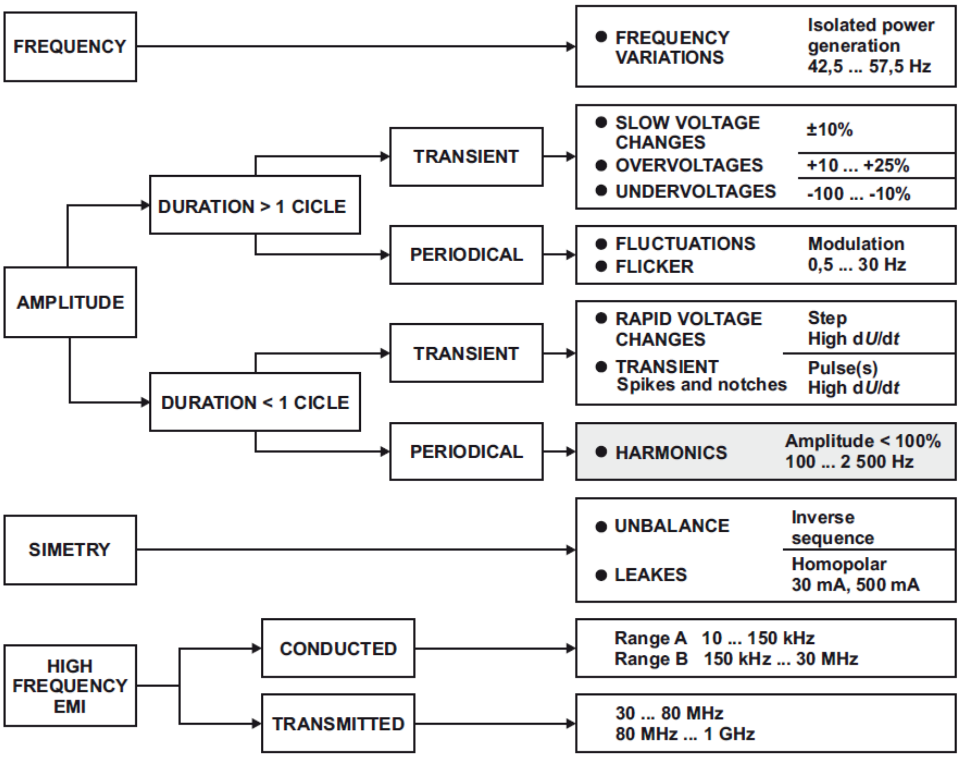


Figure 2.1: A general summarisation of the variety of phenomena and aspects that affect PQ [102].

2.5 The Overvoltage

About the bandwidth in which must be kept the voltage supply of a power system related to PQ, Microener [90] reports that: “one of the power quality criteria is that the voltage of the selected points of networks should be kept within the prescribed limits”. In general, “overvoltage refers to voltage, higher than the voltage at which equipment are designed to operate most effectively” [83]. It belongs to long-duration voltage variations that include rms deviations for time duration longer than 1min at power frequencies [106]. Also, overvoltage happens when the voltage supply has a value larger than the nominal voltage for duration greater than 1 minute [9].

The overvoltage is a significant parameter of the PQ. Gilbert M. Masters writes that “utilities have long been concerned with a set of current and voltage irregularities, which are lumped together and referred to as power quality issues". And he claims that when the voltage increases over an acceptable level for a time interval more than a few seconds, is referred as *overvoltage* [33]. In the IEEE PSRC Working Group Report is referred that "overvoltages are the equivalent of sustained voltage swell for greater than 1 minute, within a tighter bandwidth". Also, the Transmission and Distribution Committee of the IEEE Power & Energy Society [65] refers that *overvoltage* is "a variation of the rms value of the voltage from the nominal for a time greater than 1 min", which belongs to "long-duration root-mean-square (rms) variation". Utility Systems Technologies, Inc. reports that "chronic high voltage or overvoltage which is defined by the IEEE" is voltage amplitude of 110% or more than the nominal voltage, who exists for a period time equal to one minute or more (Fig. 2.2). Also can be "typically displayed as plot of rms voltage versus time" [32] (min instead of ms).

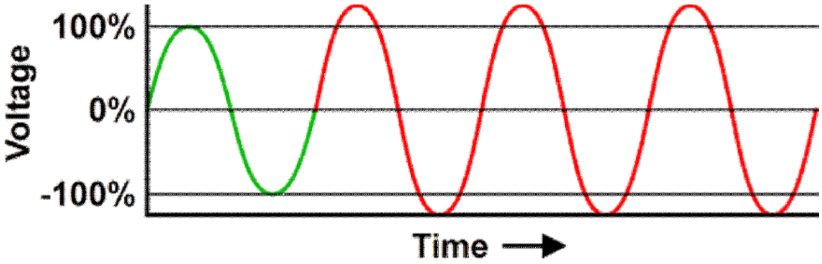


Figure 2.2: The nominal (= 100%), and overvoltage level (> 110%) in time duration longer than 1 min [48].

Joseph Seymour claims that "overvoltage can be the result of long-term problems that create swells" and can be characterised of as an extended swell [4] [48]. So, some scholars use the term swell as synonym for the momentary[7] overvoltage. Also, when the time duration of the voltage supply variation is longer than 1 min, is defined as "long-duration" [32], or "long term" variation [31]. Cease [31] specifies the overvoltage as "long term variation", with a typical variation of 1.1 – 1.2 pu and duration > 1 minute.

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[7] "Momentary" refers to a time range at the power frequency from 30 cycles to 3 s [32].

Dugan [32] defines that the “overvoltage is an increase in the rms ac voltage greater than 110 percent at the power frequency for a duration longer than 1 min”. APPENDIX B shows the categories and characteristics of power system electromagnetic phenomena, which are the main parameters of PQ. Also, there is the term of “transient overvoltages”, which unlike with the term of “overvoltages”, determine “short” and “highly damped” momentary voltage disturbances. And there are two types of transient overvoltages:

- Impulsive overvoltages
- Oscillatory overvoltages [100].

According to IEEE PSRC, Table 2.5 illustrates the limits of the supply over/under-voltage variation, regarding power quality, where “undervoltages and overvoltages are the equivalent of sustained voltage sag or swell for greater than 1 minute, within a tighter bandwidth” [31].

Table 2.5: Requirements regarding power quality in supply voltage during long term variations [15] [31].

Categories and Characteristics of Power System Electromagnetic Phenomena related		
Category	**Typical Duration**	**Typical Voltage Variation**
Overvoltages	> 1 minute	1.1 – 1.2 pu
Undervoltages	> 1 minute	0.8 – 0.9 pu

In Power guide 2009 / book 03, LEGRAND [43] makes reference to *temporary overvoltages*, which the standard IEC60064-1 distinguishes them in two categories:

- Short duration temporary overvoltage, amplitude Un + 1200 V for t < 5 s
- Long duration temporary overvoltage, amplitude Un + 250 V for t > 5s

And as for temporary overvoltages, standard EN 50-160 does not put limits; the upper long duration temporary overvoltages may be considered as *overvoltages*. Also LEGRAND refers that “this type of fault can occur both on the distribution system and on the user's installation.”

In 1970s, the Computer Business Equipment Manufacturers Association (CBEMA) has charted in curves the acceptable limits of the computer equipment's voltage supply variations (overvoltage and undervoltage). Recently, the Information Technology Industry Council (ITIC) has replaced the CBEMA curves by new, "in general usage for single-phase, 120-V, 60-Hz systems", Fig. 2.3 [44].

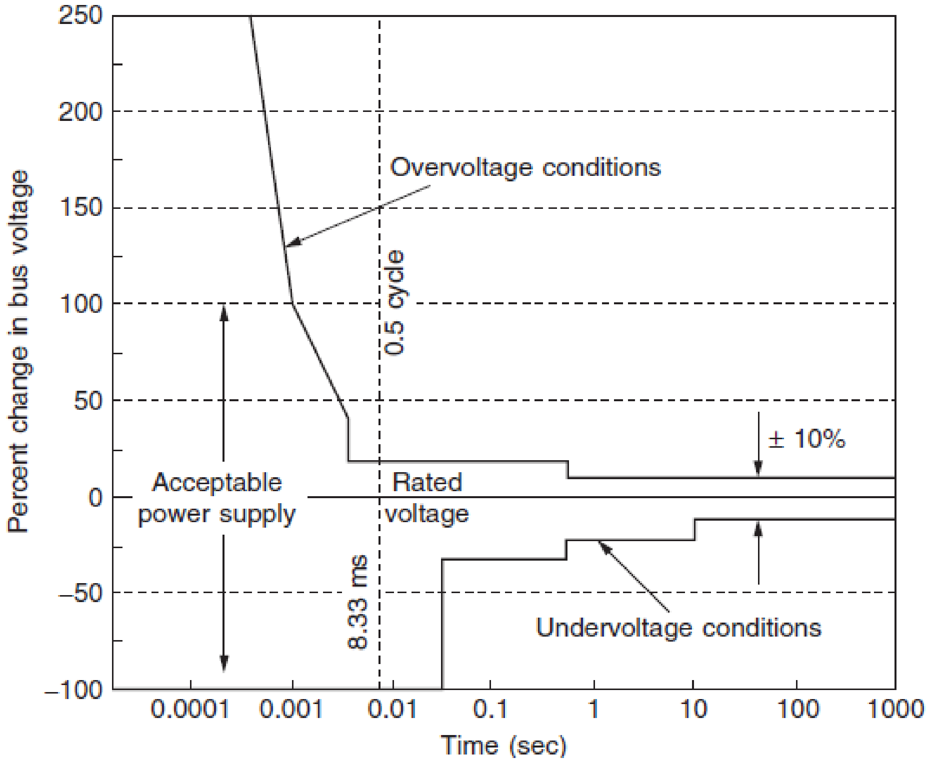

Figure 2.3: The ITIC chart, percent of nominal value (V) versus duration (sec) [44].

Overvoltage conditions are rather common phenomena and almost happen to any electrical or electronic circuit. Both, power systems such as energy generation, transmission and distribution, and low voltage electronic systems are vulnerable to overvoltages [47]. EN 50160 standard does not include overvoltage limits for the high voltage systems [43].

2.5.1 Causes of the Overvoltage

Initially, as Legrand Company supports [43], "faults on the high voltage system (fallen line) can generate overvoltages at the low voltage end", because the voltage management in distribution systems is a high priority task for the normal and safe feed of the loads [52].

In the industrial systems, Legrand Company [43] supports that “all operations create overvoltages, particularly on high power consumption”. And this happens because of “the sudden making or breaking of the current”. Also, Dugan supports that “overvoltages generally are not the result of system faults, but are caused by load variations on the system and system switching operations” [32]. He notes that overvoltages are produced by “switching off large loads or energizing a capacitor bank”, and they result because of the following main reasons:

- The power system is too weak for the desired voltage regulation
- The voltage controls are not quite effective
- On transformers, the incorrect tap settings can result in overvoltages to the system

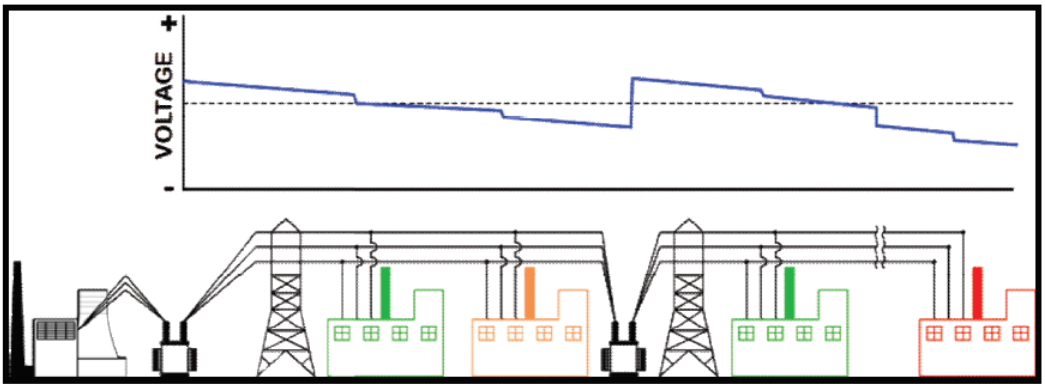

Figure 2.4: Voltage drop on the utility transmission and distribution systems [48].

Utility Systems Technologies [48] declare that a basic reason causing invariable overvoltage is most often due to overcorrection, resulting from voltage drop on the utility transmission and distribution system (Fig. 2.4), because voltage drop on electrical conductors is a common phenomenon anywhere. As current flow along the length of a conductor, its impedance causes voltage drop [32], and Blume declares that “often, loss of transmission is more serious than the loss of a generator” [59]. Mind that, as the demands in power consumption increases, the power loss in transmission lines increases too, resulting to high overvoltage conditions if there is not the proper regulation [59]. Also, in the distribution line, the level of overvoltage depends on the distribution line length, inductive reactance of the source, power consumption by the loads, and the amount of capacitance at the end of the line [51].

In a power supply system where there is no convenient apparent power because of high Reactive energy, in order to estimate the proper capacitor bank, for power correction, "accurate power analysis (calculated or simulated using software) or without preliminary measurements" must be taken in advance seriously, because inaccurate compensation leads to overvoltages in relation to the power supply [32] [43].

About *grounding*, in power supply generally, Short [46] notes that "poor facility grounding practices can introduce overvoltages at equipment from fault current". Also, *grounding* in distribution lines plays a significant role to the supplying voltage, because line-to-ground faults can lead to overvoltages, as "the grounding source fixes the neutral voltage" [46]. Also "a reduced neutral increases the overvoltages on the unfaulted phases during single line-to-ground faults" and "is one of the main defences against hazardous electric shocks and hazardous overvoltages" [46]. Overvoltage can happen when in a three phase system there is cut or false of the neutral [31] [43] [61], as can be seen in Fig. 2.5.

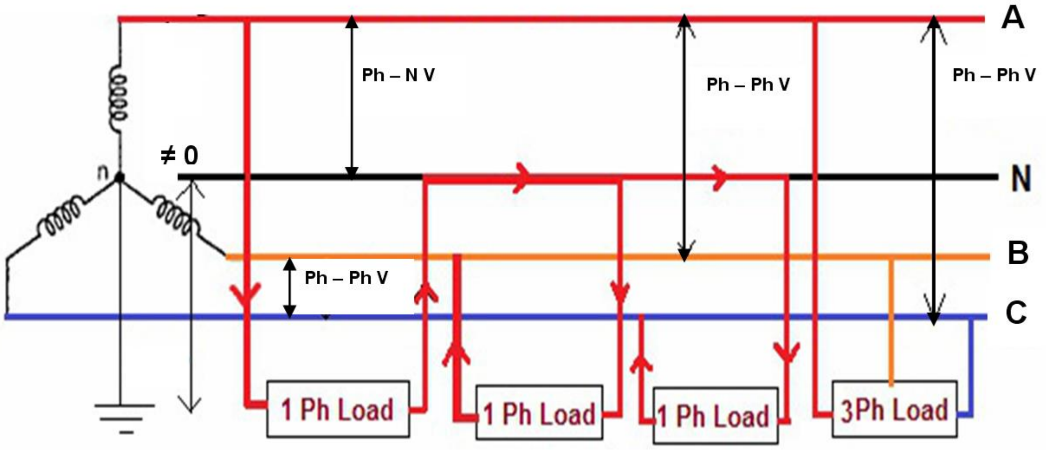

Figure 2.5: A floating neutral condition [61].

Overvoltage occurs also, when at the end of the distribution lines heavy loads exist and suddenly they are switched off [51], or there is "a sudden loss of load" [45] [32].

In this case whenever the loads are connected, the voltage is kept in normal levels, but whenever they are shut off, the voltage level increases highly with the danger of severe damage to system [31] [45] [48]. Also, islanded condition may indicate overvoltage on a grid distribution system [45].

Typical causes of overvoltages, Short [46] reports that can happen from distribution transformers who they are responsible to convert the high voltages to customer's low voltages:

- ➢ By the following type of transformers, who they are vulnerable to the shift of the neutral point, which leads to overvoltages:
  - Floating wye – grounded wye transformer,
  - Grounded wye – grounded wye transformer on a three-wire system
  - A wye – wye transformer with the primary and secondary neutrals tied together internally (the H0X0 bushing) but with the neutral left floating
  - Floating wye – floating wye transformer
- ➢ In the case of Unbalanced loads connected to a floating wye transformer, where if one phase is overloaded, this decreases the voltage to that phase and increase the voltages to the other, even if the unbalance is small.
- ➢ In the cases of grounding transformers:
  - Where the use of a grounding transformer and its connection to the line is cut,
  - Or unbalanced loads can create overvoltages [46].

Also, in the case where unbalanced loads are connected to three phase distribution transformer with no neutral and ground connection, shift of the neutral can be happened resulting to overvoltages on the phases where connected less loading [46]. LEGRAND [43] reports that "voltage unbalance is caused by high power single phase loads" in a three phase power supply system, resulting to overvoltage on less loading, where the loads "assumed to be symmetrical, i.e. identical on each phase", and described by the following relation:

$$\text{Voltage Unbalance} = \sqrt{\frac{6 \cdot (V_{ab}^2 + V_{bc}^2 + V_{ca}^2)}{V_{ab} + V_{bc} + V_{ca}} - 2} \qquad (2.1)$$

When transformer operating voltages are higher than nominal values, they are called overvoltages. In distribution system like in Fig. 2.6, overvoltages from transformers can happen when:

- Heavy loads are switched off from the mains supply
- Restarts from blackouts
- Restarting of the generators
- Increases the number of generators [51]

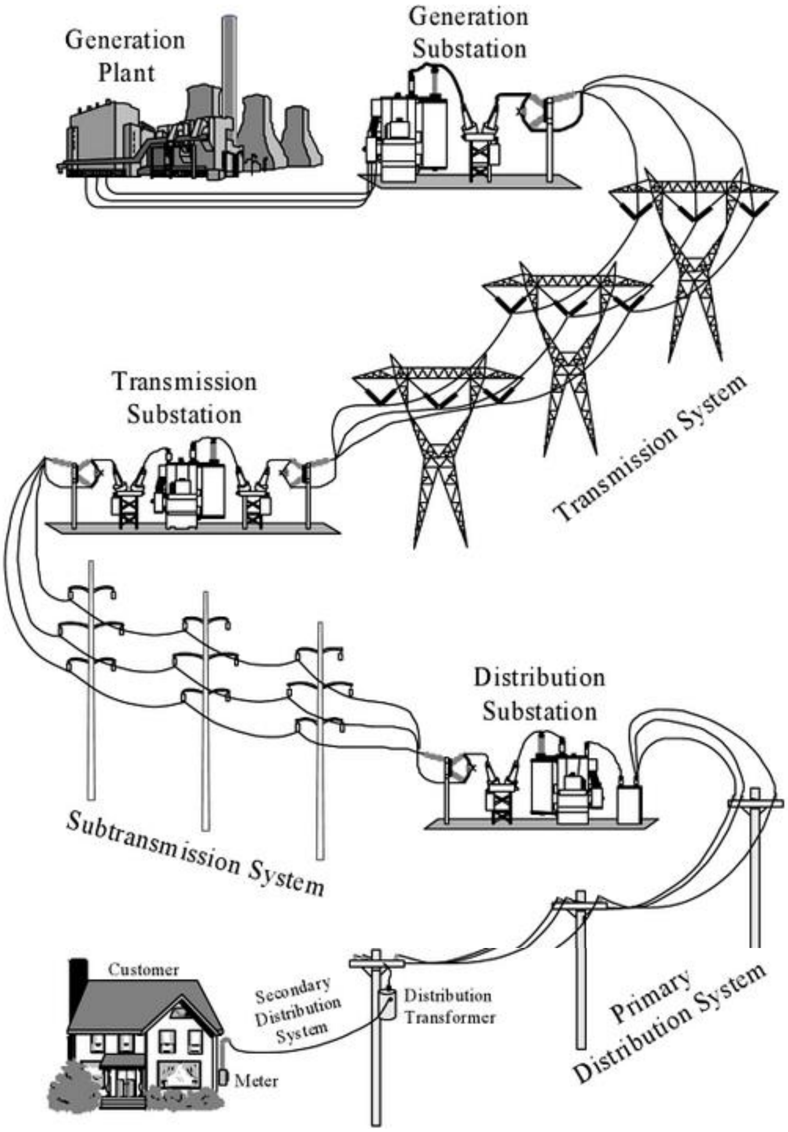

Figure 2.6: Typical distribution system with a primary feeder and consumer connections [89].

In 1920 Boucherot [63] describes the resonance oscillation of a RLC in series circuit, where the inductance is non-linear, and he calls this phenomenon as *ferroresonance*. As the *ferroresonance* is a resonance phenomenon of a RLC circuit, where the inductive reaction does not depend only on frequency but also on the magnetic flux characteristics of the coil's iron core, in the case of the power distribution transformers, the core non-linear characteristics of the connected transformers can increase the magnitude of the supplying voltages [51] [64]. So, another cause of overvoltage can be the ferroresonance, which "is characterised by a sudden jump of voltage or current from one stable operating state to another one" [62] [64], where transformer works from a linear inductive non ferroresonant stable situation to a ferroresonant capacitive stable situation (overvoltage). In power supply systems, Short notes that "ferroresonance is a special form of series resonance between the magnetizing reactance of a transformer and the system capacitance", as it can be seen in Fig. 2.7 with an ungrounded primary connection. Also, Greacen [45] writes that, *ferroresonance* can be another cause of overvoltage, which happens with a sadden isolation of a distributed generator and also "when distributed generation and the associated poletop capacitors are islanded".

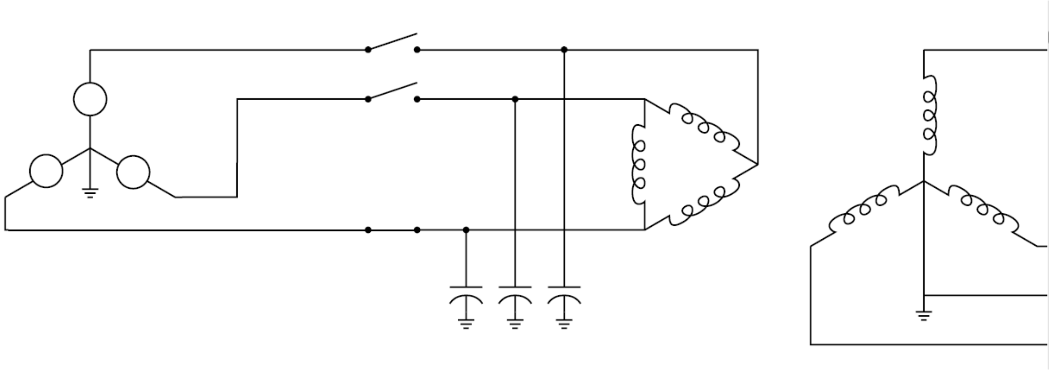

Figure 2.7: Ferroresonant circuit with a cable-fed transformer and ungrounded high-side connection [46]

Finally, the system stays working under ferroresonance, until the source is not able to provide the necessary energy to maintain the phenomenon [64].

2.5.2 The Overvoltage Effects

This is a common problem with describing power problems in a standard way, and also has to make with common types of power disturbances, what they can do to a load – component, which can be a critical equipment, and how to safeguard it. Overvoltages, as Legrand reports "they are also sources of potential malfunctions" [43]. Also, In the case of the over voltages, electrical equipment does not always have the capability of performing adequately and safely in the presence of this disturbance [1].

The higher the voltage applied, the shorter the component's life will be [1] [83].

About overvoltage effects, Campbell [83] refers that the 16th edition of the Electricians Guide BS7671 notes that:

- "A 230 V rated lamp used at 240 will achieve only 55% of its life"[8]
- "A 230 V linear appliance used on a 240 V supply will take 4.3% more current and will consume almost 9% more energy".

Generally, in the power distribution system, as Short describes, "overvoltages can enter the facility and damage equipment" [46]. Blume reports that, "overvoltage from power generation results in overloading of the public transmission lines which leads to a sequential failure conditions" [59].

Also, as it is well known, all power consumption equipment, like domestic devices, office or manufactory, on their power supply characteristics are written the voltage supply standards. Short, in his book notes that "Improper voltage regulation can cause many problems for end users". So, overvoltage effects on end-use can be:

- *"Improper or less-efficient equipment operation"* – For example, no normal illumination by the lights, or electric machines may work faster.
- *"Tripping of sensitive loads"* – For example, in the case of an uninterruptible power supply (UPS) may to activate the UPS to the battery supply and finally to exhaust them causing the stop of the operation of critical equipment [46].

Some of the more common symptoms of overvoltage stress include:

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[8] Old technology lamps, like incandescent, gas discharged or fluorescent lamps, are still remain an electrical load that has a wide use all over the world; in the streets, buildings, public areas, houses, rooms etc. and generally everywhere where the sun light is not enough for the vision. Recently, the LEDS are in great progress and continually replace the old technology lamps.

- Overheating caused by high current flow across it.
- Increase of power consumption.
- No improvement in operation.
- Internal damage to the conductors from electromigration.
- Uunnecessary tripping of downstream circuit breakers of the circuitry.
- Malfunction and probably shut down.
- The lifespan of the load – component will be decreased and probably permanent failure or damage to the circuitry [47] [66] [67] [83].

In general, as Hood [67] supports, there are three types of domestic power consumption loads:

1. Resistive
2. Inductive
3. Electronic

For a better view for the analysis of the overvoltage effects on power systems, has been fond the following categories of power loads:

- Resistive Loads
- Power Gas Discharge Lamp Loads
- Electromagnetic Loads
- Active Loads

2.5.2.1 Resistive Loads

Resistive devices for domestic applications are passive loads and their prime function is to produce heat i.e. ovens, cookers, frypan, heaters, boilers, kettles etch, and light like incandescent lights and not gas discharge (fluorescent) lights [67]. They make up 60% to 80% of most household energy usage [68].

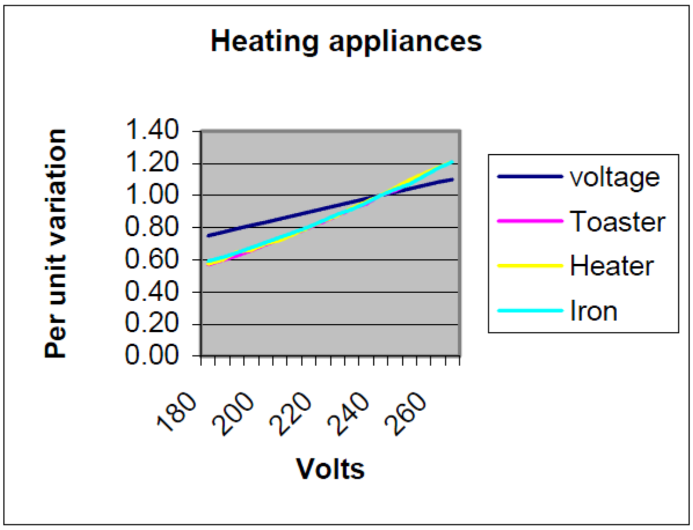


Figure 2.8: Relative variations of heating devices [67].

The nominal system voltage in Europe is now 230/400 V bringing all 220/380 V and 240/415 V systems to a common standard [69]. Under normal service conditions a variation of +10%, - 6% is allowed [67].

According to Ohm’s law, for a resistive load, the Power is calculated as:

$$P = \frac{V^2}{R} \qquad (2.2)$$

Domestic resistive load heating appliances e.g. oven, frypan and iron etc. when fed with 10% higher voltage, produce almost 21% higher power. Ohm's Law is a simple and powerful mathematical tool for helping us to analyze electric circuits, but it has limitations; the resistance (R) of these devices becomes higher as the temperature increases. The phenomenon of resistance changing with variations in temperature is common to almost all metals, of which most wires are made [70].

Fig. 2.8 shows the relative power consumption versus per unit voltage based on a 240 volt supply [67]. This means that, according to Joule’s experiment, the electric power supply to a heat producer, as mentioned above, creates an amount of heat that is:

$$W = I^2 \cdot R \cdot t = \frac{V^2}{R} \cdot t \quad (J) \qquad (2.3)$$

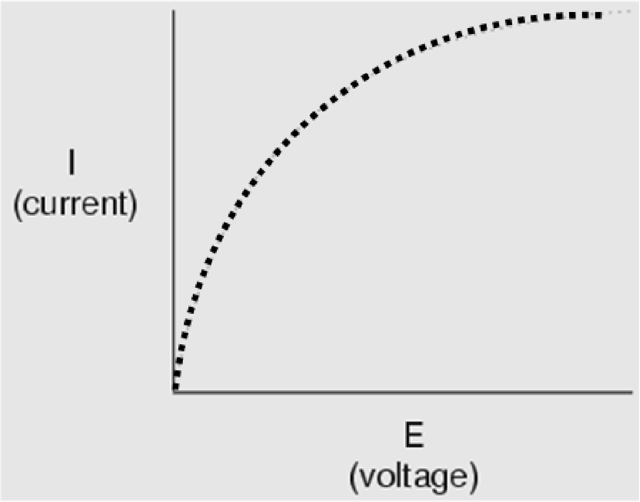


Figure 2.9: Different values of supply voltage

The incandescent lamps work by employing the principle of electric current heating a metal filament, usually tungsten, to the point that it glows white-hot. The resistance of the filament wire will increase dramatically as it warms from room temperature to operating temperature [46] [71]. Incandescent lamps are resistive devices; consequently they are sensitive to overvoltage variations that end up to significant temperature changes [67]. Like the heating elements, they tend to show an increase in resistance with voltage. An analysis of such lamp circuit, over several different values of supply voltage would generate a plot of Fig. 2.9. As voltage increases from zero to a low level, current rises sharply. But as it continues to increase, the current rise rate decreases and the circuit requires stronger increases in voltage to achieve significant increases in current. The non-linearity of the resistance of the filament is caused by the effects of high temperature on the metal wire of the lamp filament [71].

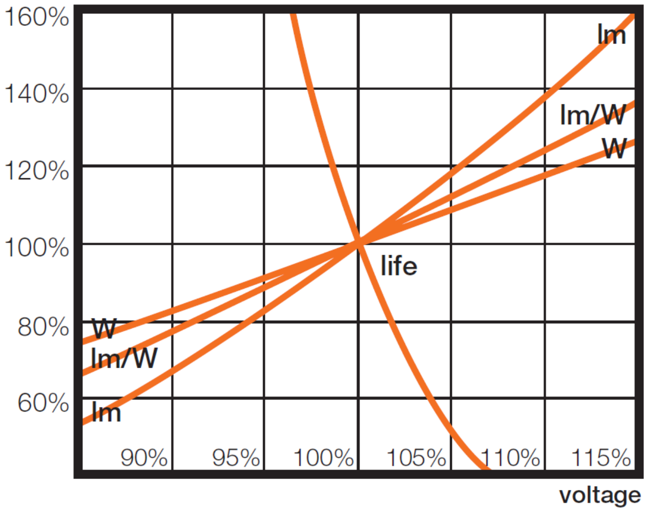


Figure 2.10: Relative variations of lamp performance [70].

On the other hand, overvoltages reduce the life span of a lamp. With lamps manufactured to run at 11.8 V_{RMS}, a 5% rise above this value reduces the life of the lamp to 50% and a 10% rise ends to 40% of its normal life (Fig. 2.10) [70]. Also, Fig. 2.10 shows the influence of variations of mains voltage on lamp performance, where lm is in lumens (the amount of visible light emitted by a lamp), W in Watts (the power consumed by the lamp), and lm/W (Lumen/Watt, Luminous efficacy) of a lamp which is a ratio of the visible light energy emitted (the luminous flux) to the total power supply of the lamp; a measure of how well a light source produces visible light, i.e. efficiency (light for money) [70]. A 5% overvoltage produces about 8% power increase consumption, but a 10% overvoltage produces an increase of power consumption of approximately 16%, reducing dramatically the life of the lamp.

2.5.2.2 Gas Discharge Lamp Loads

Gas discharge lamps are used in all areas of modern lighting technology, including common fluorescent lighting for home and office [185]. Examples of this type of load are fluorescent lamps and high-pressure sodium (HPS) as well.

Here, as the voltage supply increases the fluorescent lamps power factor decreases i.e. the reactive power increases with overvoltage [67].

Fig. 2.11 shows the intensity of the light, the power consumption and the life of the fluorescent lamp type, controlled by starter or magnetic ballast, according to voltage supply variations in percent. A 10% overvoltage increase results to 16% power rise in consumption and a 17% significant decrease of lifespan.

		Decrease of Mains Supply form 100% to 90%	Decrease of Mains Supply form 100% to 95%	Nominal Value of Mains Supply 100%	Increase of Mains Supply form 100% to 105%	Increase of Mains Supply form 100% to 110%
Fluorescent 	Light Intensity	84%	93%	100%	107%	112%
	Power Consumption (W)	81%	91%		108%	116%
	Life	95%	102%		92%%	83%
Official data in Panassonic/National Lamp Catalogue						

Figure 2.11: Fluorescent lamps (Starter or Magnetic Ballast). Voltage effects on lighting [72].

Fig. 2.12 shows the intensity of the light, the intensity of the current supply and the power consumption, of the fluorescent lamp type controlled by the inverter electronic circuit, according to voltage supply variations in percent. Here, electronic ballasts use inverter technology and work by first rectifying the input power and then ‘chopping’ it at a high frequency [72]. A 5% overvoltage increase results to: zero increase in light intensity production, 4.8% decrease of current intensity and a very small amount decrease of power consumption.

		Decrease of Mains Supply form 100% to 95%	Decrease of Mains Supply form 100% to 97%	Nominal Value of Mains Supply 100%	Increase of Mains Supply form 100% to 103%	Increase of Mains Supply form 100% to 105%
Fluorescent (inverters) 	Light Intensity	100%	100%	100%	100%	100%
	Current (A)	105.5%	103.2%		97.0%	95.2%
	Power Consumption (W)	99.9%	100.0%		99.9%	99.9%
Official data in Toshiba Lamp Catalogue						

Figure 2.12: Fluorescent lamps (Inverter technology). Voltage effects on lighting [72].

Roughly 20% of our generated energy is consumed in lighting. If fluorescent lamps are used instead of incandescent lamps, a substantial amount of energy can be saved. Again, use of high-frequency fluorescent lamps with power electronics–based lamp ballasts can save 20% to 30% in energy consumption. Such lamps have other advantages such as longer lamp life, smooth light, and dimming control capability [73].

2.5.2.3 Electromagnetic Loads

In this category belong the devices that turn electrical signals into mechanical movement, like motors, relays, etc. or transformers that "provide an efficient means of changing voltage and current levels, and make the bulk power transmission system practical" [114]. In power distribution systems the overvoltage, as Short notes [46], "stresses the transformer insulation", and in the case where "flux leaves the core" may cause tank heating.

Overvoltages across solenoids, coils (used in relays and starters), transformers of all types (including welding transformers), induce a strong stress. The same happens also in ballasts in fluorescent, mercury, and high pressure sodium light fixtures [74].

Fig. 2.13 shows in general the effects of low and high-voltage during the operation of "T" frame motors [75]. It represents only a single motor behavior, while there is a great deal of variation from one motor design to another.

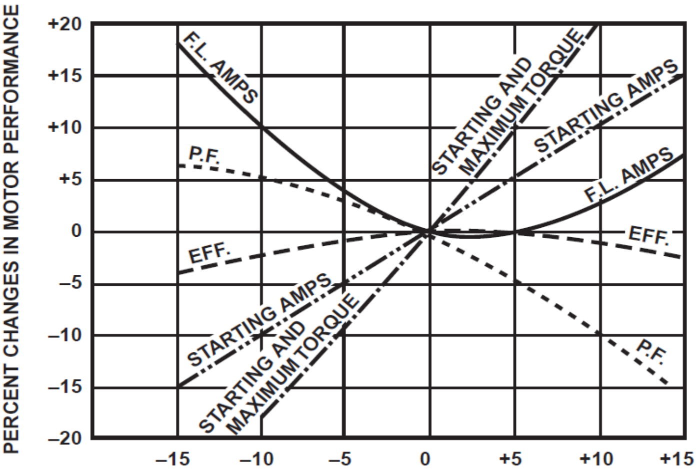


Figure 2.13: Effects of Voltage Variation on "T" frame motors [75].

Some general guidelines might be useful:

- Small motors tend to be more sensitive to overvoltage and saturation than large motors.
- Single phase motors tend to be more sensitive to overvoltage than three phase motors.
- U-frame motors are less sensitive to overvoltage than “T” frames.
- Premium efficiency Super-E motors are less sensitive to overvoltage than standard efficiency motors.
- Two pole and four pole motors tend to be less sensitive to high voltage than six pole and eight pole designs.
- Overvoltage can drive up amperage and temperature even on lightly loaded motors. Thus, motor life can be shortened by high voltage.
- Full load efficiency drops with either high or low voltage.
- Power factor improves with lower voltage and drops sharply with high voltage.
- Inrush current goes up with higher voltage [75].

Motor efficiency can be improved by reduced flux operation instead of operating with rated flux [73]. The overvoltage supply decreases current flow (I) in the device which decreases the ohmic (I^2R) or “copper” losses. Therefore, some devices such as motors, power supplies and transformers may benefit from overvoltage levels slightly above the nominal voltage but within the voltage limits for the device. For example, for an induction motor operating with overvoltage at about 110% of nameplate voltage, its efficiency is being increased from 1 to 3%, and its operating temperature is being reduced from 10 to 15%. Also, its running torque may be increased by nearly 20% [48]. Voltages at or slightly above nominal are preferred for lower operating temperatures and higher starting torques [76].

Overvoltages caused by voltage unbalance, because of high power single phase loads, in rotating machines can cause negative current components resulting to braking torques and temperature rises to the windings [43].

High voltage on a motor tends to push the magnetic portion of the motor into saturation [74]. An overvoltage supply leads the magnetic materials, like the iron core approach saturation, to increase losses and also increase losses in the copper windings. At this point, the power consumption increases much more rapidly than (v^2). Thus, a 5% overvoltage may decrease current flow (I) in the device by 4% or less, but the magnetizing current may increase by 8% or more. The power factor also becomes poor due to disproportionate increase in magnetizing current [77].

In the case of overvoltage, when a motor is operating at a load less than the rated, the magnetizing current will increase, and if the load will still decrease the line current might increase [77]. Consequently the power consumed increases by the losses with (v^2) even though there is no increase in useful work done. Also, the insulation of a motor or transformer is linked to its ability to withstand surge phenomena and overvoltages as well, likely to occur during its operation [78].

2.5.2.4 Active Loads

Active Loads are all the electronic equipment that includes passive (e.g. resistors, capacitors, inductors) and active (e.g. transistors, SCRs, TRIACs) electronic components that they manipulate electric power to produce useful work. Examples of loads containing equipment of this type are computers, printers, fax machines, TV etc. Due to the extensive use of equipment of this type, it is obvious that electrical failures may have severe economical impacts [79].

As Silicon chips (ICs) are fabricated in very small feature sizes, this makes them very susceptible to overvoltages [99]. So, the so called entertainment appliances in order to operate properly they have their own power supply electronic circuits, which can be a power converter, a regulator etc. An invariable overvoltage from mains or line supply originally will influence to that circuit.

The unregulated power supply electronic circuit AC-DC converter (Fig. 2.14) is used extensively in the last decades. The produced voltage (V_{DC}) will affect all the sensitive circuits of the Main LOAD. Under such condition the lifespan of these components is reduced under overvoltage conditions [54].

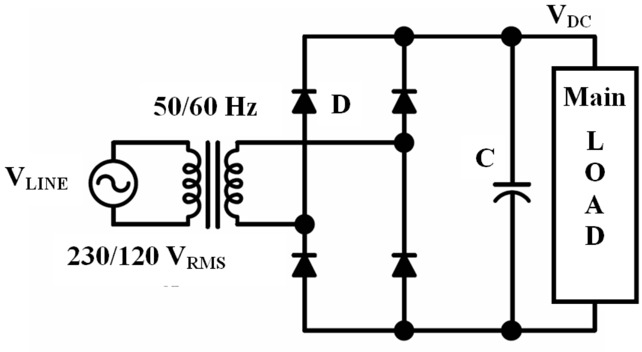


Figure 2.14: Configuration of a typical AC-DC power supply [79].

From the above short analysis, the disadvantage of an unregulated converter AC-DC power supply circuit is that when an overvoltage from the line supply appears, it can influence this circuit at first and then the rest of the Main LOAD. To solve this problem, and in order to protect the sensitive circuits of the Main LOAD, usually after the filtering capacitor a linear voltage regulator is connected in series as it can be seen in Fig. 2.15. A voltage regulator generates a fixed output voltage of a preset magnitude that remains constant regardless of changes to its input voltage or load conditions [80]. And generally, the overvoltage observed in the secondary of the power transformer does not affect the output of the electronic regulators and consequently it does not induce any changes to the load current [53].

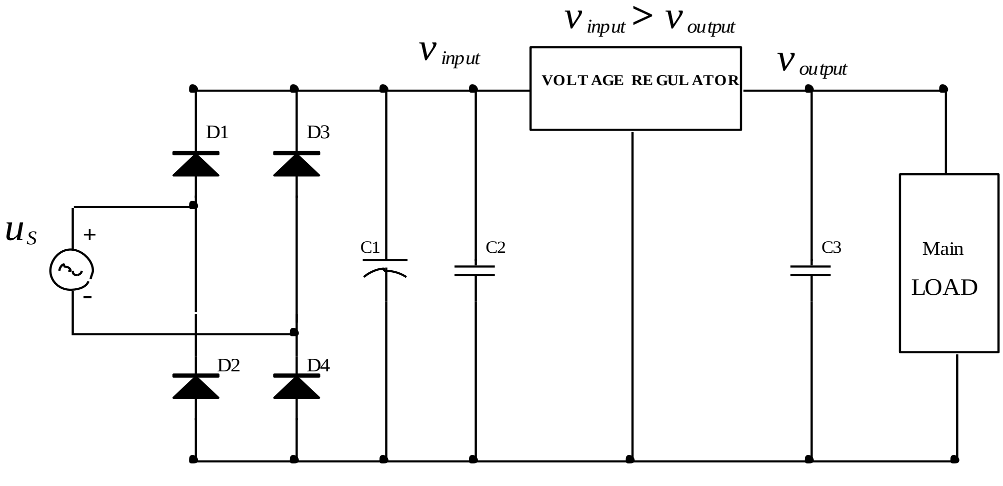


Figure 2.15: Configuration of a typical AC-DC regulated power supply [53].

Recently, the AC-DC power supply circuits of active loads are switching voltage regulators called “switch mode power supplies” (SMPS) [79]. They convert the dc input voltage to a switched voltage applied to a power MOSFET or BJT switch [80]. The devices employing SMPS, guarantee that their energy use is almost unaffected to supply voltage changes. So, for a wide variation of voltages, say between 200 to 270 volts, the power consumption by the load is only 3% over the entire 70 volt range [48].

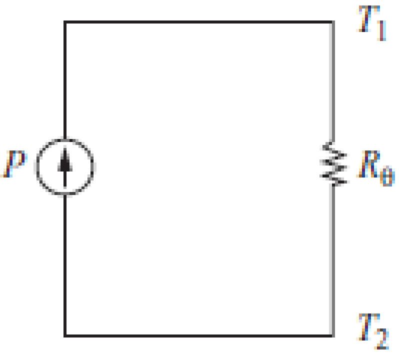


Figure 2.16: The electric equivalent for the temperature difference [60].

In electronic components (diodes, transistors, SCRs, etc), during their conduction, overvoltages create excess losses that represent the electrical energy which is converted to thermal [60]. If their internal temperature exceeds (overheat) the maximum rated value (according to their specifications) there is the danger to be burned [91]. Also, temperature affects the AC and DC characteristics of transistors [104]. So, for the safe operation of the devices it is necessary to take into account be maintained below the maximum rated value [60]. The equation 2.5.2.3 describes the temperature difference variations between two points ($T_1 - T_2$), according to thermal power P, as it is described by the Fig. 2.16.

$$P = \frac{T_1 - T_2}{R_\theta} \qquad (2.4)$$

Where:

- R_θ or $Rth_{(j-a)}$ is the thermal resistance between the junction and ambient air (^{0}C/W), including all the intermediate materials. On some datasheets is listed as K/W.

- $T_1 - T_2$ is the temperature difference in degrees (^{0}C). T_1 or Tj_{max} is the semiconductor's maximum junction temperature. T_2 or Ta is the ambient air temperature.
- P is the maximum thermal power, W [60] [91].

2.5.3 Devices for Recording and Characterizing the Factors that Affect to the PQ Parameters, Like Overvoltages

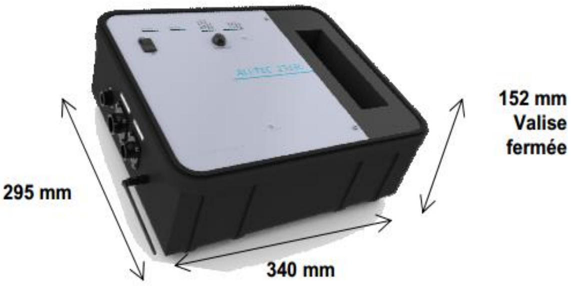


Figure 2.17: The Alptec 2333 network analyzer [88].

Figure 2.18: The Alptec 2444 network analyzer [89].

The Alptec 2333 network analyzer (Fig. 2.17) is a suitable apparatus for recording and characterizing all the electrical magnitudes and phenomena, and remotely as well, which affect to the PQ parameters of a system, like harmonics, voltage dips, overvoltages, etc., according to the applicable EN 50160 and IEC 61000-4-30 standards [88]. Also the Alptec 2444 analyzer (Fig. 2.18) is a suitable apparatus for recording, except the conventional values of voltage, current, active power P, reactive power Q and apparent power S, power factor PF, total harmonic distortion THD (in voltage and current), all the signal quality parameters like voltage dips, overvoltages, flickers, harmonics and inter-harmonics, imbalances, etc. [89].

2.6 Overview of Harmonics and Harmonic Distortion in Power Supplies Feeding Non-linear Loads

Power Quality (PQ) describes the main factors of the electricity supply like harmonic distortion [103] [122], as it has mentioned above (§ 2.3). A particular factor which influences PQ level is the harmonics [154], where their presence affects the PQ of a system [12] [97] and cause the harmonic distortion [101] [117] [162] (APPENDIX C). Saxena notes that “electric power quality, which is a current interest to several power utilities all over the world, is often severely affected by harmonics…” [97]. So, according to PQ, the characteristics of the incoming power to the equipment can prove how much deviate from the customary pure 50 / 60 Hz sine wave, that can affect the reliable and safe operation of the sensitive devices.

Non-linear loads feeding by the mains sinusoidal voltage distort the sinusoidal current, which means it contains harmonics [122]. Until 1960, the majority of power loads or customer electrical equipment, that used draw sinusoidal current, they did not affect to the waveform generally [121]. At about this time, starts a new age with a rapid growth of different type of equipment, the non-linear loads, including fax machines, electronic ballasts, photocopying machines, audio equipment, variable frequency drives, switch-mode power converters, electronic power supplies for TV sets, PCs, etc [93] [99] [109]. Although the mains voltage is sinusoidal, such equipment draws non-sinusoidal current [101]. The electronic design of these types of loads mainly is based on the semiconductors who have non-linear transfer characteristics [123]. When semiconductors act as loads, their non-linear behavior distorts the mains current by the sum of harmonics [116] [124] [125].

2.6.1 Harmonic Distortion

Generally, harmonic distortion is “the corruption of the fundamental sine wave at frequencies that are multiples of the fundamental” [4]. According to Associated Power Technologies, “harmonic distortion is the degree to which a waveform deviates from its pure sinusoidal values as a result of the summation of all these harmonic elements” [93]. In the case of power supply, harmonic distortion is the phenomenon where the waveform of voltage or current is not pure sine wave but it is consisted by frequencies that are multiples (harmonics) of 50 or 60 Hz, according to the local power frequency [45]. Also, the harmonic distortion is the phenomenon where in every cycle of the waveform is distorted equally [120]. Fig. 2.19 illustrates an ac distorted current related to ac voltage.

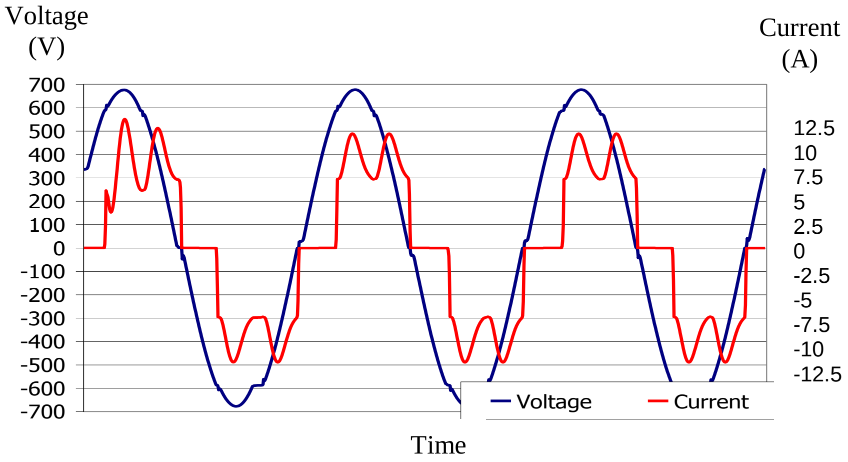


Figure 2.19: The harmonic distortion of an ac current related to non distorted voltage [115].

Professor Gosbell wrote that “harmonic distortion is not generally due to the operation of the power system, and was largely absent before the 1960s” [120] [172]. Danfoss Corp. [124] supports that “harmonic distortion is not a concern in most industrial environments”, but this phenomenon in the area of energy efficiency is very important because it is direct associated with highly used efficiency technologies, like switching technologies (DC supplies, inverters), adjustable speed motor drivers, electronic light ballasts, PCs and TVs [93] [116] [117].

Fig. 2.20 shows a sinusoidal waveform (a) (F = 60 Hz, h = 1) and a waveform (b) as a sum of the h = 1, 3, 5, 7, 9, 11 and 13 harmonics. Waveform (a) has been distorted (b) after the addition of other periodic curves, who are multiples of the h = 1 (a). It can be seen easily, that the presence of the harmonics causes the distortion of the sinusoidal shape of the mains [137].

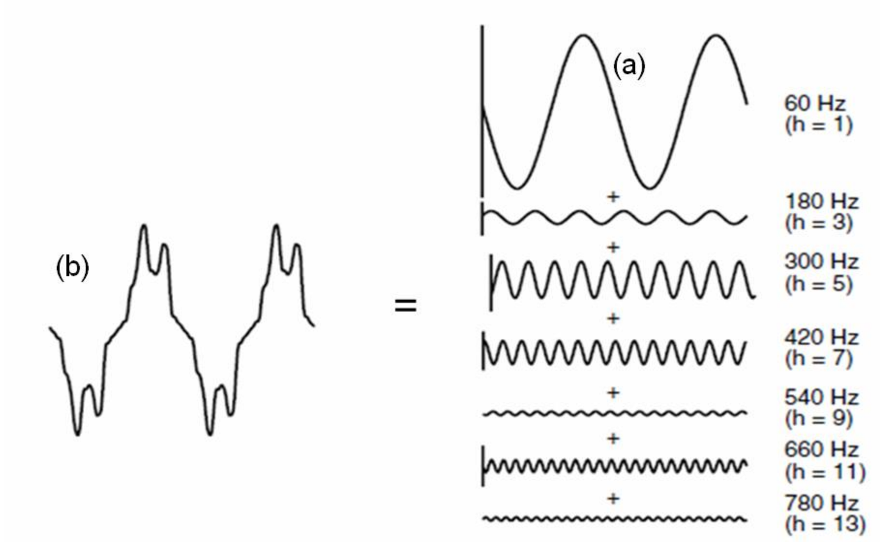


Figure 2.20: A Fourier series representation of a current periodic non-sinusoidal waveform, of a distorted waveform as a production of the sum distorted [32].

2.6.2 Harmonic Limits

There are requirements for the protection of the equipment [107]. Thomas M. Blooming notes that “the harmonic current limits specify the maximum amount of harmonic current that the customer can inject into the utility system” [126]. The European EMC Directive deals with harmonic emission levels but does not specify the exact special requirements that must be fulfilled. The basic standards that give specifically harmonic limits are included in standards IEC/EN 61000 and IEEE 519:

The standards IEC/EN 61000

IEC/EN 61000-3-2 standard specifies the limits of the values of harmonic current emissions that must be fulfilled by an electrical or electronic equipment, with an input current ≤ 16 A per phase, connected to the public low voltage distribution system [16] [182]. It specifies limits for odd and even harmonics depending on the class of the equipment [27]. Also, EN 61000-4-7 is the general guide on harmonics and interharmonics, measurements and instrumentation, for power supply systems and equipment connected to them. Table 2.6 shows the source requirements according to

IEC/EN 61000-3-2 standard (in APPENDIX D for IEC 61000-3-4, -6, -12, IEC 61000-4-13, EN 50160 limits and harmonic distortion according to IEC 61000-2-2):

Table 2.6: IEC/EN 61000-3-2 standard, the source requirements [109].

Source requirements according IEC/EN 61000-3-2, Annex A2	
- Voltage accuracy ± 2,0 % - Frequency accuracy± 0,5% - Phase angle stability± 1,5° - V_{peak} = 1.4 – 1.42 V_{rms} and between 87° and 93° after the first zero-crossing	
Maximum harmonic components	
3. harmonic	0.9%
5. harmonic	0.4%
7. harmonic	0.3%
9. harmonic	0.2%
for even harmonics of order 2 - 10	0.2%
for harmonics of order 11 - 40	0.1%

Also, in the EN 61000-3-2 there are 4 different classes of equipment as follow:

Class A: Refers to 3-phase balanced equipment, household equipment (excluding equipment identified as class D), tools (excluding portable tools), and dimmers for incandescent lamps, audio equipment and other excluded from the next classes. The applicable limits are shown in Table 2.7.

Table 2.7: IEC/EN 61000-3-2 standard, limits for class A equipment [108].

Harmonic order **n**	**Maximum permissible harmonic current (I_{harm} A)** **A**
Odd harmonics	
3	2.30
5	1.40
7	0.77
9	0.40
11	0.33
13	0.21
15≤n≤39	0.15·8/n
Even harmonics	
2	1.08
4	0.43
6	0.30
8≤n≤40	0.23·8/n

Class B: Refers to portable tools and arc welding equipment which is not professional equipment. The applicable limits are shown in Table 2.7 and must be multiplied with a factor of 1.5.

Class C: Refers to lighting equipment. The applicable limits are shown in Table 2.8.

Table 2.8: IEC/EN 61000-3-2 standard, limits for class C equipment [108].

Harmonic order **n**	**Maximum permissible harmonic current expressed as a percentage of the input current at the fundamental frequency** **% (I_{harm} %I_{fund})**
2	2
3	30·λ *
5	10
7	7
9	5
11≤n≤39 (odd harmonics only)	3
* λ is the circuit power factor	

Class D: Refers to PCs, PC monitors, receivers (TV or radio) and a rated input current P ≤ 600 W. The applicable limits are shown in Table 2.9.

Table 2.9: IEC/EN 61000-3-2 standard, limits for class D equipment [108].

Harmonic order n	**Maximum permissible harmonic current per watt (I_{harm} mA/W)**	**Maximum permissible harmonic current (I_{harm} A)**
3	3.4	2.30
5	1.9	1.14
7	1.0	0.77
9	0.5	0.40
11	0.35	0.33
11≤n≤39 (odd harmonics only)	3.85/n	Table 2.7.2

The European Power Supply Manufacturers Association notes that there are no limits for:

- Symmetrical controlled heating elements with input current of P ≤ 200 W.
- Independent dimming devices for incandescent lamps with a rated current of ≤ 1 kW [108].

Also, for class C equipment with an input current of ≤ 25 W, either the limits of Table 2.9 (column two) are applied, or the third harmonic current shall not exceed 86% and the fifth harmonic current shall not exceed 61% of the fundamental current (for further details refer to the standard) [108].

The standard IEEE 519

IEEE 519 standard specifies the limits of the values of harmonic currents and voltages that must be fulfilled by a common coupling area [106], where the equipment – load of an installation can interact to the equipment – load of another installation, the point of view by the installation. Also, this common coupling area is called point of common coupling (PCC) and it is defined as a point where both the company and the customer are connected and can measure the harmonic indices meaningful to both [45] [98]. In brief, the harmonic distortion caused by an electronic circuit, according to IEEE standards, must not exceed a total of 5% [94] [95], with a maximum of 4% due to any one even harmonic (i.e., second, fourth, etc) and 2% to any one odd harmonic (i.e., third, fifth, etc) [94]. In more details, according to IEEE 519 standard, the voltage distortion limits that must be fulfilled by the company are shown in Table 2.10 and the distorted current injection limits by the customer are shown in Table

2.11, measured at the PCC. The Total Harmonic Distortion (THD) term, here (IEEE 519 standard), is being used for voltage harmonic distortion because of harmonic currents, while Total Demand Distortion (TDD) evaluates the current distortion caused by the harmonic current at the PCC [106]. Also, IEEE 519 [127] states that the harmonic current limits:

"should be used as system design values for the 'worst case' for normal operation (conditions lasting longer than one hour). For shorter periods, during start-ups or unusual conditions, the limits may be exceeded by 50%".

Table 2.10: IEEE 519 standard, Harmonic Voltage Distortion limits, (the limits are applied on a statistical basis ["must be met 95% of the time")] [105].

Bus Voltage	**Maximum Individual Harmonic Component**	**Maximum THD**
69 kV and below	3%	5%
115 kV to 161 kV	1.5%	2.5%
Above 161 kV	1.0%	1.5%

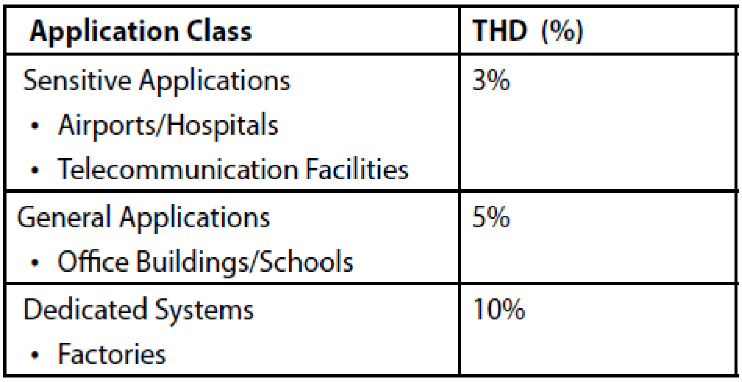
Table 2.11: IEEE 519 standard, Harmonic Current Distortion Limits (I_h in percent of I_L), [The limits are applied on a statistical basis ("must be met 95% of the time")] [105].

Maximum Harmonic Current Distortion in Percent of I_L						
Short Circuit Ratio (SCR)	Individual Harmonic Limits (Odd Harmonics)					Total
I_{SC}/I_L	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	TDD
<20*	2.0	1.0	0.75	0.3	0.15	2.5

Even harmonics are limited to 25% of the odd harmonic limits above.
* All power generation equipment is limited to these values of current distortion, regardless of actual short circuit ratio.
1. Values shown for the current distortion limits are in percent of "average maximum demand load current".
2. SCR = short circuit ratio (utility short circuit current at point of common coupling divided by the Customer average maximum demand load)
3. h = harmonic number,
4. I_{SC}= Utility short circuit at the point of common coupling,
5. I_L= Customer average demand load current at PCC,
6. TDD = Total Demand Distortion (uses maximum demand load current as the base, rather than the fundamental current)
7. Service Voltage < 69 kV.

Also, Danfoss corp. [124] sets a briefer convenient Table 2.12 for IEEE 519 standards:

Table 2.12: IEEE 519 standards for total harmonic voltage distortion.



Application Class	**THD (%)**
Sensitive Applications • Airports/Hospitals • Telecommunication Facilities	3%
General Applications • Office Buildings/Schools	5%
Dedicated Systems • Factories	10%

Fig. 2.21 illustrates a representative comparison of the IEC and IEEE standard limits, where the European IEC61000-3-2 Class-A type product limits are wider than the other.

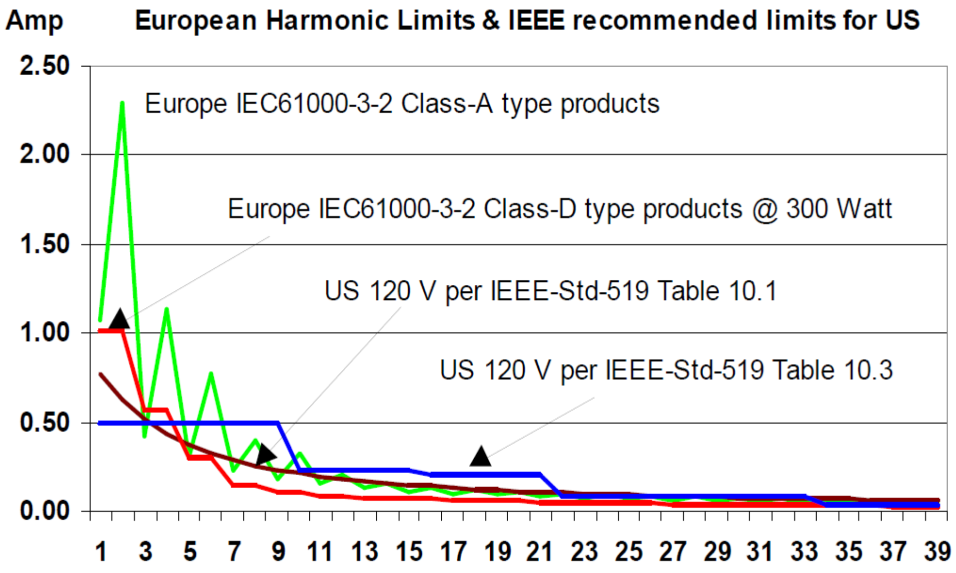
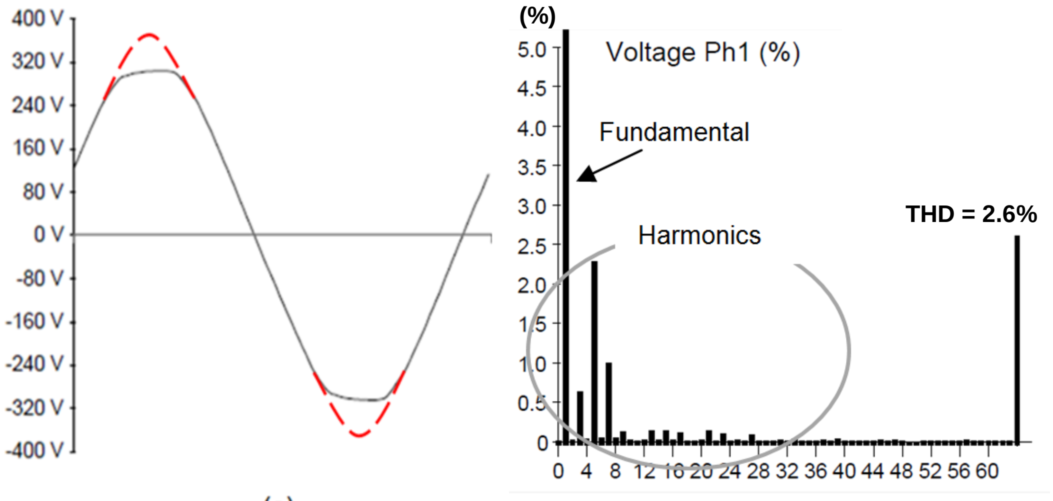


Figure 2.21: Comparison of the IEC and IEEE standard limits [111].

2.6.3 Indices to Measure and Characterise Harmonic Distortions

In power supply, the voltage or current harmonic distortion can be described through individual harmonic voltages or currents at the supply terminals with respect to the fundamental voltage V_1 (h = 1) (APPENDIX D, Table D.1), or it can be illustrated through spectrum in details (Fig. 2.22 (b)). Through this method can be determined the source of the harmonic distortion [124]. But for quick comparisons and evaluations is not practical enough. Hence, there have been developed several alternative methods for such a purpose with a single form [122]. Here follow some types of indexes of the voltage and current harmonic distortion with respect to the sine fundamental component. Fig. 2.22 illustrates a distorted voltage supply – mains (a), which is composed by its fundamental and harmonics (b).



(a) (b)

Figure 2.22: Waveform of a power supply and its harmonics [100].

Total Harmonic Distortion (THD)

Dash notes that: “total harmonic distortion is a way to evaluate the voltage distortion effects of injecting harmonic currents into the utility’s system” [106]. Also, Sankaran defines that “Total Harmonic Distortion (THD) is a term used to describe the net deviation of a non-linear waveform from ideal sine waveform characteristics” [113]. The most common and convenient formula with less detailed of view, which describes how much voltage or current sine waveforms are distorted, by the quantification of the level of harmonics, is the Total Harmonic Distortion (THD) [110] [118] which is also characterised as “the summation of all harmonics in a system” [93]. It is defined as “an index that quantifies the amount of distortion in the voltage or current waveform with respect to the fundamental component” [114]. Also, it is defined as “the ratio of the rms value of harmonics and the rms value of the fundamental” [118] [129] [32] [46] [113] and it is given by the following relation:

$$\text{Total Harmonic Distortion (THD)} =$$

$$= \frac{\sqrt{\sum_{h=2}^{h_{max}} X_h^2}}{X_1} = \frac{\sqrt{X_2^2 + X_3^2 + X_4^2 + \ldots + X_{h_{max}}^2}}{X_1} = \frac{\sqrt{X_{rms}^2 - X_1^2}}{X_1} \qquad (2.5)$$

where

X_2, X_3 …$X_{h_{max}}$ – are harmonic voltages / currents, in rms

X_1 – the fundamental wave in rms value
“h" – is the number of the harmonic. If h = 2 then the second harmonic that consists the distorted waveform is X_2 etc.
X_{rms} – the rms value of distorted wave (the sum of all harmonics)

Usually, THD it is expresses the percent of the fundamental [124] [172].

$$THD = \frac{\sqrt{\sum_{h=2}^{h_{max}} X_n^2}}{X_1} \cdot 100\% \qquad (2.6)$$

Even IEEE 519-1992 standard uses the distortion index THD for voltage and not for current [106] [138], the eq. 2.6 for voltage (V) is the same as for the current (I) THD [102] [106] [129] [130] [136]:

$$THD(V)_{\%} = \frac{\sqrt{V_{rms}^2 - V_1^2}}{V_1} \cdot 100\% \qquad (2.7)$$

$$THD(I)_{\%} = \frac{\sqrt{I_{rms}^2 - I_1^2}}{I_1} \cdot 100\% \qquad (2.8)$$

According to eq. 2.7 and eq. 2.8, the THD can be described as the ratio of RMS value of the harmonics and the RMS value of the fundamental. For example, if a distorted wave supply current has a fundamental component I_1 and harmonic components are I_2, I_3, I_4 …, the THD can be calculated as [113]

$$I_{H_{rms}} = \sqrt{I_2^2 + I_3^2 + I_4^2 + \ldots} \qquad (2.9)$$

$$THD(I)_{\%} = \frac{I_{H_{rms}}}{I_{1_{rms}}} \cdot 100\% \qquad (2.10)$$

From the above formulation of THD, as the distortion increases, the THD increases too. For standard EN 50160 harmonic number (limitation order) “h” reaches up to 40, while in other countries differs, like in UK where it reaches to 50 [5]. Also, according to eq. 2.6 the THD does not provide any detailed information about the harmonics of the signal, so it is not the proper tool for estimating the filtering design. But, as

Legrand comp. supports “it does give an interesting indication of the installation's degree of pollution and of the risks incurred” [43].

The term of Individual Harmonic Distortion (IHD) is defined by Sankaran [113] as “the ratio between the root mean square (RMS) value of the individual harmonic and the RMS value of the fundamental”:

$$\mathrm{IHD}_h = \frac{I_{h\,rms}}{I_{1rms}} \qquad (2.11)$$

Distortion Index (DIN)

An alternative definition of the Total Harmonic Distortion (THD) is the Distortion Index (DIN) [122], which is based on the ratio of the rms value of harmonics except the fundamental and the rms value of the distorted wave (the sum of all harmonics) and is given by the following relation:

$$\text{Distortion Index (DIN)} = \frac{\sqrt{\sum_{h=2}^{h_{max}} X_h^2}}{\sqrt{\sum_{h=1}^{h_{max}} X_h^2}} = \frac{\sqrt{\sum_{h=2}^{h_{max}} X_h^2}}{X_{rms}} \qquad (2.12)$$

The advantage of the above formulation is that it is always between zero and one.

Total Demand Distortion (TDD)

Total Demand Distortion (TDD) is defined by Tierney [136] as “the total root mean square harmonic current distortion, in percent of the maximum load current”. In semiconductor electronic equipment like bridge converters, it happens the THD of the current is very high, while the fundamental component approaches to zero with the existence of harmonics because of the switching action of the equipment [128]. Also, in the case of electronic variable speed drivers, who are designed for intense switching action and belong to the category of light loads, it happens the THD of the line current is very high but within acceptable limits with full load; although the THD is very high while at the same time the magnitudes of the harmonics are low and they do not affect the power system. This means that for some cases the THD of the current is not very reliable. Hence, another index [114] that quantifies the current distortion to the maximum demand load current over a 15 – 30 minute period is the Total Demand Distortion (TDD), which is part of the IEEE 519 standard [122] [126] [138], and is calculated as follow:

$$\text{Total Demand Distortion (TDD)} = \frac{\sqrt{\sum_{h=2}^{h_{max}} I_h^2}}{I_{ML}} \rightarrow \qquad (2.13)$$

$$\text{TDD} = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \ldots + I_{h_{max}}^2}}{I_{ML}} \qquad (2.14)$$

where

I_2, I_3, I_4 … – are the harmonic currents

I_{ML} – is the "maximum demand load current (fundamental frequency component), averaged over a demand interval (e.g. 15 or 30 minutes) for a given customer at PCC" [126].

From eq. 2.5 it seems that THD is very much like the TDD. They differ only to the denominator; where in the case of THD formulation there is the comparison of harmonics with the fundamental current "I_1" (with frequency of 50 or 60 Hz). In the case of TDD there is the comparison of harmonics with the maximum demand load current "I_{ML}", "instead of the fundamental "I_1" wave of the present current waveform" [122]. These Indices are equal only in the case where the fundamental frequency component is equal to the maximum demand load current i.e. at 100% load. And while the load decreases, the TDD decreases too, but the current THD increases [138]. This can be seen clearly in the table of the APPENDIX E.

2.6.4 Results of the Harmonic Distortion

Harmonic distortion is a main factor that "deteriorates" the PQ [129]. Also, Yaskawa corp. notes that the harmonic components increase the System's losses [115]. Injecting current harmonics in to the power system "produce a variety of effects that are harmful to the power system", as C. Sankaran notes [113]. Also, Derek Grant supports that “harmonics still cause us to lose monetary efficiency” [112]. Some problems of harmonic distortion many include:

- Heating of induction motors – windings, transformers – windings, capacitors and cables (extra losses).
- Overloading and heating of neutrals.
- Pulsating torques in rotating machines.
- Lose of monetary efficiency.
- Telephone transmission interference.
- Nuisance tripping.
- Increasing probability in occurrence of resonance.
- Lower system power factor decreasing of efficiency in electric machines.
- Electromagnetic interference with communication systems.
- Errors in measures when using average reading meters.
- Harmonic currents injected in the power supply system affecting adjacent installations.
- Non reliable fuse operation.
- Non reliable operation of electronic relays and solid-state devices.
- Overvoltages because of resonant conditions and power factor correction capacitors [40] [92] [93] [112] [131] [134].

2.6.5 The Power Factor and Harmonic Distortion

The Power Factor (PF) of a load is defined as “the ratio of Average power to Apparent power” [59] [60] [142]:

$$PF = \frac{P}{S} = \frac{P}{V_{rms} \cdot I_{rms}} \qquad (2.15)$$

Sankaran supports that “power factor is included for the sake of completing the power quality discussion” and power suppliers expect from the users of power, their industrial and commercial equipment to work with high power factor [113]. As Power Factor “is an economic issue in the operation of a power system”, there are penalty charges imposed if power factor is low [113] [139]. This means that harmonic distortion must be taken seriously into account as harmonics lead to low power factor [106] [139]. This is clarified in the following two sections:

- *Load connected other than non-linear*

In an ac power supply system, where the waveforms of voltage and current must be pure sinusoids, only the fundamental components (voltage and current) exists [113]. If the load is not pure resistive (R), this means that there is phase difference (*θ*), between voltage and current (Fig. 2.23, a), and if voltage (*v*) and current (*i*) are [60]:

$$v(t) = V_m \cos(\omega t) \qquad (2.16)$$

$$i(t) = I_m \cos(\omega t + \theta) \qquad (2.17)$$

The instantaneous power must be

$$p(t) = v(t) \cdot i(t) = [V_m \cos(\omega t)] \cdot [I_m \cos(\omega t + \theta)] \qquad (2.18)$$

and the Active power, Average power, or Real power (P) [32] is

$$P = \frac{1}{T}\int_0^T p(t)dt = (\frac{V_m \cdot I_m}{2})\int_0^T [\cos(2\omega t + \theta)] + \cos(-\theta)]dt \qquad (2.19)$$

$$\rightarrow \qquad P = V_{rms} \cdot I_{rms} \cos\theta \quad (W) \qquad (2.20)$$

the Reactive power (Q) is computed similarly to Average (P)

$$Q = V_{rms} \cdot I_{rms} \sin\theta \quad (VAR) \qquad (2.21)$$

and the Apparent power (S) (demand power [106]) is computed by multiplying the voltage V_{rms} with current I_{rms}

$$S = V_{rms} \cdot I_{rms} \quad (VA) \qquad (2.22)$$

In this case where there are no harmonics (no non-linear load connections – sinusoidal condition), and only exist the fundamentals of voltage and current, the quantity "cos θ" [9] is called as "power factor" and is calculated as:

$$Power \quad Factor \quad (PF) = \cos\theta \qquad (2.23)$$

From the above equations, the term PF can be also as follows:

$$PF = \frac{P}{S} = \frac{W}{VA} = \cos\theta \qquad (2.24)$$

It denotes the "displacement power factor" (DPF) [32] [116] [142] [143], which deals only with the phase difference between voltage and current [60] [116] (Fig. 2.23, a).

---

[9] In this case, by some authors is simply called "power factor" (PF) [116] [142] [143], but by others, more specifically, "displacement power factor" or "displacement factor" [32] [113] [140] [141].

The vector sum of the active (P) and reactive (Q) powers constitute the Apparent power through power triangle (Fig. 2.23, b), which means [106] [113] [135]:

$$S = \sqrt{P^2 + Q^2} \qquad (2.25)$$

If PF = cos θ = 1, this means that the Efficiency of the system is maximum, so the Reactive power (S) is zero [106].

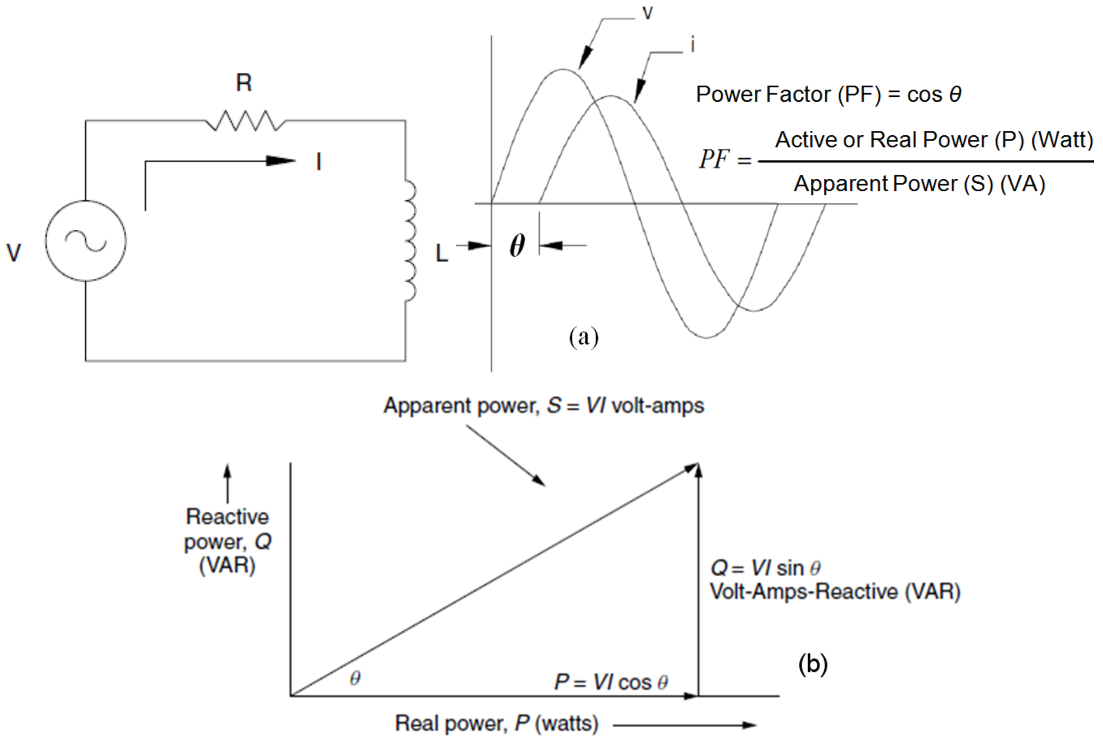


Figure 2.23: (a) Displacement Power Factor (θ), or phase difference (θ) between voltage and current at R-L load [113]; (b) Relationship between P, Q, and S in sinusoidal (linear) condition [116].

- *Non-linear load connected*

In case where are non-linear loads connected to the power system, the PF is reduced, because of the presence of harmonics [106] [140] [143]. Also, Sankaran notes that this means that “the presence of harmonics introduces additional phase shift between the voltage and the current” (composite voltage and current waveforms) [113]. Darwish notes that, in a non-linear system the current may contain a range of harmonics, even if the voltage waveform is sinusoidal, i.e. the current may not be a pure sinusoid and the waveforms of voltage and current can be described as follow, according to Fourier’s series [135]:

$$v(t) = \sum^{n} \sqrt{2} \cdot V_n \cdot \sin(n\omega t + a_n) + \sum^{m} \sqrt{2} \cdot V_m \cdot \sin(m\omega t + a_m) \qquad (2.26)$$

$$i(t) = \sum^{n} \sqrt{2} \cdot I_n \cdot \sin(n\omega t + a_n + \theta_{\mathrm{n}}) + \sum^{k} \sqrt{2} \cdot I_k \cdot \sin(k\omega t + a_k) \qquad (2.27)$$

Also, Roger C. Dugan notes that the rms values of the voltage and current waveforms are computed as follow

$$V_{rms} = \sqrt{\sum_{n=1}^{n_{\max}} \left(\frac{1}{\sqrt{2}} V_n\right)^2} = \frac{1}{\sqrt{2}} \sqrt{V_1^2 + V_2^2 + V_3^2 + \ldots V_{n_{\max}}^2} \qquad (2.28)$$

$$I_{rms} = \sqrt{\sum_{n=1}^{n_{\max}} \left(\frac{1}{\sqrt{2}} I_n\right)^2} = \frac{1}{\sqrt{2}} \sqrt{I_1^2 + I_2^2 + I_3^2 + \ldots I_{n_{\max}}^2} \qquad (2.29)$$

which is the square root of the sum of rms squares of all individual components (amplitudes), for each waveform *n*, in contrast with the non distorted waveforms (pure sinusoids) i.e.

$$V_{rms} = \frac{1}{\sqrt{2}} V_1 \quad (2.30) \qquad I_{rms} = \frac{1}{\sqrt{2}} I_1 \quad (2.31)$$

where V_1 and I_1 are the fundamental components [32]. So, in an ac power supply system (where the waveforms of voltage and current must be pure sinusoids), if there is phase difference between voltage and current and if the wave supply current is distorted because of non-linear loads, the resulting Power Factor[10] is the product of two main factors:

- Displacement Factor – Phase difference between current and voltage results in displacement
- Distortion Factor – Range of harmonics in current results in distortion [140].

Daniel notes that the Distortion Factor (DF) represents the reduction in power factor due to the nonsinusoidal property of the current" [60], which is calculated by dividing the rms value of the fundamental frequency to the total rms value [141]

$$DF = \frac{RMS \quad Value\,of\ Fundamental\,Current}{RMS \quad Value\,of\ Total\,Current} = \frac{I_{1_{rms}}}{I_{rms}} \qquad (2.32)$$

From eq. 2.8 the DF is calculated as [60] [110]

---

[10] Some authors call it, simply, "Power Factor" [60] [135] [140] [141] [143] and some other call it, more specifically, "True Power Factor" [32] [113] having the same meaning in this case.

$$DF=\sqrt{\frac{1}{1+(THD)^2}}=\frac{1}{\sqrt{1+(THD)^2}} \qquad (2.33)$$

The Power Factor (true) then, according to eq. 2.15, can be calculated by the following equation [135]

$$PF=\frac{P}{S}=\frac{\frac{1}{T}\int_0^T v\cdot i(t)dt}{\sqrt{(\sum^{n}V_{n_{rms}}^2+\sum^{m}V_{m_{rms}}^2)\cdot(\sum^{n}I_{n_{rms}}^2+\sum^{k}I_{k_{rms}}^2)}}=$$

$$\frac{\sum^{n}V_{n_{rms}}\cdot I_{n_{rms}}\cdot\cos\theta_{\mathrm{n}}}{\sqrt{(\sum^{n}V_{n_{rms}}^2+\sum^{m}V_{m_{rms}}^2)\cdot(\sum^{n}I_{n_{rms}}^2+\sum^{k}I_{k_{rms}}^2)}}=\frac{\sum^{n}V_{n_{rms}}\cdot I_{n_{rms}}\cdot\cos\theta_{\mathrm{n}}}{V_{rms}I_{rms}} \qquad (2.34)$$

If the voltage is sinusoidal[11] the eq. 2.34 is [60]

$$PF=\frac{P_1}{V_{1_{rms}}I_{rms}}=\frac{V_{1_{rms}}\cdot I_{1_{rms}}\cdot\cos\theta_1}{V_{1_{rms}}I_{rms}}=\frac{I_{1_{rms}}}{I_{rms}}\cdot\cos\theta_1 \qquad (2.35)$$

which is the “true power factor” (TPF) [32] of the system, and if [60]

$$Distortion \quad Factor \quad (DF)=\frac{I_{1_{rms}}}{I_{rms}}=\frac{1}{\sqrt{1+(THD)^2}} \qquad (2.36)$$

then [60] [140] [135][12]

$$Power \quad Factor \quad (true)=\underbrace{\frac{1}{\sqrt{1+(THD)^2}}}_{\text{Distortion Factor}}\cdot\underbrace{\cos\theta_1}_{\text{Displacement Factor}} \qquad (2.37)$$

From the above it can be seen that an additional power has been added due to harmonic existence as “Distortion” power (D)[13] [43] [60] [115] [135], which “represent all cross products of voltage and current at different frequencies, that they yield no average power” [32]. And it is calculated as [60]

$$D=V_{1_{rms}}\sqrt{\sum_{n\neq 1}^{\infty}I_{n_{rms}}^2} \qquad (2.38)$$

---

[11] As Darwish denotes “in a nonlinear system even if the voltage waveform is sinusoidal the current may not be a pure sinusoid”, but it contains an amount of harmonics [135].

[12] θ_1 : the displacement of voltage mains and fundamental current.

[13] Some authors call it, Distorting Power or harmonic power [43] and some other Distortion power [60] [135] [115] or distortion voltamperes [32] etc.

The Apparent power (S) and Real power (P), have the same definitions like previously (eq. 2.22 and eq. 2.20 respectively), but the Reactive power (Q) now, “consists of the sum of the traditional reactive power values at each frequency”, which is now [32]

$$Q = \sum_{n} V_{n_{rms}} I_{n\,rms} \sin\theta_{\mathrm{n}} \tag{2.39}$$

Therefore, the Apparent power (S) can be determined after P, Q, and D by

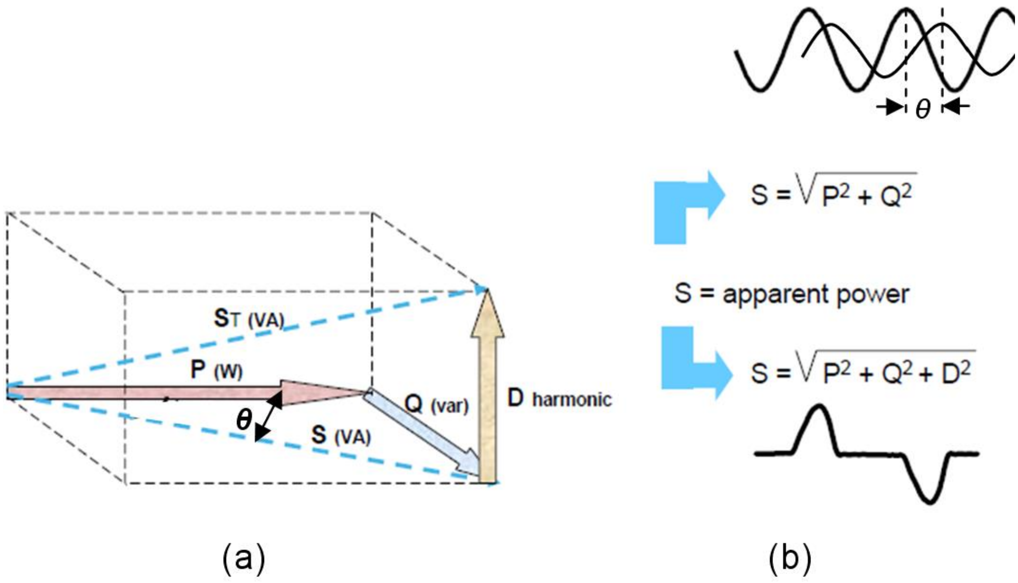
$$S = \sqrt{P^2 + Q^2 + D^2} \tag{2.40}$$

Eq. 2.37 can be also written as [43]

$$True \quad Power \quad Factor \quad (PF) = \frac{P}{\sqrt{P^2 + Q^2 + D^2}} \tag{2.41}$$

The vector sum of the Active (P) Reactive (Q) and Distortion (D) powers constitutes the Apparent (S) power as it is illustrated in Fig. 2.24 (a), [133].

From the above it can be concluded that the presence of the harmonics increase the Apparent power (S) (eq. 2.40) and decrease the Power Factor (PF) (eq. 2.37) [43]. Also, Legrand comp. supports that “the equality of the ratios between the power and the sinusoidal currents is no longer verified” [43].



(a) (b)

Figure 2.24: The vector sum of the Active (P) Reactive (Q) and Distortion (D) powers constitute the Apparent (S) power (a); the increase of S because of current harmonics (b) [133].

2.6.6 Harmonic Reduction

In order to solve the problematic harmonic distortion, detailed analysis must be done in designing specific filters that they also may be vary to their circuitry [119] [124] [160]. Power Factor Correction (PFC) is the procedure in order to reduce or mitigate the distorting harmonic presence through electronic circuitry [145] resulting to [135]:

- harmonic elimination / reduction in voltage and current waveforms
- true power factor improvement
- reduction of harmonic power losses
- combinations of the above

As a term, PFC has established recently, and mainly it has to make with true PF, in contract to Displacement PF, which has to make only with the elimination of phase difference between voltage and current supply [99]. There are two main different techniques for harmonic reduction – mitigation [108]:

- Filtering with passive components, by the use of "passive harmonic filters".
- Filtering with active electronic components, by the use of "active harmonic filters".

The following Fig. 2.25 gives a general icon of the results of the AC line input current. In case where there is not any harmonic filtering, the input current's THD is high (Fig. 2.25, a), as the current is limited only by: a) the low supply's system impedance (APPENDIX F, eq. F.2 and Fig. F.3) and b) non-linear load's input impedance. If there is filter with passive components connected, the distortion of the line current has been eliminated, but not completely (Fig. 2.25, b) [135]. And in case that a filter with active components is connected, the distortion of the line current can be eliminated so that the THD can reach to the demanded limits (Fig. 2.25, c) [108].

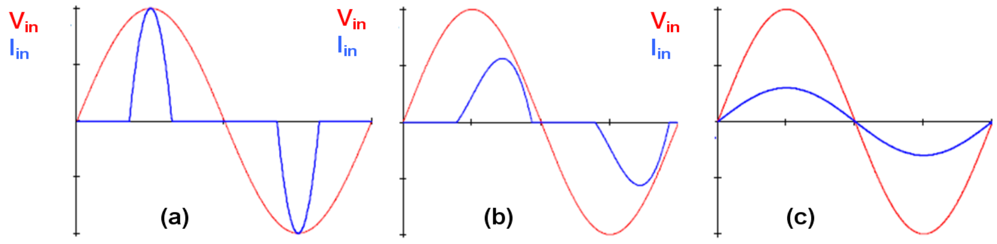


Figure 2.25: The results in current distortion (a) with respect to the kind of filtering; filters with passive (b), or active electronic (c) components [108].

2.6.6.1 Passive Filters

The passive filters entirely use passive components to filterout the undesired harmonics. This filtering method is “the simplest conventional solution” and the passive elements that uses are: resistance (R), inductance (L) and capacitance (C) [144] [148].

Firstly, the basic principal was to ground the undesired harmonics through a low impedance path. Now, two main configurations are being used through tuned L-C sub-circuits (here, passive harmonic filters) [135]:

By Series configuration

Series configuration consists of a parallel L-C or L reactor filter (Fig. 2.26). There is a high decrease of the harmonics magnitude, where the ac line reactor $Z_{a,\ b,\ c}$ (Fig. 2.26, a), or Z line (Fig. 2.26, b) is connected in series with dc link filter [145] [146] [155]. It is designed to decrease several tuned harmonics, especially the third harmonics, without undesired resonance and sufficient fundamental current flow [32] [154]. Also, it is suitable for one phase high power supply up to MVARs [153].

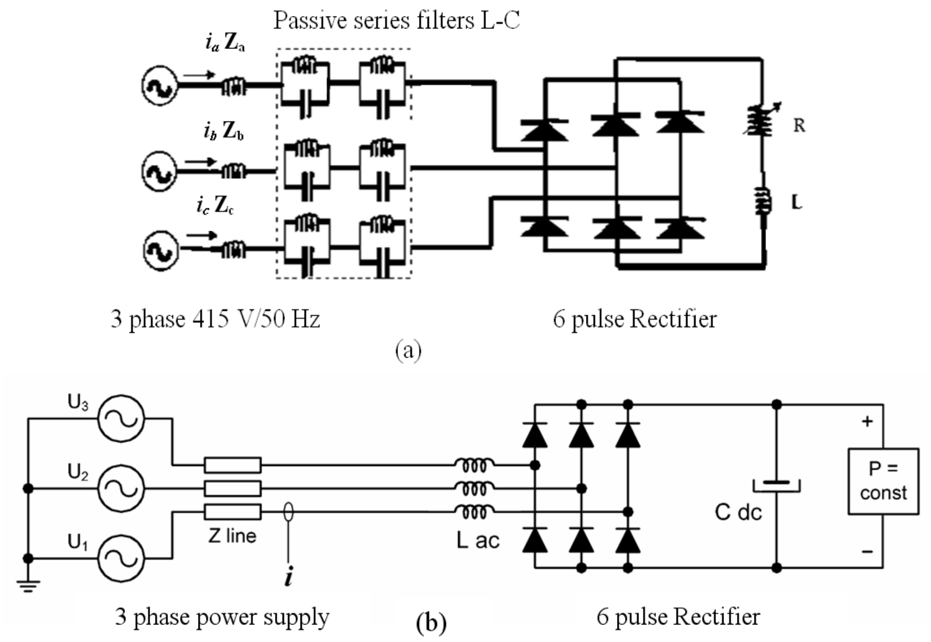


Figure 2.26: (a) passive series filters L-C [146]; (b) passive series filters Lac [155].

By shunt (parallel) configuration

By the shunt (parallel) configuration (Fig. 2.27), the harmonics are diverted to ground through low impedance path. In this case, through the electrical resonance condition, the tuned R-L-C circuit makes a path because of minimum impedance, for the maximum amount of harmonic order currents to flow out (to ground) of the system that feeds the loads [144] [148].

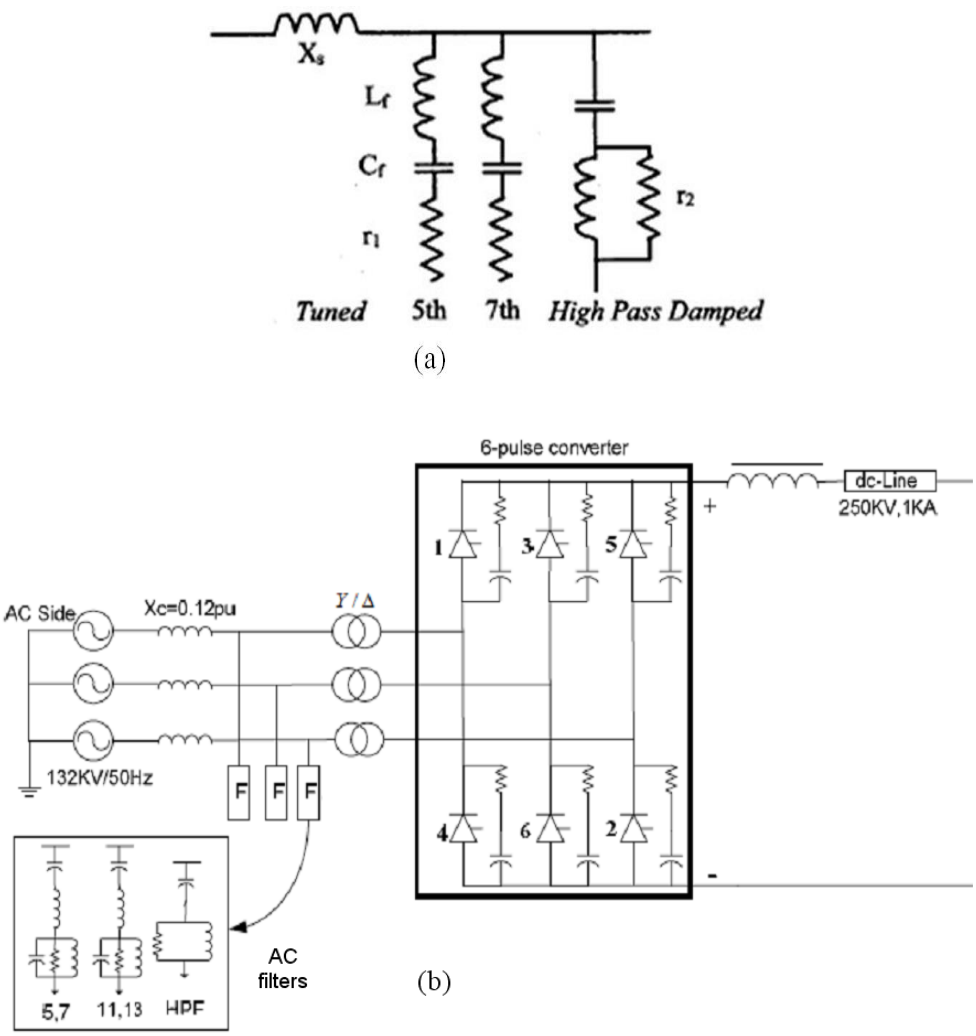


Figure 2.27: (a) shunt configuration of passive harmonic filters [157]; (b) shunt configuration of ac filters for mitigating 5th, 7th, 11th, 13th and high order (through high pass) harmonics [149].

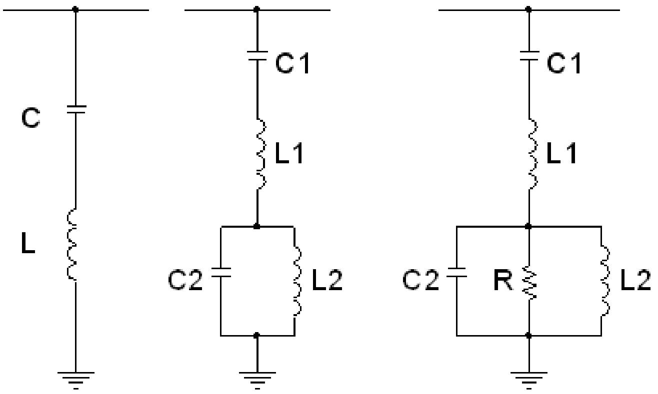
In shunt, the connection of series configuration is not necessary. But in series, the connection of shunt configuration is necessary in order to work them in conjunction [135]. Also, “shunt filters are categorised to be more practical to use than series filters” [152].

The harmonic R-L-C filters that are commonly used in shunt connection with main distribution system [32] [146] [163] are:

- single tuned,
- double tuned, damped-type double tuned
- 1st –order high-pass,

- 2nd –order high-pass and
- 3rd -order high-pass,

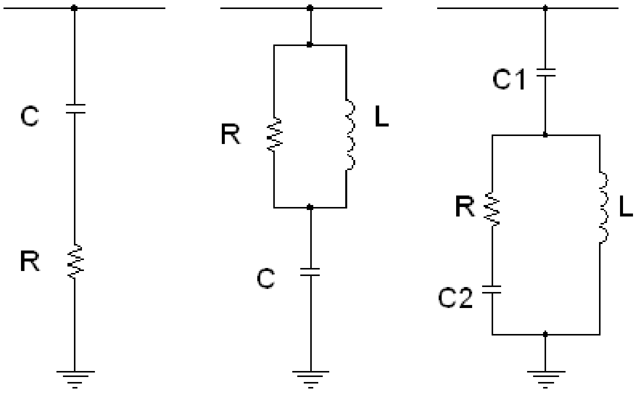
as illustrated in Fig. 2.28.



Single tuned

Double tuned

Damped-Type Double tuned



1st -order High-Pass Damped

2nd -order High-Pass Damped

3rd -order High-Pass (C – Type)

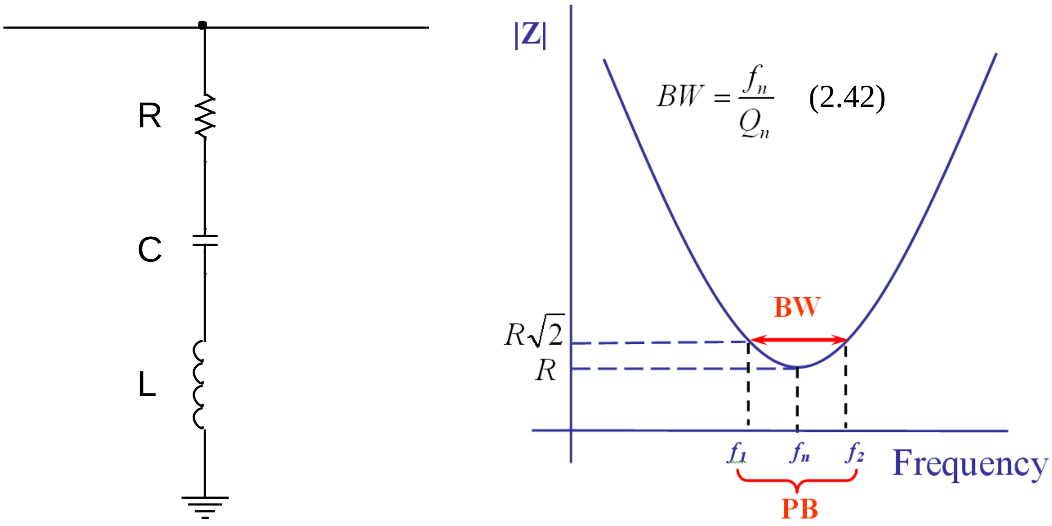
Figure 2.28: Passive harmonic filters configurations [96] [146] [148] [149].

Some of the most important of the various types of the upper passive filters are:

- the “single tuned” harmonic filters, to filter out the 7th harmonic
- the “double tuned” harmonic filters, to filter out the 3rd and 5th harmonics and
- the “high pass” harmonic filters tuned above the 3rd order [144].

Single tuned harmonic filter

This kind of filters is “the basis for understanding more advanced filtering structures” [147], the most commonly used, and mainly it consists of an inductor (L) and a capacitor (C), with or without Resistor (R) [146], as it is illustrated in Fig. 2.29. In this case the L-C tuned circuit appears the lowest impedance (Z) at its resonant frequency f_n for a single tuned harmonic (n), through which this specific harmonic is diverted to ground [147]. Each resonant circuit of the above is a branch with its own resonance frequency, through which the related harmonic diverts to ground [147]. Fig. 2.30 shows the connection of single tuned filters connected in shunt configuration with the power line supply and non-linear load (a), and also the impedances (Z) in relation to the harmonic number (n_1, n_2 … n_k) of the filters.



$$f_n = n \cdot f_1 = \frac{1}{2\pi\sqrt{LC}} \qquad (2.43)$$

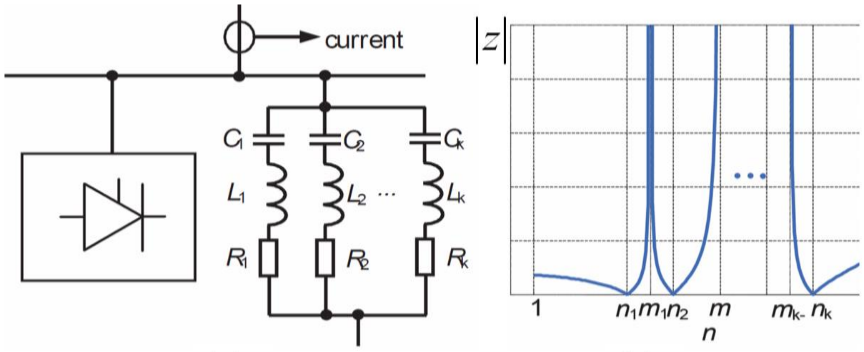
$$Q_n \cong \frac{X_L}{R} \qquad (2.44)$$

Figure 2.29: Single branch filter connection diagram and the frequency characteristic [146].

where

f_n – Frequency at resonant in Hertz

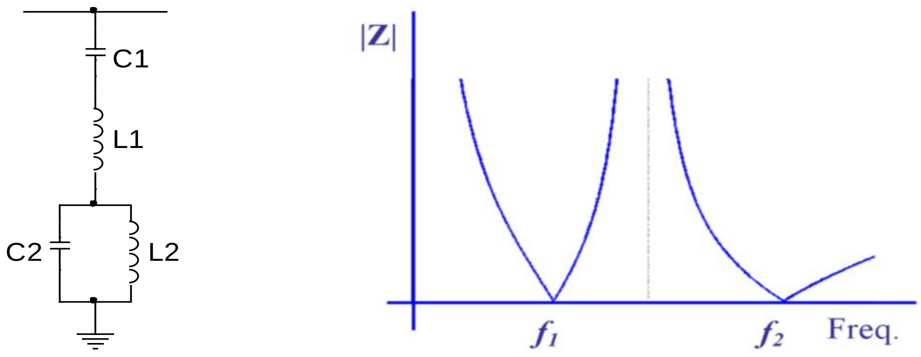
Q_n – The quality factor which determines the bandwidth (BW), which is a measure of the sharpness of the tuning frequency



(a) (b)

Figure 2.30: (a) Arrangement of single tuned filters in shunt configuration; (b) diagram of impedances (Z) vs harmonic number (n1, 2 ...k) [147].

Double tuned harmonic filter



$$f_1 \cdot f_2 = \frac{1}{4\pi^2} \cdot \frac{1}{\sqrt{L_1 C_1}} \cdot \frac{1}{\sqrt{L_2 C_2}} \qquad (2.45)$$

where

f_1 and f_2 – The resonance frequencies.

Figure 2.31: Single branch filter connection diagram and the frequency characteristic [150].

In this case the filter consists of a series resonance circuit (L1, C1) and a parallel resonance circuit (L2, C2), as it is illustrated in Fig. 2.28 and Fig. 2.31. It has two resonance frequencies $\boldsymbol{f_1}$ and $\boldsymbol{f_2}$ at which the filter presents the lowest impedance (Z), through which the relative harmonics are diverted to ground [96]. And this, like the single tuned filter, is connected in shunt arrangement with the main distribution system [149] [150].

High pass harmonic filter

A disadvantage of a single harmonic filter is to filter out only one relative harmonic. This means that for each harmonic there mast me connected its relative single harmonic filter (Fig. 2.32). So, instead of that, the high pass harmonic filter is being used to filter out harmonics above 3rd order, and here also in shunt configuration [144] [146]. Fig. 2.33 shows a second order high pass damped[14] filter with the frequency characteristic.

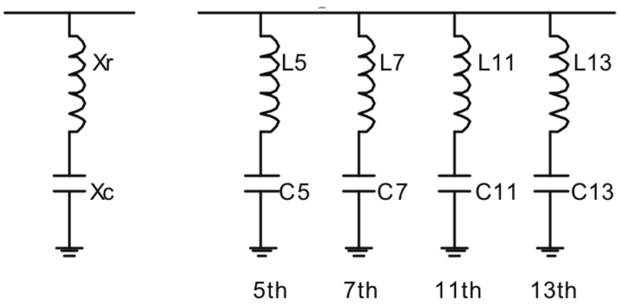
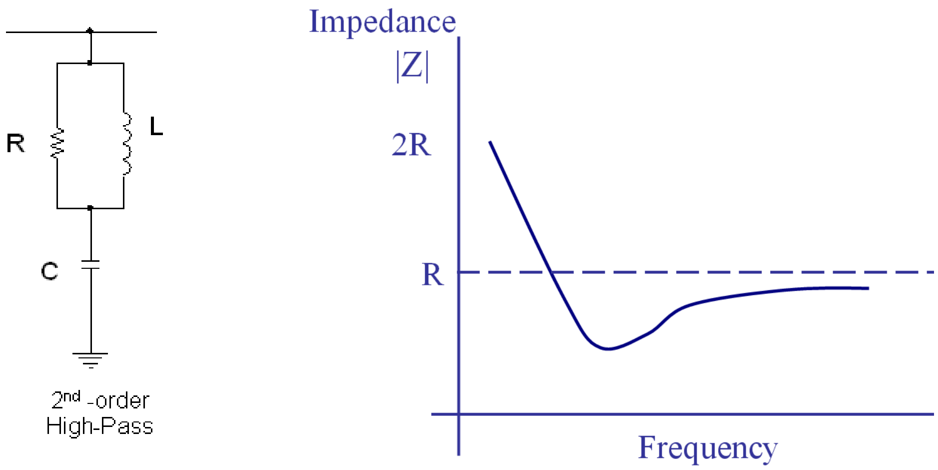


Figure 2.32: Shunt single tuned harmonic filters, each for a harmonic component [152].

Figure 2.34 illustrates the circuitry of a passive harmonic filter connected at the input power supply of a PC. For 230 V_{ac} mains supply, the switch must be set to position OFF (230 V_{ac} position) and for 115 V_{ac} mains, the switch must be set to position ON (115 V_{ac} position), where the balance the unregulated V_{dc} output of the diode rectifier depends on the mains voltage supply [119].

---

[14] Damping is the characteristic configuration of the filter, which through the addition of resistor R prevents from instability or undesired oscillations of the reactive elements of the circuit (the reactance of the power system and filter impedance) that they can lead to overvoltage harmonics on the filter and other components of the power system [114] [149] [151] [158].



$$f_n = \frac{1}{2\pi\sqrt{LC}} \qquad (2.46)$$

$$Q = \frac{R}{X_{C_n}} = \frac{R}{X_{L_n}} \qquad (2.47)$$

Figure 2.33: 2nd-order damped high pass filter connection diagram and the frequency characteristic [135].

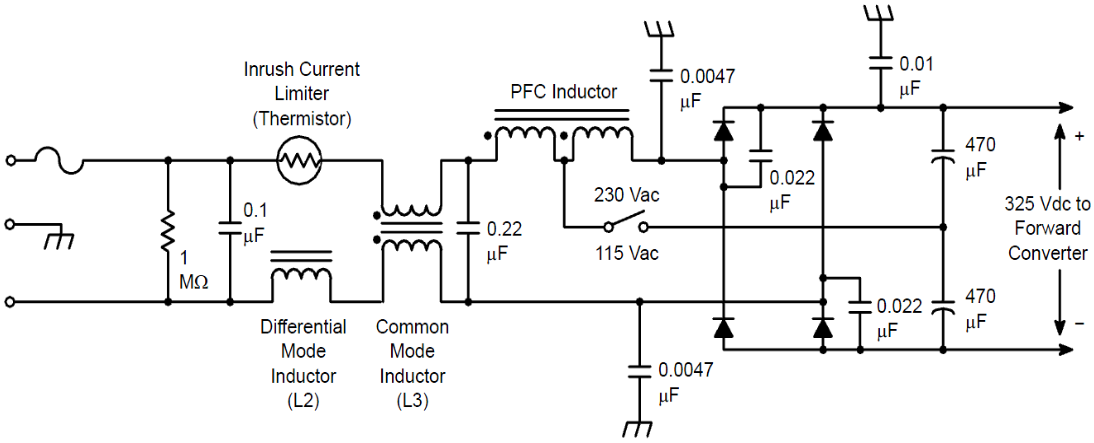
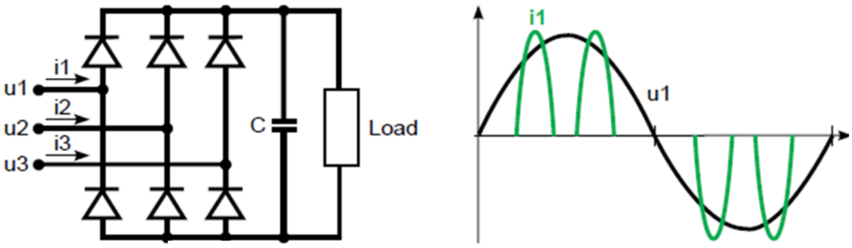


Figure 2.34: PFC through passive components, for a 250 W PC power supply [119].

Examples

Below there are some basic examples of the implementation of the passive harmonic filters.



(a) (b)

Figure 2.35: The distorted supply current without harmonic filtering [156].

Arbitrary, Fig. 2.35 (a) shows a three phase power supply system, without any filtering component, feeding a 6 pulse diode rectifier. Fig. 2.35 (b) shows the distorted line current wave, with short duration high peak current pulses that they consist of harmonics being able to cause problems to the rest of the neighboring loads [124].

Fig. 2.35 (a) shows a non-linear load (a thyristor in single line rectifier configuration), fed by a power supply that is connected with a harmonic filtering system consisted of:

- a shunt harmonic filter, the inductor L_f and capacitor C_f, and
- a series harmonic filter, dc reactors L_1 and L_1

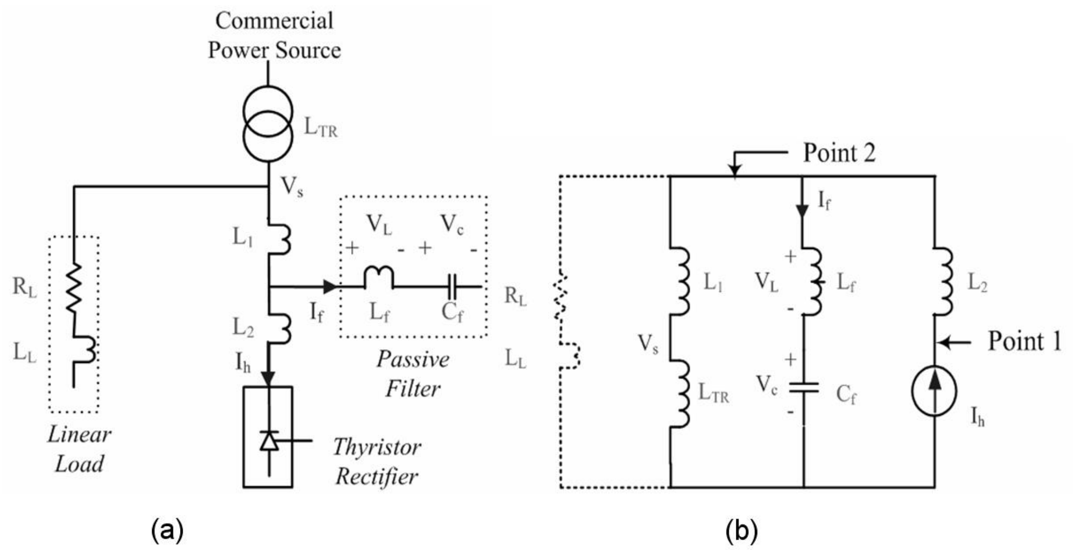


Figure 2.36: Electrical distribution system feeding a thyristor rectifier; (a) the power system diagram, (b) the equivalent circuit [145].

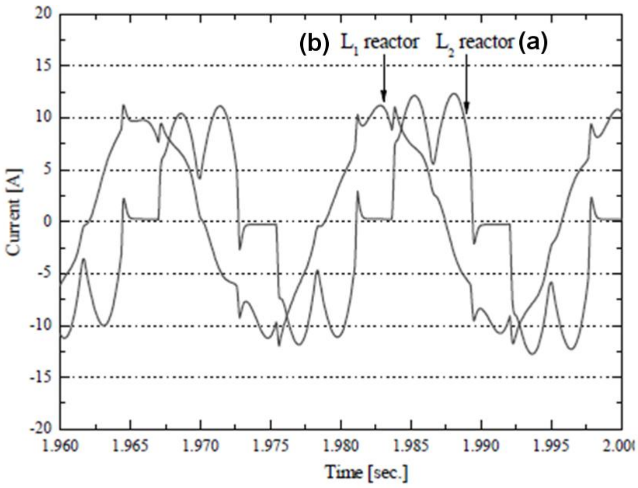


Figure 2.37: The current waveforms at both sides of the harmonic filtering system [145].

Fig. 2.36 (b) shows the equivalent circuit in order to calculate the resonance frequency from harmonics sources. According to Fig. 2.36 (a), the L_f - C_f system is a means – path to ground the undesired harmonics and L_1- L_2 reactor is to decrease them considerably. The results are illustrated in Fig. 2.37 (a), where the current wave at the input of thyristor (Point 1), and Fig. 2.37 (b) the current wave after filtering (point 2).

2.6.6.2 Active Filters[15]

The active power filters are electronic circuitries that they consist of:

- mainly active components
    - ICs (processors and/or controllers, op. amps, etc.),
    - power switching electronics, mainly transistors (MOSFETs or IGBTs) and diodes
- passive components
    - inductors
    - capacitors [119] [154].

Danfoss com. claims that the systematic progress of digital signal processing and the new power control techniques now can lead to better harmonic pollution by the active filters, satisfying in a high degree the international standards included in PQ, compared to classical passive filters [160].

The principles of operation of the active harmonic filters or active filters were established since 1970 [164]. There are various topologies of active power filters [166], but their function, basically, is based on controlling power electronic switches to charge/discharge the capacitors and inductors in such a way as to create equal current harmonics with a phase shift of 180^0 (i.e. opposite) to those generated[16] by the non-linear loads [135]. The basic idea is that the power electronic switches, in conjunction with capacitors and inductors act as non-linear loads that inject in to the ac mains power supply the corresponding harmonic current components (comp.) to that created from the non-linear loads, except the fundamental, with the same amplitude and opposite in phase [154]. So, the relative and opposite harmonics cancel to each other so that only the fundamental component flows in the line cable [157] [159] [163] as illustrated in Fig. 2.38.

---

[15] The term "Active filters" is also referred to those circuits that they work for analog signal processing [164]. At present, there is the term "Active Power filters" also [159].

[16] As Hadeed Ahmed Sher reports, "the vital and the most troublesome harmonics are thus 3rd, 5th, 7th, 9th, 11th and 13th" [154].

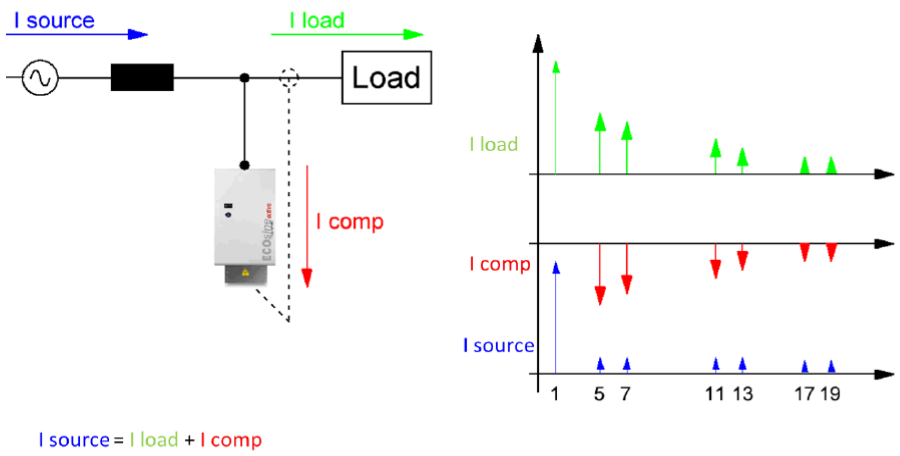


Figure 2.38: Current correction by an active harmonic filter [179].

Where

I source – the supplying current

I load – the load current

I comp – the compensating current

With respect to the circuit configuration, active filters can be classified mainly in to series active filters and shunt (parallel) active filters [154] [159].

Series configuration

By the "series configuration" the series active power filters (SAPFs) act as controllable voltage source connected in series with single-phase or three-phase power supply, in order to compensate current harmonics of the power system caused by non-linear loads [164] [165], as illustrated in Fig. 2.39; here diode rectifier with a smoothing capacitor (C) and dc load.

The SAPF is controlled on the principle of the "feedback" manner, passing the compensating voltage (v_{AF}) through its matching transformer to the ac mains, imposing high impedance path to the current harmonics that need to filter out [167] in general according to the following steps:

- A controller of SAPF detects the instantaneous supply current i_S.
- By signal processing extracts harmonic current i_{Sh} from the i_S.

- SAPF passes the compensating voltage v_{AF} (= K i_{Sh}) through its matching transformer to the ac mains, imposing high impedance path to the current harmonics that need to filter out [164].

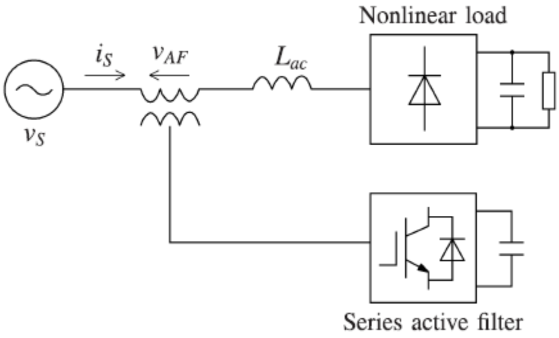


Figure 2.39: Single-phase or three-phase series SAPF [164].

The disadvantage of SAPF lies that its work is focused in the elimination of harmonics [164] [165]. Much care must be taken to the matching transformer, in the event of short circuit between phase and ground [154]. Also, P. Salmerón and S. P. Litrán note that a SAPF can compensate the reactive power of the non-linear load and balance asymmetrical loads [169].

Basically, there are three control types of series active power filters (SAPF) [168]:

- The first one is based on the generation by the SAPF a voltage proportional to the source current harmonics.
- The second one is based on the generation by the SAPF a voltage equal but in antiphase (in opposition) to the voltage harmonics at the non-linear load's side.
- The third one is based on the use of both previous types.

An example is given by a three phase SAPF topology, with a non-linear load Fig. 2.40.

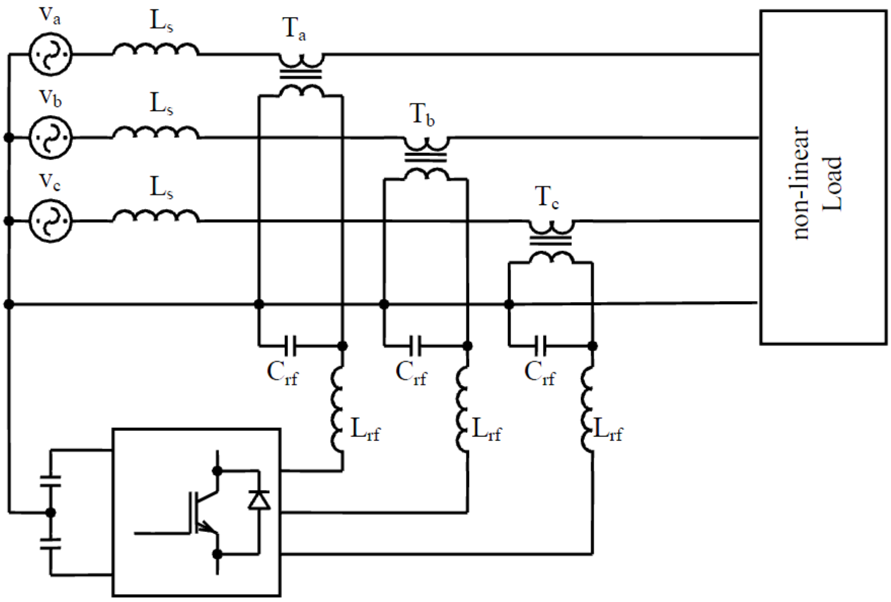


Figure 2.40: Three-phase series SAPF [168].

According to Salmerón at al. simulation experiments [169], Fig. 2.41 illustrates the phase voltage “a” and line current in time correlation without harmonic correction (no active filter connected). The measured current THD is 21.5% and the voltage THD in the PCC is 11.2%. Also the measured power factor is 0.96. And Fig. 2.42 illustrates the phase voltage “a” and line current in time correlation with harmonic correction (active filter connected), where the measured source current THD has fallen to 1.0%, the voltage THD to 1.3% and the power factor has risen to 0.99. The system now appears a resistive behaviour.

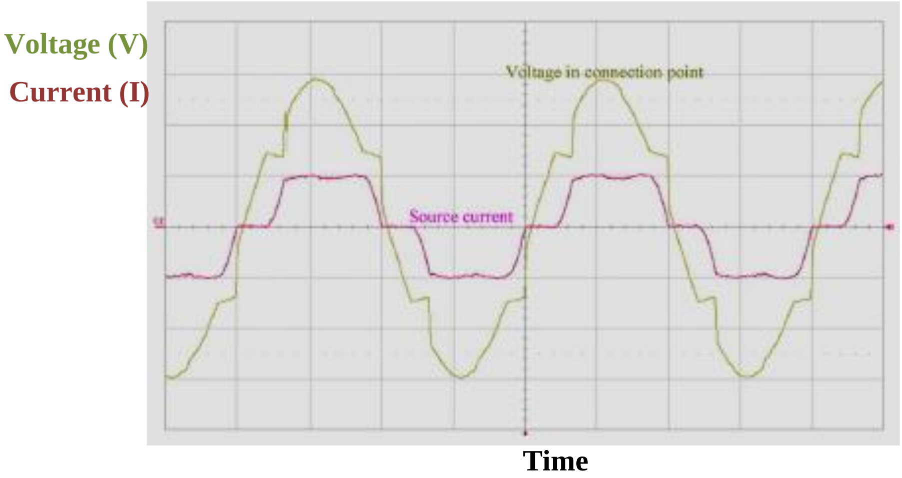


Figure 2.41: Source voltage phase “a” and current, without active filter connection [169].

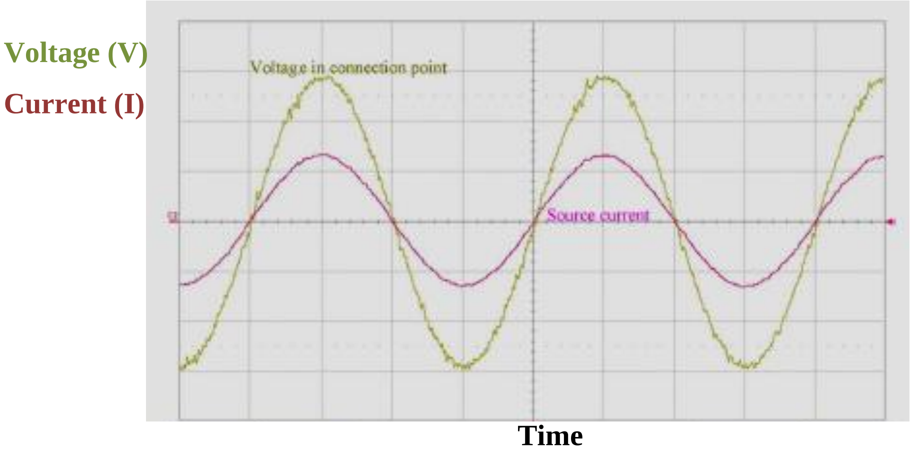


Figure 2.42: Source voltage phase “a” and current, with active filter connection [169].

Shunt (parallel) configuration

By the shunt configuration the parallel active power filters (PAPFs)[17] act as feedforward circuitries connected in parallel with single-phase or three-phase power supply, in order to compensate current harmonics of the power system caused by non-linear loads [154], as illustrated in Fig. 2.43 and in Fig. 2.44.

There are various types of active or hybrid active filters, but the shunt configuration is one of the most fundamentals [163] [164], including the advantage of reactive power compensation also [176].

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[17] For shorthand.

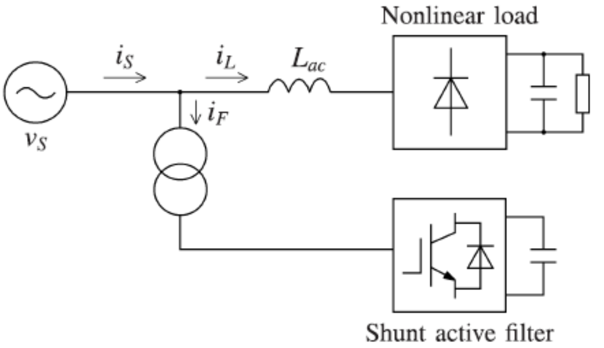

Figure 2.43: Single-phase or three-phase series PAPF [164].

The PAPF is controlled on the principle of the “closed loop” manner. It injects to the power line the current harmonics with equal amplitude and in opposite phase (180^0 phase shift) to the respective created by the non-linear load, in order to cancel each other [157] and remain only the fundamental. In general, this is accomplished according to the following steps [160] [164]:

- A controller detects instantaneous load current i_L
- Through digital signal processing it extracts the harmonic current i_{Lh}
- The PAPF injects to the line the compensating current i_{AF} (= - i_{Lh}) cancelling out the respective current harmonic i_{Lh}.

Basically, for the upper operation are involved [163]:

- Utilities for obtaining reference current.
- Use of proper power inverter.
- Use of current controller.

Some advantages of the PAPF can be [160]:

- The compensation of the power factor of the load by the addition capacitive or inductive power.
- The compensation of the flickering phenomenon, like in motor start up condition, where are involved resonances, inrush currents and switching transients[18].

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[18] Transients are defined “as the deviations from the AC sine wave having a very short duration, typically from a fraction of a microsecond to a very few milliseconds” [98].

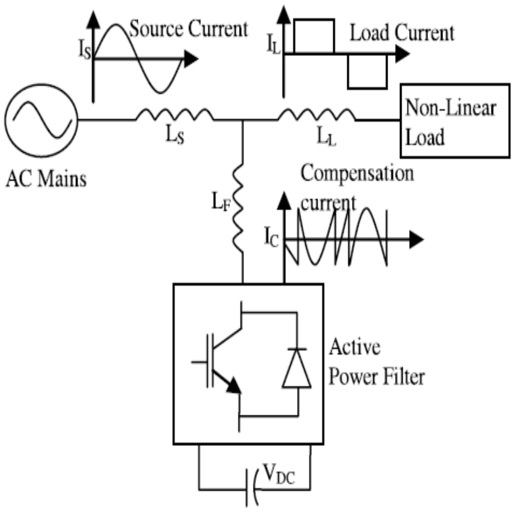

Figure 2.44: Single-phase or three-phase series PAPF current correction [277].

Some disadvantages of the PAPF configuration are [148]:

- PWM technique that is being used must be large rated.
- The speed digital signal processing must be high, in order to respond quickly to the changes of the system's parameters.
- The injected compensating currents can circulate to the passive elements in the case of hybrid filters.

An example of a three phase PAPF topology with a non-linear load (Fig. 2.44) is given, according to Karuppanan's at al. simulation experiments [173]. Fig. 2.45 (a) illustrates the three phase voltage supply, in time correlation with the distorted six pulse diode rectifier load (R-L) current or line current (iLa) (Fig. 2.45, b) before correction. At that time the measured current THD is 21.5% (Fig. 2.46, a) in the PCC is 11.2%. After the PAPF simulating application, Fig. 2.45 (c) illustrates the produced related compensating andi-harmonic current waveforms (ica), which are injected to the line cancelling the line current's harmonics in order to exist only the fundamental source current (isa) (Fig. 2.45 d). Also, Fig. 2.45 (e) illustrates the resulting real unity power factor (PF) after the current correction, where phase voltage is in phase with the load current or line current. The measured source current THD is reduced to 1.0% (Fig. 2.46, b). The same technique like the upper is applied to the other phases that they are shifted by 120^0. So, for each of the three phases the system (PAPF and load) appears now a resistive behaviour.

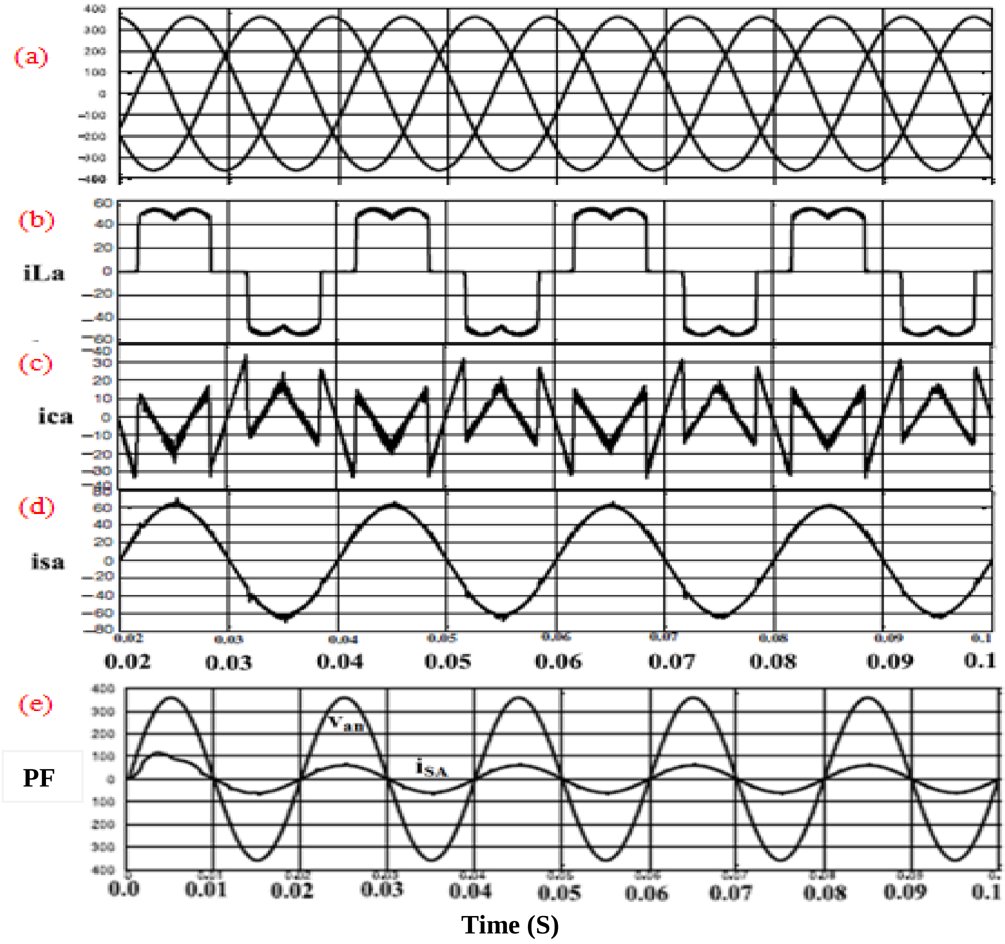

Figure 2.45: Simulation results of voltage A-phase from a three phase connection (a); source current before compensation (b), compensation current (c), corrected source current by the PAPF connected (d), and unity power factor (pf) (e) [173].

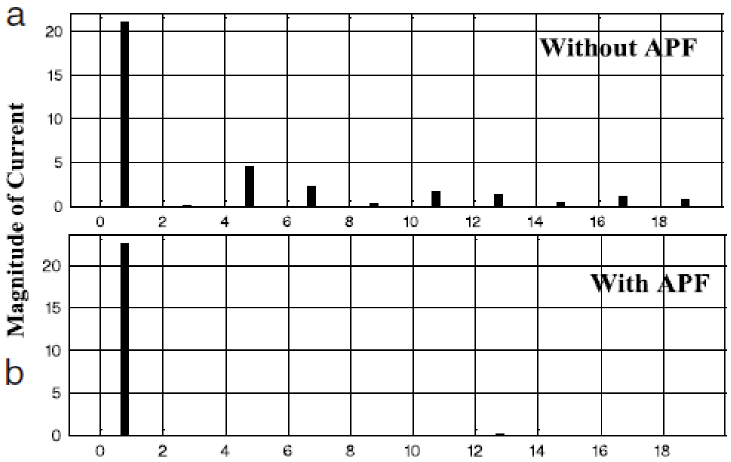

Figure 2.46: The current harmonics before the correction (a) and the current harmonics after the correction (b) by the Active Power Filter (APF) [173].

2.6.6.3 Hybrid Filters

Passive L-C power filters are designed with constant L and C values with specific reactive power and even their low cost [177] [180]:

- They are not flexible to follow variable loads or unpredictable variations of the system, like variations of the loads or overloading from harmonics coming from neighbouring non-linear loads.
- Their size is large.
- They are prone to resonance.

From the other hand, active power filters, even they are more flexible and efficient than passive L-C filters [169] their disadvantage is that they consume high power, close to load “sometimes” [176] [180]. So, hybrid filter configurations, active and passive filter combined, can reach to offer the following advantages, eliminating the problems of an active and passive power filter [169] [174] [175] [176]:

- The operation of the hybrid filter is independent to impedance of the system.
- The operation of the system consisted of the hybrid filter and the non-linear load presents a resistive behavior, which means that:
    - This system is invulnerable from the overloading current harmonics from neighboring loads.

  - Resonances (Series or parallel) related with the rest power system can be avoided.
- The hybrid filter is reliable even if in variant power operations of the load.
- It can compensate the variations of the reactive power.
- It improves the compensation characteristics.
- There is improvement in cost and performance of the harmonic filtering.

There is a variety of hybrid filters, where their configurations depend upon the type of application [174]. For example:

- A series active power filter (SAPF) can be connected with passive series filter, as illustrated in Fig. 2.47, consisting hybrid filter. It is suitable for diodes rectifiers connected to capacitive loads [154].

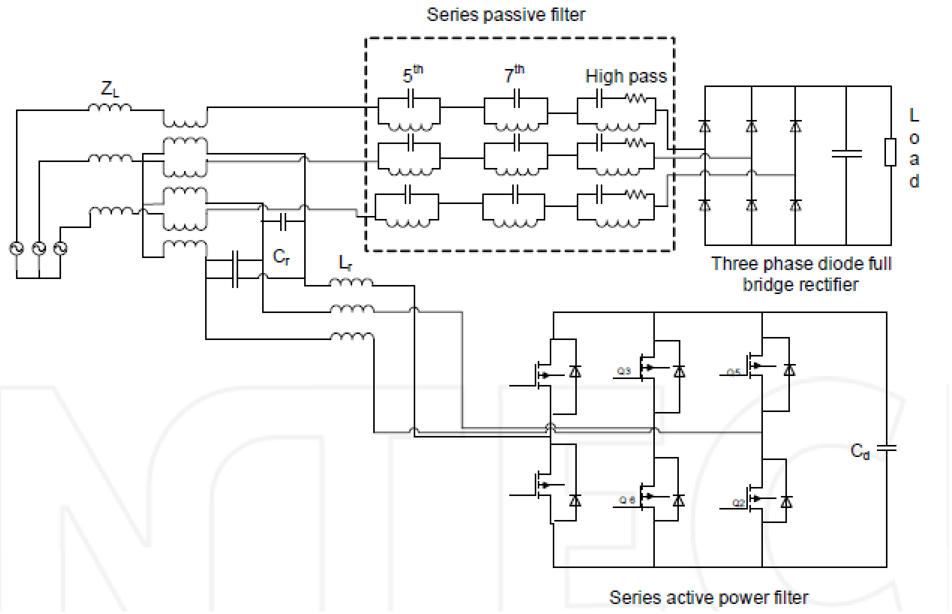

Figure 2.47: SAPF and series passive filter topology [154].

- Also, the SAPFs can be connected with passive shunt filters, as illustrated in Fig. 2.48. But Turunen et al. in comparative studies claims that the power requirement for efficient operation of this kind of filter is high compared to the load, because it utilizes very small transformation ratio [170].

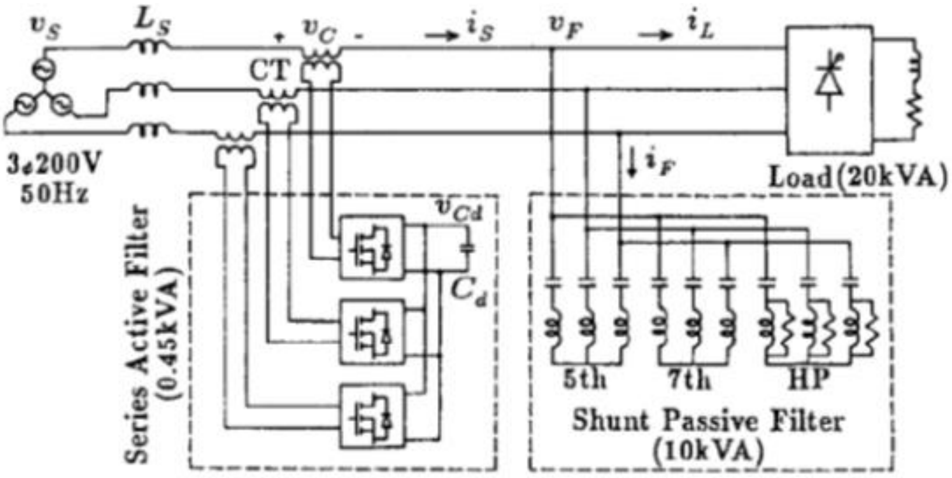

Figure 2.48: SAPF and shunt passive filter topology [154].

- A PAPF can be connected with a passive shunt filter, as illustrated in Fig. 2.49. Turunen et al. in a comparative study supports that for small loads they need enough high power and for heavy loads the current correction is poor because of dc link control problem [178].

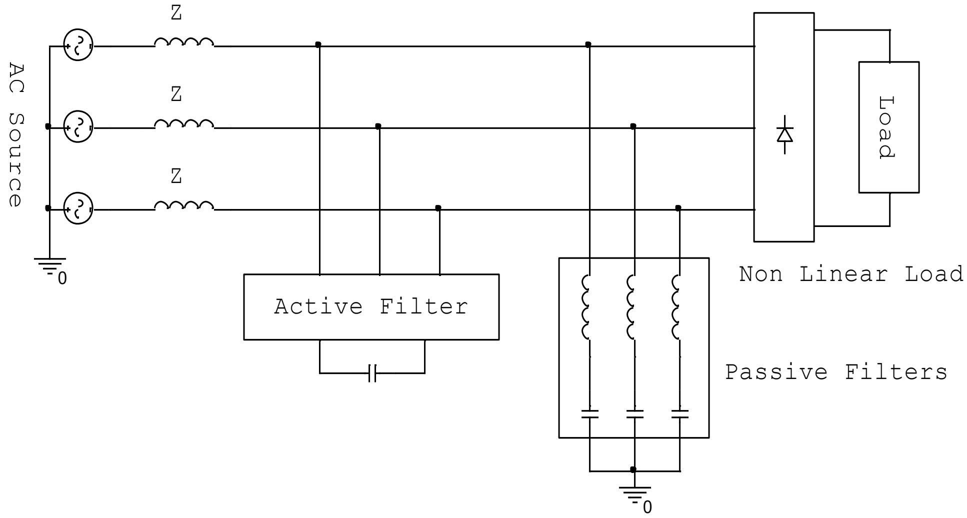

Figure 2.49: PAPF and shunt passive filter topology [154].

- Also, a PAPF can be connected with a passive L-C filter in series, as illustrated in Fig. 2.50. In this hybrid filter the PAPF improves the current correction of the system especially eliminating harmonics equal to and higher than 7th harmonic (350 Hz, 550 Hz and 650Hz) of the 50 Hz mains, which passes trough the tuned L-C filter in order to be eliminated.

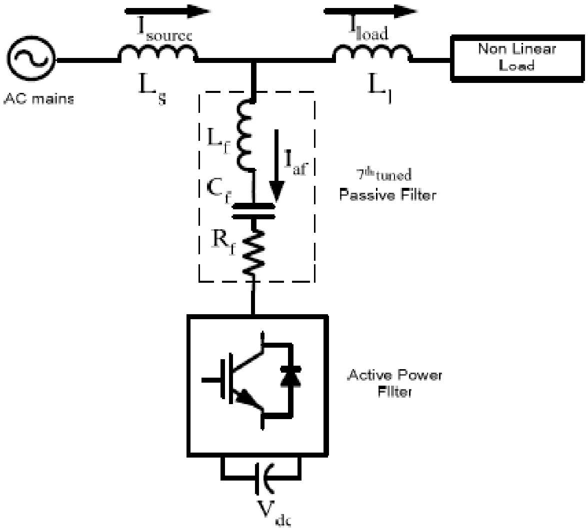

Figure 2.50: PAPF connected with a passive L-C filter in series [181].

2.7 Summary

The overvoltage and current distortion are critical factors of the power quality (PQ).

This chapter has outlined the overvoltage phenomena with their effects and the ways encountering them. Scholars and experts have searched this area highlighting this issue by proposing several solutions which applied by the responsible services. Also, international standards have been set limiting the acceptable voltage supply for the safe operation of the equipment.

The rapid increase of domestic appliances, like lights, heaters, washing machines, air conditioners, electric fans, TV, computers, etc., according to their type (resistive, inductive, active-electronic and composite), increase the consumption of the power increasing the danger of the overvoltage effects, which when they happen there is increase of the cost of power consumption simultaneously and the danger of devastating effects on electrical loads.

In the investigation of the overvoltage effects and the given solutions on them, the present research focuses on some areas in order to have more clear and integrated icon on that problem. Such basic areas can be:

- Classification of loads; i.e. passive and active.
- Overvoltage effects on each kind of the classified load, with the related graphs.

Low power devices like PCs, TVs, printers, digital electronic equipment etc. their presence increases rapidly according to the today’s demands. Also, power converters like ac-dc, inverters etc. and generally, such devices that they use switching power components for their power management they are sources of undesired harmonics. Even if this kind of equipment is helpful for human needs, manufactured under normal conditions and caring on their tablet their expected electrical ratings, the presence of the non-linearity by their power switching circuitries creates morbid conditions by generating harmonics. The harmonics, as has been clarified, can be viewed as rubbish injected in to the supplying power system resulting to low PQ. Now there is a high effort of filtering the supply power from harmonics by the addition of active filters and in many times combined with passive filters according to the kind of the produced harmonics.

In the investigation of the harmonics problem and the given solutions on it, the present research finds some areas that must be more investigated in order to have higher and more integrated solutions on harmonic correction. Such areas can be:

- Realistic circuitry – Most of the studies are based on simulations based on standard simulating programs without clarifying critical details of the circuits according to their applied theories.
- Except the current THD must be taken to the account the efficiency of the all system consisted by the non-linear load and the filtering circuit.
- Simplicity – As much complex is a system as more possibilities there are to be non reliable according to passage of time.
- Low cost – A significant role is the cost of a filtering system in relation to the non-linear equipment. It would not permissible the cost of a filtering system to be higher than the equipment.

- Circuitry connection convenience – For a better cost and electric efficiency, must be taking to the account the place of the connections of a filtering system; in the dc side of the equipment or at the ac mains. Also in which cases each solution is better.

The present research in the following chapters seeks to give solutions to the upper issues:

- Classification of power loads that are vulnerable to overvoltages.
- The overvoltage effects on each kind of the above loads.
- Cost effective realistic electronic circuitry to reduce the current harmonics in non-linear load (design, computer simulation using PSpice simulation software, realisation and evaluation).
- Cost effective realistic electronic circuitry to stabilise the nominal voltage supply on a load, despite the up to 20% mains overvoltage variations (design, computer simulation using PSpice simulation software and evaluation).

For a good overview of the research, it was necessary to classify the loads in two main categories, the passive loads which are located in chapter 3 and the active loads which are located in chapter 4. So, the chapter 3 that follows investigates overvoltage effects on passive loads.

Chapter 3: Analysis of Overvoltage Effects on Passive Loads

3.1 Introduction

In the category of passive loads are included the resistive loads and the electromagnetic loads.

The resistive loads are passive loads [293]. Examples of this type of load are cookers, heaters, boilers and kettles, incandescent lights, etc, but not gas discharge (fluorescent) lights [294]. In practice, most heating and lighting loads are purely resistive, but some may exhibit a resistance that is voltage dependant. In this type of loads the amount of power consumed (for a constant value of load) is directly proportional to v^2. So, an increase of, say, 10% in a supply voltage of 230V will result to an increase of 21% on power consumption in a purely resistive load. The same is roughly true in the cases where the resistance varies or the load is partially inductive or capacitive.

Equipment with transformers or motors come under the category of electromagnetic loads. Here, may be involved refrigeration and some types of air conditioning. Magnetic materials that are parts of the electromagnetic loads, their saturation is depended to overvoltages in terms of losses in the iron core. Also, losses in the copper windings can be influenced by overvoltages.

Many types of electric motors can be affected by overvoltages. As they usually operate at a low percentage of full load (partly, because they cannot start if the load exceeds 34% of their maximum capability), the overvoltages may affect the consumed power with doubtful increase of useful work.

In the case of refrigerators and some types of air cooling the overvoltage effects become more complex resulting to vicious compensations regarding to temperature and the consumed power.

3.2 Resistive Loads

3.2.1 Experimental Testing Through Simulating Programme

Through PSPICE simulating programme, for a better view of the voltage effects, passive load (R) is examined according to the following two sections:

- from a nominal ac voltage of 230 V_{rms} (50 Hz) up to +20% (184 V_{rms}) in 10 steps of approximately 4.6 V_{rms}
- from a nominal ac voltage of 230 V_{rms} (50 Hz) down to -20% (184 V_{rms}) in 10 steps of approximately 4.6 V_{rms}

3.2.1.1 V_{ac} Mains Variations from Nominal up to +20% Across Purely Resistive Load R

Fig. 3. 1 illustrates the nominal ac voltage of 230 V_{rms} /50 Hz at a purely resistive load (R = 50 Ω).

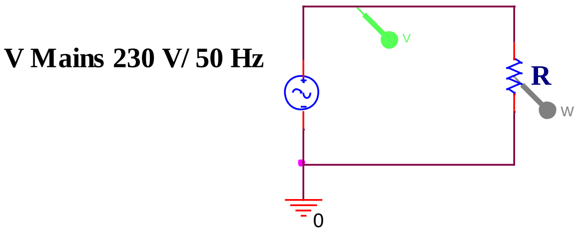

Figure 3.1: Vac mains across purely resistive load R

Fig. 3.2 illustrates the nominal ac voltage waveform of 230 V_{rms} (325.27 V peak) /50 Hz up to 276 V_{rms} (390.32 V peak, +20%), in 10 steps of approximately +4.6 V_{rms}, across the resistive load (R) (Fig. 3.1).

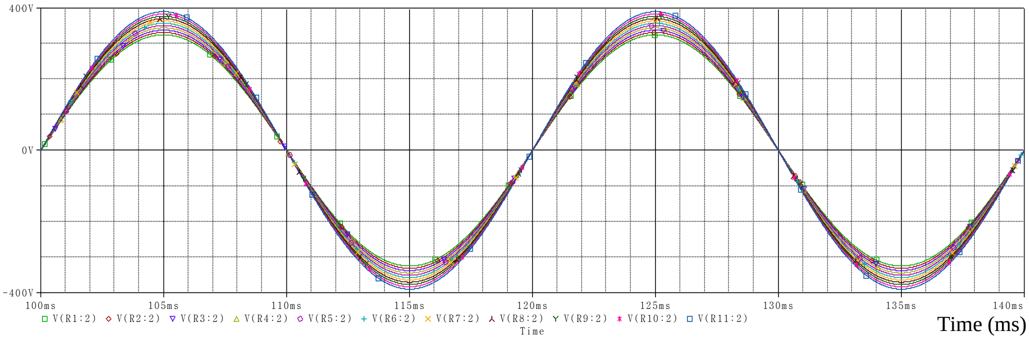

Figure 3.2: Vac mains variation from nominal up to +20% across purely resistive load R in 10 steps.

Fig. 3.3 illustrates a zoom of the peak variations of mains from Fig. 3.2, for a better view.

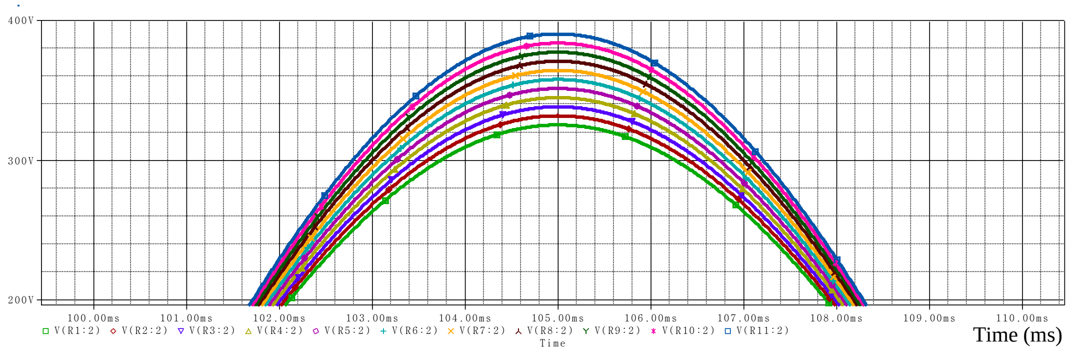

Figure 3.3: Zoom of the peak plotting of Vac mains variation, from nominal to +20%.

The equation for the power to the resistive load (R) of Fig. 3.1 is the same as for dc circuits [251]

$$p(t) = v(t) \cdot i(t) \qquad (3.1)$$

Fig. 3.4 illustrates the power waveform variation derived by the simulating program, using equation 3.1 for each value of mains, according to its relative deviation from nominal to +20%, in time domain,.

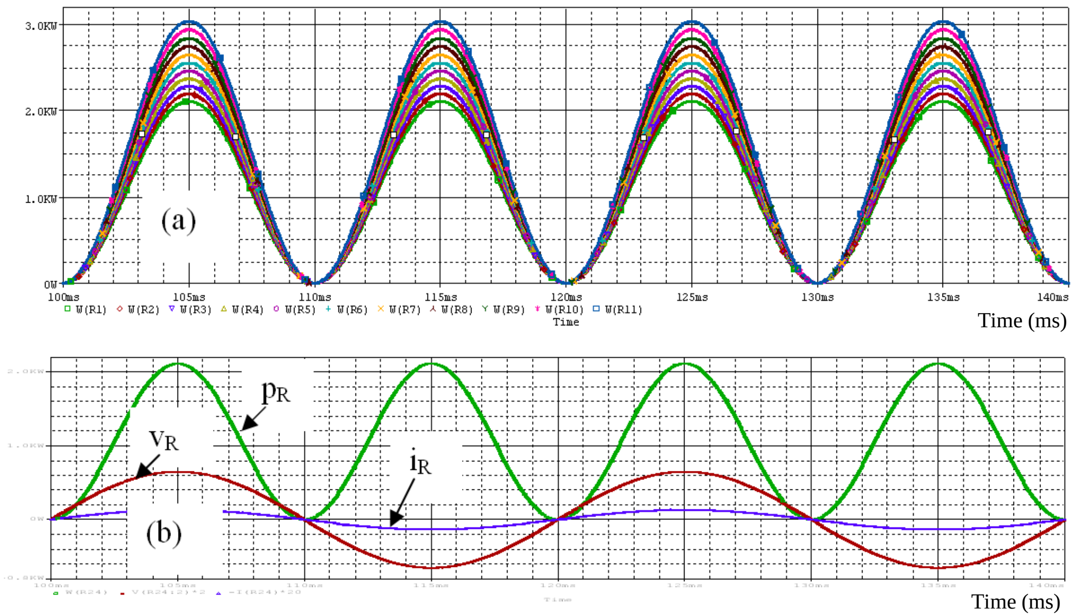

Figure 3.4: The consumed power waveforms, from nominal to +20%, across the purely resistive load R (a), in time correlation to nominal (b). (Two periods of the Vac mains).

The average or real power (W) delivered to the load using the rms values

$$P_R = V_R \cdot I_R = I^2{}_R \cdot R = \frac{V^2{}_R}{R} \qquad (3.2)$$

is illustrated in Fig. 3.5, according to related V_{ac} mains variation, from nominal to +20%, in 10 steps gradually, across the purely resistive load R, in time interval of 100ms – 140ms.

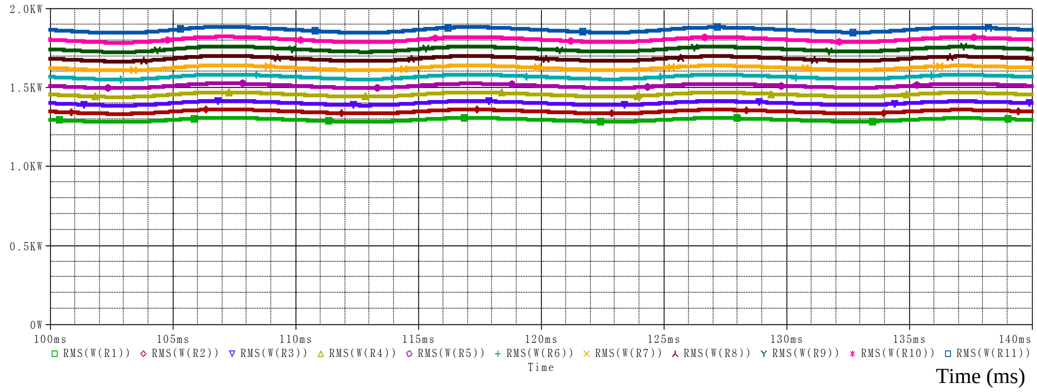

Figure 3.5: Consumed Power (W) to the related Vac mains variation from nominal to +20%.

3.2.1.2 V_{ac} Mains Variations from Nominal Down to -20% Across Purely Resistive Load *R*

Fig. 3.6 illustrates the nominal ac voltage waveform of 230 V_{rms} (325.27 V peak) /50 Hz down to 184 V_{rms} (260.27 V peak, -20%), in 10 steps gradually of approximately -4.6 V_{rms}, across the resistive load (R) (Fig. 3.1).

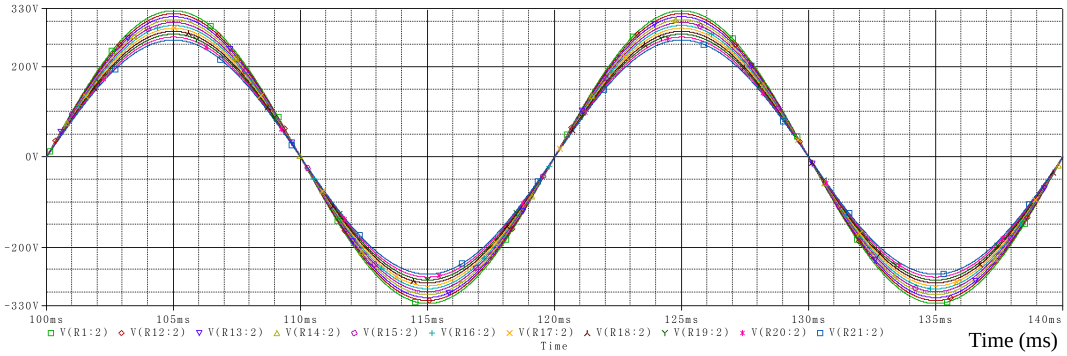

Figure 3.6: Vac mains variation from nominal down to -20%, across purely resistive load R in 10 steps.

Fig. 3.7 zooms on the peak variations of mains from Fig. 3.6, for a better discrimination.

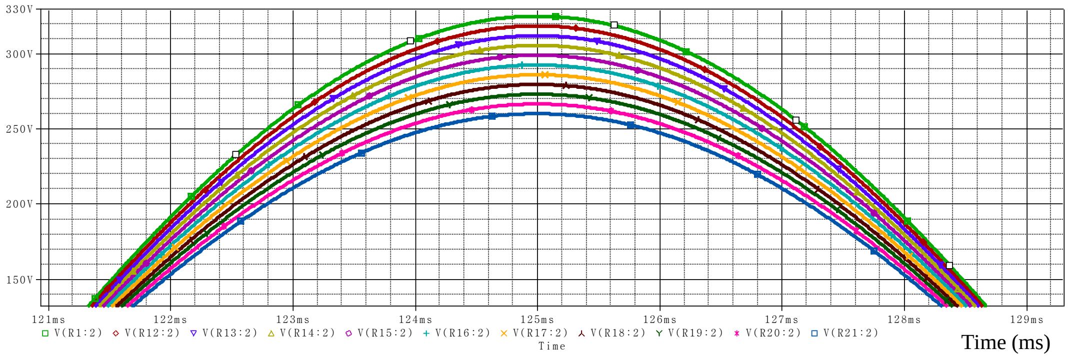

Figure 3.7: Zoom of the peak plotting of Vac mains variation, from nominal to -20%.

Plotting the equation 3.1 the simulating program, at each instant time, shows the power waveform (Fig. 3.8) for each value of mains, according to its relative variations from nominal to -20%.

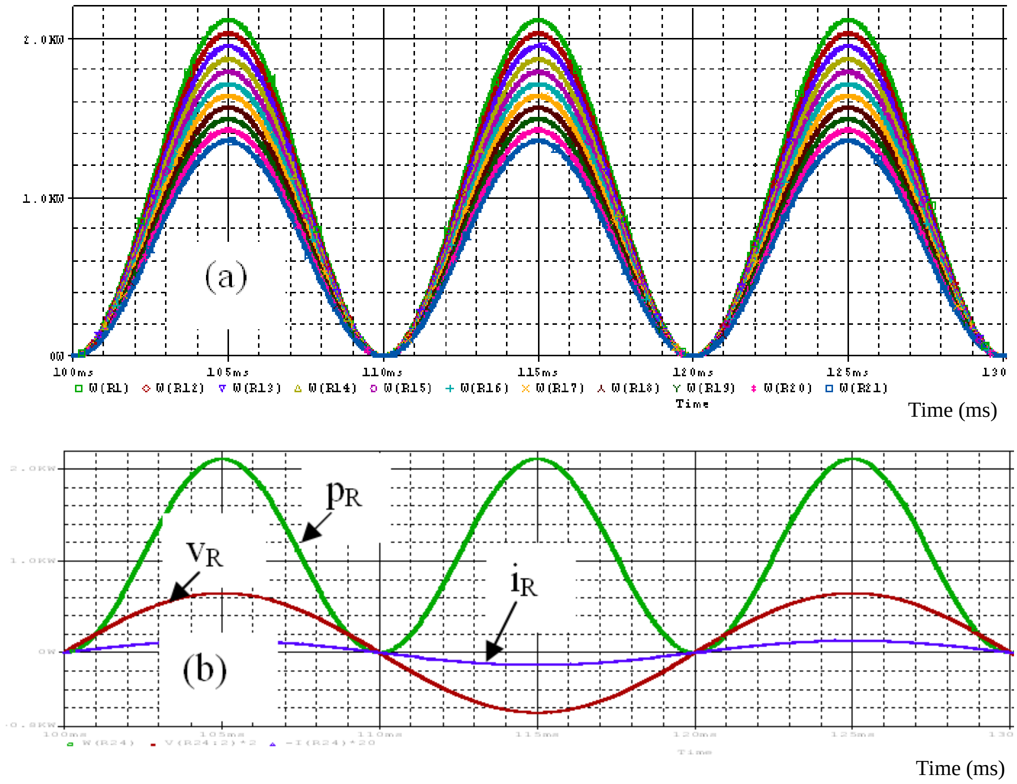

Figure 3.8: The consumed power waveforms, from nominal to -20%, across the purely resistive load R (a), in time correlation to nominal (b) (Two periods of the Vac mains).

The average or real power delivered to the load in rms values is illustrated in Fig. 3.9, according to related V_{ac} mains variation, from nominal to -20%, in 10 steps gradually, across the purely resistive load R, in time interval of 100ms – 140ms.

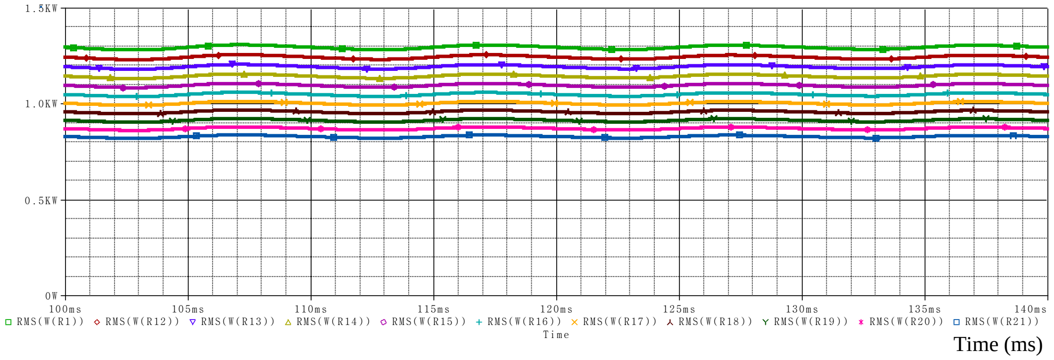

Figure 3.9: Consumed Power (W) to the related Vac mains variation from nominal to -20%.

From sections 3.1 and 3.2, Fig. 3.10 illustrates the variations of the power delivered to a purely resistive load (P_R), related to the variations of the mains (230 V_{rms}/50 Hz) across the load at a range of ±20% of its nominal value, in steps of 4.6 V_{rms}. For a better view of this event Fig. 3.11 and Table 3.1 describe the variations of the power delivered to a purely resistive load (P_R) in percentage, according to the linear variation of a mains supply. For example, for an increase of 12% in a supply voltage of 230V, increase in power consumption of 25% will be observed and a 20% increase in a supply voltage of 230V will result in an increase of 44% in power consumption.

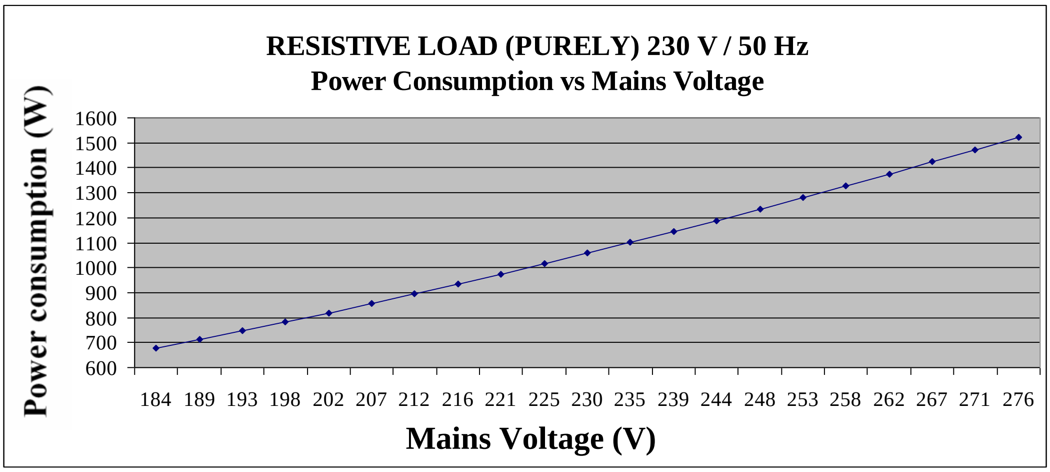

Figure 3.10: Variations of power consumption according to variation of the mains nominal supply of 230 Vrms.

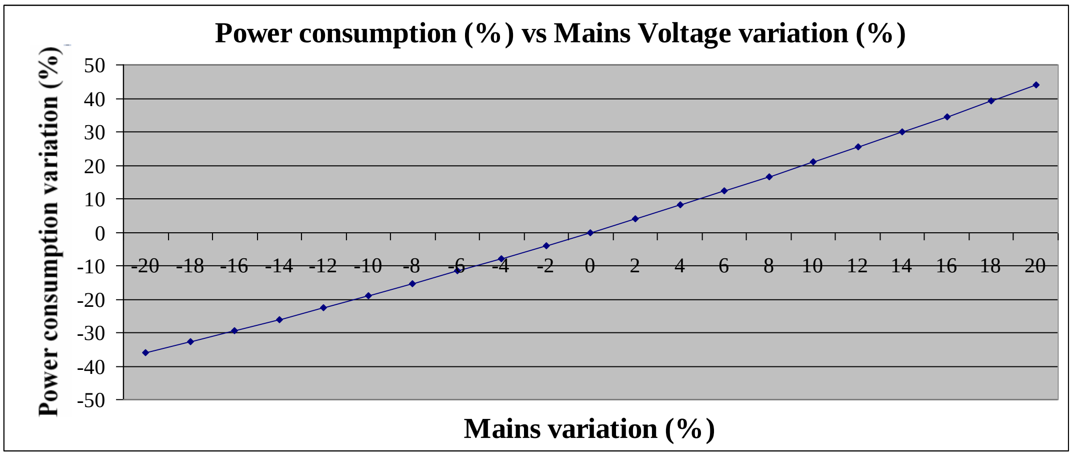

Figure 3.11: Variations of power consumption by a resistive load (PR) in percentage, according to variation of the mains nominal voltage supply by ±20%.

Table 3.1: Simulating results; variations of power consumption and variation of the mains nominal voltage supply by ±20%.

V_{rms} variation (%)	**W variation (%)**
20	44
18	39
16	35
14	30
12	25
10	21
8	17
6	12
4	8
2	4
0	0
-2	-4
-4	-8
-6	-12
-8	-15
-10	-19
-12	-23
-14	-26
-16	-29
-18	-33
-20	-36

3.2.2 V_{ac} Mains Variations on Passive Load through Practical Testing

This practical experimental testing summarises the effects of supply voltages at higher or lower values, gradually from -20%[19] to +20%, with respect to the nominal supply voltage of 230 V/ 50 Hz on two resistive loads of different kind; a heater and an incandescent lamp.

From the secondary winding of the variable transformer – variac, a single phase was used. Heater and incandescent lamp, were fed in 5 steps gradually, of approximately 23 V_{rms} each, from 184V to 276V i.e. in a voltage range of (+/- 20%). For each of these 5 values, the corresponding values were calculated and recorded with respect to the current voltage supply.

For the testing setup (Fig. 3.12), the following stuff (measuring equipment and power supply) (Table 3.2) was used.

Table 3.2: Measuring equipment and power supply

Instrument	Manufacturer	Type
V-meter	FLUKE	179 TRUE RMS MULTIMETER
A-meter	FLUKE	179 TRUE RMS MULTIMETER
Power supply – Mains Voltage	-	Through variable transformer – variac: 230/0-280 V/50 Hz

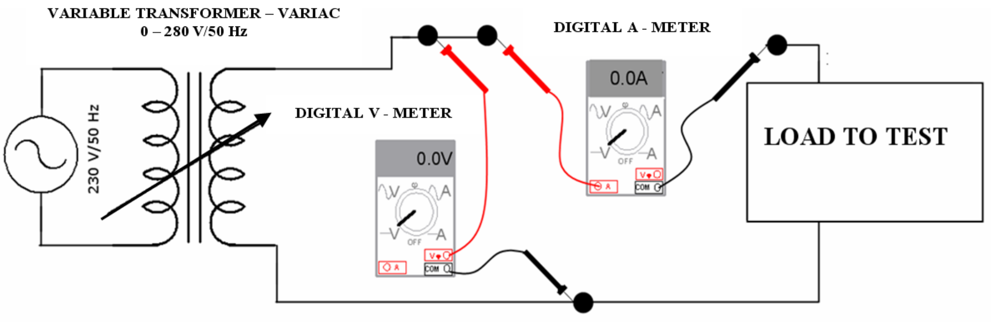

Figure 3.12: Connections for the experiments, using one phase voltage supply from the variac.

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[19] And here for a better view of overvoltage effects.

3.2.2.1 V_{ac} Mains Variations on Heater

The heater is a purely resistive load and the one that was used had the following characteristics:

HEATER – 230 V_{ac}, 1 KW, R = 50.5 Ω.

For the testing measurement a container with water and a mercury thermometer were used also.

Fig. 3.13 illustrates the consumed power that varies linearly with voltage on the load - heater. Also, Fig. 3.14 and Table 3.3 illustrate, in percentage, the consumed power variation according to mains voltage on the load. It is clear, that the consumed power on the load is changing at a rate as to the nominal respectively. For example, an increase of 20% in a supply voltage of 230V will result in an increase of power consumption of 39%. And a decrease of -20% in a supply voltage, will result in decrease of power consumption of -35%.

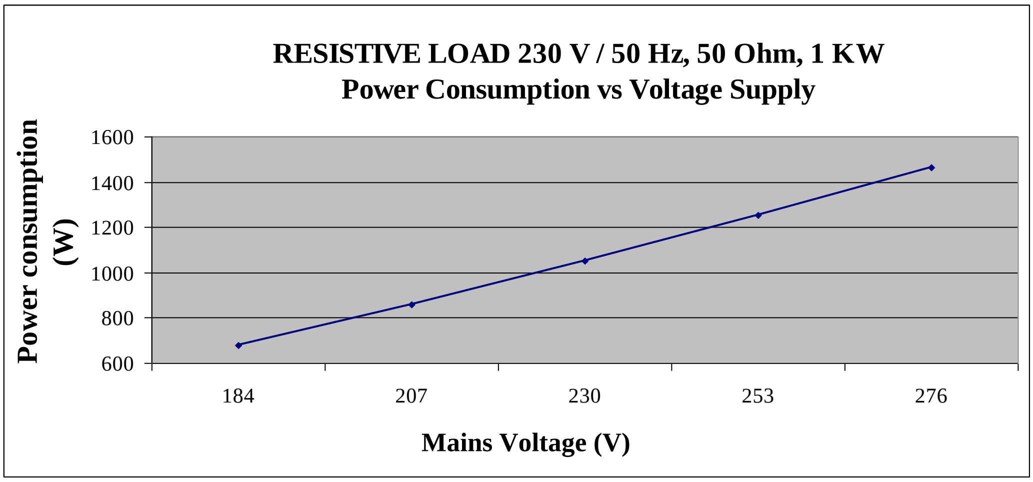

Figure 3.13: Power Consumption vs Voltage Supply.

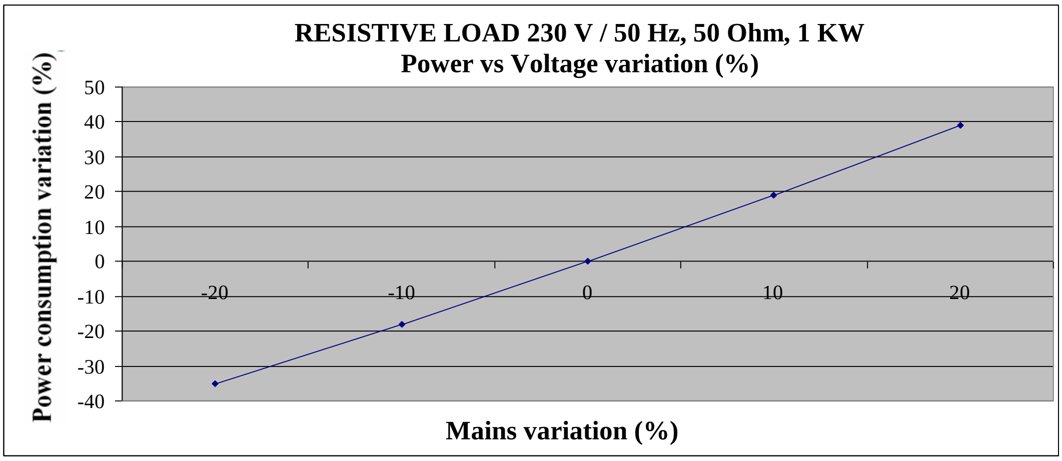

Figure 3.14: In percentage, power consumption vs mains variation.

Table 3.3: Experiment results; variations of power consumption and variation of the mains nominal voltage supply by ±20%.

V_{rms} variation (%)	**W variation (%)**
20	39
10	19
0	0
-10	-18
-20	-35

Yet, although the power consumption varies linearly on voltage variations, there are some deviations to the delay time until the water in the container starts to boil (fig. 3.15).

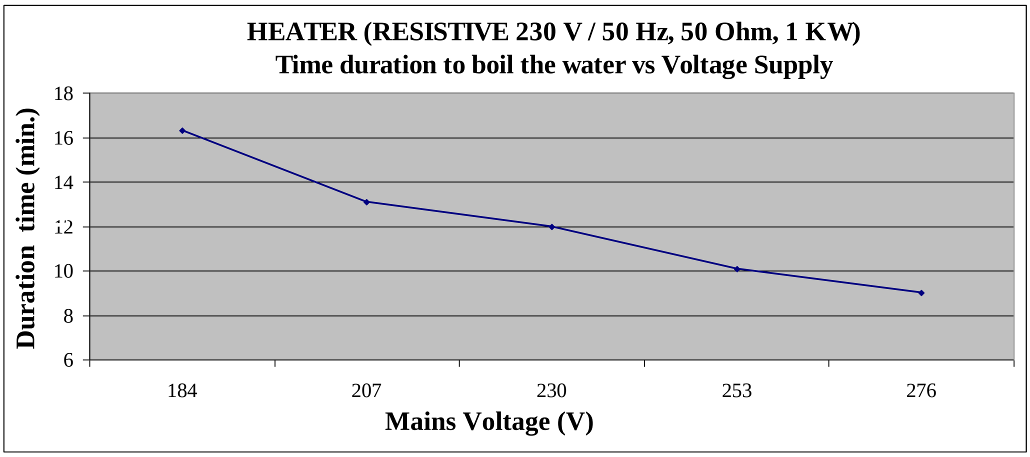

Figure 3.15: Time duration until the water starts to boil according to mains variation.

3.2.2.2 Vac Mains Variations on Incandescent Lamp

For the experimental testing, incandescent lamp with the following characteristics was chosen:

INCANDESCENT LAMP - BULB: Philips 230 V_{ac}, 40 W.

Also, for the light intensity has been chosen:

LIGHT METER: LUX HI TESTER YF-1065 Yu Fong.

For the testing measurements the light meter (Lux meter) was placed under the bulb. The light meter and the under test bulb were covered with a black box, in a dark room, to avoid possible influence of external lighting (Photo 3.1).

Fig. 3.16 illustrates the consumed power that varies linearly with voltage on the load – lamp. Also, Fig. 3.17 and Table 3.4 illustrate, in percentage, the consumed power variation according to mains voltage on the load. Here, the consumed power on the load is changing as to the nominal respectively. For example, a 20% increase in a supply voltage of 230V, will result to a 37% increase of power consumption whereas, a 20% decrease in the supply voltage, will result to a 29% power consumption decrease.

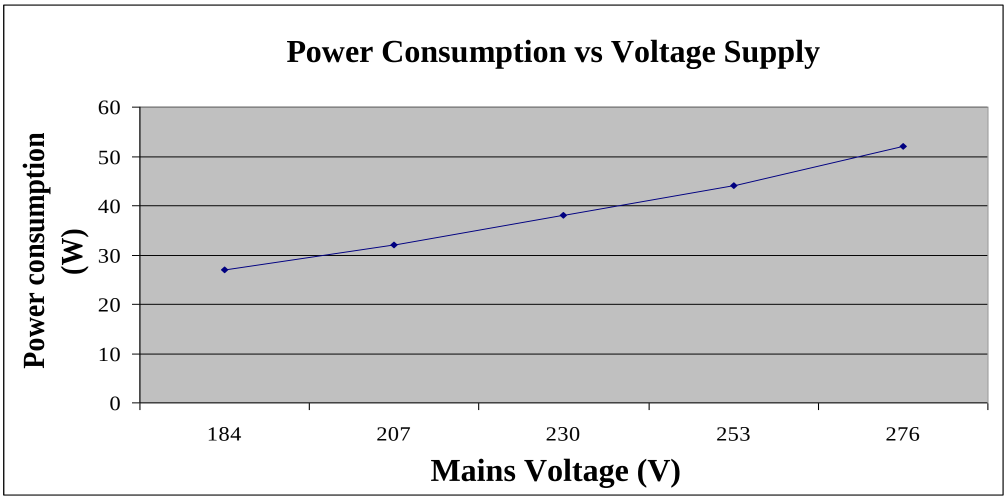

Figure 3.16: Incandesced Lamp, 230 V_{ac} / 40 W, power consumption vs voltage supply variation.

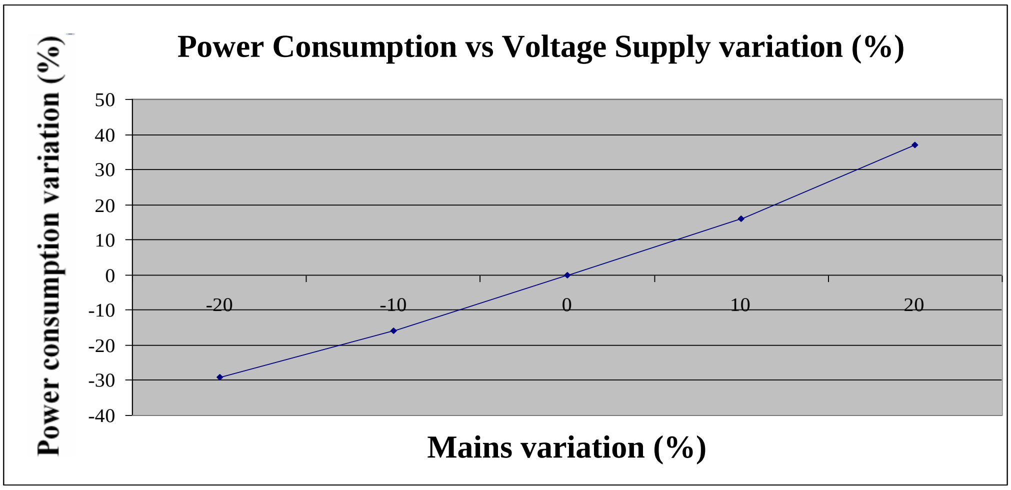

Figure 3.17: In percentage, power consumption vs mains variation.

Table 3.4: Experiment results; variations of power consumption and variation of the mains nominal voltage supply by ±20%.

V_{rms} Variation (%)	W Variation (%)
20	37
10	16
0	0
-10	-16
-20	-29

Although the light intensity (Lux) varies linearly with voltage variations, some deviation can be observed when the voltage drops below 10% with respect to mains voltage (Fig. 3.18).

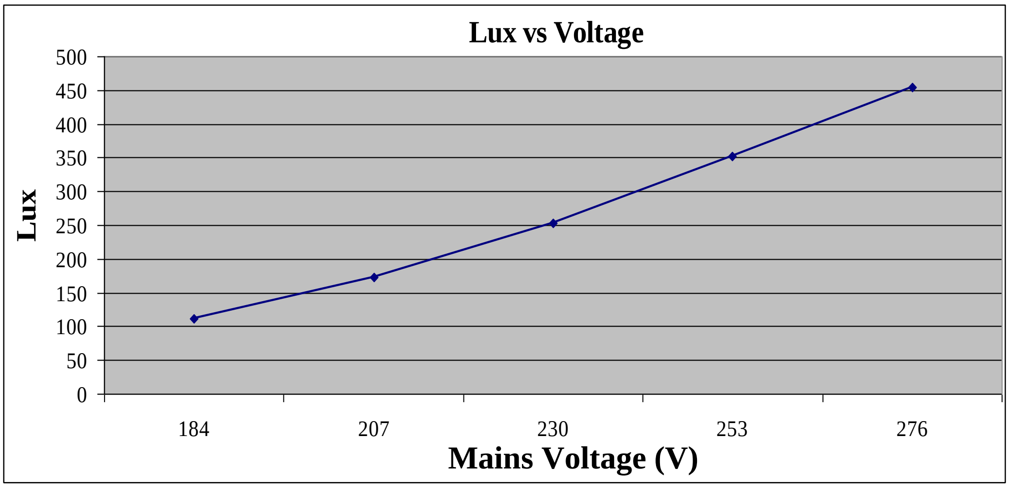

Figure 3.18: The light intensity of an incandescent lamb according to mains variation.

The following Photo 3.1 shows the system used for the experimental testing[20] for lamps.

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[20] For the experimental metering of the heater was used the same measuring instruments (digital V-meter and digital A-meter) and for power supply was used the transformer with 21 outputs from the secondary winding.

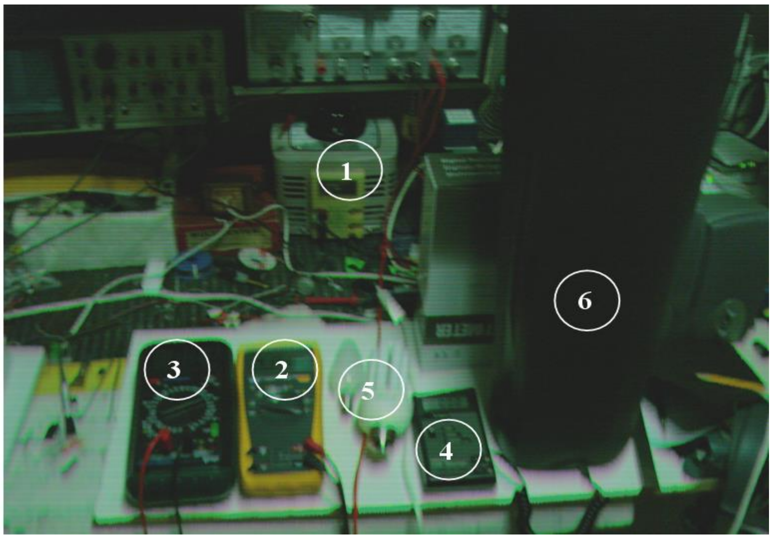

Photo 3.1: The measuring equipment and power supply for incandescent lamp test.

1: The single phase variable transformer (VARIAC).
2: The digital V-meter, connected in parallel to the voltage source.
3: The digital A-meter, connected in series too.
4: The light meter (Lux meter), placed under the bulb.
5: Lamps to test.
6: The black cover.

3.3 Electromagnetic Loads

3.3.1 V_{ac} Mains Variations on Electromagnetic Loads through Practical Testing

The following practical experimental tests summarise the effects of supply variable AC voltages with respect to the V_{ac} nominal supply on two kinds of electromagnetic loads:

- Two single phase transformers:
  - a toroidal transformer
  - a transformer with steel lamination core
- two AC motors:

- a single phase motor
- a three phase motor

Also, for the two transformers, the inductance ($L_{p\text{-}t}$) of the primary winding of the toroidal is $L_{p\text{-}t} = 2.1$ mH and the inductance ($L_{p\text{-}s}$) of the transformer with steel lamination core is $L_{p\text{-}s} = 730$ mH. From the measurements of (true), V_{rms} and I_{rms}, by the instruments, the power consumption (W) in the primary winding, according to the relation of the apparent power (VA) and the reactive power (VAR), was calculated as

$$P = \sqrt{S^2 - Q^2} \quad (W) \qquad (3.1)$$

Where

S – Apparent power

Q – Reactive power

3.3.1.1 V_{ac} Mains Variations on Toroidal Transformer

For a toroidal transformer was chosen transformer with the following characteristics: TOROIDAL TRANSFORMER: 230 V/7 V, 300 VA.

For the testing setup (Fig. 3.19), the same stuff like in resistive loads (Table 3.2) was used.

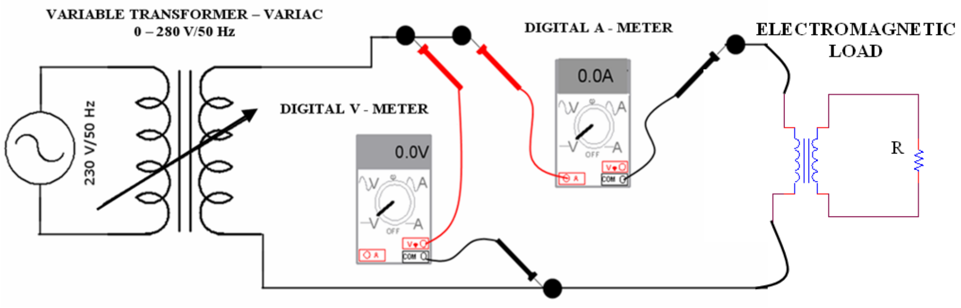

Figure 3.19: Connections for the experiments, using one phase voltage supply from the variac.

The transformer was fed in 5 steps gradually, of approximately 23 V_{rms} each, from 184V to 276V i.e. in a voltage range of (+/- 20%). For each of these 5 values, the corresponding values were calculated and recorded with respect to the current voltage supply. Across the secondary winding was connected a pure resistive load of 2.5 Ohm.

Primary winding

Fig. 3.20 illustrates the consumed power (W)[21] that varies linearly with the voltage supply on the primary winding. Also, Fig. 3.21 and Table 3.5 illustrate in percentage, power (W) variation according to mains voltage variation. Here, the consumed power in the primary winding – load is changing almost as to the nominal respectively. For example, a 20% increase in a supply voltage of 230V, will result to a 45% increase of power consumption (W) whereas, a 20% decrease in the supply voltage will result to a 38% decrease.

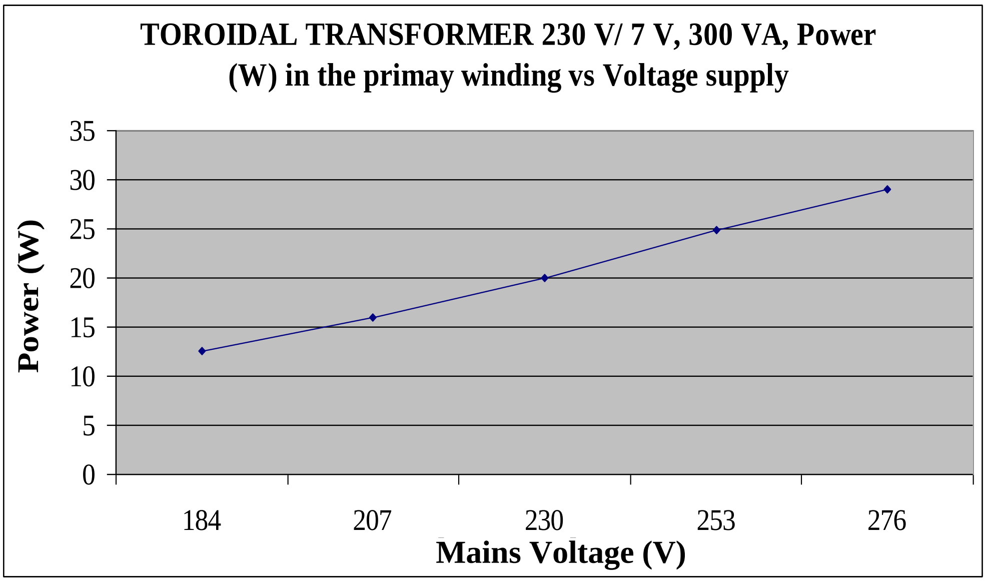

Figure 3.20: Power consumption in the prime winding of the transformer vs mains variations.

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[21] APPENDIX I for power (VA).

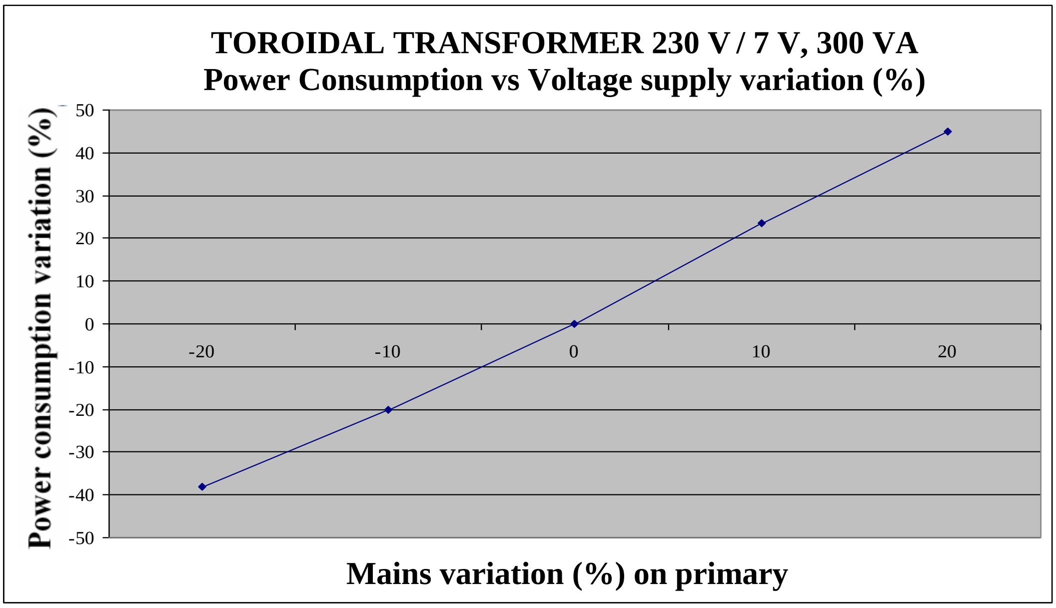

Figure 3.21: In percentage, power (W) vs mains variation on the primary winding of the transformer.

Table 3.5: Experiment results; variations of power (W) and variation of the mains nominal voltage supply by ±20% on the primary winding.

V_{rms} Variation (%)	**W Variation (%)**
20	45
10	23.5
0	0
-10	-20
-20	-38

Secondary winding

Fig. 3.22 illustrates the voltage (V) on the secondary winding of the transformer, connected to the resistive load of R = 2.5 Ohm (Fig. 3.19), that varies almost linearly with the voltage supply on the primary. Fig. 3.23 illustrates in percentage, the voltage variation on the secondary according to voltage supply variation to the primary. Here, the voltage (V) on the secondary load – winding changes almost as to the voltage on the primary, respectively. For example, a 20% increase in a supply voltage of 230V on the primary, will result to a 16% increase of voltage (V) on the secondary, whereas a 20% decrease in mains will result to a 21% decrease to the secondary.

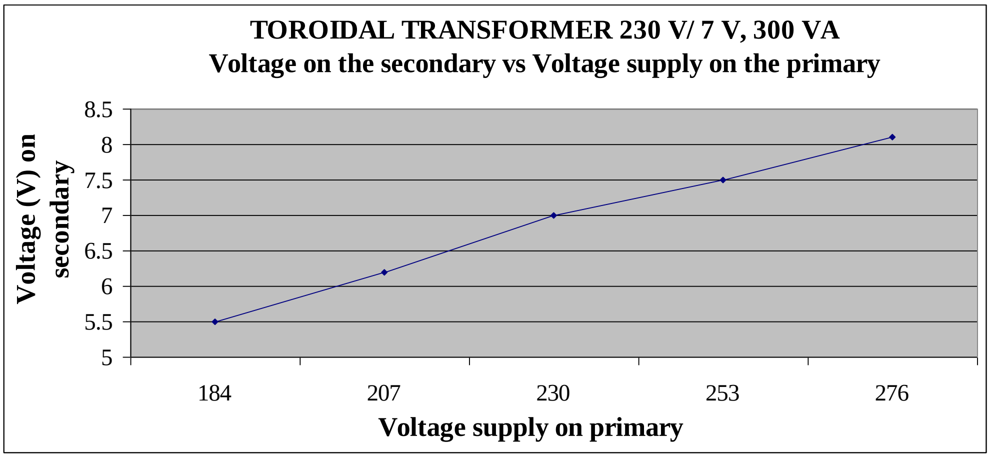

Figure 3.22: Voltage (V) on the secondary winding of the transformer vs Voltage supply variation on the primary.

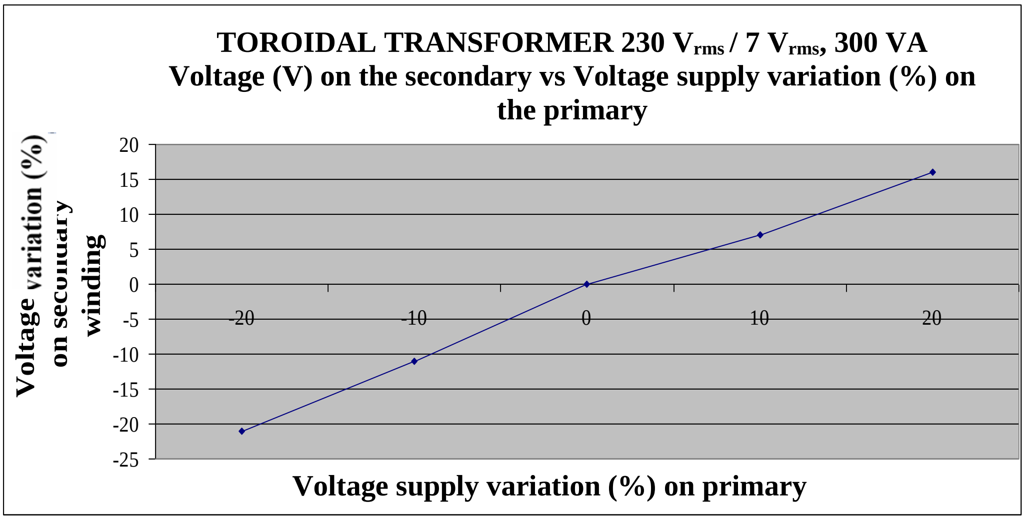

Figure 3.23: In percentage, Voltage (V) on the secondary winding of the transformer vs Voltage Supply variation on the primary.

Fig. 3.24 illustrates the consumed power (W) in the load (R), connected to the secondary winding that varies linearly with voltage supply on the primary. Also, Fig. 3.25 and Table 3.6 illustrate, in percentage, the consumed power variation in the load

(R), in relation with the mains voltage supply on the primary winding. The consumed power is almost straight proportional to mains variations, changing at a rate as to the nominal respectively. For example, an increase of 20% in a supply voltage of 230V will result to an increase of power consumption in the load (R) of 36.3%. And a decrease of -20% in a supply voltage, will result in decrease of power consumption of -38.2%[22].

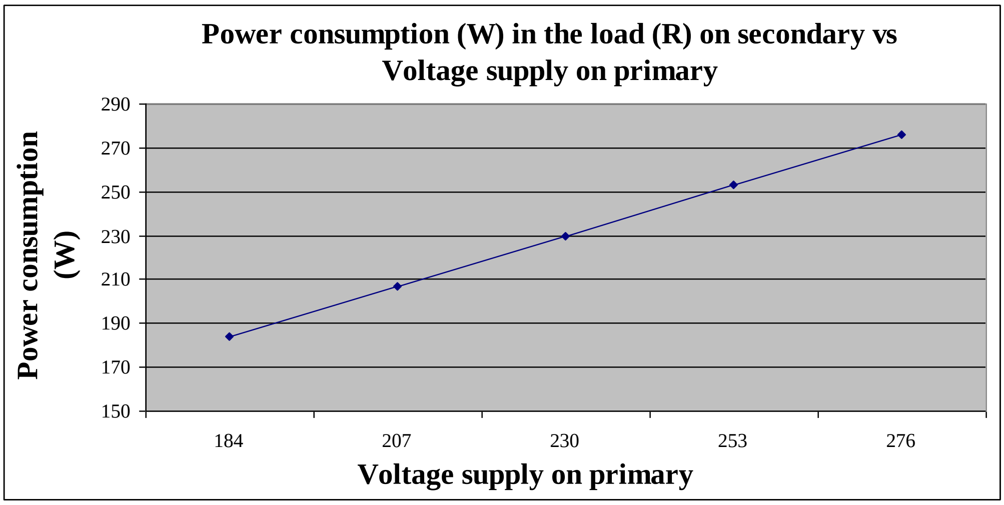

Figure 3.24: TOROIDAL TRANSFORMER 230 V_{rms} / 7 V_{rms}, 300 VA, Power consumption (W) in the load (R) vs mains variation.

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[22] As the load (R) at the secondary is ohmic (Fig. 3.19) there is no phase difference between current and voltage, and consequently the power factor is unitary. This means that, according to mains supply variation, the variation of the apparent power (VA) on the secondary winding is matching with the variation of the power (W) on the resistive load (R).

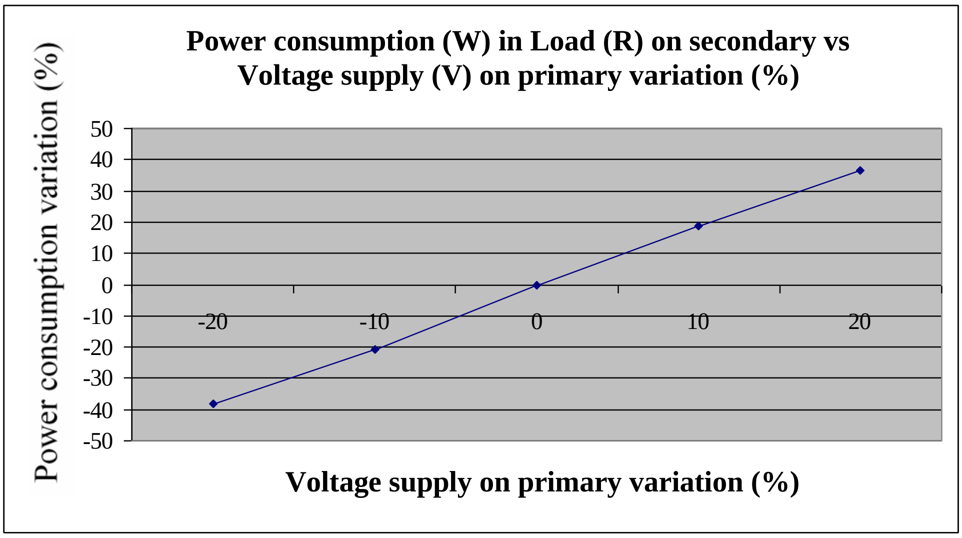

Figure 3.25: TOROIDAL TRANSFORMER 230 V_{rms} / 7 V_{rms}, 300 VA, in percentage, power consumption in the load (R) vs mains variation.

Table 3.6: Experimental results; variations of power consumption in the load (R) and variation of the mains nominal voltage supply by ±20%.

V_{rms} Variation (%)	W Variation (%)
20	36.37
10	18.62
0	0
-10	-20.91
-20	-38.26

3.3.1.2 V_{ac} Mains Variations on Transformer with Steel Laminations Core

For a steel laminations core transformer was chosen transformer with the following characteristics:
STEEL LAMINATIONS CORE TRANSFORMER : 230 V/ 39 V, 300 VA

And here, the same testing setup (Fig. 3.19) and the same stuff (Table 3.2) were used.

The transformer was fed in 5 steps gradually, of approximately 23 V_{rms} each, from 184V to 276V i.e. in a voltage range of (+/- 20%). For each of these 5 values, the corresponding values were calculated and recorded with respect to the current voltage supply. Across the secondary winding was connected a pure resistive load of 21 Ohm.

Primary winding

Fig. 3.26 shows the power consumption (W)[23] in the prime winding of the transformer with steel laminations, according to mains variations from -20% to +20%. The consumed power (W) varies linearly with voltage supply on the primary winding. Also, Fig. 3.27 and Table 3.7 illustrate in percentage, the consumed power (W) variation, according to mains voltage variation. Here, the power consumption on the primary load – winding is changing almost as to the nominal, respectively. For example, a 20% increase in a supply voltage of 230V, will result to about of a 40% increase of power consumption (W) whereas, a 20% decrease in the supply voltage, will result to about of a -36% decrease.

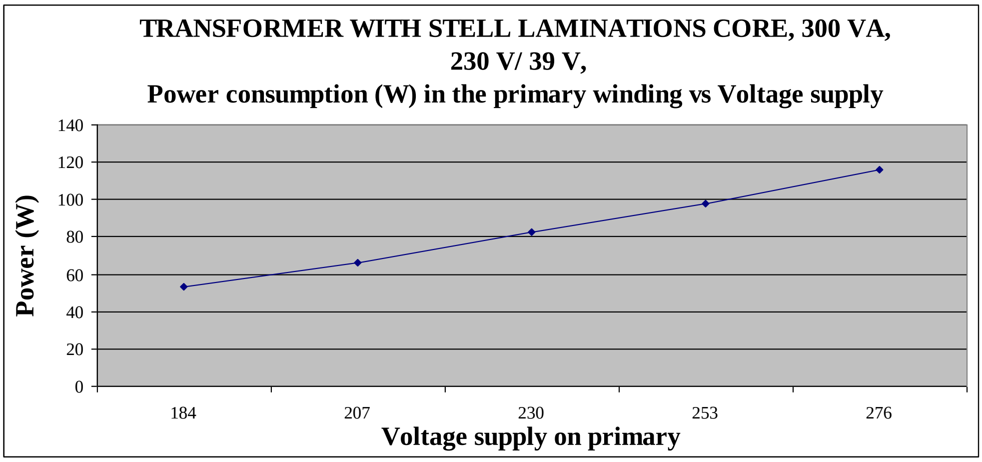

Figure 3.26: Power consumption (W) in the prime winding of the transformer vs mains variations.

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[23] APPENDIX I for power (VA).

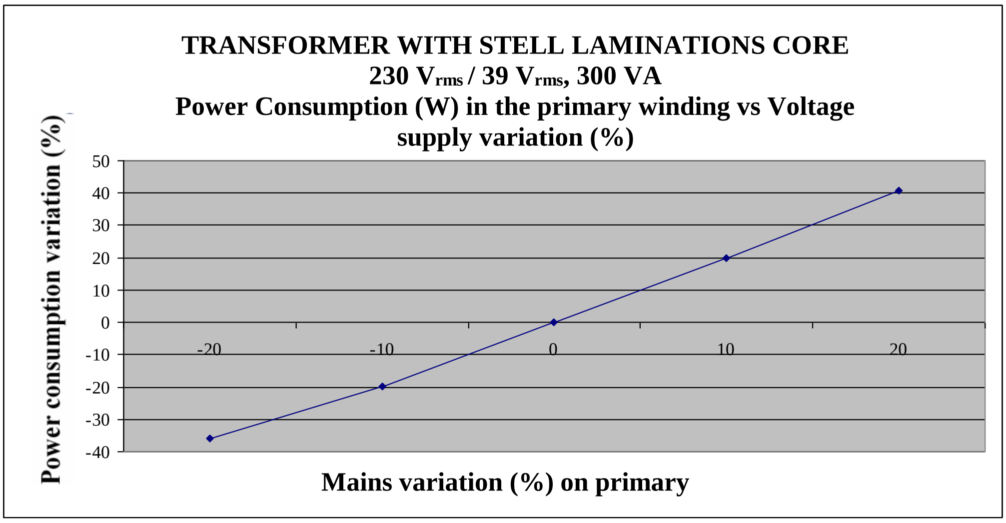

Figure 3.27: In percentage, power (VA) vs mains variation on the primary winding of the transformer.

Table 3.7: Experimental results, variations of power consumption (W) and variation of the mains nominal voltage supply by ±20%.

V_{rms} Variation (%)	W Variation (%)
20	40.67
10	20
0	0
-10	-19.86
-20	-35.83

Secondary winding

Fig. 3.28 illustrates the voltage (V) on the secondary winding of the transformer connected to the resistive load of R = 21 Ohm (Figure 3.19), that varies almost linearly with the voltage supply on the primary. Fig. 3.29 illustrates in percentage, the voltage variation on the secondary according to voltage supply variation to the primary. Here, the voltage (V) on the secondary load – winding changes almost as to the voltage on the primary, respectively. For example, a 20% increase in a supply voltage of 230V on the primary, will result to a 16% increase of voltage (V) on the secondary, whereas a 20% decrease in mains will result to a 20% decrease.

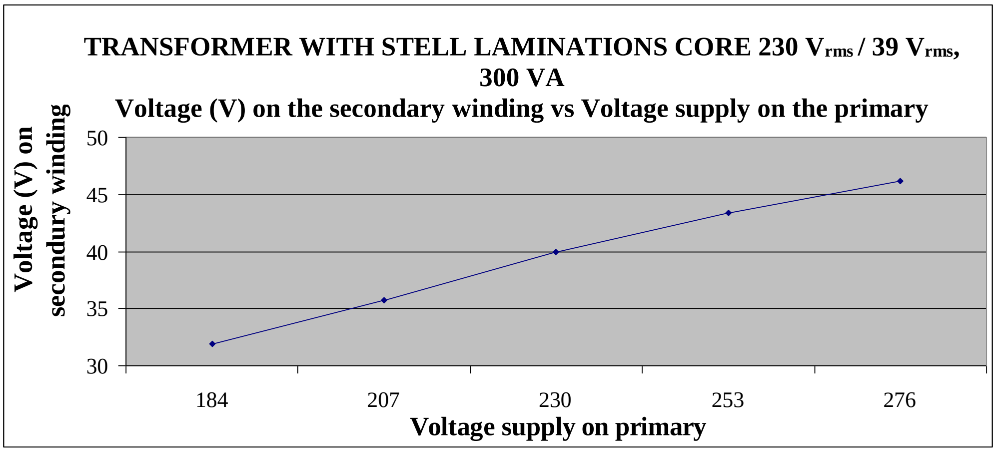

Figure 3.28: Voltage (V) on the secondary winding vs Voltage Supply variation on the primary winding of the transformer.

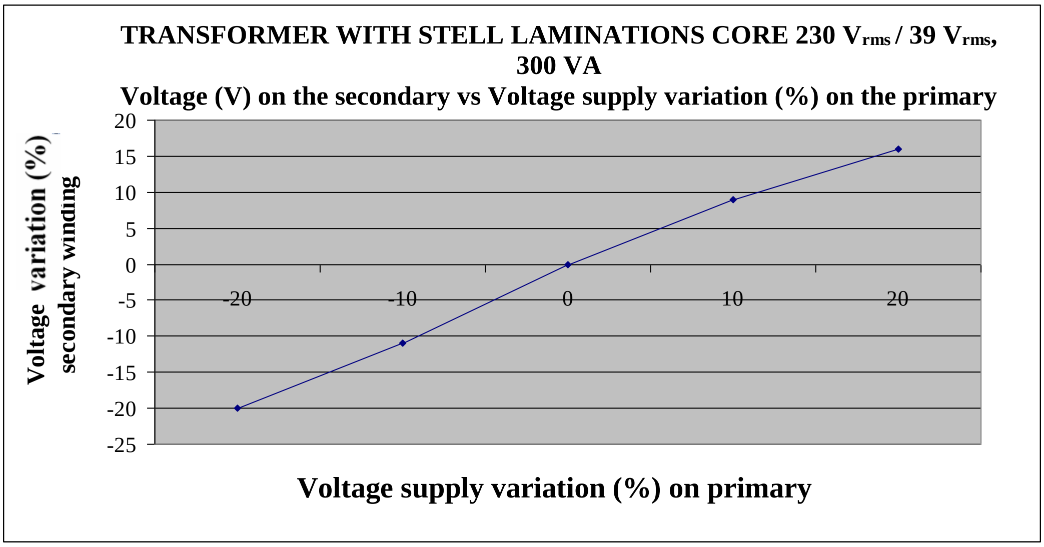

Figure 3.29: In percentage, Voltage (V) on the secondary winding vs Voltage Supply variation on the primary winding of the transformer.

Fig. 3.30 illustrates the consumed power (W) in the load (R), connected to the secondary winding that varies linearly with voltage supply on the primary. Also, Fig. 3.31 and Table 3.8 illustrate, in percentage, the consumed power variation in the load (R), in relation with the mains voltage supply on the primary winding. The consumed power is almost straight proportional to mains variations, changing at a rate as to the nominal respectively. For example, an increase of 20% in a supply voltage of 230V will result to an increase of power consumption in the load (R) of 34%. And a decrease of -20% in a supply voltage, will result in decrease of power consumption of -37%[24].

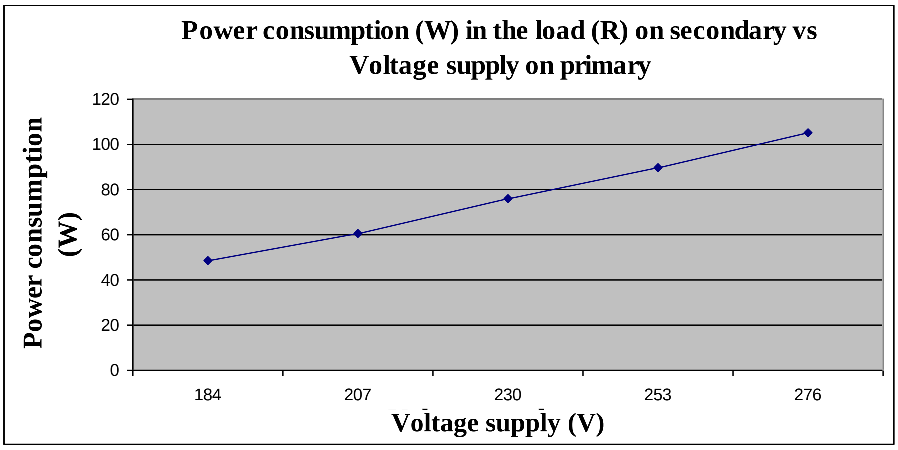

Figure 3.30: TRANSFORMER WITH STELL LAMINATIONS CORE 230 Vrms / 39 Vrms, 300 VA, Power consumption in the load (R) vs mains variation.

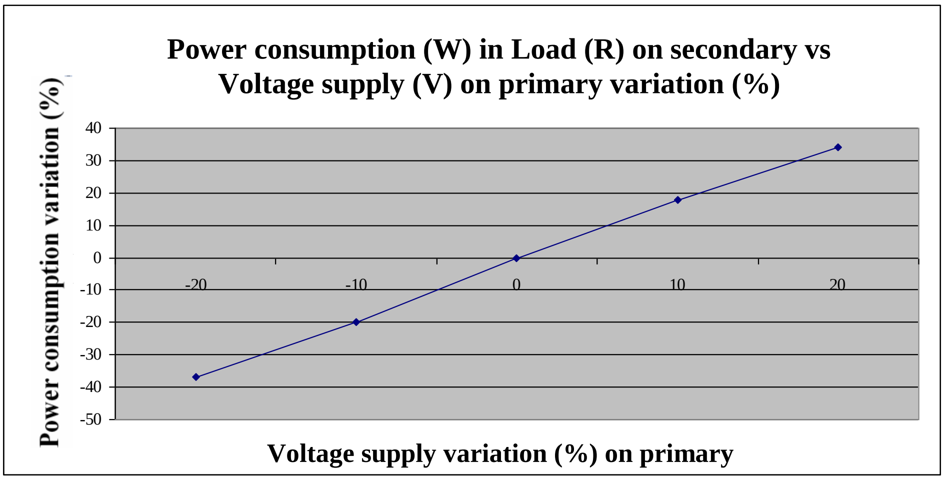

Figure 3.31: TRANSFORMER WITH STELL LAMINATIONS CORE 230 Vrms / 39 Vrms, 300 VA, Power consumption (W) in the load vs mains variation.

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[24] As the load (R) at the secondary is ohmic (Fig. 3.19) there is no phase difference between current and voltage, and consequently the power factor is unitary. This means that, according to mains supply variation, the variation of the apparent power (VA) on the secondary winding is matching with the variation of the power (W) on the resistive load (R).

Table 3.8: Experimental results; variations of power consumption in the load (R) and variation of the mains nominal voltage supply by ±20%.

V_{rms} variation (%)	**W variation (%)**
20	34
10	18
0	0
-10	-20
-20	-37

3.3.1.3 V_{ac} Mains Variations on Single Phase AC Motor

For a single phase ac motor, was chosen a motor with the following characteristics: FEED BACK 64 - 110: Single phase induction motor, capacitor start/induction run, 220 V/300 VA.

Also, the motor was connected with a constant load – break, a swinging field programmable dynamometer, the FEED BACK 67 – 502, in order to measure the torque of the motor according the voltage supply variation.

For the practical experiments (Photo 3.2) the following stuff (Table 3.9), measuring equipment and power supply was used.

Table 3.9: Measuring equipment and power supply.

Instrument	Manufacturer	Type
V-meter	Digimess	DM 200 Digital Multimeter
A-meter	Digimess	DM 200 Digital Multimeter
Power digital meter	Voltech	Power Analyser – PM 1000
Power supply – Mains Voltage	-	Through variable transformer – variac: 230/0-280 V /50 Hz.

The motor was fed in 10 steps gradually, of approximately 4.6 V_{rms} each, from 230 V (nominal phase voltage) to 276V i.e. in a voltage range of 0% to +20%. For each of the 11 values, the corresponding following values:

- Power consumption (W) in the motor
- in percentage, power consumption (W) in the motor
- power factor (PF) by the motor
- the speed of the axis of the motor RPM (rotation per minute)
- the torque (Nm) of the motor

were recorded with respect to the current voltage supply.

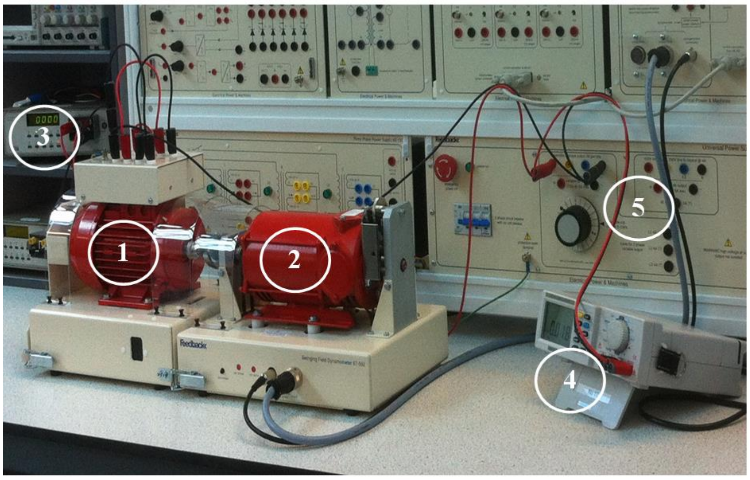

Photo 3.2: The measuring equipment and power supply for single phase electric motor.

1: The single phase electric motor.
2: The swinging field dynamometer working as a brake.
3: The digital power analyzer.
4: The digital V-meter, connected in parallel too to V_{ac} source.
5: The ac power supply.

Fig. 3.32 illustrates the power consumption (W) on the load – motor according to the voltage supply variation from the nominal value up to +20%[25]. Here, the power consumption tends to decrease linearly, as the voltage supply increases until a specific area, and then tends to increase linearly until the voltage (V) arises up to +20%.

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[25] APPENDIX G for power (VA).

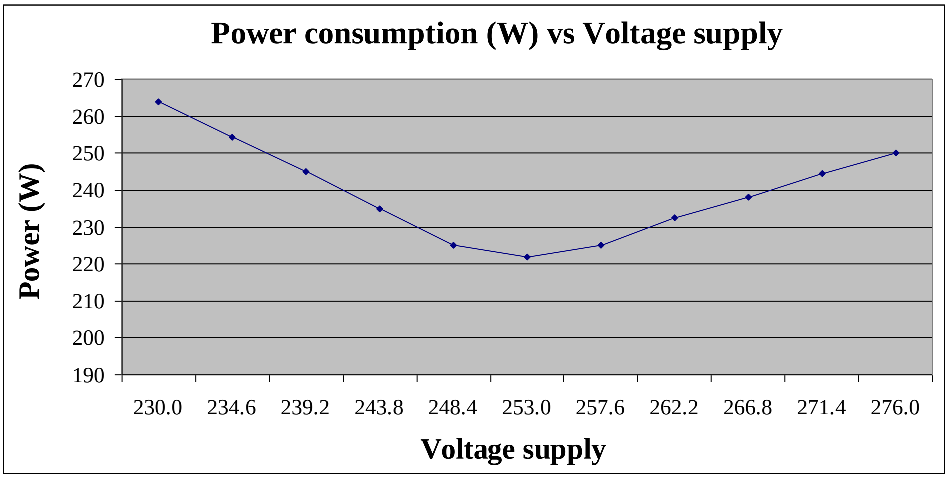

Figure 3.32: Power consumption (W) on the ac single phase motor vs the voltage supply.

Fig. 3.33 and Table 3.10 illustrate in percentage, the power consumption (W) variation on the motor according to mains voltage variation. The power (W) is decreasing linearly as the voltage supply increases up to about +10%, and then increases almost linearly with respect to the supply (V). For example, a 10% increase in a supply voltage of 230V, will result to a -16% of the power consumption (W), and a 20% increase of the supply will result to a -5.3% of the power (W).

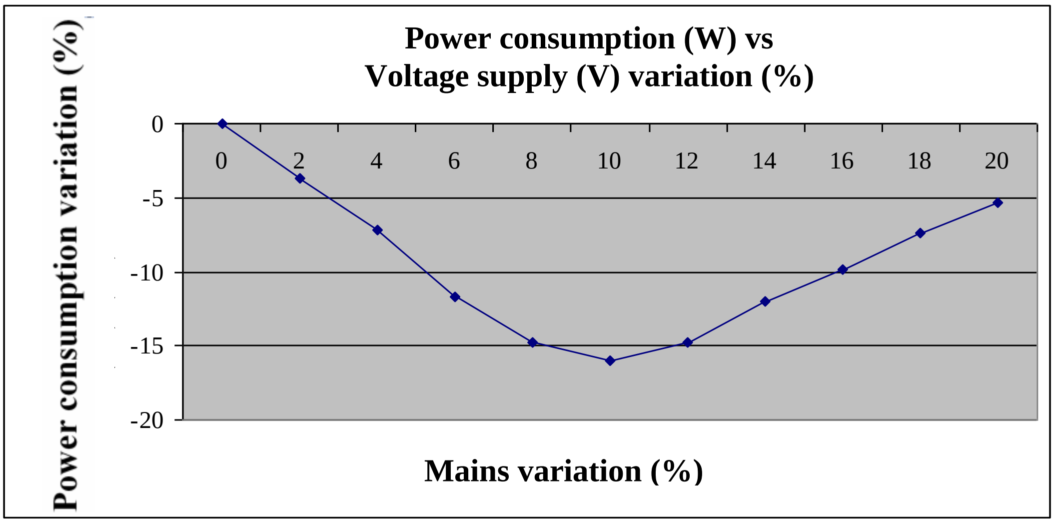

Figure 3.33: In percentage, power (W) in motor vs mains variation.

Table 3.10: Experiment results; variations of power consumption (W) on the motor and variation of the nominal voltage supply by up to +20%.

V_{rms} variation (%)	W variation (%)
20	-5.3
18	-7.38
16	-9.84
14	-12
12	-14.77
10	-16
8	-14.77
6	-11.66
4	-7.2
2	-3.67
0	0

Fig. 3.34 illustrates the power factor (PF) of the motor that decreases significantly and approximately linearly with the increase of the voltage supply.

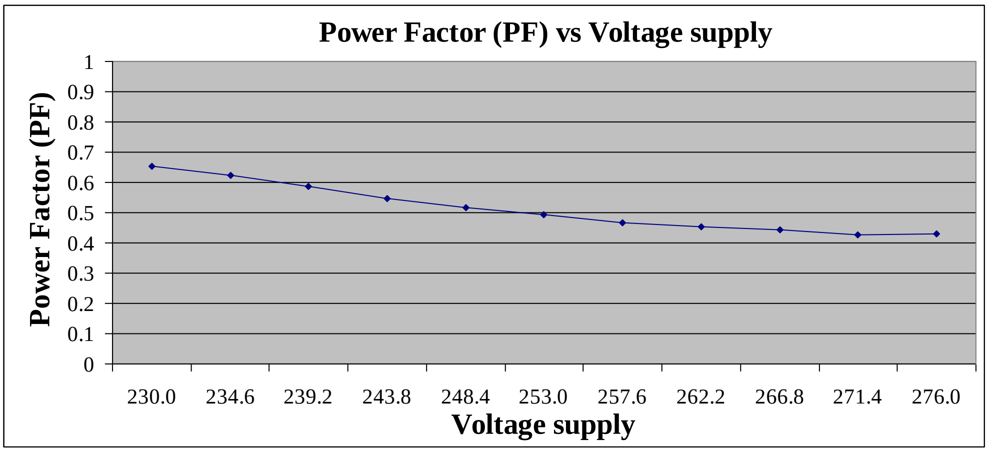

Figure 3.34: Power factor (PF) on motor vs the voltage supply.

Fig. 3.35 illustrates the speed (rotations per minute RPM) of the motor axis that varies not significantly according to voltage supply variation.

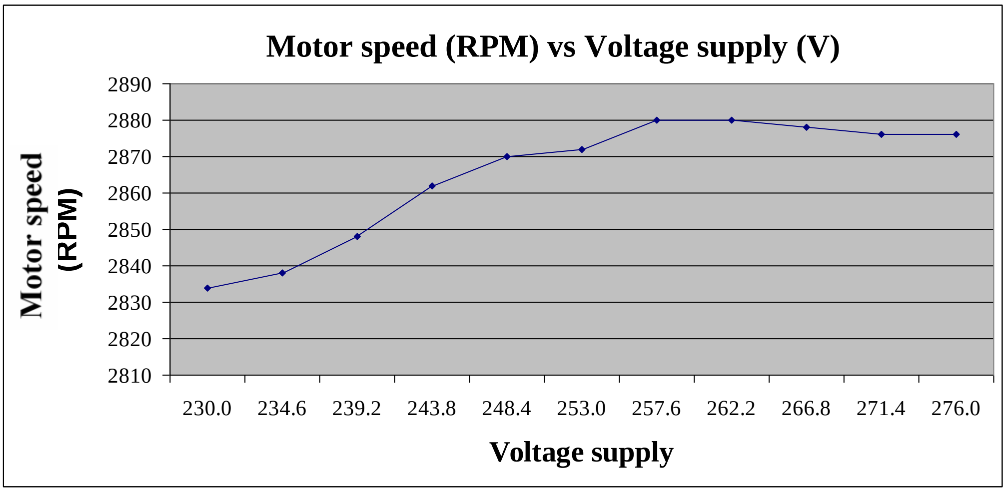

Figure 3.35: The speed of the axis vs voltage supply.

Fig. 3.36 illustrates the torque (Newton x meter, Nm) of the motor that is reduced according to voltage supply increase. The load – brake was set so that the torque was at 0.44 Nm, at the nominal phase voltage of 230 V on the motor.

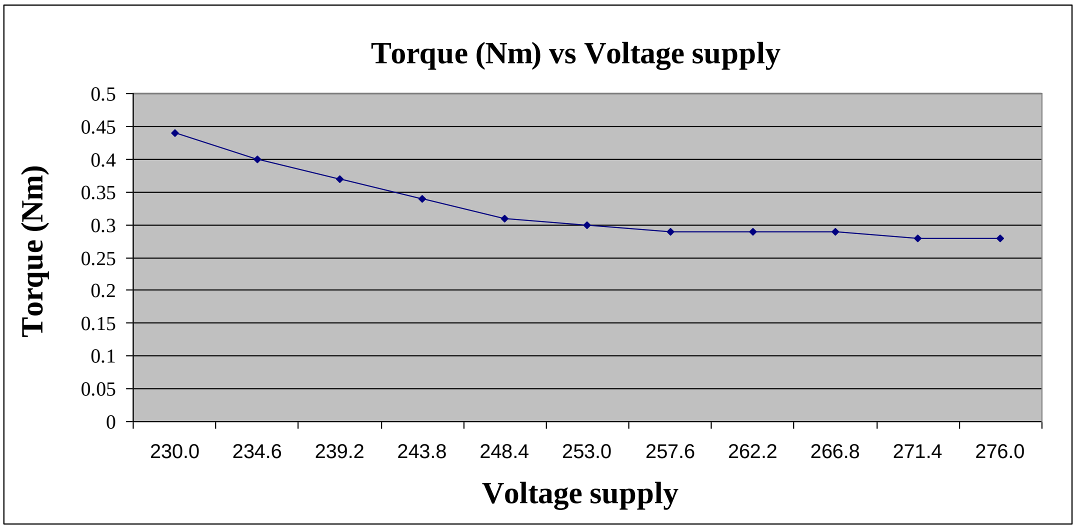

Figure 3.36: The Torque (Nm) vs Voltage supply.

3.3.1.4 V_{ac} Mains Variations on a Three Phase AC Motor

For a three phase ac motor, was chosen a motor with the following characteristics: FEED BACK 64 - 501: Three phase induction motor, squirrel cage, 3-Phase, 300 VA.

Also, the motor was connected with a load – brake, a swinging field programmable dynamometer, the FEED BACK 67 – 502, in order to measure the torque of the motor according the voltage supply variation.

For the practical experiments the same stuff (measuring equipment and power supply[26]) (Table 3.9) was used.

The motor was fed in 10 steps gradually, of approximately 4.6 V_{rms} each, from 230 V (nominal phase voltage) to 276 V i.e. in a voltage range of 0% to +20%. For each of the 11 values, the corresponding following values:

- Power consumption (W) on the motor
- In percentage, power consumption (W) on the motor
- power factor (PF) by the motor
- the motor speed, RPM (rotation per minute)
- the torque (Nm) of the motor

were recorded with respect to the current voltage supply.

Fig. 3.37 illustrates the power consumption (W) in the load – motor according to the voltage supply variation up to +20%[27]. Here, in contrast to one single phase ac motor, the three phase motor appears a linear increase in relation to linear increase of the voltage supply.

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[26] Three phase now.

[27] APPENDIX G for power (VA).

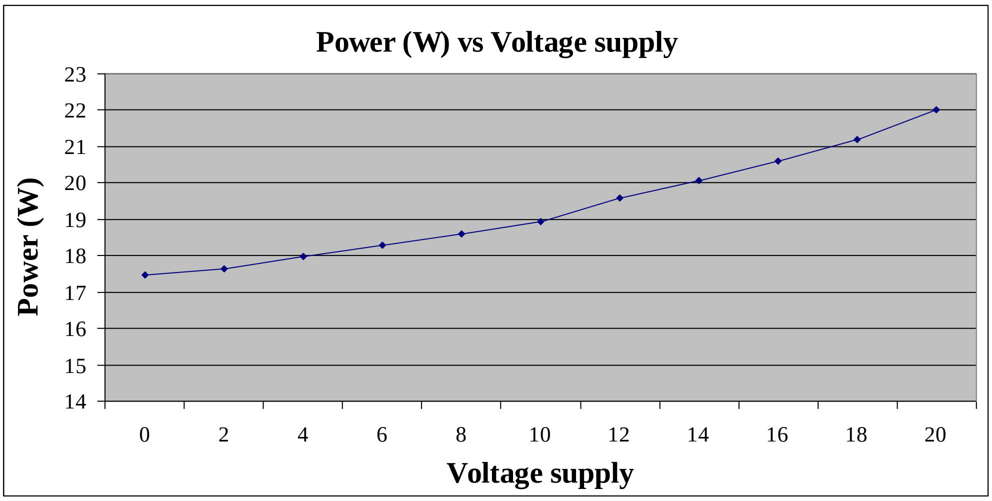

Figure 3.37: Power consumption (W) on the three phase ac motor vs the voltage supply.

Fig. 3.38 and Table 3.11 illustrate in percentage, the power consumption (W) variation on the motor according to mains voltage variation. Here, the power (W) is increasing almost linearly as to the nominal respectively. For example, a 10% and 20% increase in a supply voltage of 230V, will result to 8.5% and 26% increase of the power consumption (W) respectively.

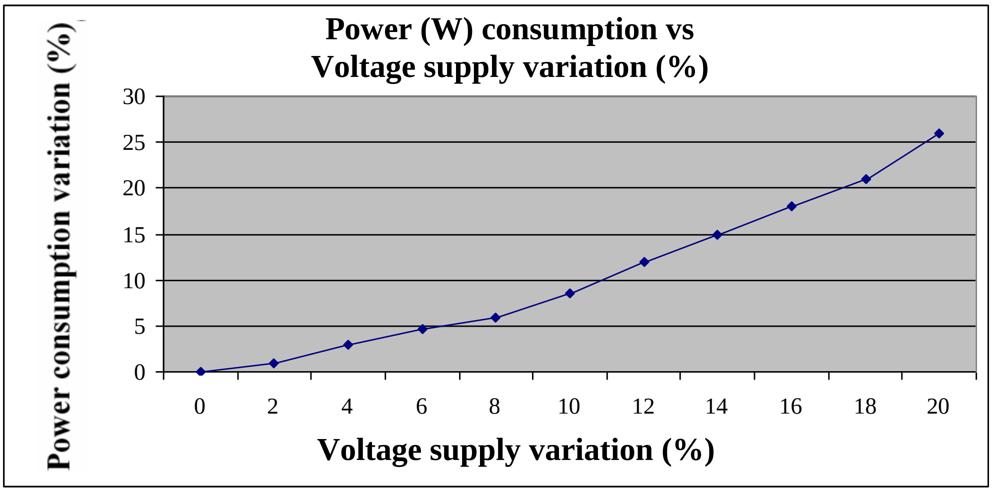

Figure 3.38: In percentage, power (W) on the motor vs mains variation.

Table 3.11: Experiment results; variations of power consumption (W), on the motor and variation of the nominal voltage supply by up to +20%.

V_{rms} variation (%)	W variation (%)
20	26
18	21
16	18
14	15
12	12
10	8.5
8	5.95
6	4.7
4	3
2	1
0	0

Fig. 3.39 illustrates the power factor (PF) of the motor that decreases significantly and approximately linearly with the increase of the voltage supply.

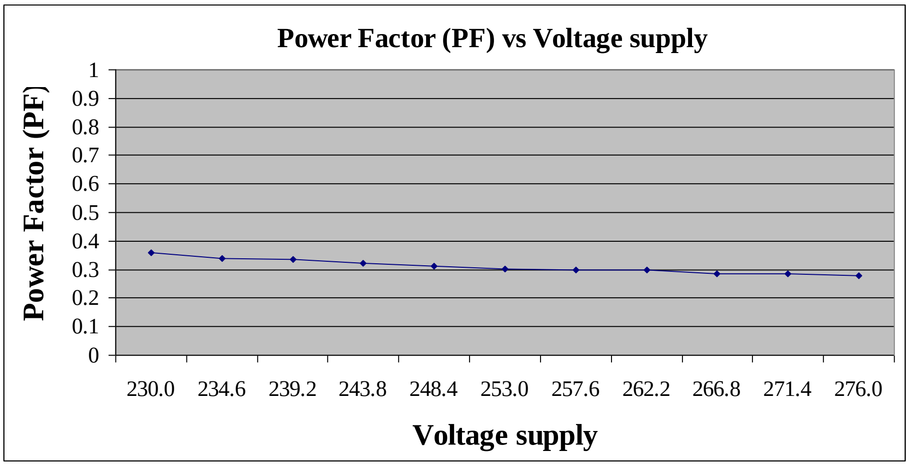

Figure 3.39: Power factor (PF) on motor vs the voltage supply.

Fig. 3.40 illustrates the speed (rotations per minute RPM) of the motor axis that varies not significantly according to voltage supply variation.

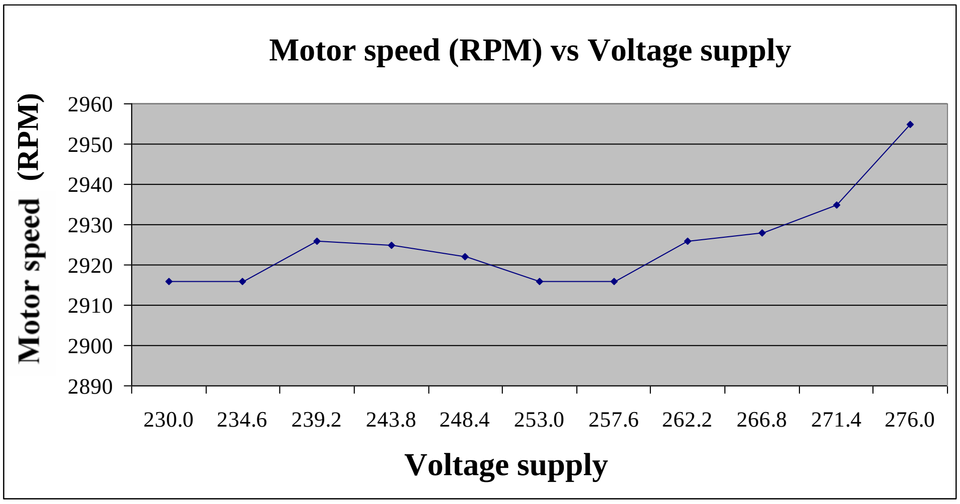

Figure 3.40: The speed of the axis vs voltage supply.

Fig. 3.41 illustrates the torque (Newton x meter Nm) of the motor that in low load (low level brake) is almost constant according to voltage supply increase. The load – brake was set so that the torque was at 0.05 Nm, at the nominal phase voltage of 230 V on the motor.

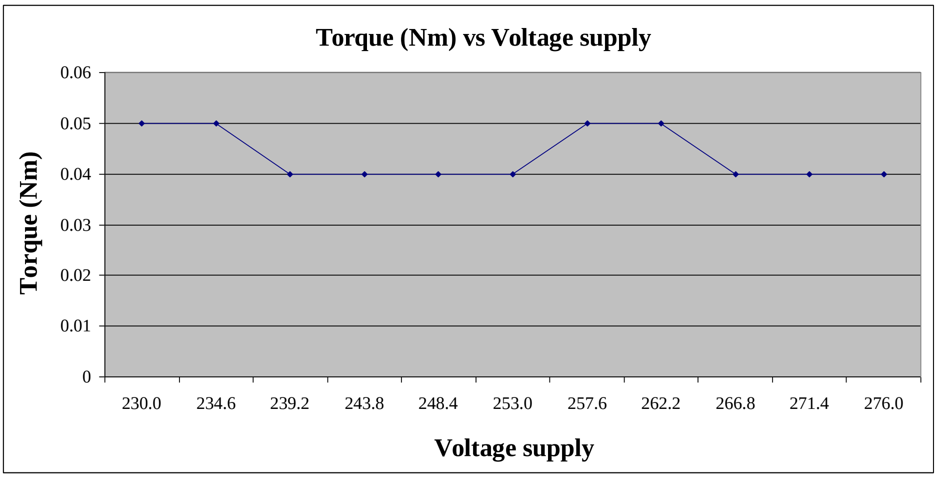

Figure 3.41: The Torque (Nm) vs Voltage supply.

3.4 Summary

In passive loads, if the voltage supply increases on a purely resistive load, the power consumption on the load increases accordingly.

In the case of the heater (Ohmic load, R), the power consumed in it, is converted to heat. As mentioned above, the power consumed by a resistor (R) can be estimated by the equation 3.2. Since the energy dissipated by the resistive element during a time interval of the applied voltage is

$$W = P \cdot t \text{ (Wattseconds, Joules, J)} \quad (3.2)$$

Where
P – Power consumption in a resistive (Ohmic, R) load
t – Time interval in seconds
W – Energy dissipated

Therefore a 20% overvoltage with respect to the voltage mains of the heater will result to a relative heating increase.

In the case of incandescent lamp, the +20% overvoltage with respect to the voltage mains of, will cause the relative increase of the light intensity of the lamp – load.

In the case of electromagnetic loads, the amount of power consumed in doing useful work is the primary factor in determining power demand and a small amount of overvoltage will result in only a slight increase of power consumption. Generally the power consumed is approximately proportion to (v).

In the case of transformers, when the secondary winding is connected with a pure resistive load (R), the power (VA) on the windings varies almost linearly according the linear variations of mains.

In the case of motors, when voltage supply increases up to +20%:

- Power Factor decreases at about 10 – 20%

- an increase of Apparent Power (VA) at about 50 – 65%
- an almost non significant variation of consumed power (W)
- an increase of motor speed at about 1.4% with constant brake
- the torque is reduced at about 32% with a constant brake, but as the brake is minimised the torque remains constant

A different category of power loads are the non-linear loads. In this case, the currents through them are not directly proportional to the supplied voltages but they depend on the nature of the loads. This means that the overvoltage effects on non-linear loads depend on the nature of the loads. Chapter 4 will investigate overvoltage effects on non-linear loads.

Chapter 4: Analysis of Overvoltage Effects on Non-linear Loads

4.1 Introduction

A load is defined as non-linear when the drawn current is not direct proportional to the applied voltage, but it depends on the impedance of the load. Consequently, when a supply voltage is sinusoidal the current passing through the non-linear load is other than sinusoidal, depending on the impedance variations. In this category of non-linear loads are included fluorescent or gas discharge lamps and active loads.

Fluorescent or gas discharge lamps in contrast to incandescent they consume less energy and their work is not based on the luminance from the ohmic filament, but they contain a gas that is stimulated to emit visible light by current passing through. Also, they show a decrease in resistance with voltage, which is often called “negative resistance”. This resistance is inherently unstable, and additional components are required to limit the current. This may be either a simple inductor, or a complex electronic circuit.

All types of electronic equipment or equipment with switch-mode power supplies come under the category of active loads. Examples of this type of load are computers, printers, fax machines, TV etc. The relationship between efficiency and applied voltage is determined by the design of the electronics.

With the fact that there is big number of active loads, from simple single phase ac-dc converters, ac-ac regulators to complex, like computers, printers, fax machines, TVs etc. the amount of power consumed is delivered in response to the load demand. This load demand mainly comes from the individual passive loads, like resistive, electromagnetic etc. who need the power to produce the useful work. The semiconductors who drive the power supply must have the proper power specifications to withstand the load demands. Therefore the power consumed in an active load depends mainly on these individual passive loads. So, the overvoltages, it is understandably, will affect all the system of an active load.

The power requirement of an active load is the main factor in the value of the power consumed. It is clear, that most of them contain electronic power converters in order to covert the ac supply voltage according to voltage demands of the analog and digital circuits. Also, the abilities of these converters can ensure, as much as possible, protection from overvoltages of mains, for correct operation to the rest of the circuits (analogues and digital). This programmed (software or/and hardware) power management makes the active loads to consume power not proportional to the variations of the voltage supply.

4.2 Fluorescent Lamps

For the testing setup (Fig. 4.1), the following stuff (measuring equipment and power supply) (Table 4.1) was used.

Table 4.1: Measuring equipment and power supply.

Instrument	Manufacturer	Type
Power digital meter	Fluke	Power Quality Analyzer – 433/434
Light meter	Yu Fong	LUX HI TESTER YF-1065
Power supply – Mains Voltage	-	Through variable transformer – variac: 230/0-280 V /50 Hz.

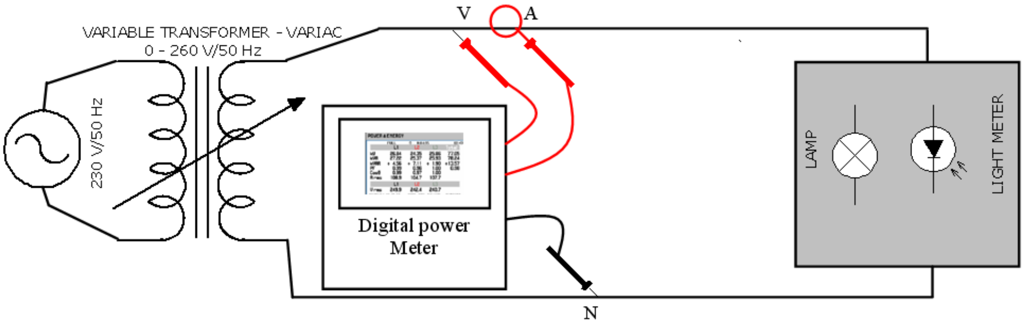

Figure 4.1: Connections for the experiments.

The light intensity meter (Lux meter) was placed under the bulb. Both, the light meter and the under test bulb were covered with a black box, in a dark room, to avoid possible influence of external lighting.

4.2.1 V_{ac} Mains Variations on Fluorescent Lamp – Experimental Testing

This experimental testing summarises the effects of supply voltages at higher or lower values, gradually up ±20%, with respect to the nominal supply voltage of 230 V/ 50 Hz on:

FLUORESCENT LAMP – Philips Master TLD 36 W/840 (with magnetic ballast L ≈ 1 H).

From the secondary winding of a single phase transformer, a fluorescent lamp was fed in 5 steps gradually, of approximately 23 V_{rms} each, from 184V to 276V, i.e. in a voltage range of +/- 20%. For each of these 5 values, the corresponding values of power were calculated and recorded with respect to the current voltage.

Fig. 4.2 illustrates the power consumed (W) that varies almost linearly with voltage variations. Some deviation on power (W) can be observed when the voltage drops below 10% or rises above 10% with respect to mains voltage.

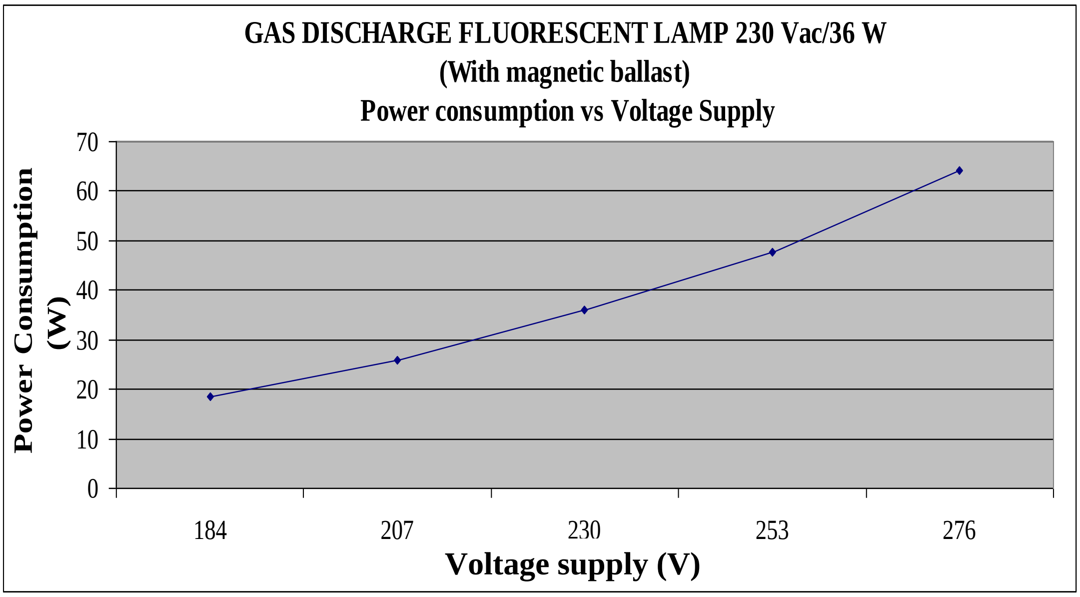

Figure 4.2: Power Consumption (W) vs Voltage Supply (V).

Fig. 4.3 and Table 4.2 illustrate, in percentage, the consumed power variation according to mains voltage on the load. Here, the consumed power on the load is changing as to the nominal respectively. For example, a 20% increase in a supply voltage of 230V, will result to a 78% increase of power consumption whereas, a 20% decrease in the supply voltage, will result to a 49% decrease power consumption.

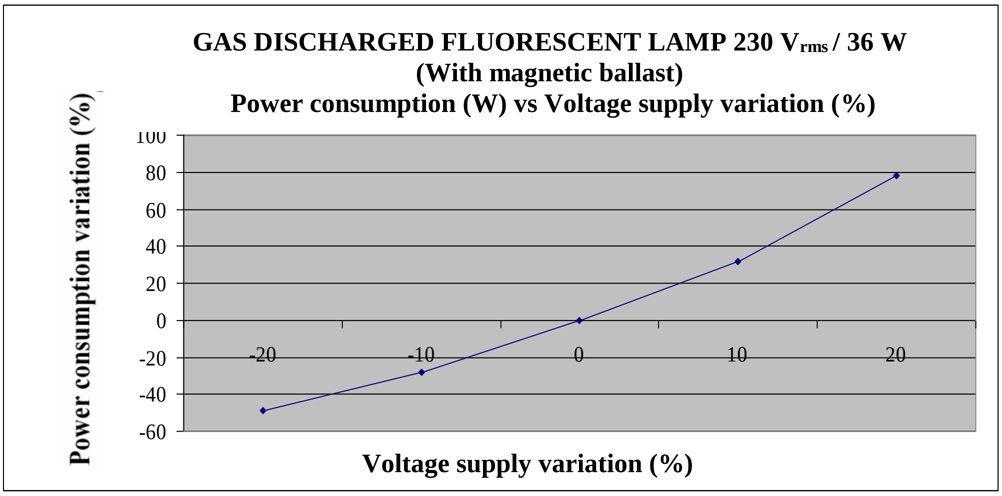

Figure 4.3: In percentage, power consumption vs mains variation.

Table 4.2: Experiment results; variations of power consumption and variation of the mains nominal voltage supply by ±20%.

V_{rms} variation (%)	W variation (%)
20	78
10	32
0	0
-10	-28
-20	-49

Fig. 4.4 illustrates the light intensity (LUX), according to mains voltage variation on the load. Here, light intensity from the load is changing almost linearly, as to the mains supply.

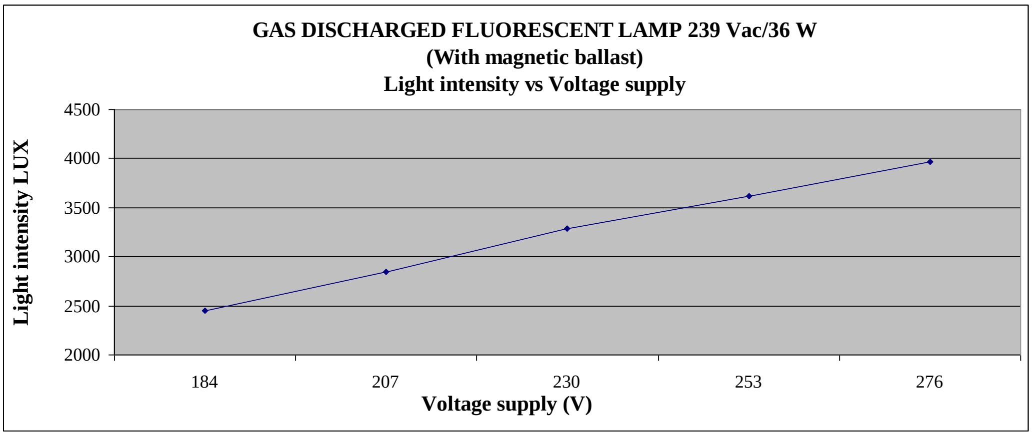

Figure 4.4: Light intensity (Lux (/10)) vs Voltage supply.

Next section examines more specifically the mains variations of up to +20%, on Energy Saving Lamps or Compact Fluorescent Lamps (CFLs).

4.2.2 V_{ac} Mains Variations on Energy Saving Lamps or Compact Fluorescent Lamps (CFLs) – Experimental Testing

In this section the experimental testing summarises the effects of supply voltages at higher values, gradually from 0% up to +20%, with respect to the nominal supply voltage of 230 V/ 50 Hz, on some CFLs.

From the secondary winding of a single phase variable transformer (VARIAC) 230/0-280 V (sec. 2 A_{rms})/50 Hz, Energy Saving Bulbs (CFLs) – loads were fed in 10 steps gradually, of approximately 4,6 V_{rms} each, from 230 V to 276 V i.e. in a voltage range of 20% from the nominal value. For each of these 10 values the mains power and the light intensity (Lux) were calculated and recorded with respect to the current voltage supply.

Each test is followed by two figures:

- The first figure shows the changes of the power consumption and the light intensity of the bulb (Lux/10) with respect to the current supply voltage.
- The second figure shows in percentage (%), the changes of the power consumption and the changes of the bulb – load with respect to the nominal voltage supply of 230 V/ 50 Hz varying gradually from 0% up to +20%.

For the experiment, five (5) lighting bulbs – loads have been tested:

- Five (5) CFLs, of 3, 5, 14, 20 and 25 W/230V/50Hz:
    - OKES LIGHTING, 3 W/230V/50Hz
    - OKES LIGHTING, 5 W/230V/50Hz
    - OKES LIGHTING, 14 W/230V/50Hz
    - GLOU, 20 W/230V/50Hz
    - TCL LIGHTING, 25 W/230V/50Hz

was examined.

4.2.2.1 V_{ac} Mains Variations on Low Cost Power Lamp CFL, 230 V/ 3 W

Fig. 4.5 shows that the power consumption (W) in the load – lamp and the intensity of the light (Lux) varies almost as to the nominal. Yet, although the light intensity varies linearly too, there are some deviations to be seen.

Fig. 4.6 shows that the power consumption (W) is changing from 0% to 17% and the intensity of the light (Lux) varies from 0% to 6.8%, with respect to power supply.

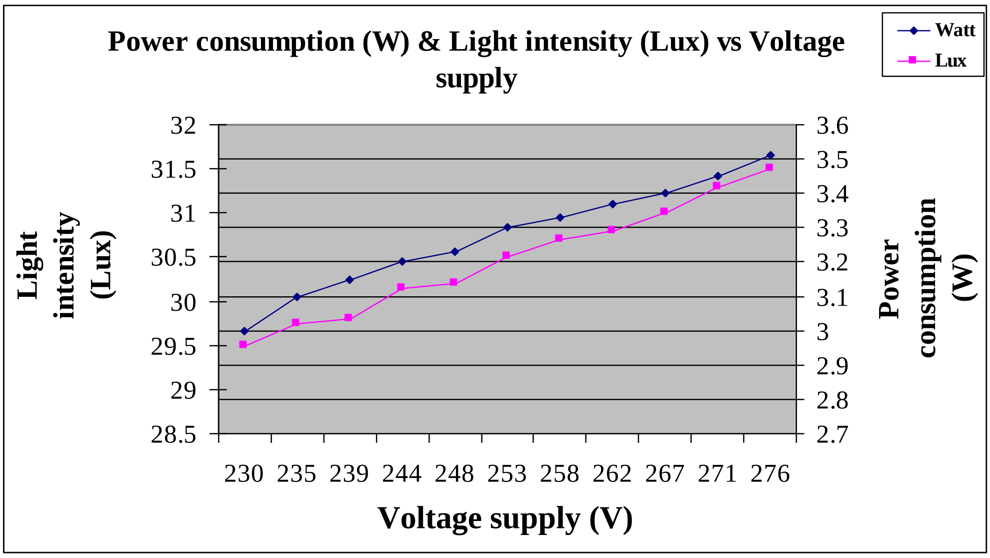

Figure 4.5: Power consumption (W) and Light intensity (Lux (/10)) vs Voltage supply variation.

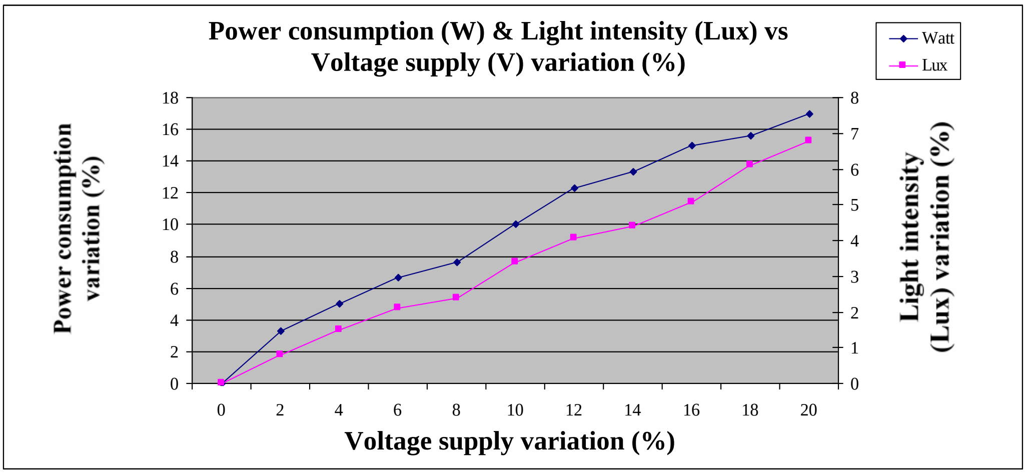

Figure 4.6: Power consumption (W) and Light intensity (Lux (/10)) vs mains voltage variation (%).

4.2.2.2 V_{ac} Mains Variations on Low Cost Power Lamp CFL, 230 V/ 5 W

From Fig. 4.7 can be seen that the power consumption (W) on the load varies linearly with voltage. Yet, although the light intensity varies linearly too, there are some deviations to be seen.

From Fig. 4.8 can be seen that:

The power consumption (W) is changing from 0% to 12.1% and the intensity of the light (Lux) varies from 0% to 6.49%, with respect to power supply.

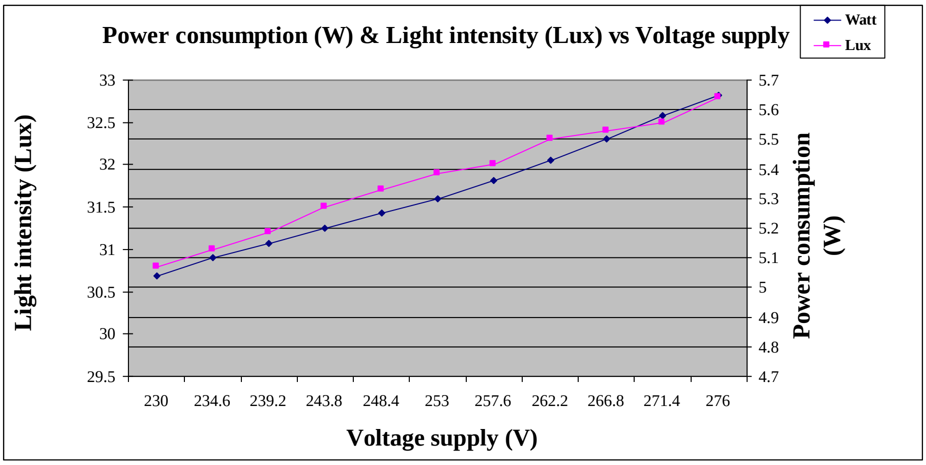

Figure 4.7: Power consumption (W) and Light intensity (Lux (/10)) vs Voltage supply (V) variation.

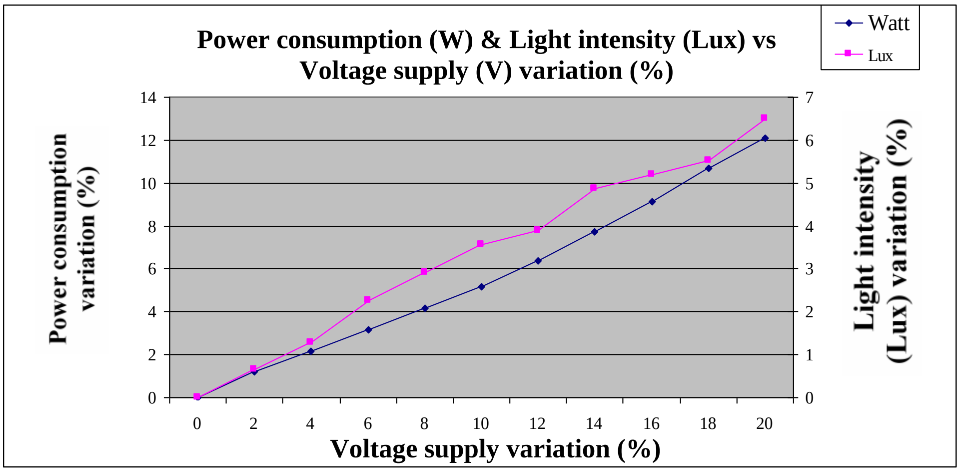

Figure 4.8: Power consumption (W) and Light intensity (Lux (/10)) vs mains voltage variation (%).

4.2.2.3 V_{ac} Mains Variations on Low Cost Power Lamp CFL, 230 V/ 14 W

From Fig. 4.9 can be seen that the power consumption (W) on the load varies almost linearly with voltage. Also, here, although the light intensity varies linearly too, there are some deviations to be seen.

From Fig. 4.10 can be seen that:

The power consumption (W) is changing from 0% to 9.28% and the intensity of the light (Lux) varies from 0% to 8.07%, with respect to power supply.

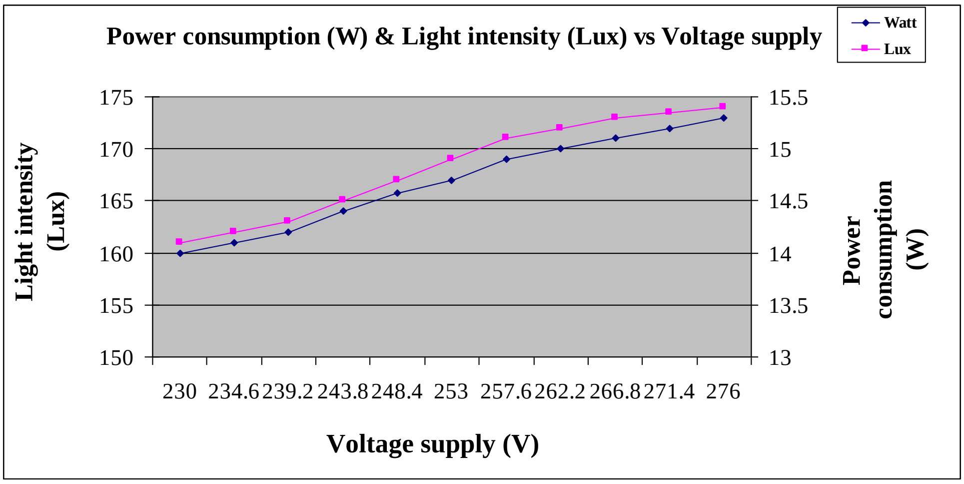

Figure 4.9: Power consumption (W) and Light intensity (Lux (/10)) vs Voltage supply variation.

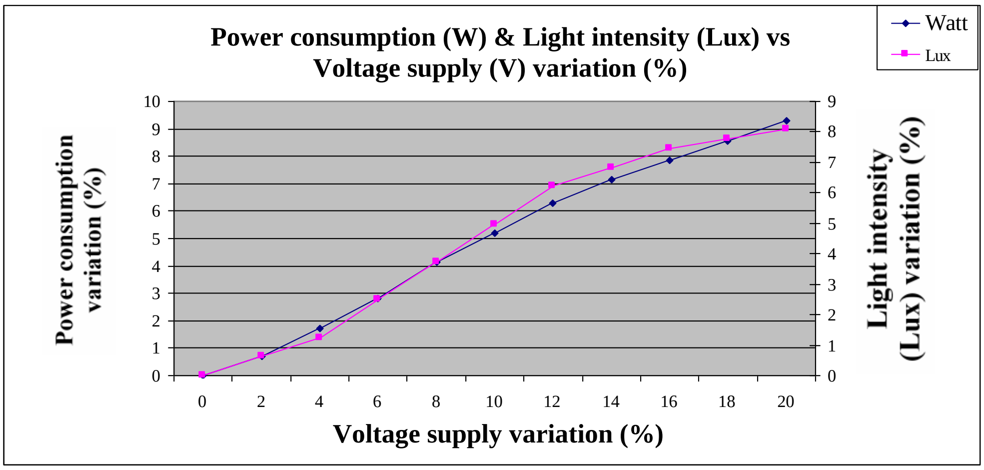

Figure 4.10: Power consumption (W) and Light intensity (Lux (/10)) variation vs mains voltage variation (%).

4.2.2.4 V_{ac} Mains Variations on Low Cost Power Lamp CFL, 230 V/ 20 W

From Fig. 4.11 can be seen that the power consumed varies linearly with voltage. Yet, although the light intensity varies almost linearly, there are some deviations to be seen.

From Fig. 4.12 can be seen that:

The power consumption (W) is changing from 0% to 30% and the intensity of the light (Lux) varies from 0% to 4.62%, with respect to power supply.

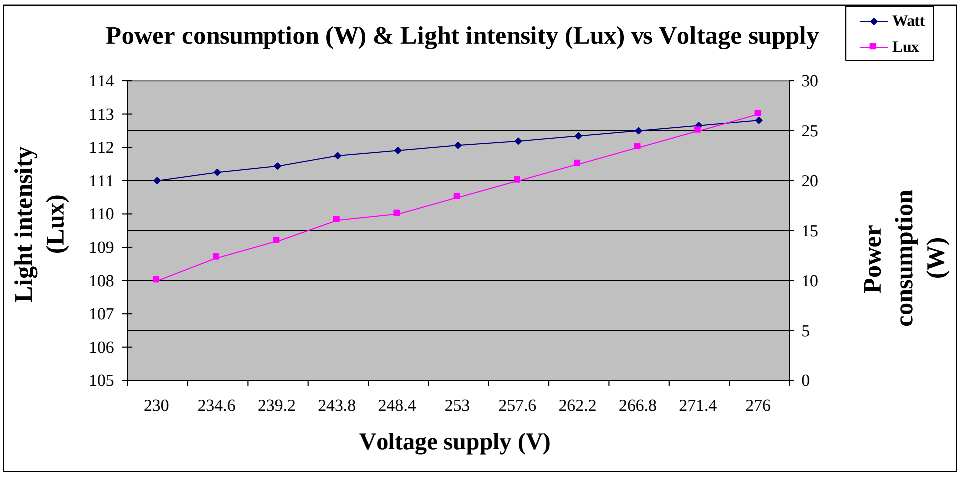

Figure 4.11: Power consumption (W) and Light intensity (Lux (/10)) vs Voltage supply variation.

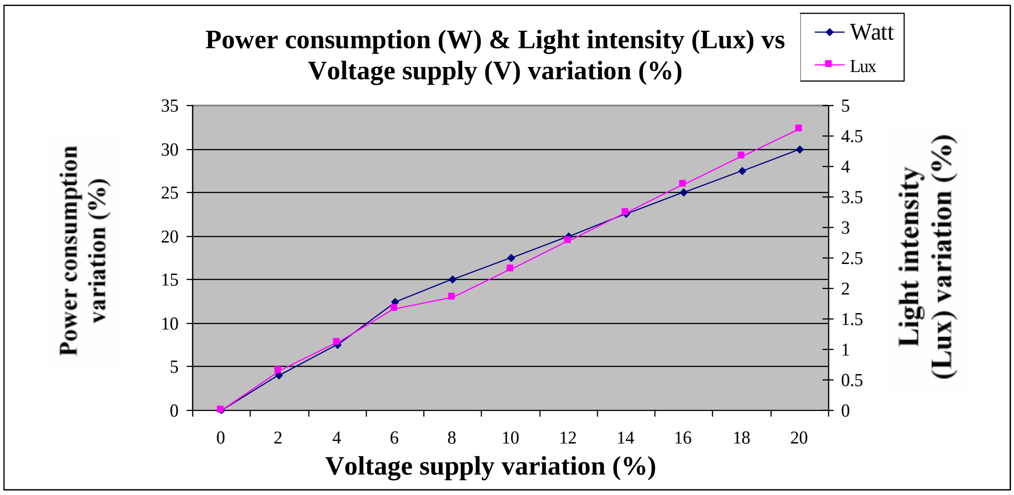

Figure 4.12: Power consumption (W) and Light intensity (Lux (/10)) variation vs mains voltage variation (%).

4.2.2.5 V_{ac} Mains Variations on Low Cost Power Lamp CFL, 230 V/ 25 W

From Fig. 4.13 can be seen that the power consumed varies almost linearly with voltage. Yet, although the light intensity varies almost linearly too, there are some deviations to be seen. Also, from Fig. 4.14 can be seen that:

The power consumption (W) is changing from 0% to 12% and the intensity of the light (Lux) varies from 0% to 10.25%, with respect to power supply.

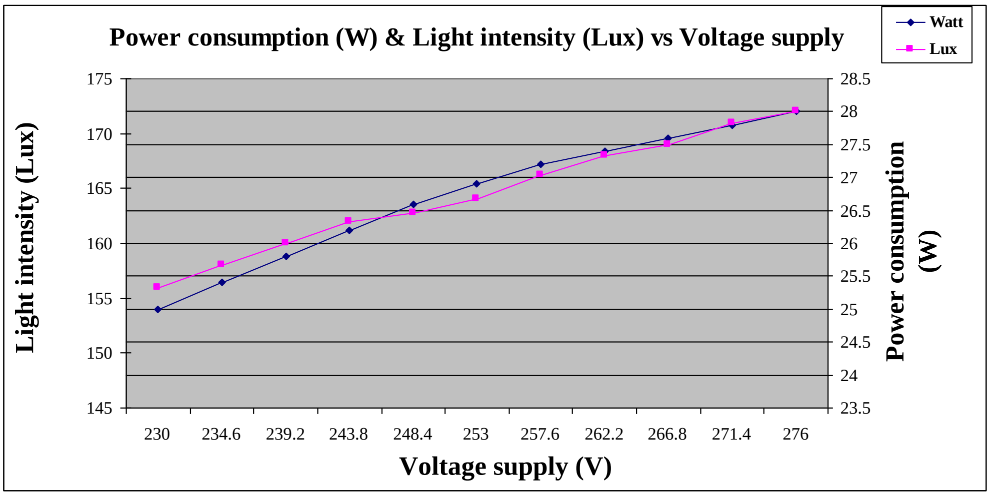

Figure 4.13: Power consumption (W) and Light intensity (Lux (/10)) vs Voltage supply variation.

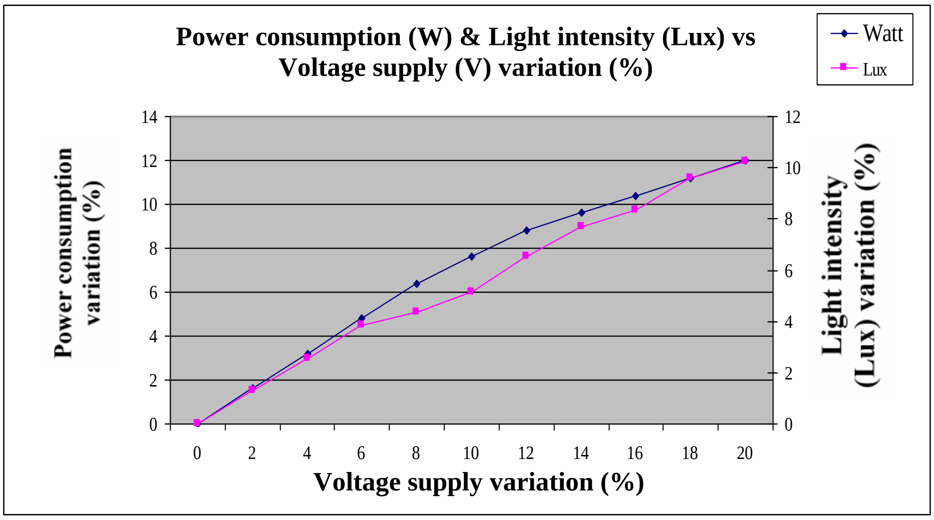

Figure 4.14: Power consumption (W) and Light intensity (Lux (/10)) ratio (%) vs mains voltage variation (%).

4.3 Active Loads

A Personal Computer (PC) system, combing the desktop, monitor, keyboard and mouse may be a representative load for practical experiments on mains overvoltage effects on active loads.

4.3.1 V_{ac} Mains Variations on Active Loads through Practical Testing

The following practical experimental tests summarise the effects of supply variable AC voltages with respect to the V_{ac} nominal supply on the following three different types of PCs-active loads[28], of 230 V / 50 Hz:

- PC1: 350 W
- PC2: 250 W
- PC3: (laptop) 65 W

For the testing setup (Fig. 4.15), the same stuff (Table 4.1) was used.

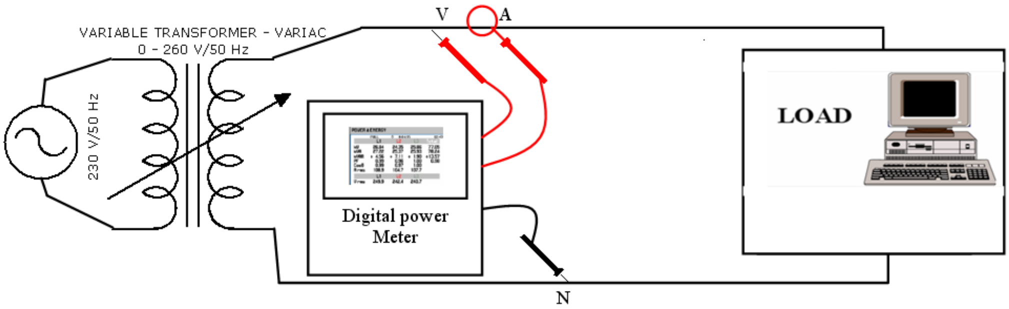

Figure 4.15: Connections for the experiments, wising one phase voltage supply from the variac.

The loads were fed in 10 steps gradually, of approximately 4.6 V_{rms} each, from 230V to 276V i.e. in a voltage range of 0% up to 20%. For each of these 10 values – steps, the corresponding values were calculated and recorded with respect to the current voltage supply.

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[28] There is no reference to the marks for safety reasons.

4.3.1.1 V_{ac} Mains Variations on PC1 (350 W) Load Through Practical Testing

Fig. 4.16 illustrates the power consumption (W) in the PC that remains almost constant as the value of voltage supply increases from the nominal value up to +20%. Also, Table 4.3 and Fig. 4.17 illustrate, in percentage, the power (W) variation according to mains voltage in the load (PC).

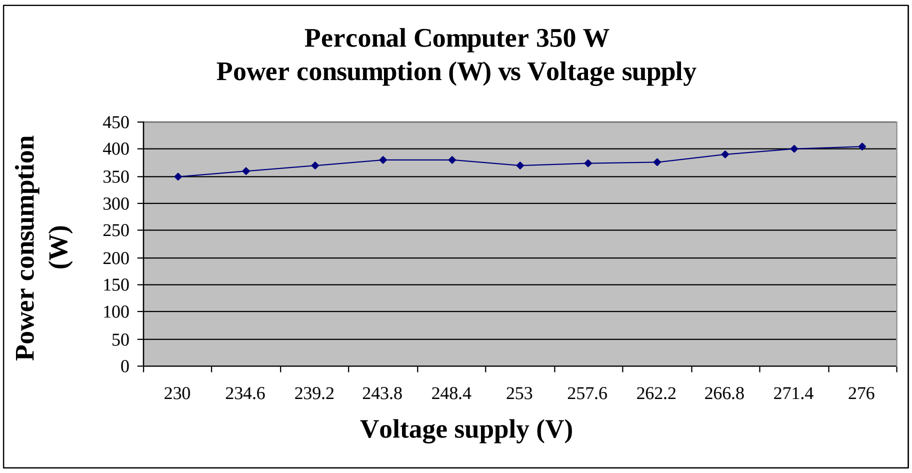

Figure 4.16: PC1 (350 W), Power (W) vs mains voltage.

Table 4.3: Experiment results, variations of power consumption (W) and variation of the mains nominal voltage supply by +20%.

V_{rms} variation (%)	W variation (%)
20	15.71
18	14.29
16	11.43
14	7.71
12	7.14
10	5.71
8	8.57
6	8.57
4	5.71
2	2.86
0	0

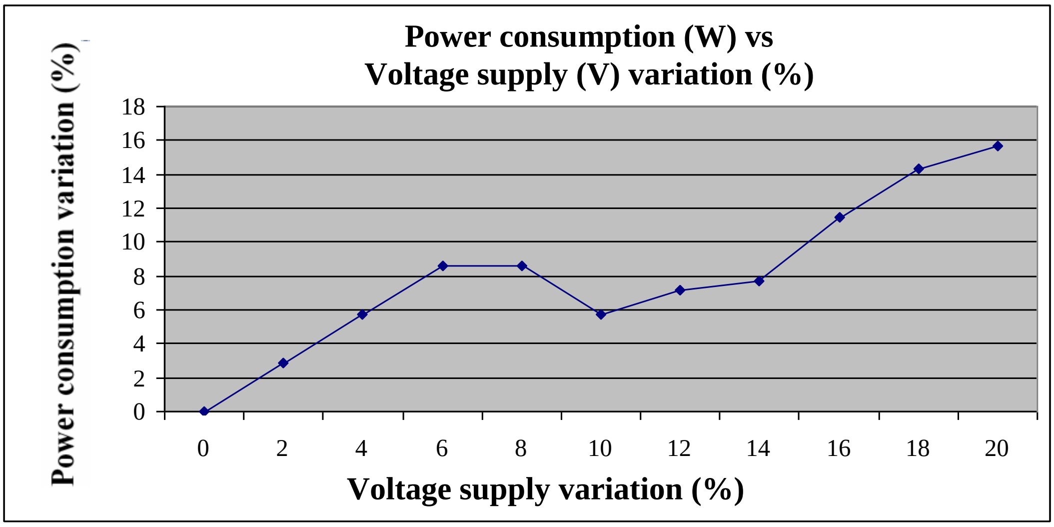

Figure 4.17: PC1 (350 W), in percentage, power (W) vs mains variation.

Here, the power on the PC is not changing at a rate as to the nominal mains respectively.

Photo 4.1 illustrates the testing setup for V_{ac} mains variations on PC2 (350 W) load – PC system.

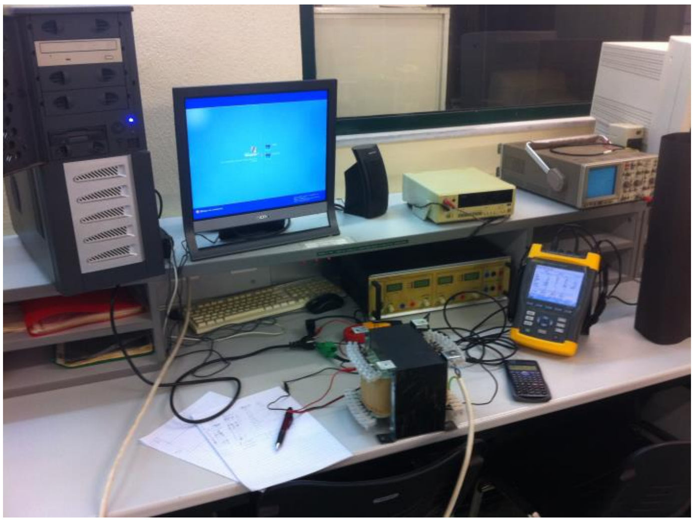

Photo 4.1: Practical testing through V_{ac} mains variations on PC load system.

4.3.1.2 V_{ac} Mains Variations on PC2 (250 W) Load Through Practical Testing

Fig. 4.18 illustrates the power consumption (W) in the PC2 that remains almost constant as the value of voltage supply increases from the nominal value up to +20%. Here, the power supplying electronic system of the PC, with its voltage regulating parts, keeps the voltage supply of the rest parts of the system (digital, analog) almost constant; avoiding the excessive power consumption because of the overvoltage event. Also, Fig. 4.19 and Table 4.4 illustrate, in percentage, the power (W) variation according to mains voltage in the load (PC).

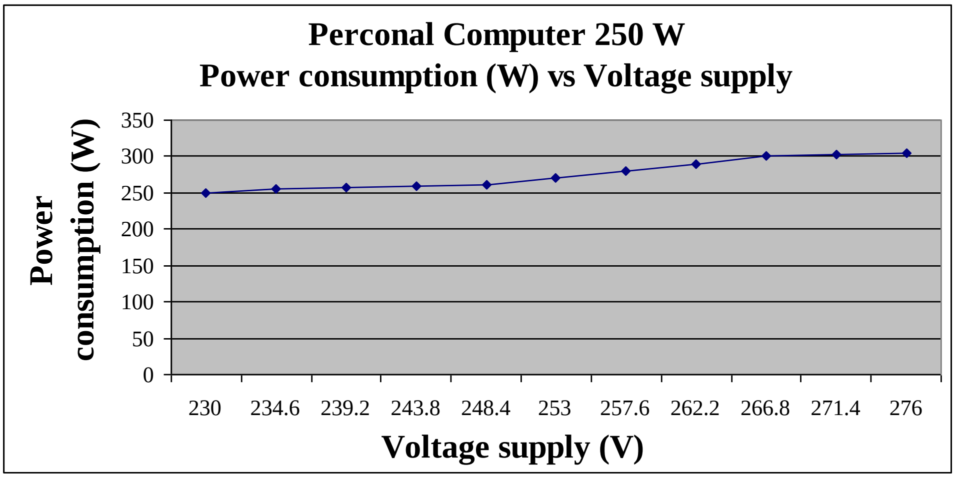

Figure 4.18: PC2 (250 W), power (W) vs mains voltage.

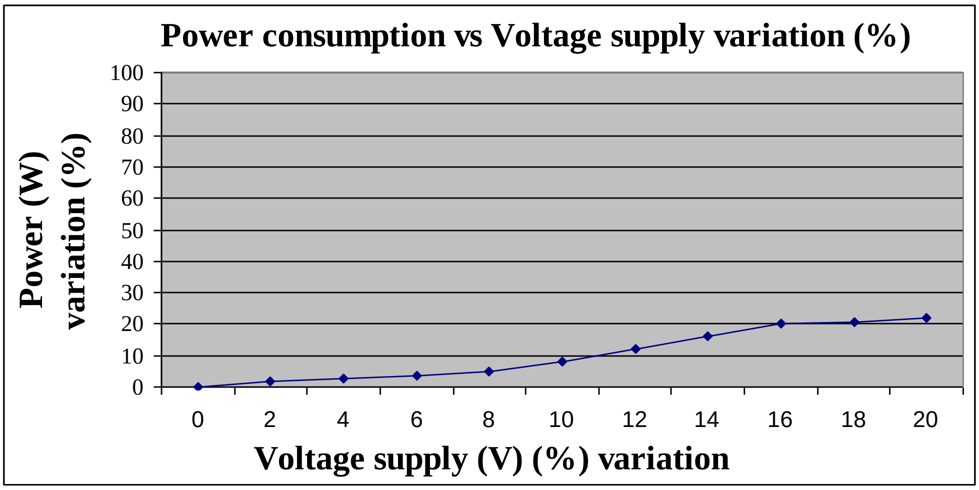

Figure 4.19: PC2 (250 W), in percentage, power (W) vs mains variation.

Table 4.4: Experiment results, variations of power consumption (W) and variation of the mains nominal voltage supply by +20%.

V_{rms} variation (%)	W variation (%)
20	22
18	20.8
16	20
14	16
12	12
10	8
8	4.8
6	3.6
4	2.8
2	2
0	0

Here, the power consumption in the load is changing at a rate approximately as to the nominal, with a deviation of 0 – +22% with respect to mains of 0 – +20%.

4.3.1.3 Vac Mains Variations on PC3 - Laptop (65 W) Load Through Practical Testing

Fig. 4.20 illustrates the power consumption (W) ιn a Laptop, which remains to an almost constant level as the voltage supply increases from nominal value to +20%. Also, Fig. 4.21 and Table 4.5 illustrate, in percentage, the power consumption (W) variation according to mains voltage on the load.

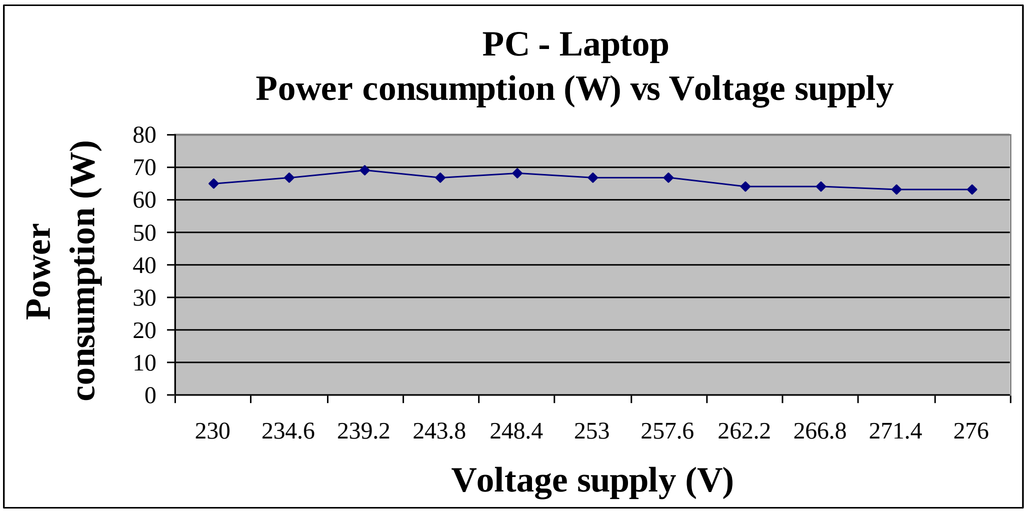

Figure 4.20: Laptop (PC3, 65 W), power (W) vs mains Voltage.

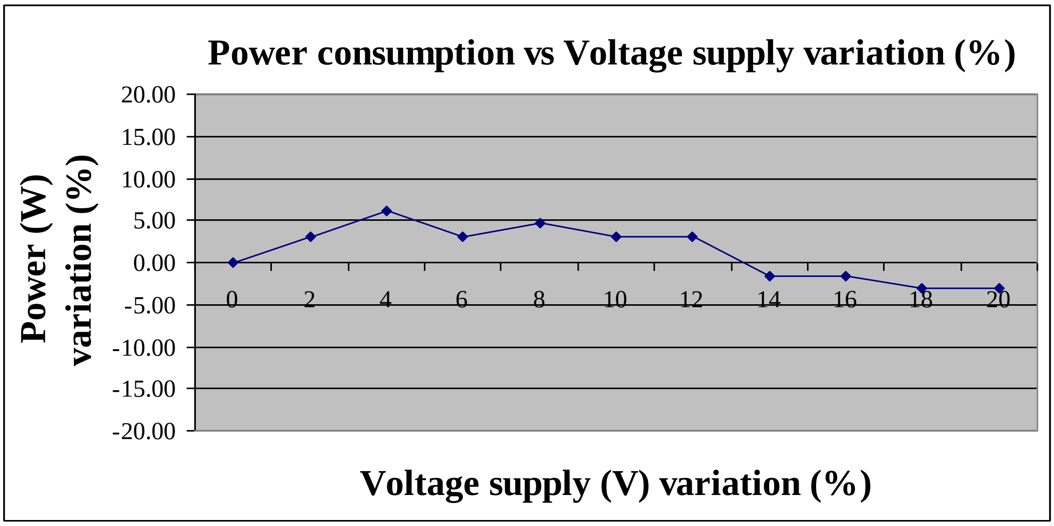

Figure 4.21: Laptop (PC3, 65 W), in percentage, Power (W) vs mains variation.

Table 4.5: Experiment results; variations of power consumption (W) and variation of the mains nominal voltage supply by ±20%.

V_{rms} variation (%)	W variation (%)
20	-3.08
18	-3.08
16	-1.54
14	-1.54
12	3.08
10	3.08
8	4.62
6	3.08
4	6.15
2	3.08
0	0.00

Here, the power consumption in the load remains almost constant with the increase of the voltage.

Photo 4.2 illustrates the testing setup for V_{ac} mains variations on PC3 (65 W) load system.

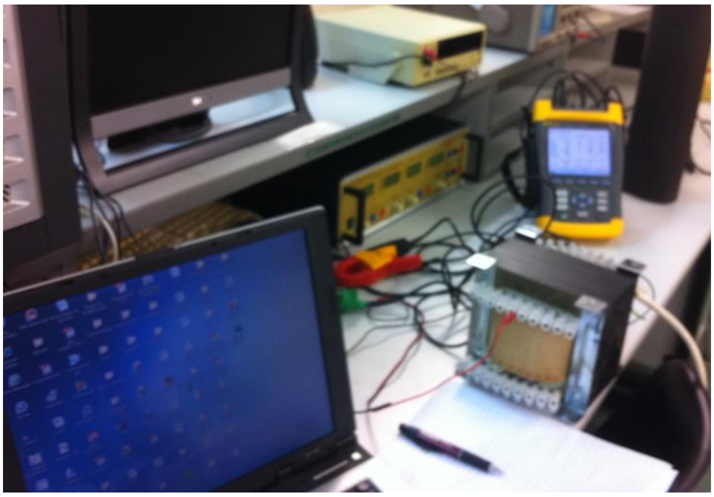

Photo 4.2: Practical testing through Vac mains variations on PC - Laptop load.

4.3.1.8 V_{ac} mains variations on single phase diode bridge rectifier

In the case of ac-dc conversion, where there is not included voltage regulation, like three or single-phase diode rectification, the consumed power in the circuit is straight proportional to the voltage supply variations.

For the testing setup, the following stuff (measuring equipment and power supply) (Table 4.6) was used (photo 4.3).

Table 4.6: Measuring equipment and power supply.

Instrument	Manufacturer	Type
V-meter	Digimess	DM 200 Digital Multimeter
A-meter	Digimess	DM 200 Digital Multimeter
Power digital meter	Voltech	Power Analyser – PM 1000
Power supply – Mains Voltage	-	Through variable transformer – variac: 230/0-280 V /50 Hz.

Fig. 4.22 illustrates a single phase diode bridge rectifier supplying a resistive load (R = 33Ω) with a filtering capacitor (C = 2200 uF). The nominal voltage supply of the system is 23 V_{rms} / 50 Hz. From the secondary winding of a single phase transformer, the system was fed in 15 steps gradually, of approximately 4.6 V_{rms} each, from 20.7V to 27.6V, i.e. in a voltage range of – 10% to + 20%. For each of these 15 values, the corresponding following values:

- power (VA) on the system
- power consumed (W) by the system
- the V_{dc} across the resistor
- the Current Total Harmonic Distortion (THD_i)
- power factor (PF)

were recorded with respect to the current voltage supply.

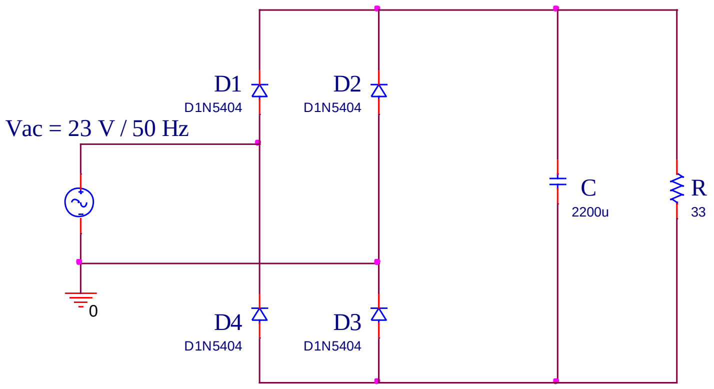

Figure 4.22: A single phase diode bridge rectifier with a resistive load and filtering capacitor.

Fig. 4.23 and Fig. 4.24 illustrate the power (VA) and the power consumed (W) in the system respectively, that varies linearly with the voltage supply.

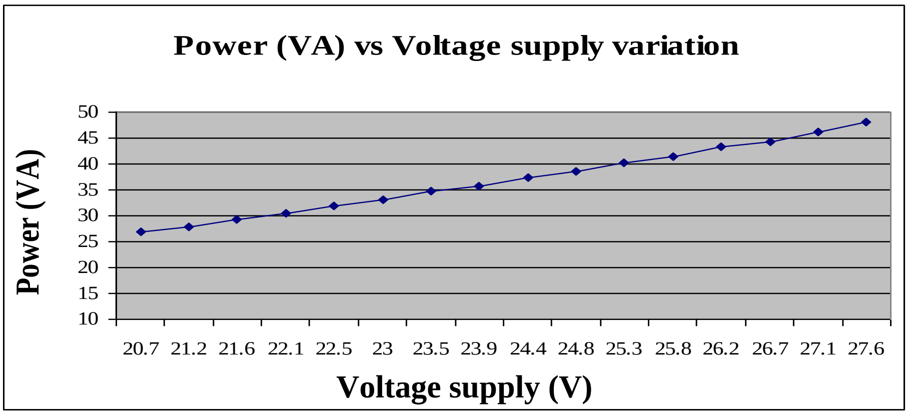

Figure 4.23: Power (VA) vs voltage supply.

The power on the system (Fig. 4.22) is almost proportional to voltage supply variation. It varies according to supply's variations, like almost to a resistive load. For example, a 20% increase in a supply voltage of 23 V_{rms}, will result to a 45.45% increase of power (VA) whereas, a 10% decrease in the supply voltage, will result to an 18.18% decrease of power.

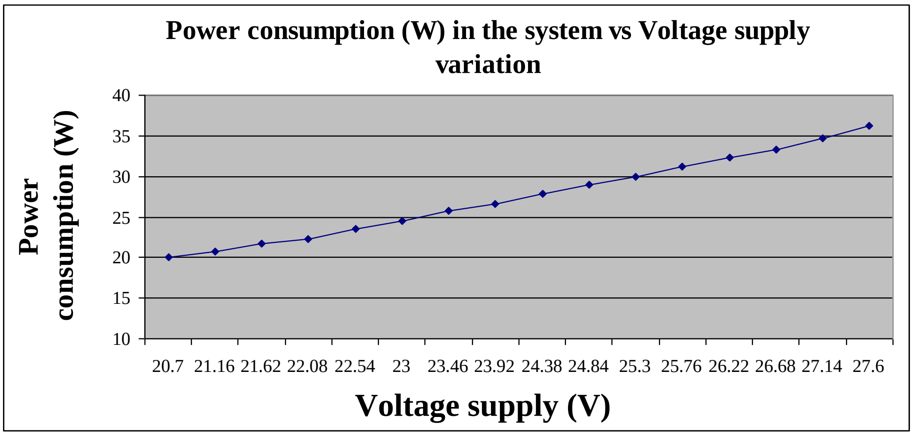

Figure 4.24: Power (W) vs voltage supply.

Here, the consumed power in the load is almost proportional to voltage supply variation. It varies according to supply's variations, like almost to a resistive load. For example, a 20% increase in a supply voltage of 23 V_{rms}, will result to a 47.7% increase of power consumption (W) whereas, a 10% decrease in the supply voltage, will result to a 13.04% decrease of power consumption[29].

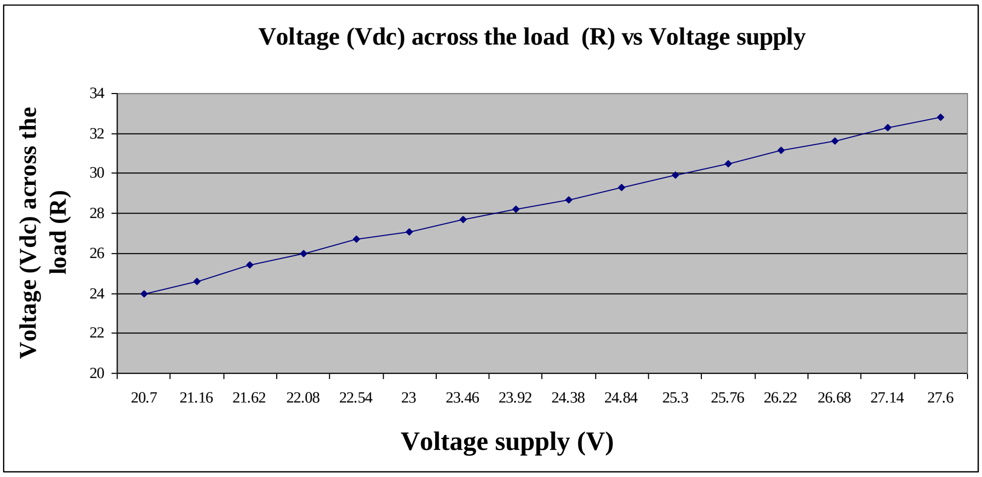

Figure 4.25: Voltage across the resistive load (R) vs voltage supply.

The V_{dc} variation across the resistive load (R) varies linearly according to voltage supply (V_{rms}), (Fig. 4.25).

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[29] There is a significant role that plays the connection of a resistive component (R), which consume power straight proportional to mains supply.

The Current Total Harmonic Distortion (THD_i, in percent) is also affected by the voltage variations (Fig. 4.26), which means that, by the increase of the voltage supply it happens to increase the distorted supply current. This overvoltage effect is not only undesired for the load, but it can influence to the neighbouring loads in the supply line.

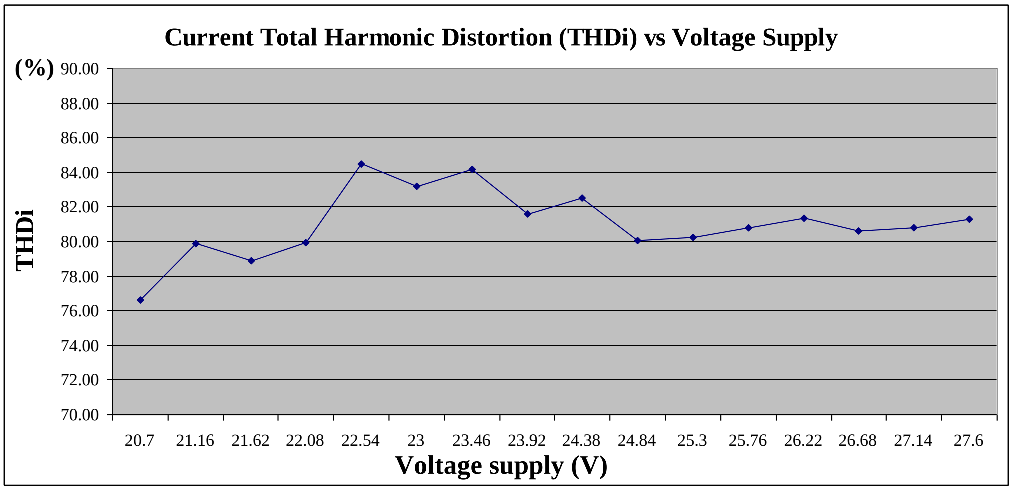

Figure 4.26: Current Total Harmonic Distortion (THDi, in percent) vs voltage supply.

Fig. 4.27 shows the power factor (PF) that was invariable in relation to voltage supply variations.

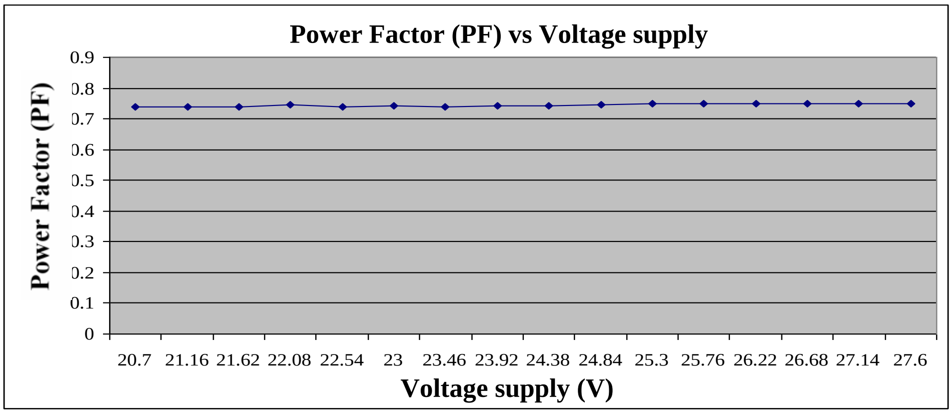

Figure 4.27: Power factor (PF) vs voltage supply.

As the true power factor PF = (displacement factor, cos θ) x (distortion factor, DF), where

$$DF = \sqrt{\frac{1}{1+THD_i^2}} \qquad (2.33)$$

and displacement factor, cos $\theta \approx 1$

Fig. 4.28 shows the true power factor (PF)[30] vs voltage supply variations. It remains almost invariable in relation to voltage supply variations.

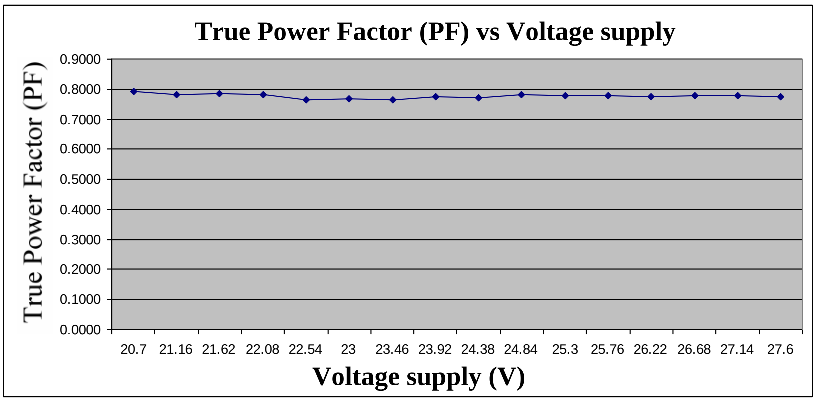

Figure 4.28: The true power factor (PF) vs voltage supply.

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[30] The distortion here happens only to the current's waveform.

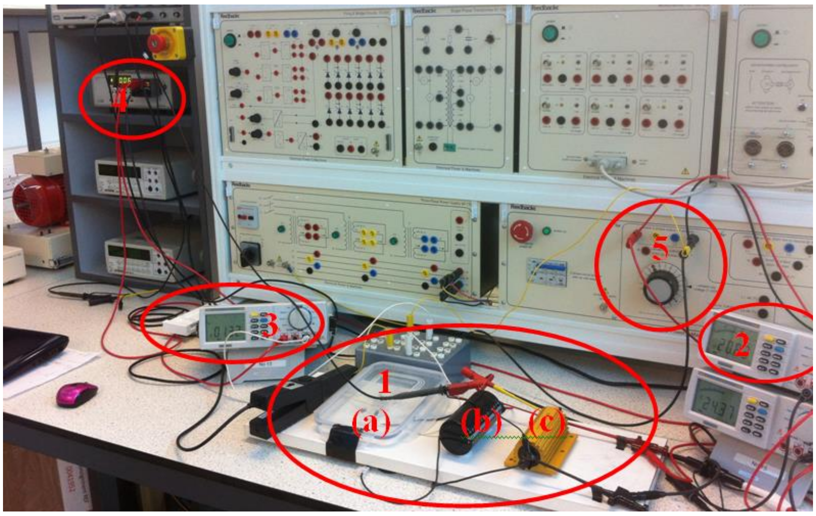


Photo 4.3: The measuring equipment and power supply for non-linear load system test.

1: The nonlinear load system: the single phase diode bridge (a), the filtering capacitor (b), the resistor (c).

2: The digital V-meter, connected in parallel to the voltage source.

3: The digital A-meter, connected in series too.

4: The digital power analyzer.

5: The ac power supply.

4.4 Summary

- On Fluorescent or gas discharge lamps, from the above experimental testing, in a variation of +/- 20% in the feeding voltage – mains with respect to the nominal 230V$_{rms}$, it has been indicated that:
    - In general, the consumed power is almost directly proportional to the voltage – mains supply. Although the power varies linearly with voltage variations, some deviation can be observed when the voltage drops below 10% or rises above 10% with respect to mains voltage.
    - The light intensity from the load is changing almost linearly, as to the mains supply.

- On Low Cost Power or Compact Fluorescent Lamps (CFL), in a variation of +/- 10% in the feeding voltage – mains with respect to the nominal $230V_{rms}$, it has been indicated that:
  - The consumed power is almost directly proportional to the voltage supply.
  - The percentage variation of power consumed with respect to that observed when nominal voltage values vary, is generally greater than the percentage variation of the corresponding light intensity.
  - On the other hand, the percentage variation of the consumed power observed in the case of the incandescent bulbs is generally lower than the corresponding variation of the light intensity.

- On active loads – PCs, from the above experimental testing, in a variation of +/- 20% in the feeding voltage – mains with respect to the nominal $230V_{rms}$, it has been indicated that:
  - Despite the voltage supply – mains variations, they still continue to work like the nominal supply conditions, because the built-in supporting power management systems (regulators, software support etc.).
  - The power consumption remains in low level rates with about +8% maximum deviation (by the majority) with respect to the voltage supply – mains variations of up to +20%.

- Also, in the case of active loads, although overvoltage results in a small increase of power consumption, other effects of overvoltage include the reduction in the lifespan of various components (e.g. capacitors).

- Most active loads have internal transformers which are susceptible to saturation (even if they are not operating at mains frequency), and high voltage transistors, whose losses increase with voltage faster than (v^2).

- It should be considered that modern power supply systems are also active loads, which are so designed (in hardware/software) to control the currents and voltages in order to satisfy power requirements of the remaining circuits. Therefore, the hardware/software designed power supply systems are charged to make power management by such way so, to not be affected the normal functioning of the remaining circuits, despite overvoltages.

In the cases of power conversion, if there is not any power quality management, semiconductors behave as non-linear loads, distorting the supplying current. Also, with the event of overvoltages the current distortion increases, becoming a serious danger for the same non-linear loads and also to the neighbouring loads in the supply line. Therefore, as the use of such loads overgrows, there is need of circuitry support for current supply correction, in order to reduce undesired stackable harmonics in the power line. The following chapter 5 deals with harmonic mitigation in non-linear load, with a cost effective harmonic reduction system.

Chapter 5: Harmonic Reduction in Non-linear Load

5.1 Introduction

In AC/DC power supplies, the use of smoothing capacitor causes a much distorted input current waveform. This is mainly due to the fact that the input current at the AC side is the result of a reflection of the charging and discharging current of the capacitor at the DC side. A typical Total Harmonic Distortion (THD) of the input current in such power supplies is greater than 100%, depending mainly on the value of the filtering capacitance, which increases even more in the case of overvoltages. Also, this may cause problems to other loads including linear loads.

The proposed electronic circuit can be used in conjunction with the power supplies used at the input of non-linear loads (computers, TV sets, etc.) in order to filter out the input current harmonics in such loads. The electronic circuit will fill the gaps of the distorted current waveform so that it becomes as much sinusoidal and also in phase with the mains supply.

5.2 Current Distortion Caused by the Single Phase Diode Bridge Rectifier

Small distributed loads, such as computer loads and TV sets with switched-mode power supplies at their inputs, add up to a large increase in the amount of harmonic current injected in power distribution systems [135]. The circuit shown in Fig. 5.2.1 is a typical bridge rectifier circuit which could be used in the power supplies of several applications (TV's, computers, printers, UPS systems, etc.).

A smoothing – filtering capacitor (C) (Fig. 5.1) is usually used to filter out the output voltage across the dc load. The event is that during the time interval 2 (Fig. 5.2 c) the capacitor re-charges and the rest of the half period, intervals 1 and 3 the source current becomes zero. This causes the source current to be discontinuous – non sinusoidal (Fig. 5.2 c) and consequently full of odd order harmonics.

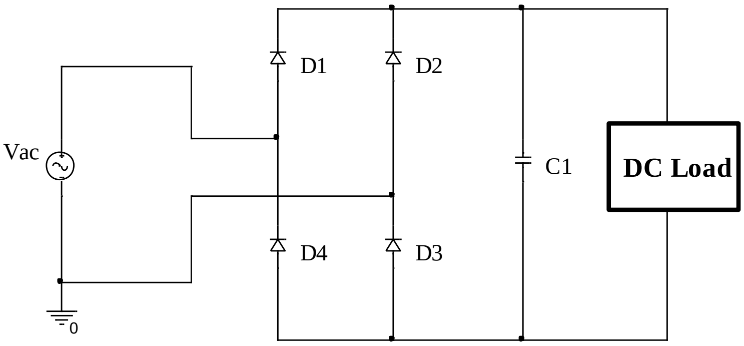


Figure 5.1.: A typical diode bridge rectifier with a dc load.

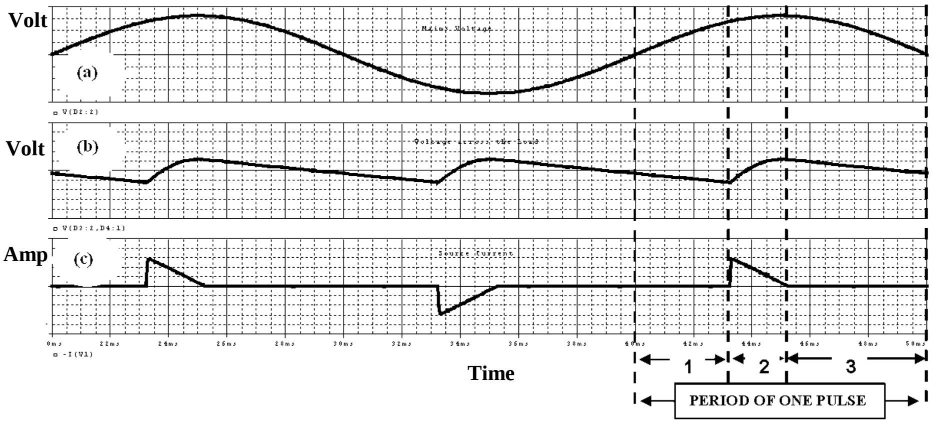


Figure 5.2: The mains ac voltage supply waveform (a), the output voltage waveform across the dc load (b) and the distorted source current waveform (c) of the circuit shown in Fig. 5.1.

An experimental testing through PSpice program according to the circuit in Fig. 5.3 gives the following results:

- Efficiency η = 93.14%
- Power factor (true) PF = (displacement factor, cos θ) x (distortion factor, D) = 1 x 0.521 = 0.521
- Current Total Harmonic Distortion $THD_{i(\%)}$ = 163.48%

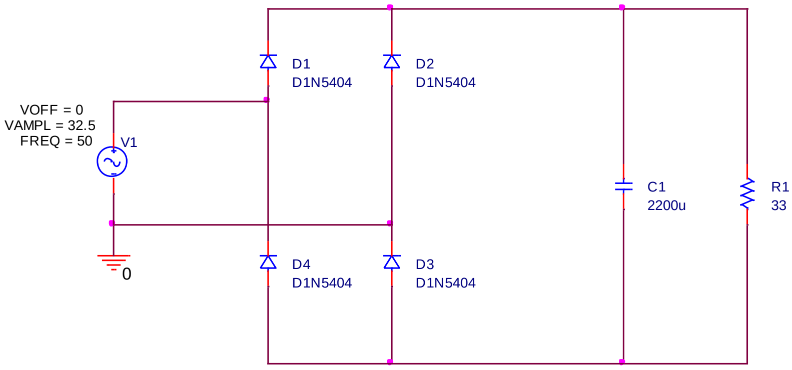


Figure 1 (5.3): A diode bridge rectifier with a dc load.

Fig. 5.4 (a) and (b) show the mains waveform in time correlation with the distorted supply current respectively. The current's waveform is not any more sinusoidal as it is illustrated with more details in Fig. 5.5 and in the harmonic spectrum Fig. 5.6.

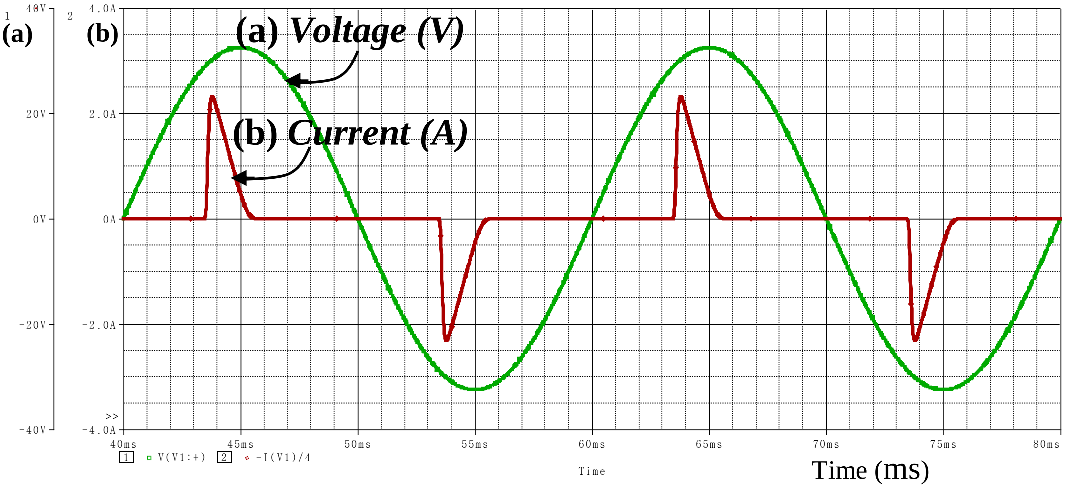


Figure 5.4: The voltage mains (a) and the source current (b) waveforms in time

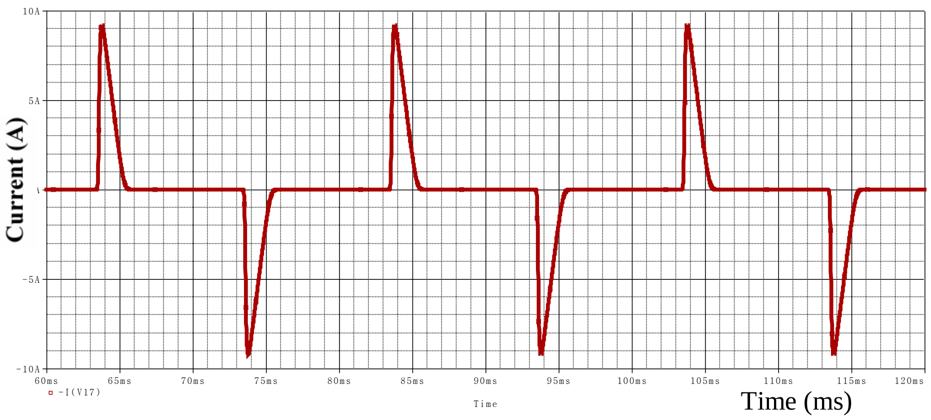


Figure 5.5: The source current waveform after harmonic distortion.

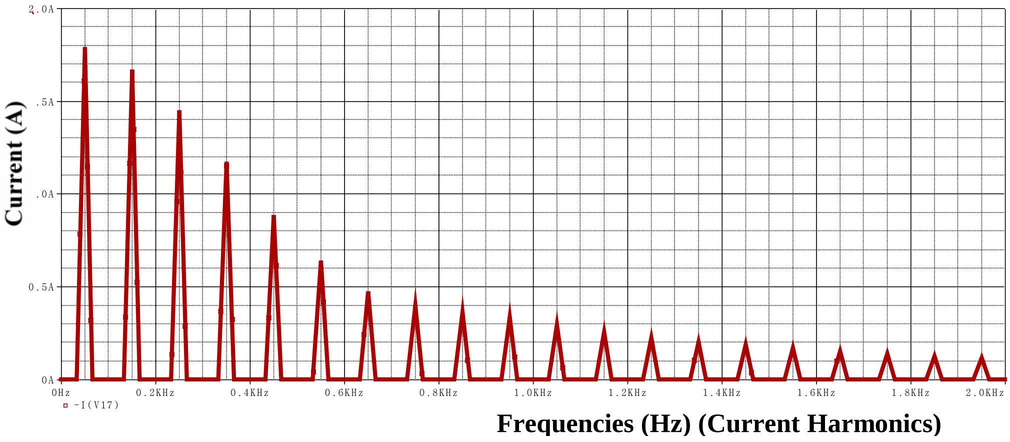


Figure 5.6: The FFT analysis of the current waveform.

5.2.1 Practical Testing of the Non-linear Load

There has been made a practical experiment of the evaluation of the harmonics created by the non-linear load. For the testing, as a generator of harmonics, the system (non-linear load) in Fig. 5.7 has been used, as in Fig. 5.3.

For the experiment, the same measuring equipment and power supply were used, plus the oscilloscope, TEKTRONIX TPS 2024 (100 – 200 MHz), for waveform recording.

Fig. 5.7 illustrates the circuit under practical testing of the diode bridge rectifier with the filtering capacitor (C = 2200 uF) and the dc load (R = 33 Ω). From the testing, there are the following results:

- Efficiency η = 90.83%
- Power factor (true) PF = (displacement factor, cos θ) x (distortion factor, DF) = 1 x 0.768= 0.768
- Current Total Harmonic Distortion $THD_{i(\%)}$ = 83.2%

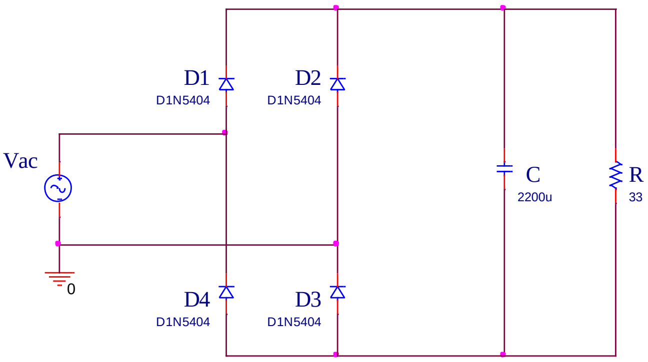


Figure 5.7: A single phase diode bridge rectifier with a resistive load (R) and filtering capacitor (C).

Fig. 5.8 (a) and (b) show the recorded waveforms of voltage and current supply respectively. It can be seen clearly from the related waveform, that the supply current passing the non-linear load is being distorted, according to the above reason. This level of distortion of the supply current is undesirable, especially when many such loads are neighbouring, connected also on the same power line. Therefore, the usage of a harmonic reducer in such loads is necessary.

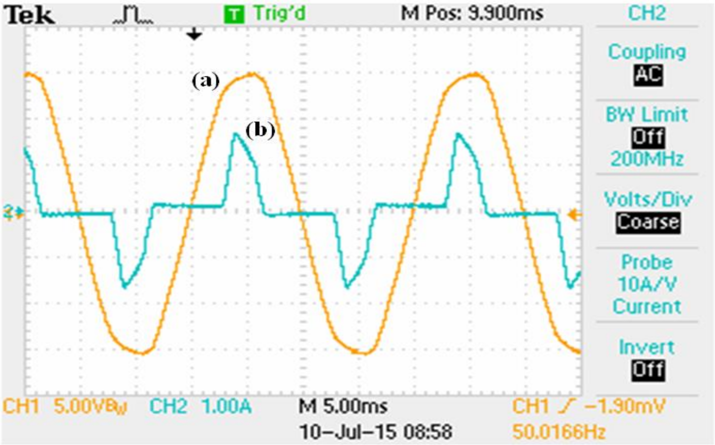


Figure 5.8: The voltage supply (a) and the distorted supply current (b) waveforms in time correlation.

5.3 Harmonic Reduction

The harmonic reduction topology (based on the boost scheme [55] [84] [85]) connected to the system of the non-linear load (Fig. 5.1) is described in Fig. 5.9. The booster here is consisted of the inductor L, the diode D5 and the power MOSFET (S) in switch mode. Also, there is a square pulse generator with a fixed frequency (period T) using the pulse width modulation (PWM) technique, which triggers the power MOSFET[31] with a constant duty cycle of about 75% ratio.

According to Fig. 5.9 topology, when the MOSFET is ON, passes – injects an amount of supply current (i_s) in time intervals of 0.75% ratio of the triggering fixed period (T). Fig. 5.10 illustrates the voltage supply (v_{ac} mains) in time correlation to the total supply current (i_{tot}), after harmonic reduction.

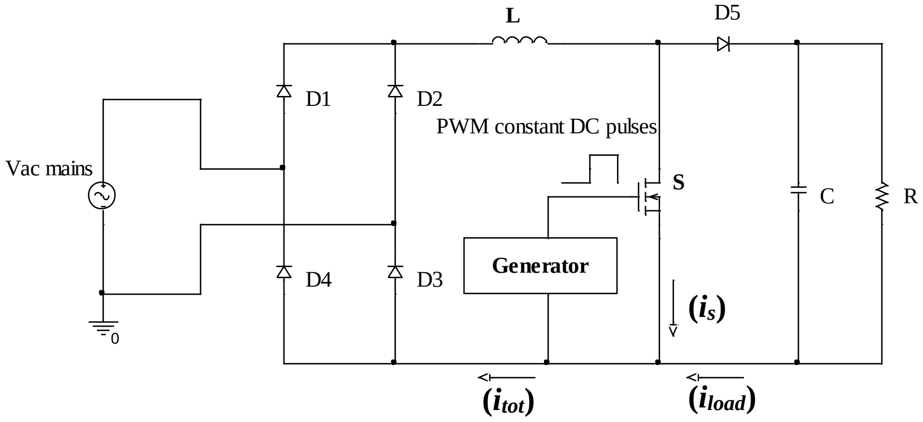


Figure 5.9: A diode bridge rectifier with the harmonic reducer topology.

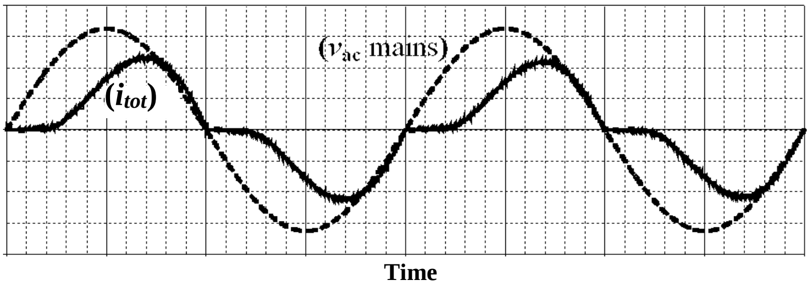


Figure 5.10: The voltage supply waveform (v_{ac} mains), the expected total supply current (i_{tot}) waveform.

---

[31] Power MOSFET has a broad application in switch mode power supplies [55] [85].

The following mathematic formulations are based on the value of the inductor (L) and the duty cycle (D)[32] of the switch S (MOSFET):

- When switch S is ON:

$$\left[T_{s-ON} = D \cdot T\right]: \qquad V_{in}(t) = V_{L(T_{s-ON})}(t) \rightarrow$$

$$\rightarrow V_{in(\max)} \cdot \left|\sin(\omega t)\right| = L \cdot \frac{di}{dt} \qquad (5.1)$$

But if

T_m mains (20 ms) >> T_s switching (μs), the following relation is valid

$$\frac{di}{dt} = \frac{\Delta i}{\Delta t} \qquad (5.2)$$

where $\Delta i = i_{\max} - i_{\min}$, and $\Delta t = T_{s-ON}$, as it is shown in Fig. 5.11.

Finally

$$V_{L(T_{ON})}(t) = V_{in(\max)} \cdot \left|\sin(\omega t)\right| = L \cdot \frac{\Delta i}{T_{ON}} = L \cdot \frac{\Delta i}{D \cdot T} \qquad (5.3)$$

- Also, when switch S is OFF:

$$\left[T_{OFF} = 1 - D \cdot T\right]: \qquad V_{L(T_{OFF})}(t) = V_{in}(t) - V_{Load}(t) = L \cdot \frac{di}{dt} = L \cdot \frac{\Delta i}{\Delta t} =$$

$$= L \cdot \frac{\Delta i}{T_{OFF}} = L \cdot \frac{\Delta i}{1 - D \cdot T} \rightarrow$$

$$\rightarrow V_{L(T_{OFF})}(t) = V_{in}(t) - V_{Load}(t) = L \cdot \frac{\Delta i}{1 - D \cdot T} \qquad (5.4)$$

where $\Delta i = i_{\max} - i_{\min}$, and $\Delta t = T_{OFF}$, as it is shown in Fig. 5.11.

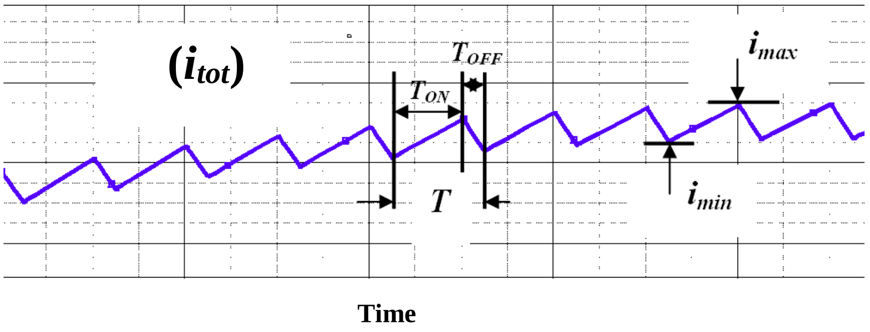


Figure 5.11: Time details from total supply current (i_{tot}).

---

[32] Where 0 < D < 1, L = Henry and period T = second.

An experimental testing through PSpice program according to the circuit in Fig. 5.12 gives the following results:

- Efficiency η = 76%
- Power factor (true) PF = (displacement factor, cos θ) x (distortion factor, D) = 1 x 95.95 = 95.95
- Current Total Harmonic Distortion $THD_{i(\%)}$ = 29.36%

where L = 1.35 mH and duty cycle D = 75%.

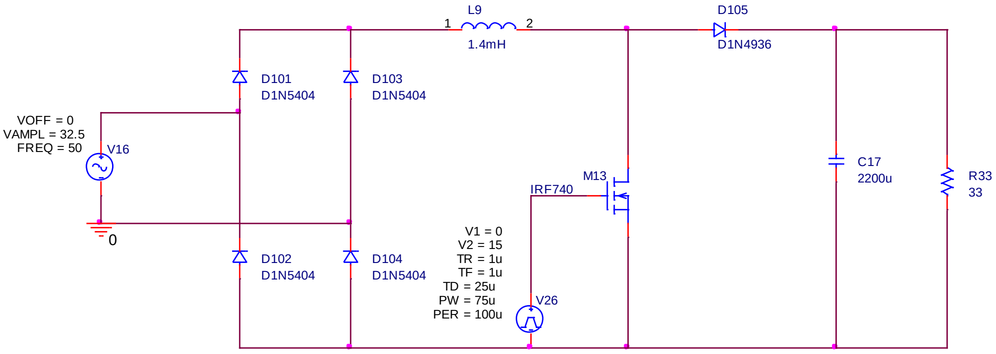


Figure 5.12: A diode bridge rectifier with the harmonic reducer.

Fig. 5.13 shows the mains (v_{ac}) waveform in time correlation with the total supply current (i_{tot}), respectively. Now the current tends to have a waveform close to sinusoidal, after harmonic reduction, as it is illustrated with more details in Fig. 5.14 and in the harmonic spectrum Fig. 5.15.

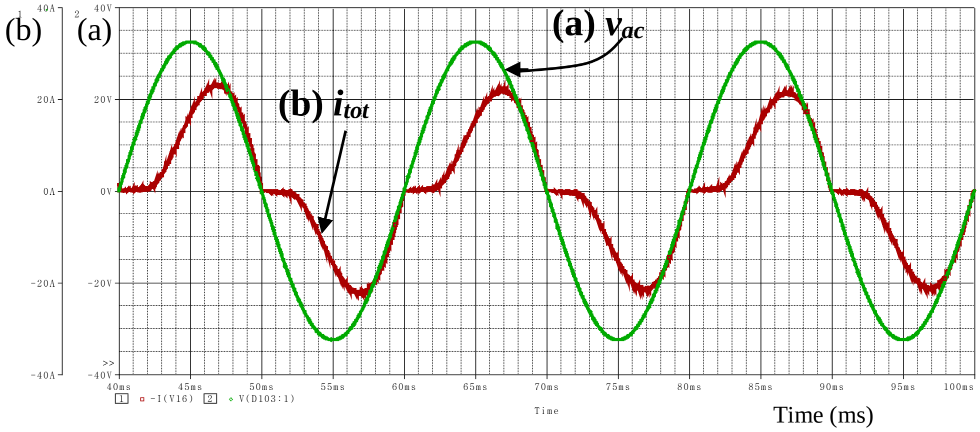


Figure 5.13: The voltage mains (a) and the total supply current (b) waveforms in time correlation.

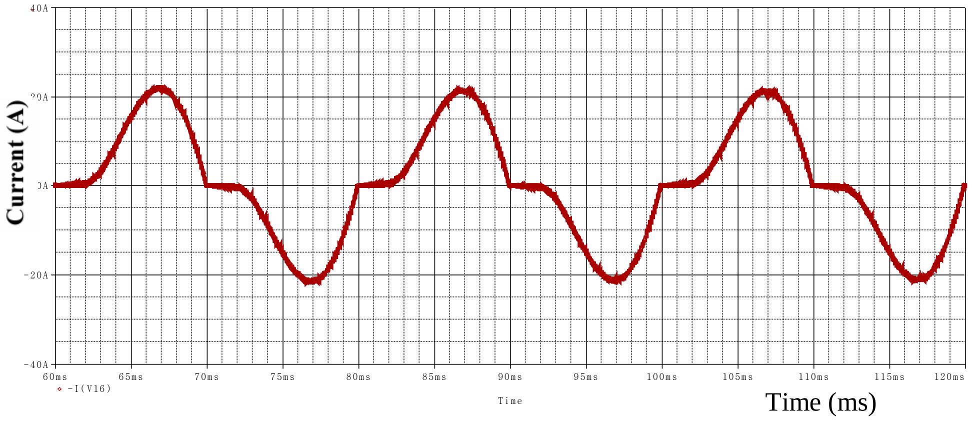


Figure 5.14: The supply current (total) waveform after harmonic reduction.

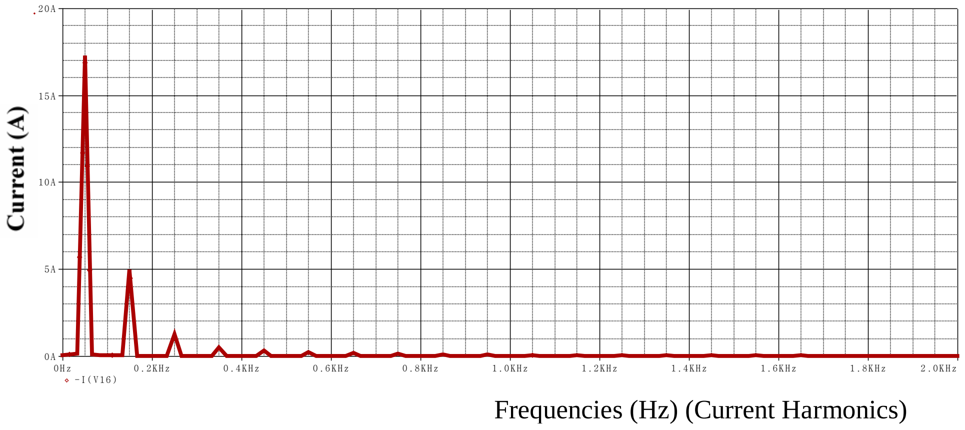


Figure 5.15: The FFT analysis of the current waveform.

Fig. 5.16 illustrates the supply current (i_s) that is added with the load's current (i_{load}) resulting to the total supply current (i_{tot}). Fig. 5.17 shows the three currents in more detail in time domain.

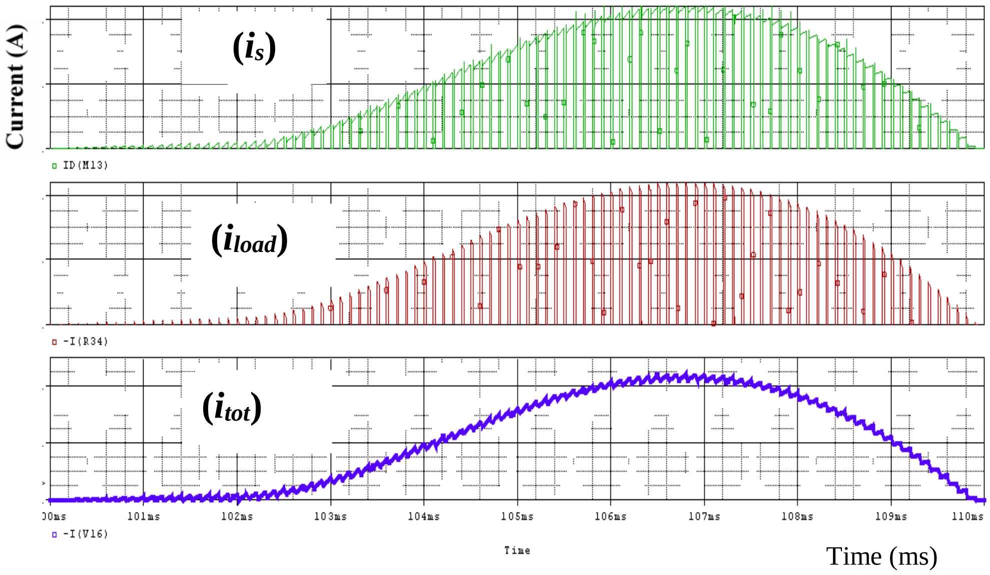


Figure 5.16: The supply current (i_s) that is added with the load's current (i_{load}) resulting to the total supply current (i_{tot}).

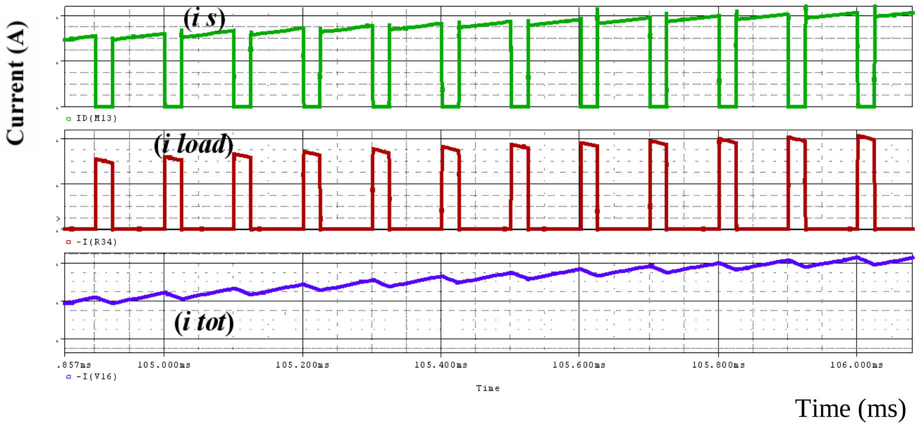


Figure 5.17: In more details, the supply current (i_s) that is added with the load's current (i_{load}) resulting to the total supply current (i_{tot}).

5.3.1 Practical Testing of the Harmonic Reduction

For the experiment the same measuring equipment and power supply were used, like in chapter 4, section 4.3.1.8, plus the oscilloscope, TEKTRONIX TPS 2024 (100 – 200 MHz), for waveform recording.

Fig. 5.18 illustrates the system of the harmonic reducer connected to the non-linear load (photo 4.3), under practical testing. The pulse generator triggers the MOSFET with fixed frequency of 10 kHz and constant duty cycle of 75%. From the testing there are the following results:

- Efficiency η = 63.77%
- Power factor (true) PF = (displacement factor, cos θ) x (distortion factor, DF) = 1 x 0.963 = 0.963
- Current Total Harmonic Distortion $THD_{i(\%)}$ = 27.08%

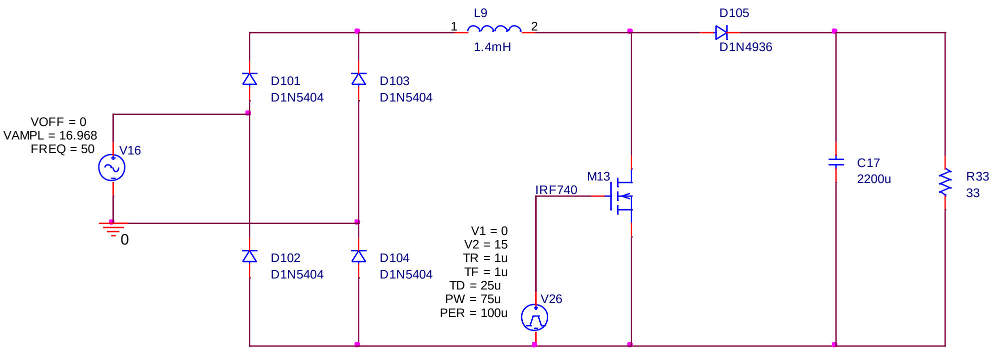
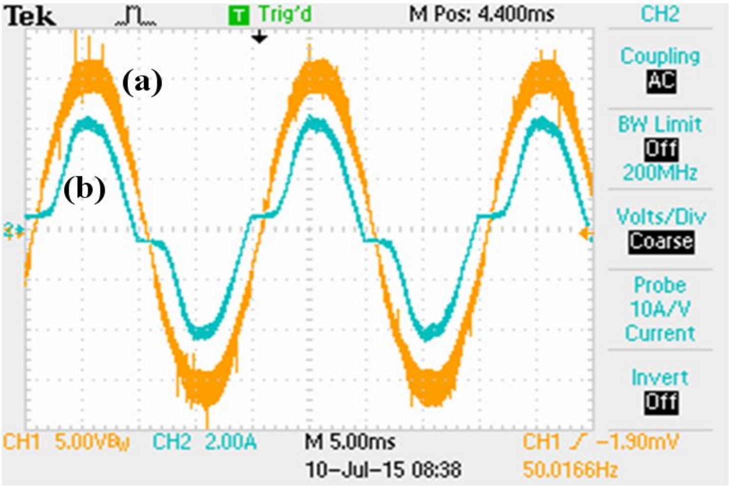


Figure 5.18: The non-linear load with the harmonic reducer.

Fig. 5.19 (a) and (b) show the recorded waveforms of the voltage and supply current[33] respectively. It can be seen clearly from the related waveform, that the THD_i has been reduced enough, from 83.2% to 27.8%.

---

[33] Total.

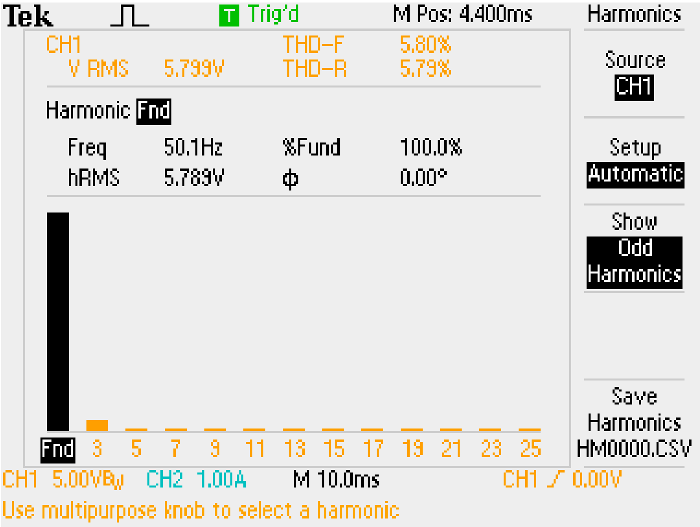


Coupling AC
BW Limit Off 200MHz
Volts/Div Coarse
Probe 10A/V Current
Invert Off

CH1 5.00V B_W CH2 2.00A M 5.00ms CH1 ∕ −1.90mV
10−Jul−15 08:38 50.0166Hz

Figure 5.19: The voltage supply (a) and the corrected supply current (total) (b) waveforms in time correlation.

Fig. 5.20 shows the harmonic spectrum of the supply current[34] after the harmonic reduction, where through the above method, the total harmonic distortion has been reduced from 83.2% to 27.08%.



CH1 V RMS 5.799V THD−F 5.80% THD−R 5.79%

Harmonic Fnd
Freq 50.1Hz %Fund 100.0%
hRMS 5.789V ɸ 0.00°

Source CH1
Setup Automatic
Show Odd Harmonics
Save Harmonics HM0000.CSV

CH1 5.00V B_W CH2 1.00A M 10.0ms CH1 ∕ 0.00V
Use multipurpose knob to select a harmonic

Figure 5.20: The FFT analysis of the current waveform.

The proposed booster scheme here, working under the above technique, has the following *advantages* and *disadvantages*:

---

[34] Total.

Advantages

- It is a simple low cost compact system and easy to use
- The circuit is consisted by few simple components:
    - a diode
    - a power MOSFET[35]
    - a square pulse generator, which can be an integrated circuit[36] or any circuits with discrete components
    - an inductor whose diameter depends on the source current
- The circuit does not accept any external commands
- It has nothing to do with the complexity of programs or any signal processing, analog or digital
- It is reliable during its operation, no matter how much time it works
- It can reduce the current total harmonic distortion (THD_i) from 83% to 27%
- It keeps the true power factor (PF) over high levels, i.e. PF = 0.96
- The efficiency is found on a good level of $\eta = 63\%$

Disadvantages

- It does not have the proper software and hardware support for controlling voltage or current[37] in order to reduce the THD_i lower than 5%.

5.4 Summary

As the use of non-linear loads is growing up, the connection with a harmonic mitigation circuit is necessary.

In this chapter has been proposed a simple, low cost and easy to use circuit for harmonic reduction, whose main advantages are:

- THD_i reduction, and

---

[35] The power depends on the power consumption in the load

[36] It can be a 555, a TL 494 or any other suitable.

[37] Referring to series active power filters or shunt active power filters respectively in **chapter 2**, paragraph 2.6.6.2 Active filters.

- high power factor
- good efficiency

It can be built and connected easily to non-linear loads, like diode bridge rectifiers which can be applied as power supplies to several low or medium power equipment, such as TV's, digital or computerised systems, UPS systems, etc.

Despite the harmonic mitigation, overvoltages remain a danger to the power systems with the undesirable effects. The following chapter (No 6) focuses on the designing of an electronic system which "holds" the mains voltage across a load within the limits of the nominal values. When an overvoltage by mains even up to 20% happens, this electronic system is able to keep mains amplitude to nominal level across the load.

Chapter 6: Overvoltage Protection

6.1 Introduction

Until now it has become clear that overvoltages is a remarkable factor of Power Quality (PQ) that can influence the normal operation of the equipment forcing them to work out of the operating and manufacturing specifications with the danger of damage. Under overvoltage protection, through voltage supply stabilisation, the equipment – load consumes the expected nominal power without the fear of undesired effects that have been described in chapter 2. Overvoltage reduction to international standard levels, through voltage management or power regulation, may end to reduce the excessive power to the desired values. Therefore, it is necessary the equipment to be protected by proper voltage stabilisation systems – circuitries, especially those which under overvoltages the undesired effects of power consumption are in high level.

Chapter 6 describes a proposed electronic circuit which acts as a voltage stabiliser in order to maintain the ac voltage supply ($V_{peak-peak}$) constant across a load, despite the mains overvoltages. The electronic circuit keeps the ac voltage supply of an ac load constant, according to nominal level ($V_{peak-peak}$), even there is overvoltage up to 20% by mains supply.

6.2 The Use of AC/AC Voltage Controller to Reduce the Overvoltage

According to Fig. 6.1 (a), as the mains increases over its nominal value (say up to +20%), a Power Regulation system (Fig. 6.1 b) through continues voltage supply level testing may keep the ac voltage supply amplitude across the load constant, to the permissible limits, eliminating the overvoltage effects on it. Moreover, load power is reduced in several cases of passive loads i.e. resistive, capacitive or inductive or in some cases of passive load combinations, and non-linear loads e.g. when semiconductor components are included (transistors or diodes) as in the case of radio transmitter/receiver electronics, ac-dc bridge converters etc. But this can be happen by applying the method of phase angle control, where triacs or thyristors are mainly used as drivers [2] [142] in order to regulate the rms supply voltage. In the case of overvoltage reduction, this can be achieved by the PWM technique with a chopper ac-dc converter, controlling a MOSFET driver. Fig 6.2 illustrates the mains voltage stabilisation system through PWM for single phase ac load. This system is a Power Regulator system consisted of the Voltage Control, the MOSFET driver and the diode bridge rectifier (D) as a chopper ac-dc converter. The capacitor (C) smoothes the waveform of the voltage so that to become as much as sinusoidal. Finally, the amplitude of the nominal of voltage depends on the duty cycle (DC) for a given value of the capacitor.

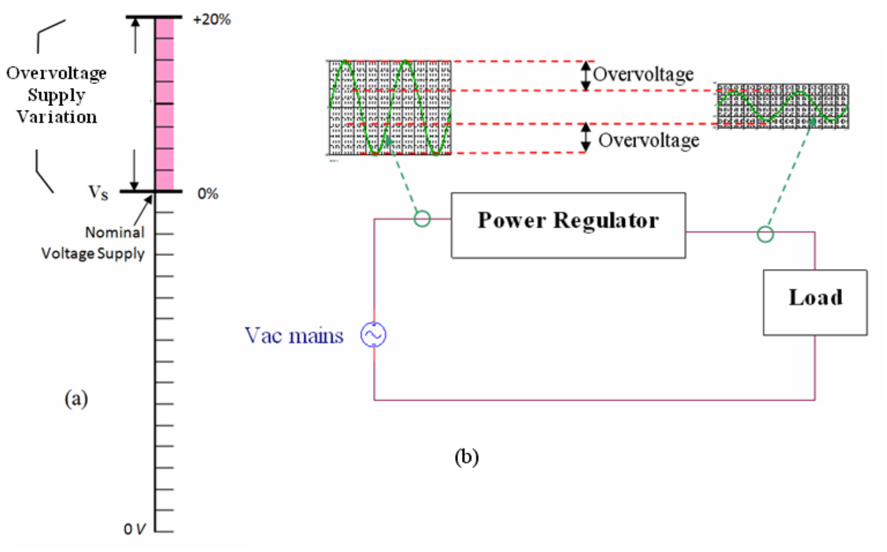


Figure 6.1: Overvoltage variation of power supply (a), voltage management for supply stabilisation (b).

Here, the system is a Power Regulator (or Voltage Stabiliser) (Fig. 6.1 b), which checks continuously the amplitude level of mains supply (Fig. 6.1 a) and reacts as follows:

- As long as there is not overvoltage, the MOSFET is switched ON by the controller, at each zero crossing time of the mains supply, until to the half of each half period (Fig. 6.3). Consequently, this pulse train that triggers the transistor driver has fixed, double frequency than mains supply (50/60 Hz), with a duty cycle of 50%.

- In the case of overvoltage detection by the controller, the controller reduces the duty cycle of the triggering pulses from 50% to such ratio, resulting to the voltage (V_{max} amplitude) across the load remain constant. So, as overvoltage from the power supply increases, the duty cycle decreases too (Fig. 6.4), remaining the voltage across the load constant, at the nominal value.

Therefore, by monitoring continuously the voltage supply – mains, for voltage supply stabilization, by the use of the above PWM technique, may reduce the undesired overvoltages across a load.

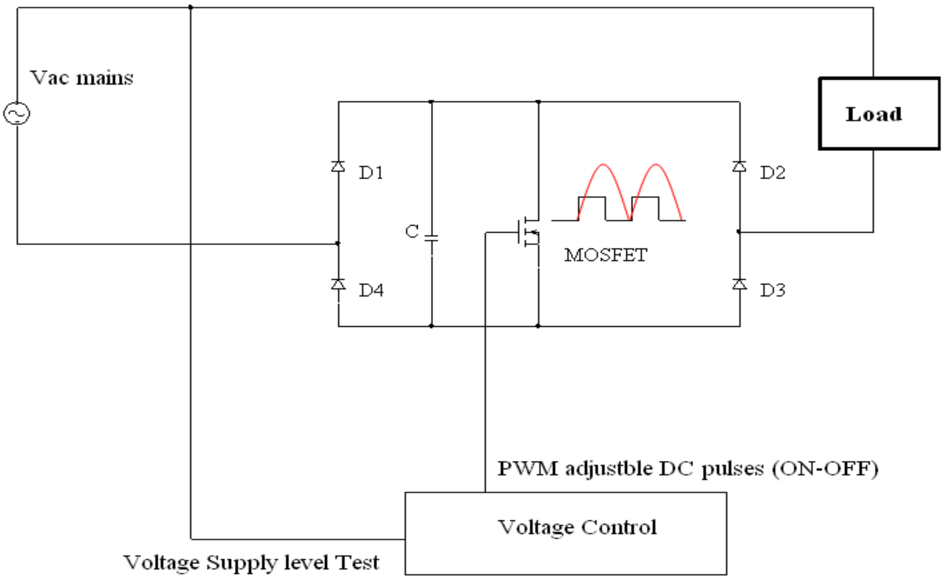


Figure 6.2: Mains voltage stabilisation through PWM for single phase ac load; the Power Regulator system consisted of the Voltage Control, the MOSFET driver and the diode bridge rectifier (D).

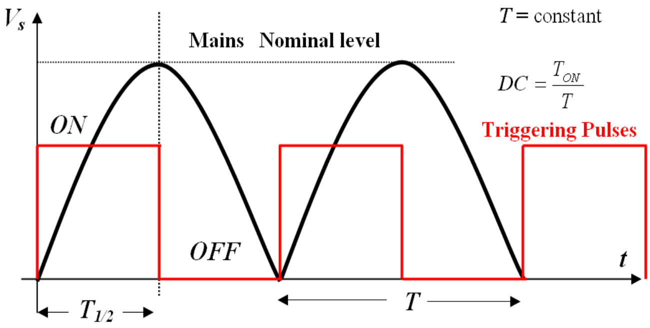


Figure 6.3: The on-off switching timing diagram in time domain with the rectified mains when there is not overvoltage.

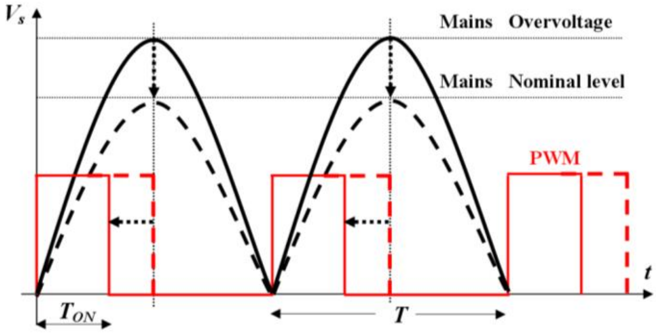


Figure 6.4: Voltage supply stabilization through PWM when it happen overvoltage.

6.2.1 Experimental Testing of a Voltage Stabilizer

Arbitrarily, in the present work, for single phase voltage, low to medium power application[38], the use of dc chopping of rectified ac current through PWM technique by the use of MOSFET as driver has been preferred. (For farther details in APPENDIX H).

With the help of PSpice simulating program, an example of overvoltage reduction on a load is given by the following proposed voltage stabiliser (Fig. 6.5). Fig. 6.6 (a) illustrates the amplitude of the 20% mains overvoltage (276 V_{rms} (390.323 V_{max}) / 50 Hz), having a nominal value of 230 V_{rms}, where through the above PWM technique, it is reduced to its nominal level of 230 V_{rms} (325.27 V_{max}) (Fig. 6.6, b) across a

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[38] Mainly, depending on the power of the driver transistor.

resistive load (R = 33 Ω). A MOSFET is triggered by a fixed frequency of 100 Hz of constant square pulses, with the corresponding duty cycle of 2.5%, (Fig. 6.7 a, b).

For an overvoltage of about 20%, the duty cycle (D) must be set at 2.53%, and the proposed solution gives the following results:

- Efficiency, $\eta = 81.78\%$

  As the mains voltage increases, the efficiency undergoes a small reduction. This is because the power consumption in the load remains almost constant and the rest of the offered power is dissipated by the stabiliser system.
- Power factor (true), PF = 0.995 (displacement factor ≈ 1, distortion factor = 0.995)
- Current Total Harmonic Distortion, THD_i (%) = 9.54%. Fig. 6.8 shows the harmonic current spectrum.

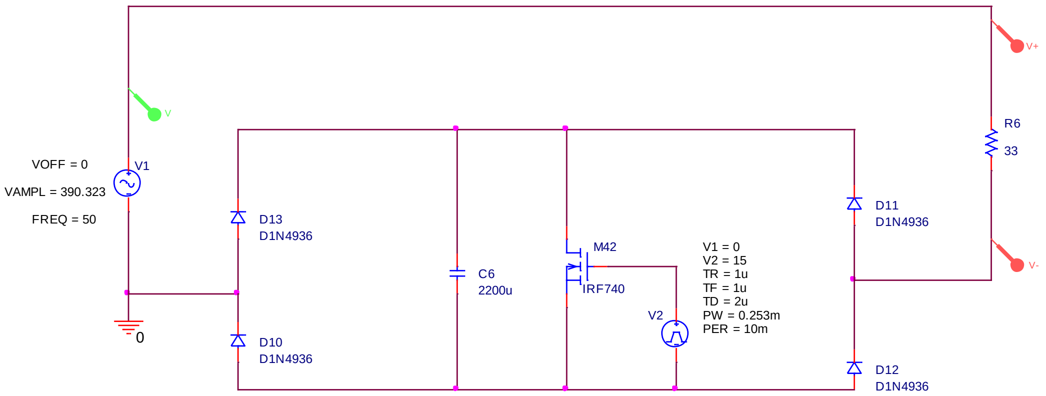

Figure 6.5: Mains overvoltage reduction system, for 20% of voltage amplitude Vmax, through PWM across a resistive load.

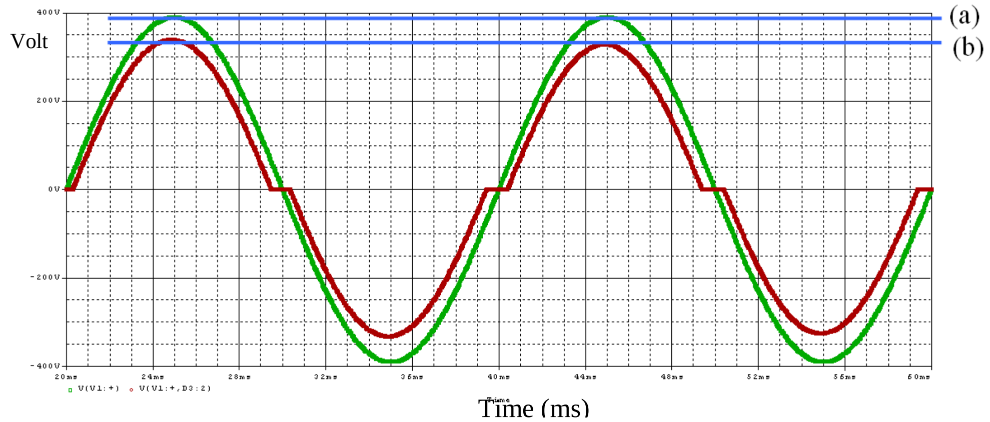

Figure 6.6: Mains overvoltage amplitude of 20% (390.323 Vmax) (a), Nominal voltage amplitude (325.27 Vmax) across the load (b).

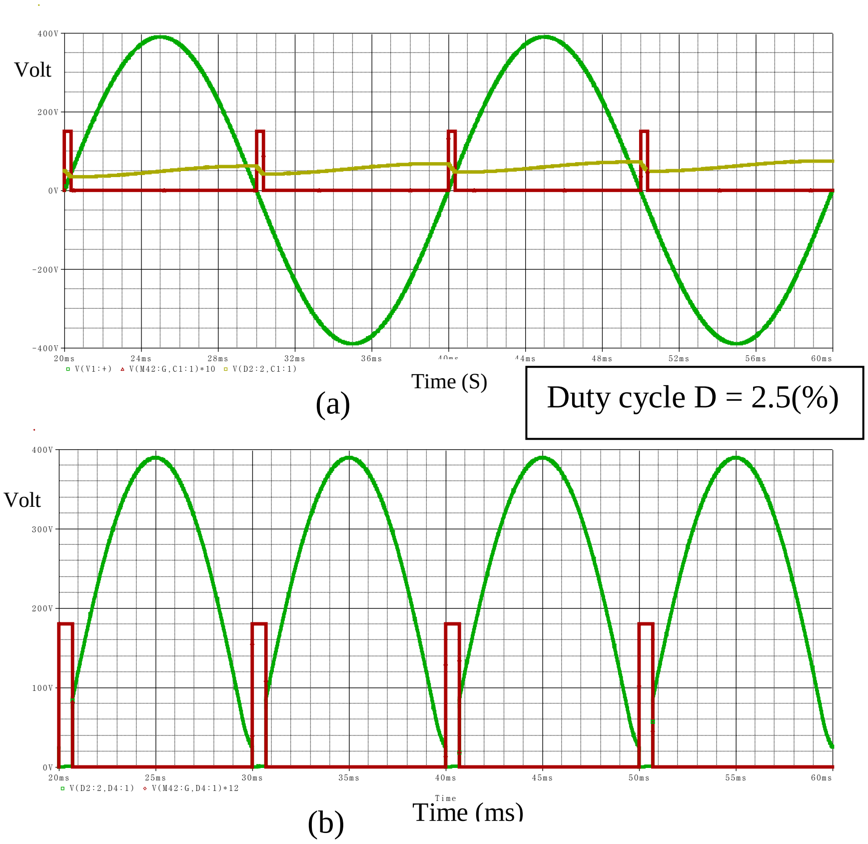

Figure 6.7: the triggering square pulses in time correlation with mains (a), the triggering square pulses in time correlation with the rectified mains (b).

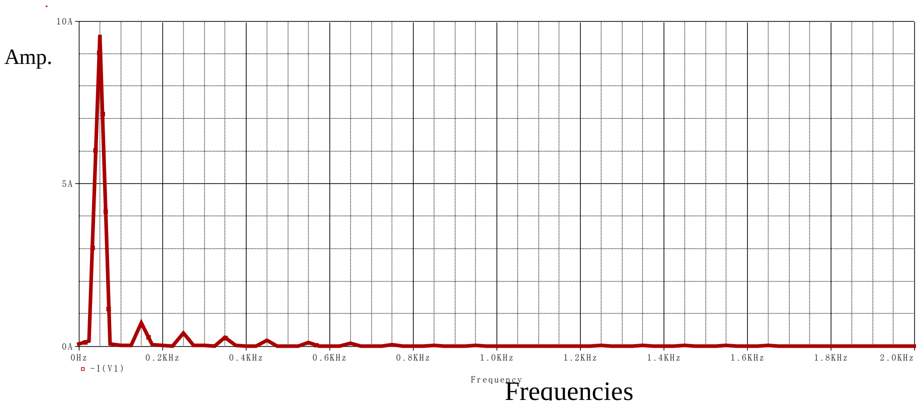

Figure 6.8: The harmonic current spectrum, trough PWM proposed solution.

With an overvoltage of 13.53%, the duty cycle must be set at 6.6%, and the proposed solution gives the following results:

- Efficiency, η = 86.64%
- Power factor (true), PF = 0.997 (displacement factor ≈ 1, distortion factor = 0.997)
- Current Total Harmonic Distortion, THD_i (%) = 6.67%.

When there is not overvoltage, the duty cycle must be set at 50%, where the resulting voltage supply across the load is given by Fig. 6.9 (b)[39] (red line), and the proposed solution gives the following results:

- Efficiency, η = 96.36%
- Power factor (true), PF = 0.999 (displacement factor ≈ 1, distortion factor = 0.999)
- Current Total Harmonic Distortion, THD_i (%) = 2.8%.
- Voltage difference between input and output is negligible, in the range of about 5 V[40].

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[39] Fig. 6.9 (a) illustrates the mains waveform (green line).

[40] Because of the switching devises, transistor and diodes.

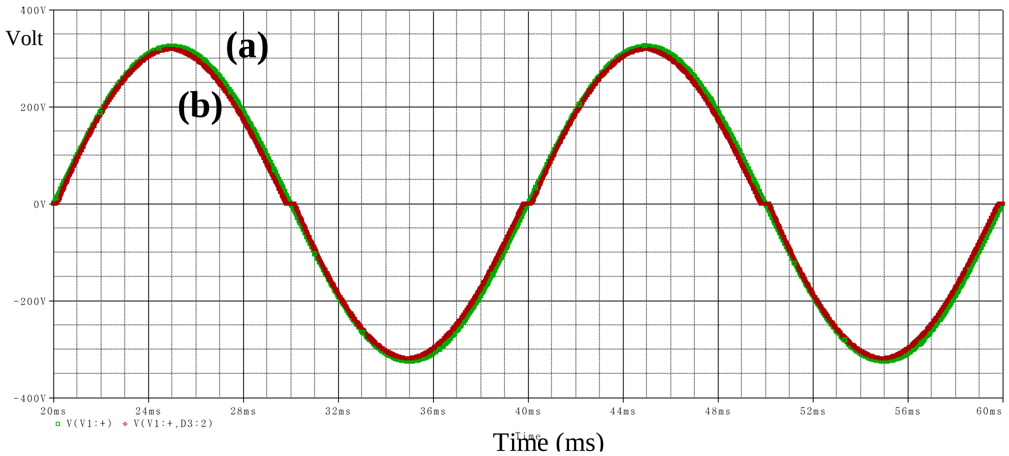

Figure 6.9: Mains nominal of 325.27 Vmax (green line, a), and 320.61 Vmax voltage supply across the load (red line, b).

This means that under normal conditions (no overvoltages) the voltage stabilizer system does not affect substantially the mains amplitude. But in the case of voltage increase up to 20%:

- the efficiency remains at high level
- the power factor (true) remains at high level too
- the Current Total Harmonic Distortion is lower than 10%
- the equipment works normally, with a voltage supply at nominal level across it.

According to the above experimental testing, the relation between supply voltages and duty cycles (%) is given by Fig. 6.10.

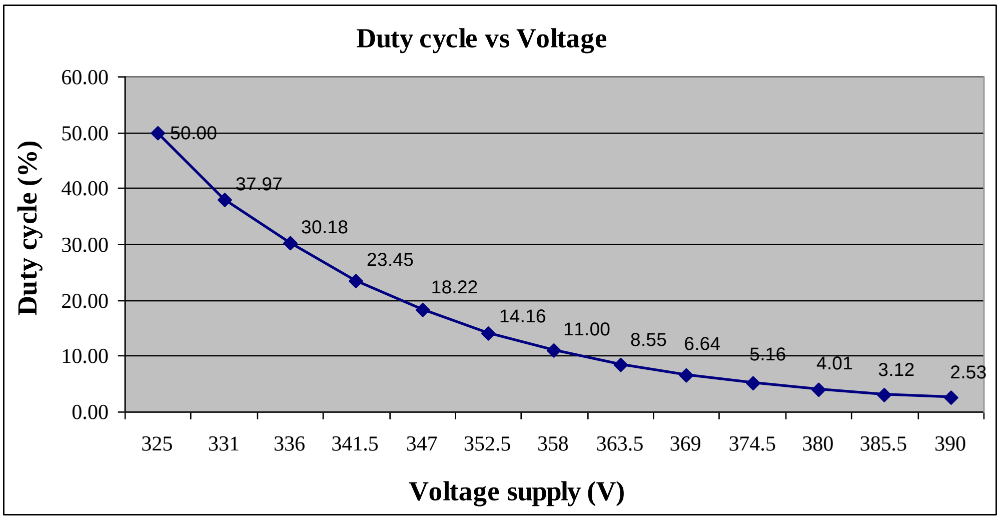

Figure 6.10: The relation between voltage supply (V_{peak}), from 0% up to 20% overvoltages, and duty cycle (%) of the triggering pulses.

The relation between the duty cycle (D) in percentage and the voltage supply from the power source of 230 V_{rms}, in order to remain the voltage supply across the load constant (230 V_{rms}, 325 V_{peak}), for a given capacitance (C, Fig. 6.2), is given by the following equation

$$\text{Duty cycle} \qquad D_{(\%)} = 149469064 \cdot e^{-0.045878 \cdot V_p} \qquad (6.1)$$

The value of the capacitor (C, Fig. 6.2) is directly related with the total harmonic distortion of the current (THD_i) caused by the stabilizer system. The relation between the value of the capacitor (C uF) and the THD_i by the stabilizer, in normal power supply (no overvoltages, DC = 50%), is given by the following equation

$$C_{uF} = 7259 \cdot e^{-0.429 \cdot THD_{(\%)}} \qquad (6.2)$$

The equation is available for THD_i (%) from 1% to 5%, according to the IEEE 519 standard[41]. The value of the capacitor has been chosen when there is no happen overvoltages (DC = 50%). As the capacitance (C uF) increases, the THD_i by the stabilizer decreases too. The value of C = 2200 uF resulting to THD_i (%) = 2.8% by the stabilizer is satisfactory. Despite the THD_i decrease, the increase of the

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[41] For Bus Voltage = 69 kV and below

capacitance denotes higher dimensions, higher weight and higher cost of the capacitor.

By the application of the above proposed voltage stabilizer system, with the use of PWM technique, by adjusting the duty cycle in relation to the mains variations, the voltage supply across a load can remain constant.

6.3 Summary

Voltage supply control or stabilization is necessary, in order to protect the loads from the undesired overvoltages.

In this chapter has been proposed a simple, low cost and easy to use circuit with low power consumption, for voltage stabilization to any low or medium power equipment[42].

Its main advantages are:

- High efficiency
- High power factor
- Low THDi

Its main disadvantage is:

- When overvoltages increase from 10% up to 20%, the THD_i increases relatively up to 9.54%, while the THD_i, according to IEEE 519 standard, should remain up to 5% at the most.

The equipment can be protected from overvoltages up to 20%. But, with proper software in the voltage control system (Fig. 6.2), the power supply can be interrupted since the voltage supply tends to become higher or lower than 20%, according to the operating demands of the user, the equipment or any other circumstance.

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[42] With relation to how much power can manipulate the voltage stabiliser.

The power manipulation by the stabilizer depends on the driver transistor and the diode bridge rectifier.

The conclusion of the all theses is presented in the following chapter 7 and also refers to recommendations and future work about overvoltages effects for the safe operation of power loads.

Chapter 7: Conclusions, Recommendations and Future Work

7.1 Introduction

The aim of this research was to study the effects of the overvoltages on power consumption in different types of loads or equipment. For a good overview of the research, it was necessary to classify the loads in two main categories:

- the passive loads and
- the non-linear loads

In the research about the non-linear loads it was necessary to focus the attention about a new threat for the equipment and power supply line, which is the harmonics that are produced mainly by the active loads. For the above reason, it was considered necessary the trial for an easy and cost effective system for harmonic mitigation.

All the same, still remaining the fear of overvoltage effects on the power consumption in the loads, it was necessary the trial for an easy and cost effective system for voltage stabilisation across the loads.

Besides, with the rapid increase of active loads, as sources of harmonic currents, it is necessary, the power supply organisations to review the structures of power distribution and their supporting electrical technologies with relation to overvoltages. Also, manufacturers and designers it is necessary to focus about the problematic harmonic disturbances by these active loads.

Every day, electrical and electronic technology invents new and more convenient solutions to satisfy the human needs. Besides, some new serious factors that they influence the PQ, like overvoltages and harmonics must come under intensive research for effective solutions about their undesired effects in the loads.

7.2 Conclusions

The purpose of this thesis was mainly the study and analysis of the effects of overvoltages on power consumption of different categories of loads. Also, during the process of the thesis appeared two remarkable problems that were considered necessary to investigate and resolve: (a) the fact that the amplitudes of harmonic currents of non-linear loads increase with the overvoltage and (b) the stabilisation of the supply voltage at the input of the loads.

In specific, based on exhaustive experimental testings (both via software simulations and, most importantly, via practical testings in the laboratory), it was proved that overvoltages result to:

- Increased power consumption, which means unnecessary increase in expenditure, i.e., money and energy. This, also, raises the need of voltage supplying stabilisation by proper stabilisation circuitry, when not available from the power supplying system itself.
- Decrease of the lifespan of the materials because of overheating, which further results in unnecessary expense of components and items.
- Increased amplitude of the current harmonics due to non-linear loads, resulting to extra unnecessary increase of power consumption and undesired power quality (PQ) problems in utility systems. This raises the need to use a harmonic current reduction circuitry, too.

In addition, the study of overvoltages, provided a better knowledge of the behaviour of loads having different nature in power consumption.

For the current harmonic reduction, the proposed relative circuitry is consisted of a minimum number of components and its connection to non-linear load results to the following advantages:

- Reduction of the harmonic currents at a satisfactory level.
- The existence of extra protection or relief of the load or equipment, when the supplying voltage or mains increases from its nominal value to undesired overvoltages.
- As less as possible influence of the current harmonics to the utility system and neighboring loads.

The harmonic current reducer is a cheap and easy to use electronic circuit that can be easily connected between the power supplying source or mains and the non-linear load. From the practical experimental testings it was proved that the current harmonic reducer circuitry: (a) reduces satisfactorily the Total Harmonic Distortion ($THD_{\%}$) of the supplying current, (b) has a high Power Factor (PF), and (c) has an acceptable Efficiency (η).

Also, for the protection of the loads or equipment against the undesirable effects on power consumption, due to overvoltages, the proposed prototyping electronic circuit (voltage stabiliser) has the following advantages:

- Connected between the supplying voltage or mains and a load or equipment, it keeps the desired or nominal voltage supply (voltage amplitude, $V_{\text{peak to peak}}$) constant, across a load or equipment, despite the supplying overvoltage variations.
- It can be easily connected to the input of the load or equipment.
- It is consisted of a minimum number of components.

From the experimental testings it was proved that, when the supplying voltage increases up to 20% (overvoltage level), the stabiliser creates a low Total Harmonic Distortion ($THD_{\%} \approx 9.5\%$) of the supplying current, while the system[43] has high Power Factor ($PF \approx 0.99$) with high Efficiency ($\eta \approx 82\%$), and the voltage supply (voltage amplitude, $V_{\text{peak to peak}}$) across the load or equipment remains constant[44].

7.2.1 Passive Loads

In this category belong the resistive and the electromagnetic loads.

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[43] The load or equipment.

[44] When there is not overvoltage, the system appears a Power Factor (PF) ≈ 0.99, its Efficiency (η) is ≈ 96%, and the Total Harmonic Distortion of the current ($THD_{\%}$) is ≈ 9.5%.

7.2.1.1 Resistive Loads

Resistive loads behave as ohmic loads which may be heaters, kitchen appliances, lights (incandescent lamps), etc. where the power consumption is straight proportional to the voltage supply. So, an increase of, say, 20% in a supply voltage of 230V will result to an increase of 44% on power consumption in an ohmic or purely resistive load. But in real conditions will result to an increase of 37% - 39%:

- If the load is a cooker, heater, boiler or kettle an overvoltage of mains will result to more power consumption with a relative heating increase and therefore more charges on energy bill.
- For an incandescent lamp an overvoltage of mains will result to the relative increase of the light intensity of the lamp and consequently more charge on energy bill. Also, the percentage variation of the consumed power observed is generally lower than the corresponding variation of the light intensity.

Also, incandescent lamps and heating elements tend to show a slight increase in resistance with voltage. Resistive loads sometimes appear with a negligible amount of inductance or capacitance according to their infrastructure.

7.2.1.2 Electromagnetic Loads

Equipment with transformers or motors are under the category of electromagnetic loads:

- The primary factor here is the power consumption in doing the useful work.
- An increase of the voltage supply will increase a small amount of power consumption in the load. Consequently, the loads of this category consume power not straight but approximately proportional to the voltage (v) variations.
- However, as voltage increases, the magnetic materials approach saturation, leading not only to increased losses in the iron core, but also to increased losses in the copper windings. At this point, the power consumption increases much more rapidly than (v^2). If the voltage rises to the level that causes

saturation, the power consumed will continue to rise until catastrophic failure occurs. This applies, regardless of the amount of useful work done.

- Many types of mains driven motors are affected by overvoltages in another way: They commonly operate at a low percentage of full load (partly, because they cannot start if the load exceeds 34% of their maximum capability). The power consumed increases with the voltage, even though there is no increase in useful work done. While they are very efficient at full load (over 90% is possible), typically, the efficiency at loads of less than 20% is very poor (under 50% is common), and most of the power drawn is because of losses. The power consumed by the losses increases with (v^2).
- In the special case of refrigeration and some types of air conditioning, additional cooling is required to cope with heat or compensate the heat produced by overvoltage. This, in turn, causes increased power requirements leading to vicious circles of decreasing efficiency. The power consumed, increases more rapidly than with (v^2) for almost all levels of useful work done, and failure due to saturation is also possible.

7.2.2 Non-linear Loads

In this category of non-linear loads belong fluorescent or gas discharge lamps and active loads.

7.2.2.1 Fluorescent or Gas Discharge Lamps

Including the Energy Saving Lamps or Compact Fluorescent Lamps (CFLs) also, in this type of load the amount of power consumed is almost proportional to voltage (v^2).

In general, an increase of 10% in a supply voltage of 230V will result in about 32% power consumption and about 10% light intensity increase. And an increase of 20% will result in about 78% power consumption and about 20% light intensity increase. Consequently, during overvoltages the percentage variation of power consumed is generally greater than the percentage variation of the corresponding light intensity.

While the behaviour of any model of lamp can only be determined by measurement, the overall behaviour of a large number of gas discharge lamps is predictable. However, almost all designs suffer marked reduction in life with over voltage.

7.2.2.2 Active Loads

The amount of power consumed is delivered in response to the load demand.

- Overvoltages result in a small increase of power consumption.
- Most active loads have internal transformers which are susceptible to saturation (even if they are not operating at mains frequency), and high voltage transistors, whose losses increase with voltage faster than (v^2).
- Other effects of overvoltage include the reduction of the lifespan of various components, like semiconductors (diodes, resistors, SCRs, triacs), capacitors, resistors etc.
- Overvoltages result to a small increase of current distortion. But this becomes a serious danger in the case when such many active loads are neighboring and they are connected to the same line power.
- The relationship between efficiency and applied voltage is determined by the design of the electronics.
- Also, in some cases, where there is a built-in supporting power management system (regulators, software support etc.), active loads still continue to work like the nominal supply conditions, even if overvoltage exists.

7.3 Recommendations and Future Work

Overvoltage effects on power consumption are an undesired phenomenon that should be removed or reduced as much as possible. The power production and distribution companies should be aware of the rapid increase of the power consumption in the electrical appliances, which may result to the rapid increase of the overvoltage effects too. The increase of the overvoltage effects finally, results to negative implications for the safe operation of the loads or equipment and also the consequences on the economy of the users and/or country will be severe.

The existence of the overvoltages, with the continuous increase of power consumption, creates an urgent need for re-evaluation of the existing power generators and the technological infrastructure of the distribution systems. Because, the continuous increasing of the number of loads or equipment, the new electronic technologies applied on them, the use of more and more sensitive electronic devices with new technologies (i.e. computerised systems, digital control systems, robotics, mobile communication systems, wired or wireless communication systems, sensor systems, microelectronics etc.) puts the constant voltage supply across them as a high priority condition for their safe operation.

Another factor that may adversely affect the operation of the loads, of mainly sensitive devices of new technologies, with finally extra economic charges, is the harmonic distortion of the waveshape of the current by the non-linear loads that increase continuously.

In the present thesis has been proposed a proper topology, and a relative effort took place through PSpice program, for voltage supply stabilisation across a load. For the safe operation of the loads or equipment, it should be reasonable the connection of a voltage stabiliser, between voltage supply and consumer – load. Hence, despite the mains increasing (overvoltage), the voltage supply across the load remains constant (invariable), according to its nominal value supply.

Also, an effort took place through PSpice program and in practice too, for current harmonic reduction of non-linear load. It is necessary power active filters to be connected to non-linear loads, or the loads themselves contain in their circuitries such filters, in order to eliminate, reduce or mitigate the current harmonics.

A compact system with the abilities of voltage supply stabilisation across the load and current correction (if there are current harmonics), could be a fine protector against the undesired overvoltages from mains supply and the created current harmonics. This system could be additionally connected to the topology of a load or equipment, or a part in the circuitry during its construction procedure in the construction company.

As future work, an investigation in deep and application of such compact system – voltage stabilizer and current corrector – could be done for the safe operation of the loads or the equipment and at the same time the whole system[45] to operate as much economically as possible.

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[45] The voltage stabiliser and current corrector system connected to the load or the equipment.

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APPENDIXES

APPENDIX A

Voltage Characteristics of Public Distribution Systems

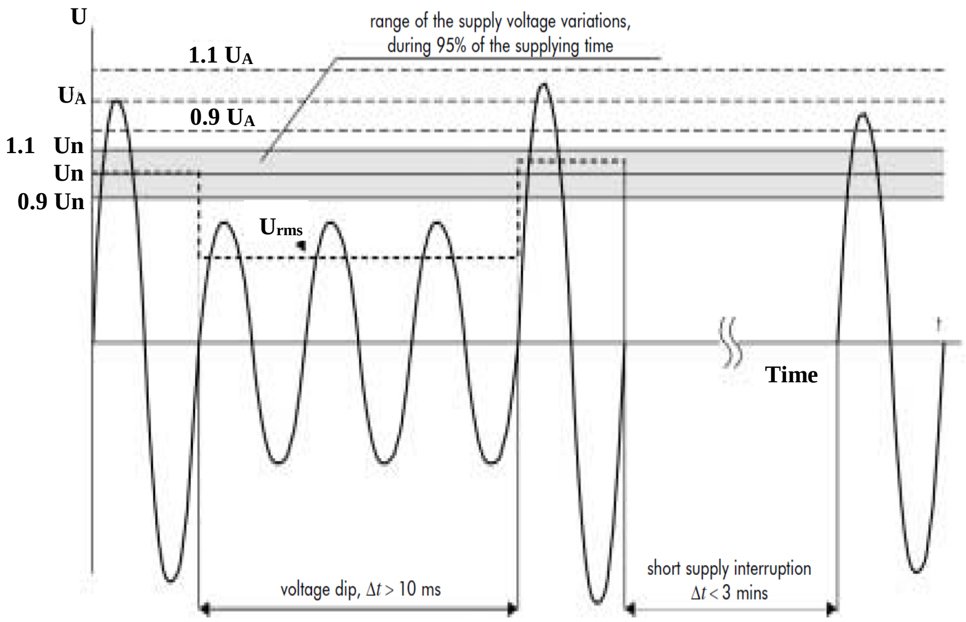


Figure A.1: Illustration of a voltage dip and a short supply interruption [26].

U_n – nominal voltage of the supply system (rms).

U_A – amplitude of the supply voltage.

U(rms) – the actual rms value of the supply voltage [26].

Table A.1: Values of individual harmonic voltages at the supply terminals for orders up to 25, given in percent of Un [26].

Odd harmonics				Even harmonics	
Not multiples of 3		Multiples of 3			
Order n	Relative voltage (%)	Order n	Relative voltage (%)	Order n	Relative voltage (%)
5	6	3	5	2	2
7	5	9	1.5	4	1
11	3.5	15	0.5	6…24	0.5
13	3	21	0.5		
17	2				
19	1.5				
23	1.5				
25	1.5				

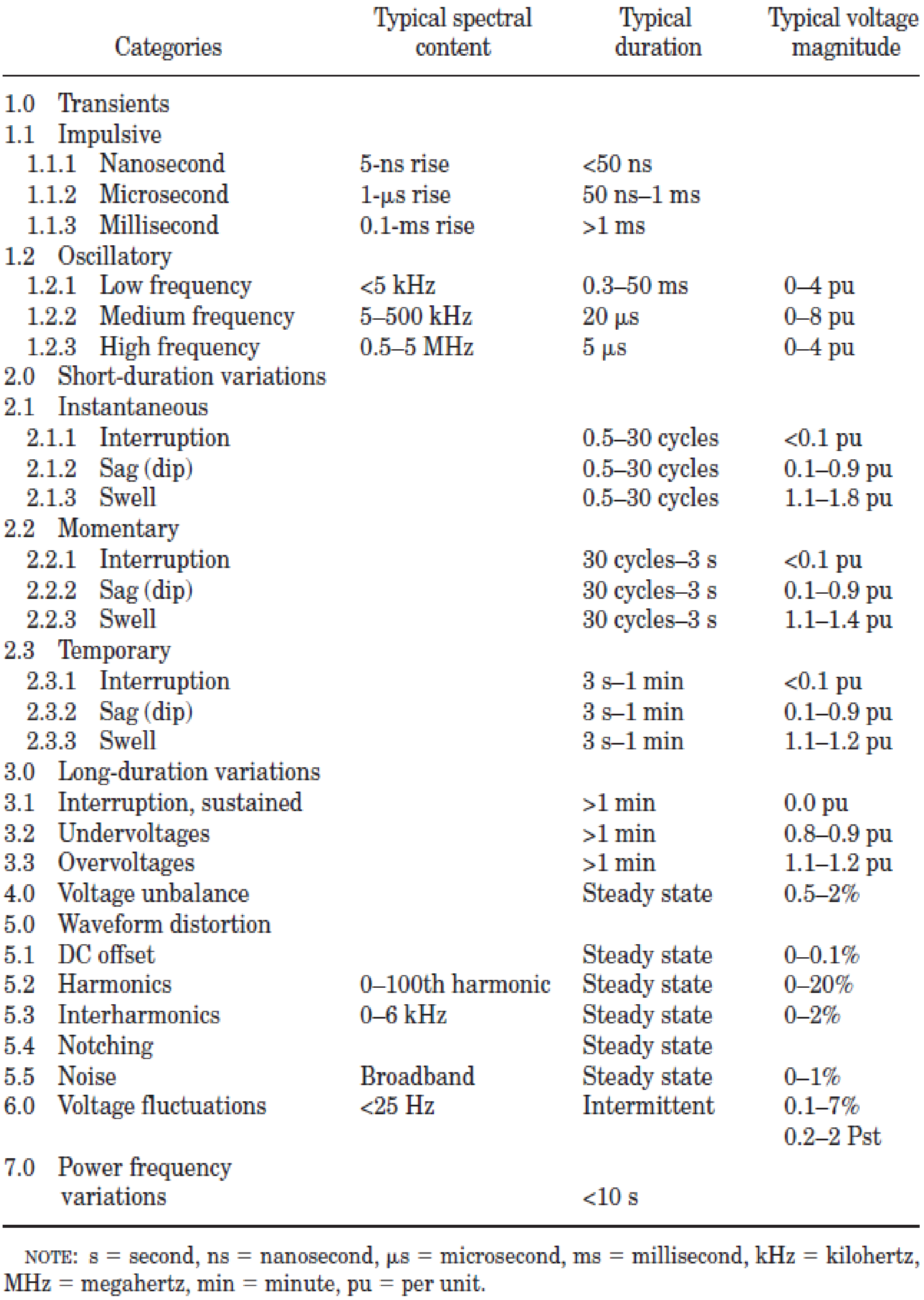
Table A.2: Comparison of supply voltage requirements according to EN 50160 and the EMC standards EN 61000 [3] [26].

No	Parameter	Supply voltage characteristics according to EN 50160	Low voltage characteristics according to EMC standard EN 61000	
			EN 61000-2-2	Other parts
1	Power frequency	LV, MV: mean value of fundamental measured over 10 s ±1% (49.5 - 50.5 Hz) for 99.5% of week -6%/+4% (47- 52 Hz) for 100% of week	2%	
2	Voltage magnitude variations	LV, MV: ±10% for 95% of week, mean 10 minutes rms values (Figure 1)		±10% applied for 15 minutes
3	Rapid voltage changes	LV: 5% normal 10% infrequently $P_{lt} \leq 1$ for 95% of week MV: 4% normal 6% infrequently $P_{lt} \leq 1$ for 95% of week	3% normal 8% infrequently $P_{st} < 1.0$ $P_{lt} < 0.8$	3% normal 4% maximum $P_{st} < 1.0$ $P_{lt} < 0.65$ (EN 61000-3-3) 3% (IEC 61000-2-12)
4	Supply voltage dips	Majority: duration <1s, depth <60%. Locally limited dips caused by load switching on: LV: 10 - 50%, MV: 10 - 15% (Figure 1)	urban: 1 - 4 months	up to 30% for 10 ms up to 60% for 100 ms (EN 61000-6-1, 6-2) up to 60% for 1000 ms (EN 61000-6-2)
5	Short interruptions of supply voltage	LV, MV: (up to 3 minutes) few tens - few hundreds/year Duration 70% of them < 1 s		95% reduction for 5 s (EN 61000-6-1, 6-2)
6	Long interruption of supply voltage	LV, MV: (longer than 3 minutes) <10 - 50/year		
7	Temporary, power frequency overvoltages	LV: <1.5 kV rms MV: 1.7 U_c (solid or impedance earth) 2.0 U_c (unearthed or resonant earth)		
8	Transient overvoltages	LV: generally < 6kV, occasionally higher; rise time: ms - µs. MV: not defined		±2 kV, line-to-earth ±1 kV, line-to-line 1.2/50(8/20) Tr/Th µs (EN 61000-6-1, 6-2)
9	Supply voltage unbalance	LV, MV: up to 2% for 95% of week, mean 10 minutes rms values, up to 3% in some locations	2%	2% (IEC 61000-2-12)
10	Harmonic voltage	LV, MV: see Table 2	6%-5th, 5%-7th, 3.5%-11th, 3%-13th, THD <8%	5% 3rd, 6% 5th, 5% 7th, 1.5% 9th, 3.5% 11th, 3% 13th, 0.3% 15th, 2% 17th (EN 61000-3-2)
11	Interharmonic voltage	LV, MV: under consideration	0.2%	

APPENDIX B

Categories and Characteristics of Power System Electromagnetic Phenomena

Table B.1: Categories and Characteristics of Power System Electromagnetic Phenomena [32].



Categories	Typical spectral content	Typical duration	Typical voltage magnitude
1.0 Transients			
1.1 Impulsive			
1.1.1 Nanosecond	5-ns rise	<50 ns	
1.1.2 Microsecond	1-µs rise	50 ns–1 ms	
1.1.3 Millisecond	0.1-ms rise	>1 ms	
1.2 Oscillatory			
1.2.1 Low frequency	<5 kHz	0.3–50 ms	0–4 pu
1.2.2 Medium frequency	5–500 kHz	20 µs	0–8 pu
1.2.3 High frequency	0.5–5 MHz	5 µs	0–4 pu
2.0 Short-duration variations			
2.1 Instantaneous			
2.1.1 Interruption		0.5–30 cycles	<0.1 pu
2.1.2 Sag (dip)		0.5–30 cycles	0.1–0.9 pu
2.1.3 Swell		0.5–30 cycles	1.1–1.8 pu
2.2 Momentary			
2.2.1 Interruption		30 cycles–3 s	<0.1 pu
2.2.2 Sag (dip)		30 cycles–3 s	0.1–0.9 pu
2.2.3 Swell		30 cycles–3 s	1.1–1.4 pu
2.3 Temporary			
2.3.1 Interruption		3 s–1 min	<0.1 pu
2.3.2 Sag (dip)		3 s–1 min	0.1–0.9 pu
2.3.3 Swell		3 s–1 min	1.1–1.2 pu
3.0 Long-duration variations			
3.1 Interruption, sustained		>1 min	0.0 pu
3.2 Undervoltages		>1 min	0.8–0.9 pu
3.3 Overvoltages		>1 min	1.1–1.2 pu
4.0 Voltage unbalance		Steady state	0.5–2%
5.0 Waveform distortion			
5.1 DC offset		Steady state	0–0.1%
5.2 Harmonics	0–100th harmonic	Steady state	0–20%
5.3 Interharmonics	0–6 kHz	Steady state	0–2%
5.4 Notching		Steady state	
5.5 Noise	Broadband	Steady state	0–1%
6.0 Voltage fluctuations	<25 Hz	Intermittent	0.1–7% 0.2–2 Pst
7.0 Power frequency variations		<10 s	

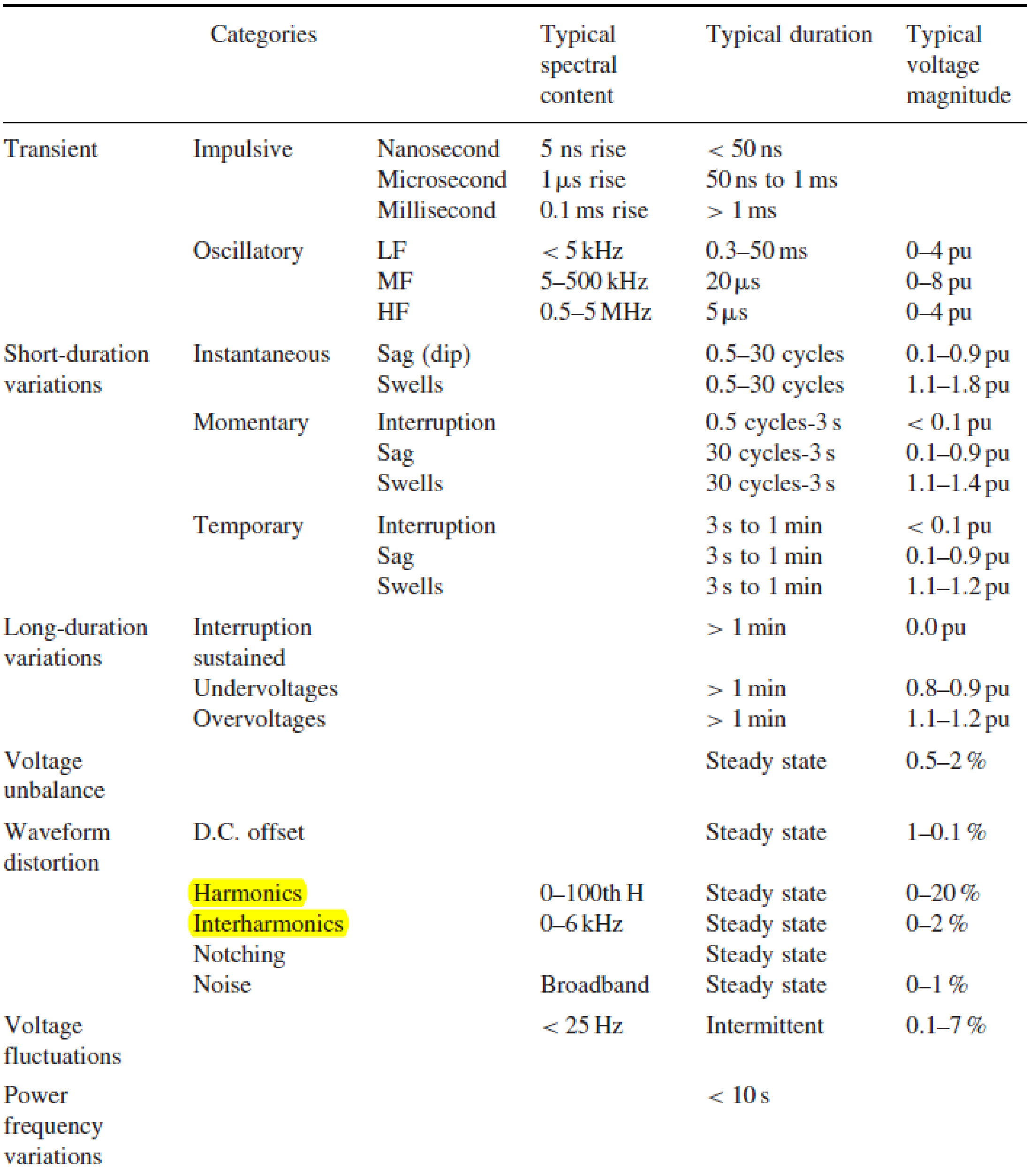
NOTE: s = second, ns = nanosecond, µs = microsecond, ms = millisecond, kHz = kilohertz, MHz = megahertz, min = minute, pu = per unit.

APPENDIX C

Voltage Harmonics and Interharmonics According to International Electronical Commission (IEC)

According to International Electronical Commission (IEC), voltage harmonics and interharmonics are included in the set of the parameters (Table C.1).

Table C.1: Categories of power quality variation [161].



Categories			Typical spectral content	Typical duration	Typical voltage magnitude
Transient	Impulsive	Nanosecond	5 ns rise	< 50 ns	
		Microsecond	1 µs rise	50 ns to 1 ms	
		Millisecond	0.1 ms rise	> 1 ms	
	Oscillatory	LF	< 5 kHz	0.3–50 ms	0–4 pu
		MF	5–500 kHz	20 µs	0–8 pu
		HF	0.5–5 MHz	5 µs	0–4 pu
Short-duration variations	Instantaneous	Sag (dip)		0.5–30 cycles	0.1–0.9 pu
		Swells		0.5–30 cycles	1.1–1.8 pu
	Momentary	Interruption		0.5 cycles-3 s	< 0.1 pu
		Sag		30 cycles-3 s	0.1–0.9 pu
		Swells		30 cycles-3 s	1.1–1.4 pu
	Temporary	Interruption		3 s to 1 min	< 0.1 pu
		Sag		3 s to 1 min	0.1–0.9 pu
		Swells		3 s to 1 min	1.1–1.2 pu
Long-duration variations	Interruption sustained			> 1 min	0.0 pu
	Undervoltages			> 1 min	0.8–0.9 pu
	Overvoltages			> 1 min	1.1–1.2 pu
Voltage unbalance				Steady state	0.5–2 %
Waveform distortion	D.C. offset			Steady state	1–0.1 %
	Harmonics		0–100th H	Steady state	0–20 %
	Interharmonics		0–6 kHz	Steady state	0–2 %
	Notching			Steady state	
	Noise		Broadband	Steady state	0–1 %
Voltage fluctuations			< 25 Hz	Intermittent	0.1–7 %
Power frequency variations				< 10 s	

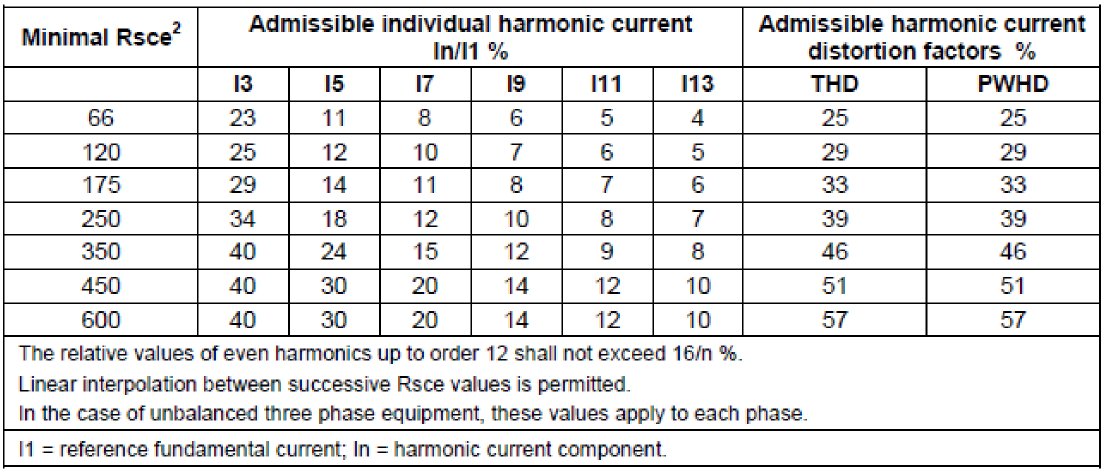
APPENDIX D

Requirements According to Harmonic Limit Standards

Requirements according to IEC 61000-3-4, 6, 12, IEC 61000-4-13 and EN 50160 standards [27]:

- IEC 61000-3-4 specifies the limits of the values of harmonic current emissions, in low-voltage power supply systems, for equipment with rated current ≥ 16 A per phase [183]:

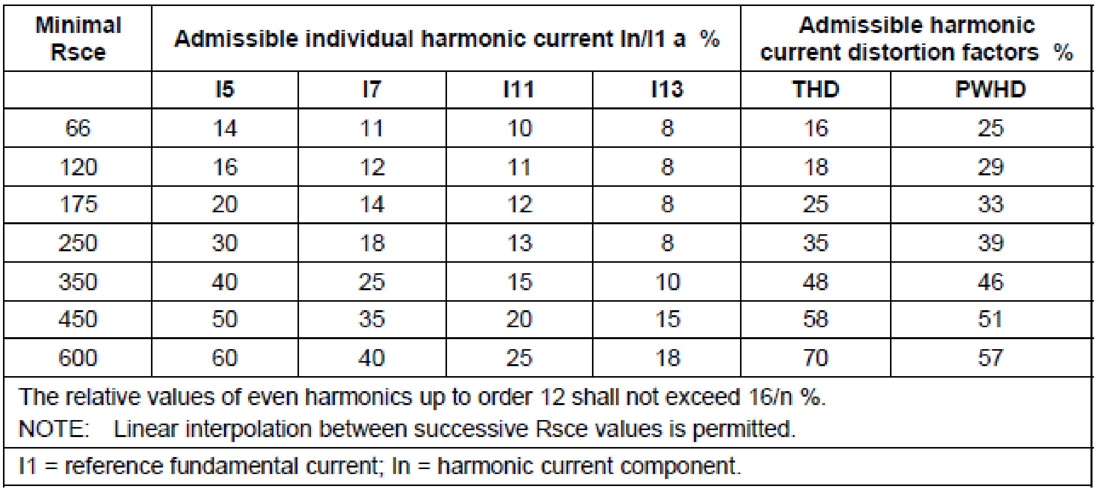
Table D.1: Current emission limits for single phase, inter phase and unbalance three phase system equipment [27].



Minimal Rsce[2]	Admissible individual harmonic current In/I1 %						Admissible harmonic current distortion factors %	
	I3	I5	I7	I9	I11	I13	THD	PWHD
66	23	11	8	6	5	4	25	25
120	25	12	10	7	6	5	29	29
175	29	14	11	8	7	6	33	33
250	34	18	12	10	8	7	39	39
350	40	24	15	12	9	8	46	46
450	40	30	20	14	12	10	51	51
600	40	30	20	14	12	10	57	57
The relative values of even harmonics up to order 12 shall not exceed 16/n %. Linear interpolation between successive Rsce values is permitted. In the case of unbalanced three phase equipment, these values apply to each phase.								
I1 = reference fundamental current; In = harmonic current component.								

[2] Short Circuit Ratio (Rsce): the following definitions apply for this characteristic value of a piece or a customer’s installation.
Rsce=Ssc/ (3 Sequ) for single phase equipment.
Rsce=Ssc/ (2 Sequ) for interphase equipment.
Rsce=Ssc/Sequ for all three phase equipment.

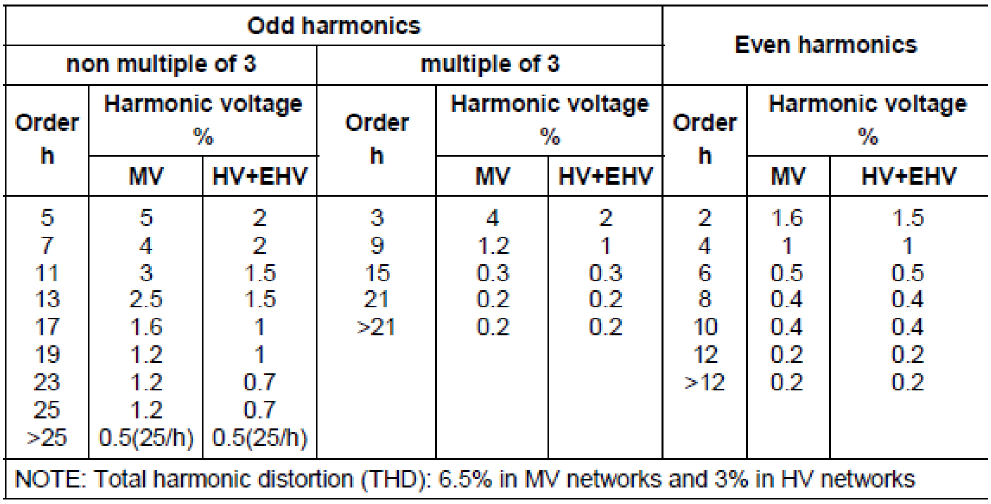
Table D.2: Current emission limits for balanced three-phase equipment [27].



Minimal Rsce	Admissible individual harmonic current In/I1 a %				Admissible harmonic current distortion factors %	
	I5	I7	I11	I13	THD	PWHD
66	14	11	10	8	16	25
120	16	12	11	8	18	29
175	20	14	12	8	25	33
250	30	18	13	8	35	39
350	40	25	15	10	48	46
450	50	35	20	15	58	51
600	60	40	25	18	70	57
The relative values of even harmonics up to order 12 shall not exceed 16/n %. NOTE: Linear interpolation between successive Rsce values is permitted.						
I1 = reference fundamental current; In = harmonic current component.						

- <u>IEC 61000-3-6 Limits [289]:</u>

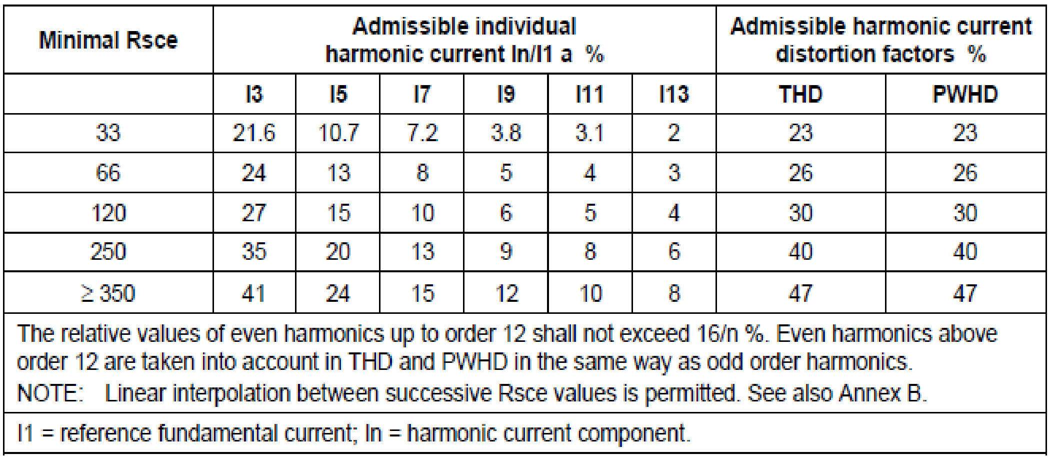
Table D.3: Indicative values of planning levels for harmonic voltage (in percent of the nominal voltage) in MV, HV and EHV power systems [27].



Odd harmonics						Even harmonics		
non multiple of 3			multiple of 3					
Order h	Harmonic voltage %		Order h	Harmonic voltage %		Order h	Harmonic voltage %	
	MV	HV+EHV		MV	HV+EHV		MV	HV+EHV
5	5	2	3	4	2	2	1.6	1.5
7	4	2	9	1.2	1	4	1	1
11	3	1.5	15	0.3	0.3	6	0.5	0.5
13	2.5	1.5	21	0.2	0.2	8	0.4	0.4
17	1.6	1	>21	0.2	0.2	10	0.4	0.4
19	1.2	1				12	0.2	0.2
23	1.2	0.7				>12	0.2	0.2
25	1.2	0.7						
>25	0.5(25/h)	0.5(25/h)						
NOTE: Total harmonic distortion (THD): 6.5% in MV networks and 3% in HV networks								

- <u>IEC 61000-3-12 Limits (“product test” for limits is based ≤ 75 A per phase) [290]:</u>

Table D.4: Current emission limits for equipment other than balanced three-phase equipment [27].

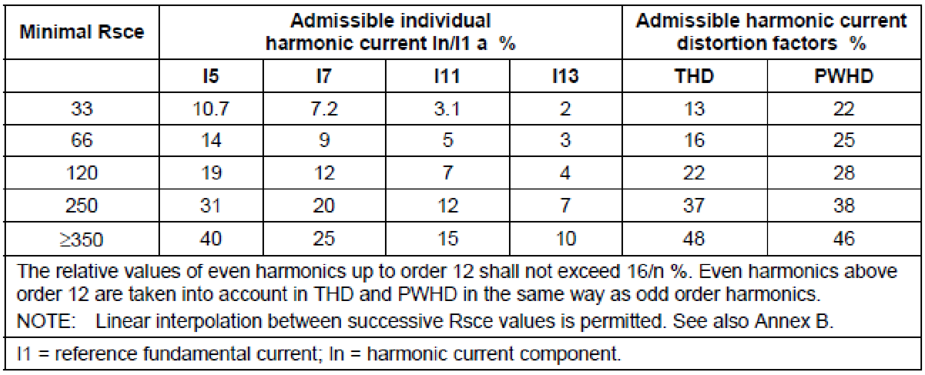


Minimal Rsce	Admissible individual harmonic current In/I1 a %						Admissible harmonic current distortion factors %	
	I3	I5	I7	I9	I11	I13	THD	PWHD
33	21.6	10.7	7.2	3.8	3.1	2	23	23
66	24	13	8	5	4	3	26	26
120	27	15	10	6	5	4	30	30
250	35	20	13	9	8	6	40	40
≥ 350	41	24	15	12	10	8	47	47

The relative values of even harmonics up to order 12 shall not exceed 16/n %. Even harmonics above order 12 are taken into account in THD and PWHD in the same way as odd order harmonics.
NOTE: Linear interpolation between successive Rsce values is permitted. See also Annex B.

I1 = reference fundamental current; In = harmonic current component.

Table D.5: Current emission limits for balanced three-phase equipment [27].

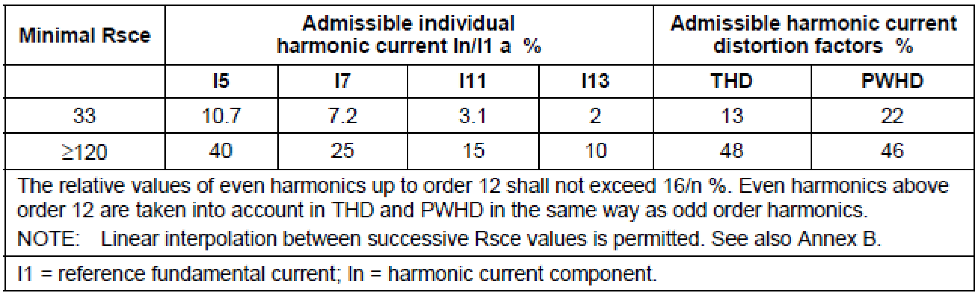


Minimal Rsce	Admissible individual harmonic current In/I1 a %				Admissible harmonic current distortion factors %	
	I5	I7	I11	I13	THD	PWHD
33	10.7	7.2	3.1	2	13	22
66	14	9	5	3	16	25
120	19	12	7	4	22	28
250	31	20	12	7	37	38
≥350	40	25	15	10	48	46

The relative values of even harmonics up to order 12 shall not exceed 16/n %. Even harmonics above order 12 are taken into account in THD and PWHD in the same way as odd order harmonics.
NOTE: Linear interpolation between successive Rsce values is permitted. See also Annex B.

I1 = reference fundamental current; In = harmonic current component.

Table D.6: Current emission limits for balanced three-phase equipment under specified conditions [27].



Minimal Rsce	Admissible individual harmonic current In/I1 a %				Admissible harmonic current distortion factors %	
	I5	I7	I11	I13	THD	PWHD
33	10.7	7.2	3.1	2	13	22
≥120	40	25	15	10	48	46

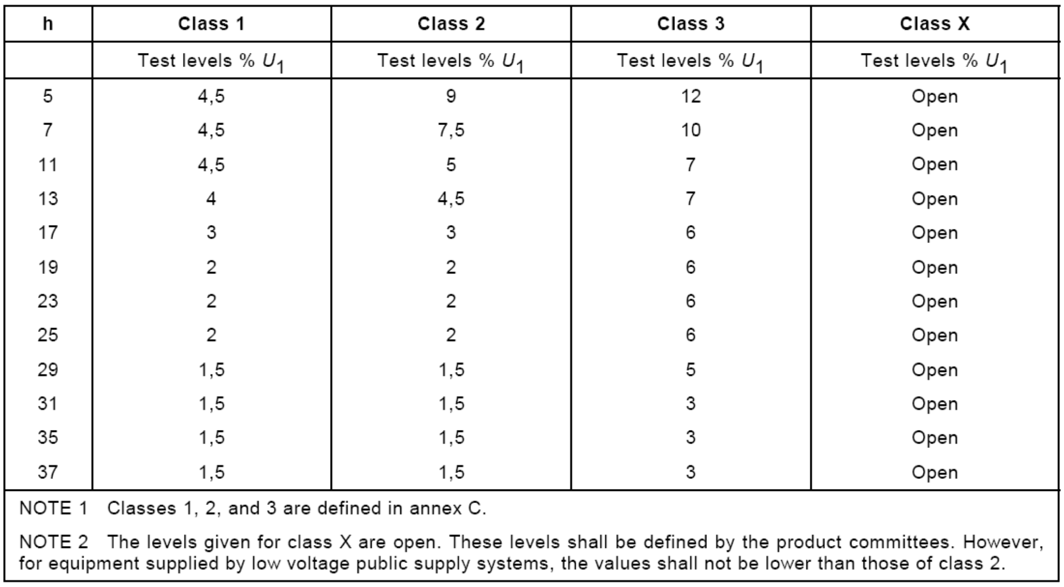
The relative values of even harmonics up to order 12 shall not exceed 16/n %. Even harmonics above order 12 are taken into account in THD and PWHD in the same way as odd order harmonics.
NOTE: Linear interpolation between successive Rsce values is permitted. See also Annex B.

I1 = reference fundamental current; In = harmonic current component.

- IEC 61000-4-13 limits:

  EMC basic standard) "harmonics and interharmonics including mains signaling at a.c. power port, low frequency immunity tests" (Tables E.7 – E.9 containing the test levels for individual harmonics as a percentage of the fundamental voltage) [184]:

Table D.7: Odd harmonics non-multiple of 3 harmonics [184].

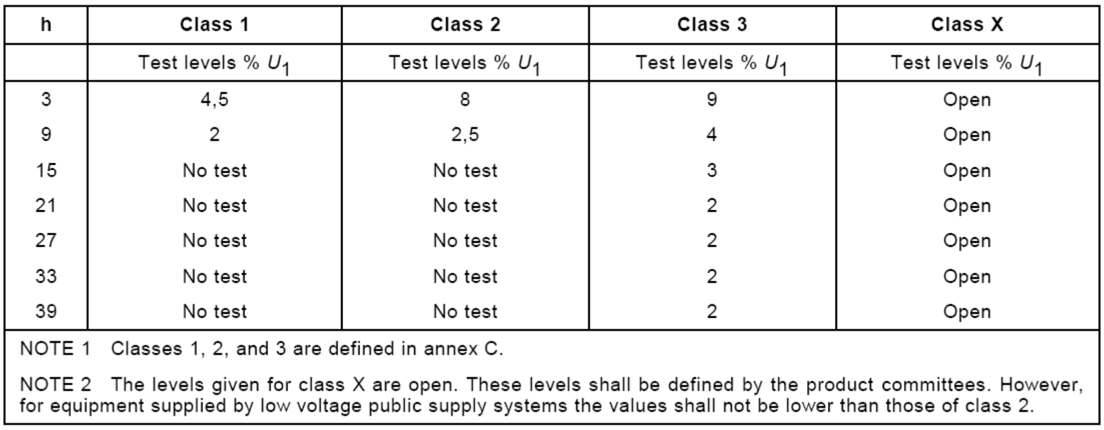


h	Class 1	Class 2	Class 3	Class X
	Test levels % U_1	Test levels % U_1	Test levels % U_1	Test levels % U_1
5	4,5	9	12	Open
7	4,5	7,5	10	Open
11	4,5	5	7	Open
13	4	4,5	7	Open
17	3	3	6	Open
19	2	2	6	Open
23	2	2	6	Open
25	2	2	6	Open
29	1,5	1,5	5	Open
31	1,5	1,5	3	Open
35	1,5	1,5	3	Open
37	1,5	1,5	3	Open

NOTE 1 Classes 1, 2, and 3 are defined in annex C.

NOTE 2 The levels given for class X are open. These levels shall be defined by the product committees. However, for equipment supplied by low voltage public supply systems, the values shall not be lower than those of class 2.

Table D.8: Odd harmonics multiple of 3 harmonics [184].

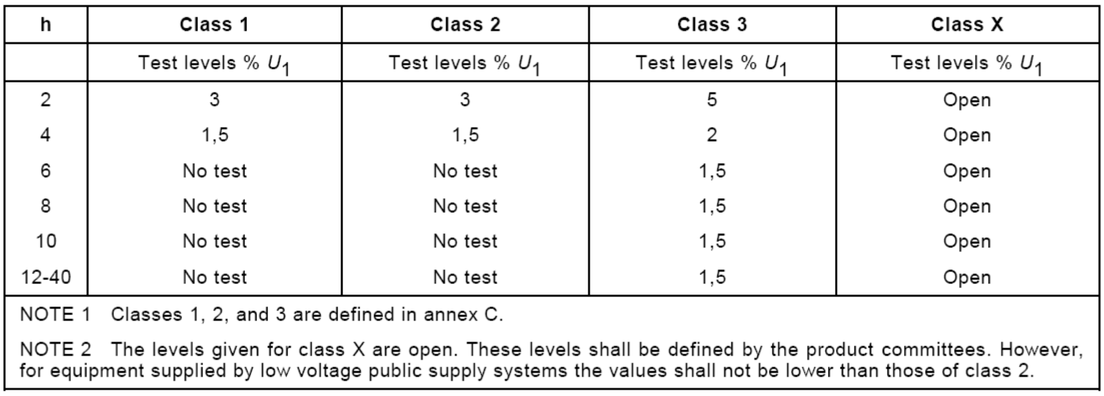


h	Class 1	Class 2	Class 3	Class X
	Test levels % U_1	Test levels % U_1	Test levels % U_1	Test levels % U_1
3	4,5	8	9	Open
9	2	2,5	4	Open
15	No test	No test	3	Open
21	No test	No test	2	Open
27	No test	No test	2	Open
33	No test	No test	2	Open
39	No test	No test	2	Open

NOTE 1 Classes 1, 2, and 3 are defined in annex C.

NOTE 2 The levels given for class X are open. These levels shall be defined by the product committees. However, for equipment supplied by low voltage public supply systems the values shall not be lower than those of class 2.

Table D.9: Even harmonics [184].

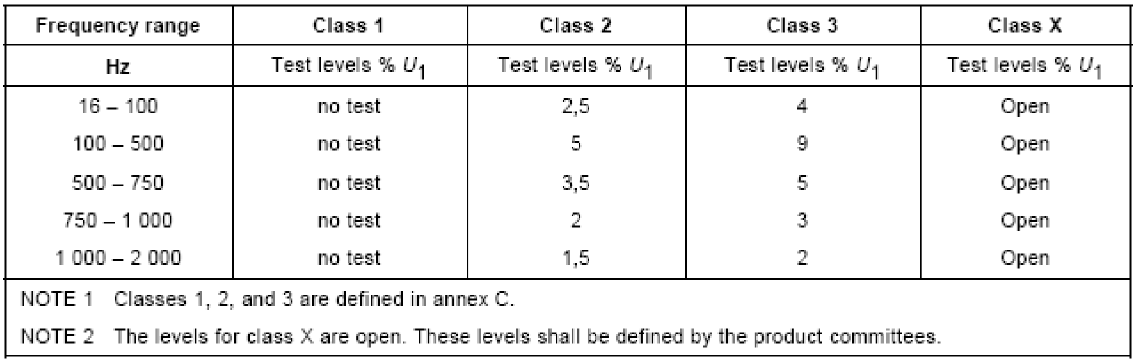


h	Class 1	Class 2	Class 3	Class X
	Test levels % U_1	Test levels % U_1	Test levels % U_1	Test levels % U_1
2	3	3	5	Open
4	1,5	1,5	2	Open
6	No test	No test	1,5	Open
8	No test	No test	1,5	Open
10	No test	No test	1,5	Open
12-40	No test	No test	1,5	Open

NOTE 1 Classes 1, 2, and 3 are defined in annex C.

NOTE 2 The levels given for class X are open. These levels shall be defined by the product committees. However, for equipment supplied by low voltage public supply systems the values shall not be lower than those of class 2.

Table D.10: Frequencies between harmonic frequencies for 50 Hz mains [184].



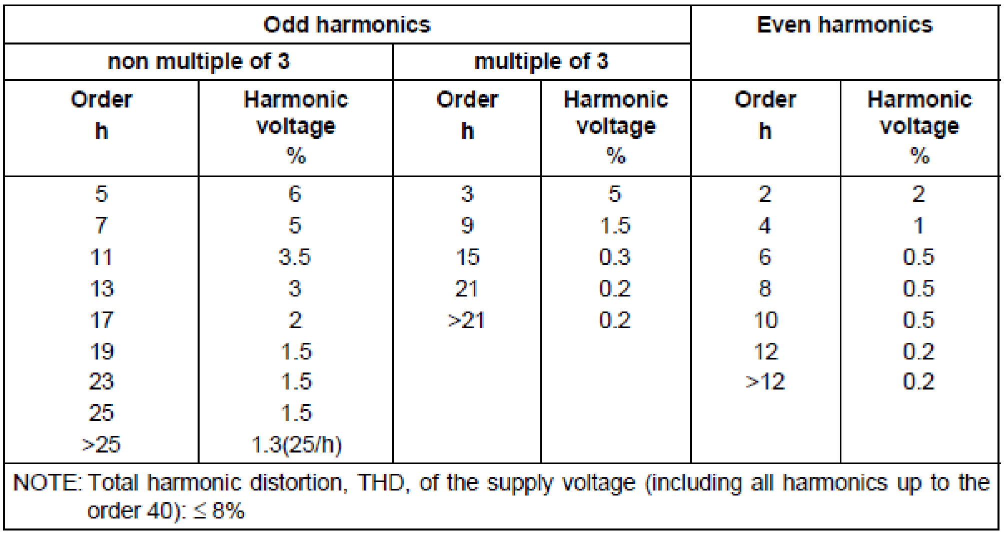
Frequency range	Class 1	Class 2	Class 3	Class X
Hz	Test levels % U_1	Test levels % U_1	Test levels % U_1	Test levels % U_1
16 – 100	no test	2,5	4	Open
100 – 500	no test	5	9	Open
500 – 750	no test	3,5	5	Open
750 – 1 000	no test	2	3	Open
1 000 – 2 000	no test	1,5	2	Open

NOTE 1 Classes 1, 2, and 3 are defined in annex C.

NOTE 2 The levels for class X are open. These levels shall be defined by the product committees.

- EN 50160 Limits [292]:

Table D.11: Values of individual harmonic voltages at the supply terminals for orders up to 25 given in percent of the nominal voltage, in LV and MV power systems [27].

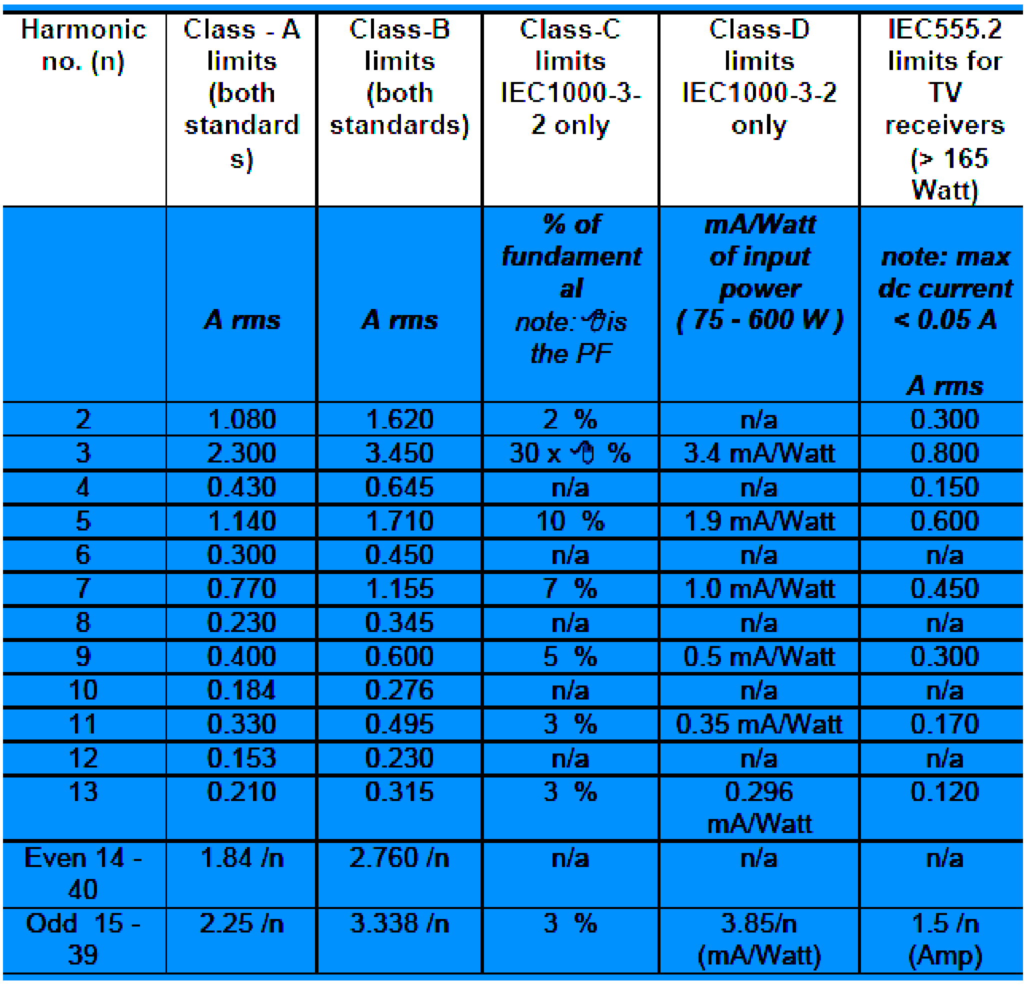


Odd harmonics				Even harmonics	
non multiple of 3		multiple of 3			
Order h	**Harmonic voltage %**	**Order h**	**Harmonic voltage %**	**Order h**	**Harmonic voltage %**
5	6	3	5	2	2
7	5	9	1.5	4	1
11	3.5	15	0.3	6	0.5
13	3	21	0.2	8	0.5
17	2	>21	0.2	10	0.5
19	1.5			12	0.2
23	1.5			>12	0.2
25	1.5				
>25	1.3(25/h)				

NOTE: Total harmonic distortion, THD, of the supply voltage (including all harmonics up to the order 40): ≤ 8%

Mathieu van den Bergh gives the following summary Table E.12 for the EN 61000-3-2 and 555.2 Harmonic limits:

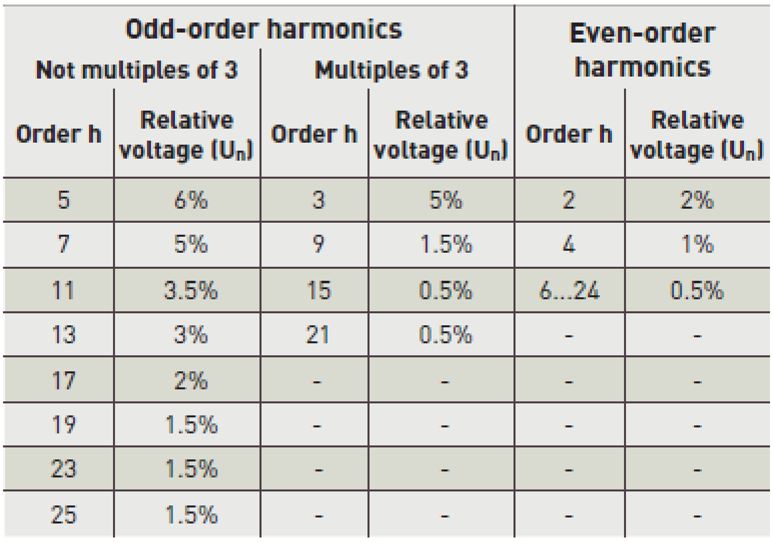
Table D.12: EN 61000-3-2 and 555.2 Harmonic limits [111].



Harmonic no. (n)	Class - A limits (both standards)	Class-B limits (both standards)	Class-C limits IEC1000-3-2 only	Class-D limits IEC1000-3-2 only	IEC555.2 limits for TV receivers (> 165 Watt)
	A rms	***A rms***	***% of fundamental*** *note: 🖰is the PF*	***mA/Watt of input power (75 - 600 W)***	***note: max dc current < 0.05 A*** ***A rms***
2	1.080	1.620	2 %	n/a	0.300
3	2.300	3.450	30 x 🖰 %	3.4 mA/Watt	0.800
4	0.430	0.645	n/a	n/a	0.150
5	1.140	1.710	10 %	1.9 mA/Watt	0.600
6	0.300	0.450	n/a	n/a	n/a
7	0.770	1.155	7 %	1.0 mA/Watt	0.450
8	0.230	0.345	n/a	n/a	n/a
9	0.400	0.600	5 %	0.5 mA/Watt	0.300
10	0.184	0.276	n/a	n/a	n/a
11	0.330	0.495	3 %	0.35 mA/Watt	0.170
12	0.153	0.230	n/a	n/a	n/a
13	0.210	0.315	3 %	0.296 mA/Watt	0.120
Even 14 - 40	1.84 /n	2.760 /n	n/a	n/a	n/a
Odd 15 - 39	2.25 /n	3.338 /n	3 %	3.85/n (mA/Watt)	1.5 /n (Amp)

Also, Legrand comp. gives through Table D.13 the maximum harmonic distortion at the point of supply, expressed as a percentage of the fundamental voltage according to IEC 61000-2-2:

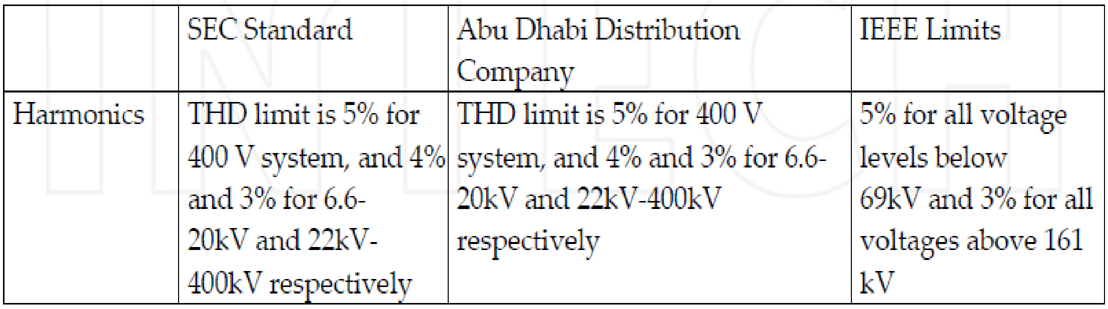
Table D.13: IEC 61000-2-2 Harmonic limits [43].



Odd-order harmonics				Even-order harmonics	
Not multiples of 3		Multiples of 3			
Order h	Relative voltage (U_n)	Order h	Relative voltage (U_n)	Order h	Relative voltage (U_n)
5	6%	3	5%	2	2%
7	5%	9	1.5%	4	1%
11	3.5%	15	0.5%	6...24	0.5%
13	3%	21	0.5%	-	-
17	2%	-	-	-	-
19	1.5%	-	-	-	-
23	1.5%	-	-	-	-
25	1.5%	-	-	-	-

In Table D.14 Hadeed Ahmed Sher shoes a comparison of harmonic standards:

Table D.14: Comparison of Harmonic Standards [154].

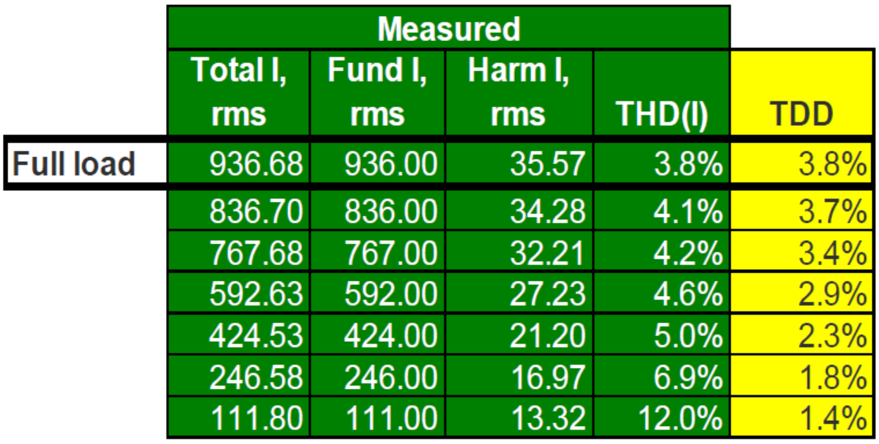


	SEC Standard	Abu Dhabi Distribution Company	IEEE Limits
Harmonics	THD limit is 5% for 400 V system, and 4% and 3% for 6.6-20kV and 22kV-400kV respectively	THD limit is 5% for 400 V system, and 4% and 3% for 6.6-20kV and 22kV-400kV respectively	5% for all voltage levels below 69kV and 3% for all voltages above 161 kV

APPENDIX E

Comparisons of Current THD and TDD According to Load Variations

Table E.1: Comparisons of current THD and TDD according to load variations [138].



	Measured				
	Total I, rms	Fund I, rms	Harm I, rms	THD(I)	TDD
Full load	936.68	936.00	35.57	3.8%	3.8%
	836.70	836.00	34.28	4.1%	3.7%
	767.68	767.00	32.21	4.2%	3.4%
	592.63	592.00	27.23	4.6%	2.9%
	424.53	424.00	21.20	5.0%	2.3%
	246.58	246.00	16.97	6.9%	1.8%
	111.80	111.00	13.32	12.0%	1.4%

APPENDIX F

Non-linear Loads

Non-linear load is any equipment – device that the current which draws is non proportional to the supplied voltage [124]. A non-linear load draws a sum of harmonics (distorted current) from the supply (V_S) that they are integer multiples of the supply frequency also. Agilent corp. [132], through Fig. F.1 illustrates in time correlation the sine load current and the voltage supply, across a non-linear load. All harmonics passing through the impedance of the system (Z_S) induce their respective individual (h) voltage drops on it ($V_h = I_h \times Z_S$), where their vector sum results to the distortion (non sinusoidal) of the voltage supply across the load (V_L) (Fig. F.2, a) [27] [100] [101] [109] [114] [122].

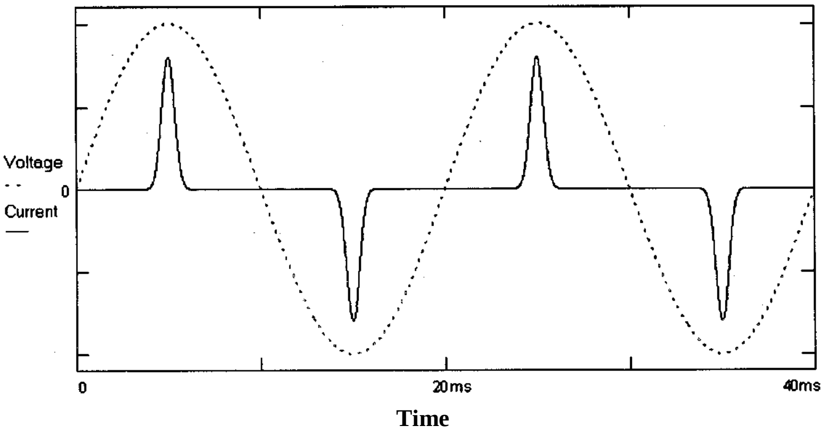


Figure F.1: Non-linear load, non sinusoidal currents [132].

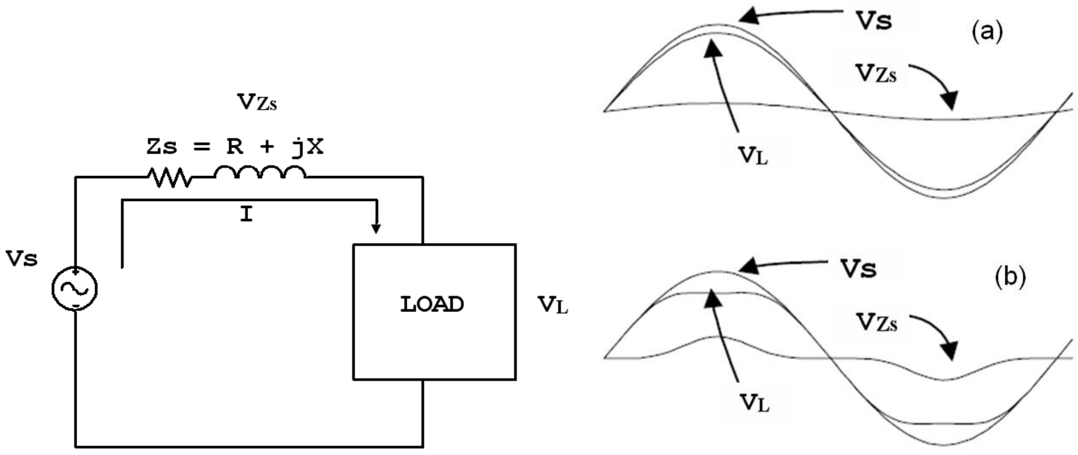


Figure F.2: Distorted current induce voltage distortion [100].

Fig. F3 illustrates in detail the voltage reductions because of the impedances of the system from the power generation until the non-linear load and the effect of the

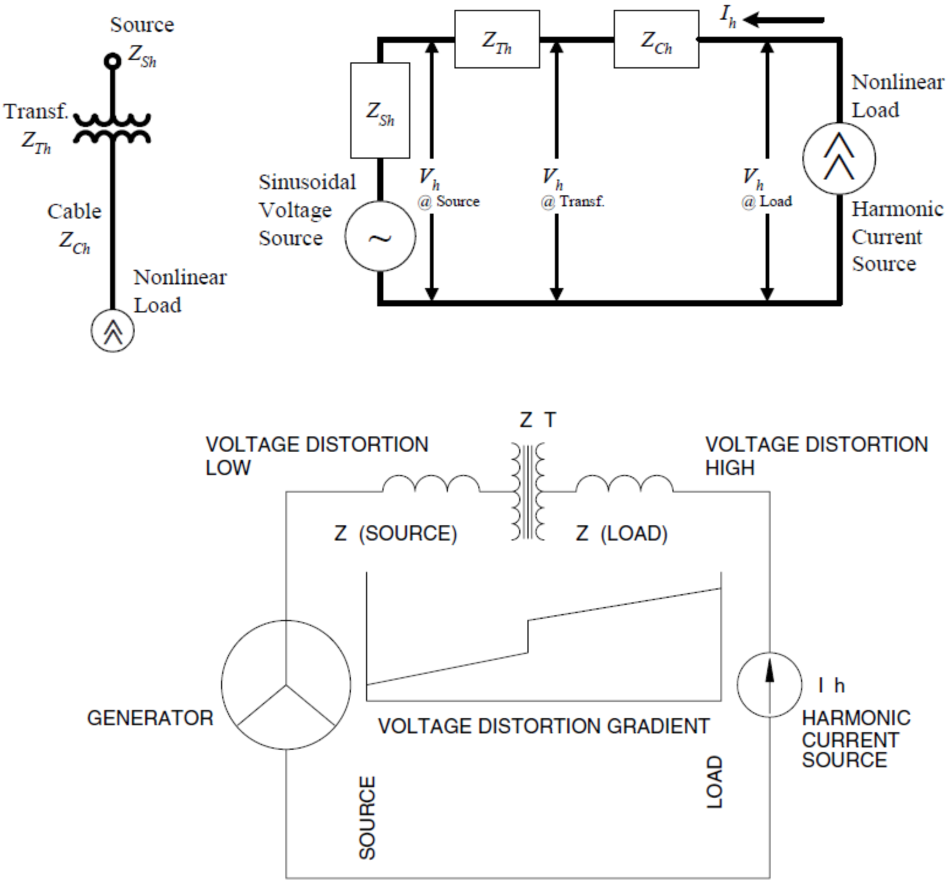


Figure F.3: Harmonic voltage (due to current distortion) drops across system impedances [113] [172].

voltage distortion because of the harmonic currents. According to the vector sum of the associated individual harmonics, as many impedances are introduced between the power source and the non-linear load, as the voltage Total Harmonic Distortion (THD) increases, [220] [137] [172].

According to Ohm’s Law the voltage drop for each harmonic (h) is as follow [46] [137]:

For an h^{th} harmonic current passed through impedance $R + jX$, the h^{th} voltage across it is: $V_h = I_h R + jh \cdot I_h \cdot X$ (F.1)

Across the load: $V_h = I_h \times (Z_{Ch} + Z_{Th} + Z_{Sh})$ (F.2)

Across the transformer: $V_h = I_h \times (Z_{Th} + Z_{Sh})$ (F.3)

Across the source: $V_h = I_h \times Z_{Sh}$ (F.4)

Z_h = impedance at frequency f_h of harmonic h (e.g. for h = 5, f_5 = 5 x 50 = 250 Hz), for 50 Hz of fundamental

V_h = harmonic voltage at h^{th} harmonic (e.g., 5^{th})

I_h = harmonic current at h^{th} harmonic (e.g., 5^{th})

From the above is concluded that:

- as Marek Farbis denotes [134] the flow of harmonic currents through system impedance causes harmonic voltage distortion
- and also, as higher is the magnitude of the distorted current, as higher is the voltage distortion for a give system impedance.

APPENDIX G

Power (VA) on Single and Three Phase AC Motors

Power (VA) on a Single Phase AC Motor

Fig. G.1 illustrates the power (VA) on the load motor that varies approximately linearly with the voltage supply.

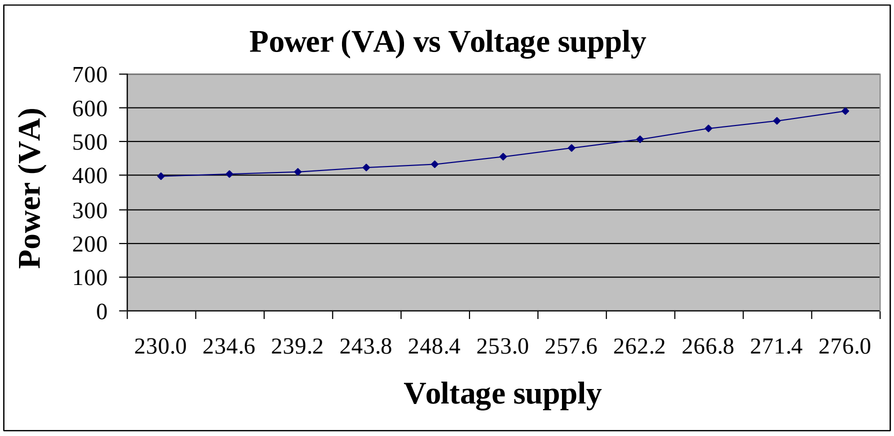


Figure G.1: Power (VA) on single phase ac motor vs the voltage supply.

Power (VA) on Three Phase AC Motor

Fig. G.2 illustrates the power (VA) on the load – motor that varies approximately linearly with the voltage supply.

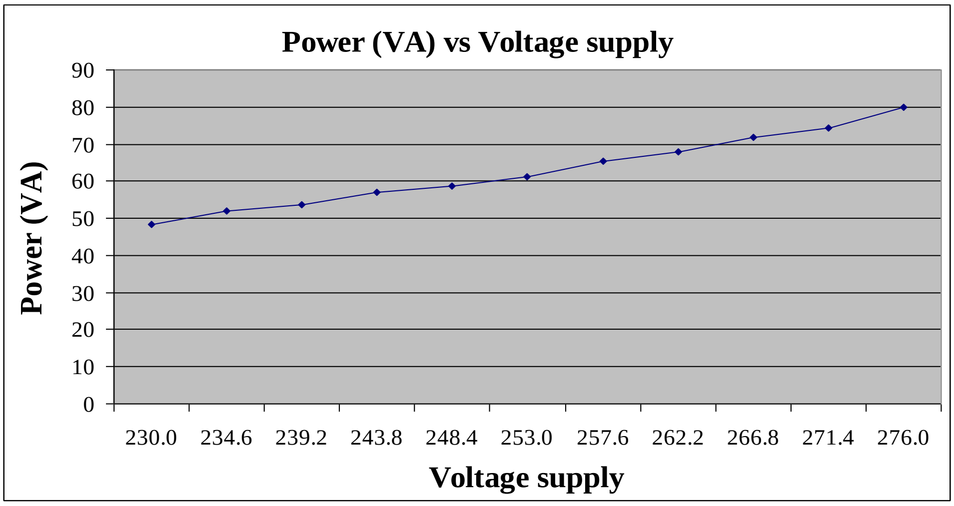


Figure G.2: Power (VA) on three phase ac motor vs the voltage supply.

APPENDIX H

Choosing MOSFET Driver for PWM Control

The reason for choosing this control method is:

- The power MOSFET is a full controllable ON/OFF switch.
- It can be controlled by low power switching losses instead of power BJTs.
- This makes the transistor ideal for PWM (Pulse Width Modulation) or SMPS (Switch Mode Power Supply) applications, in order to have full or programmable power management at up to about 1 kV blocking and 300 A draining. On the other hand, Triac or Thyristor even they manipulate higher voltages and currents, are not full controllable, but the ON/OFF condition depends mainly on *latching* and *holding* currents.
- The ON/OFF switching speed of the MOSFET can rise up to several megahertz, while the switching frequency of Triac or Thyristor to about 20 kHz. This makes the transistor suitable for fast power manipulations.
- For higher currents, MOSFETs can be connected in parallel, too.
- MOSFET as power controller has high enough efficiency.
- A main advantage by the use of the MOSFET for the present case, is that the produced harmonics are less problematic than these produced by triac or thyristor, resulting to vibration reduction of the electrical motors mechanical support (Fig. H. 1[46]) [49] [50] [53] [56] [58] [60] [73] [82] [91].

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[46] The MOSFET is switched at 2 kHz frequency, while the triac works with mains frequency of 50 Hz.

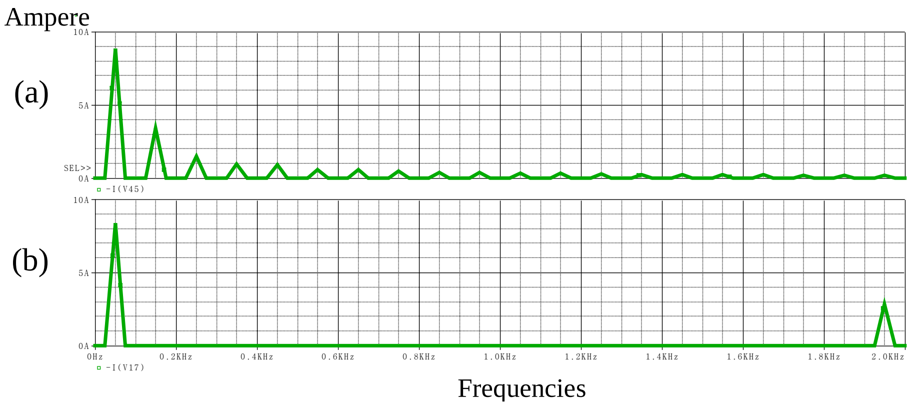

Figure H.1: Current harmonic spectrum of a triac as driver (a), and relative harmonic spectrum of a MOSFET as driver (b), for the same rms current supply.

Fig. H. 2 shows the power consumed by the MOSFET in the case of 20% overvoltage by mains:

- The transistor power consumption, P = 240 W
- The average current drawn by the transistor, I_{AVG} = 4.53 A
- The instant current peeks of 175 A, for some micro seconds drawn by the transistor.

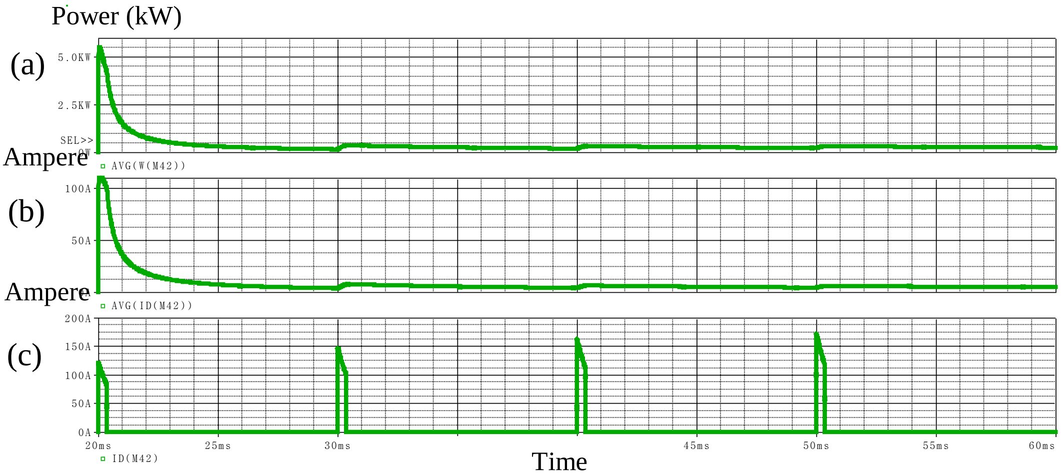

Figure H.2: The transistor average power consumption (a), the average current drawn by the transistor (b), the instant current peeks (c).

APPENDIX I

Power (VA) on Transformers (Toroidal and with Steel Laminations)

Toroidal Transformer

Fig. I.1 shows the power (VA) on the prime winding of the toroidal transformer according to mains variations from -20% to +20%. The apparent power (VA) varies linearly with voltage supply on the primary winding. Also, Fig. I.2 and table I.1 illustrates in percentage, power (VA) variation according to mains voltage variation. Here, the apparent power on the primary winding – load is changing almost as to the nominal respectively. For example, a 20% increase in a supply voltage of 230V, will result to a 45% increase of apparent power (VA) whereas, a 20% decrease in the supply voltage, will result to a 35% decrease.

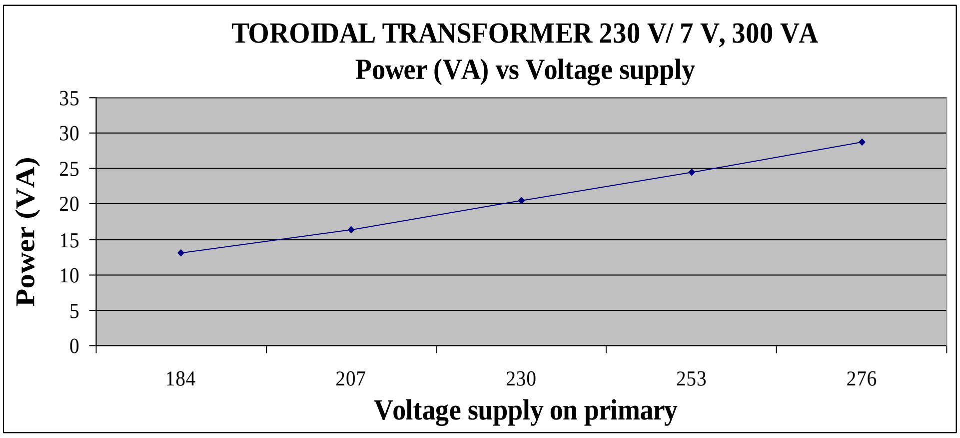

Figure I.1: Power (VA) vs Voltage Supply variation on the primary winding of the transformer.

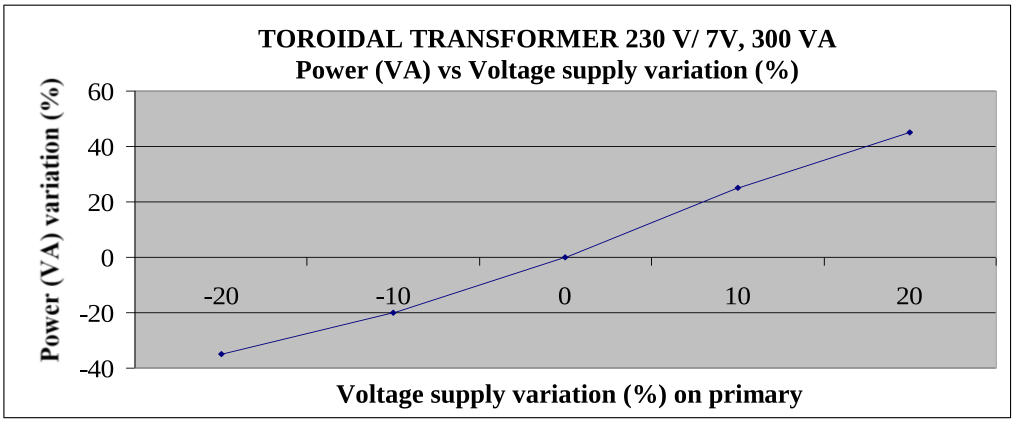

Figure I.2: In percentage, power (VA) vs mains variation on the primary winding of the transformer.

Table I.1: Experiment results, variations of power (VA) and variation of the mains nominal voltage supply by ±20% on the primary winding.

V_{rms} variation (%)	VA variation (%)
20	45
10	25
0	0
-10	-20
-20	-35

Fig. I.3 illustrates the power (VA) on the secondary winding of the transformer that varies linearly with the voltage supply on the primary winding. Fig. I.4 and Table I.1 illustrates in percentage, power (VA) variation on secondary winding according to mains voltage variation on primary winding. Here, the apparent power on the second load – winding is changing almost as to the nominal respectively. For example, a 20% increase in a supply voltage of 230V, will result to a 35% increase of the apparent power (VA) whereas, a 20% decrease in the supply voltage, will result to a 40% decrease[47] to the secondary.

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[47] Also, as the load (R) at the secondary is ohmic (Fig. 3.3.1.1) there is no phase difference between current and voltage, and consequently the power factor is unitary. This means that, according to mains supply variation, the variation of the apparent power (VA) on the secondary winding is matching with the variation of the power (W) on the resistive load (R).

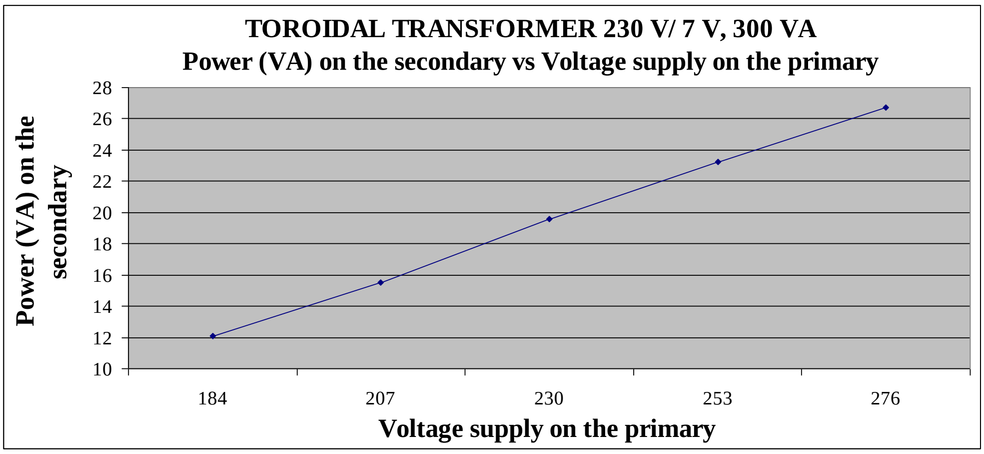

Figure I.3: Power (VA) on the secondary winding vs Voltage supply variation on the prime winding.

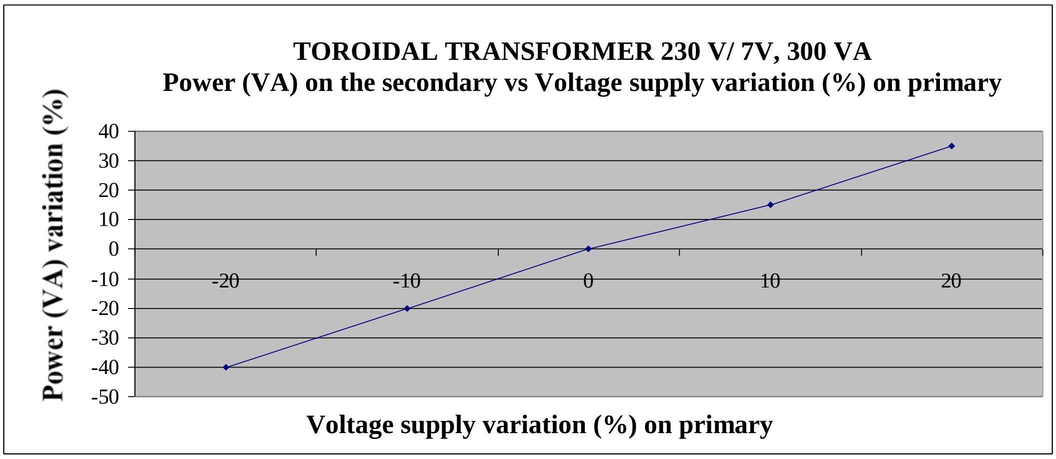

Figure I.4: In percentage, power (VA) on the secondary winding vs mains variation on the prime winding of the transformer.

Table I.2: Experiment results, variations of power (VA) on the secondary winding and variation of the mains nominal voltage supply by ±20%.

V_{rms} variation (%)	VA variation (%)
20	35
10	15
0	0
-10	-20
-20	-40

Transformer with Steel Laminations

Fig. I.5 illustrates the apparent power (VA) that varies linearly with voltage supply on the primary winding. Also, Fig. I.6 and table I.3 illustrate in percentage, power (VA) variation according to mains voltage variation. Here, the apparent power on the primary load – winding is changing almost as to the nominal respectively. For example, a 20% increase in a supply voltage of 230V, will result to a 40% increase of apparent power (VA) whereas, a 20% decrease in the supply voltage, will result to a -36% decrease.

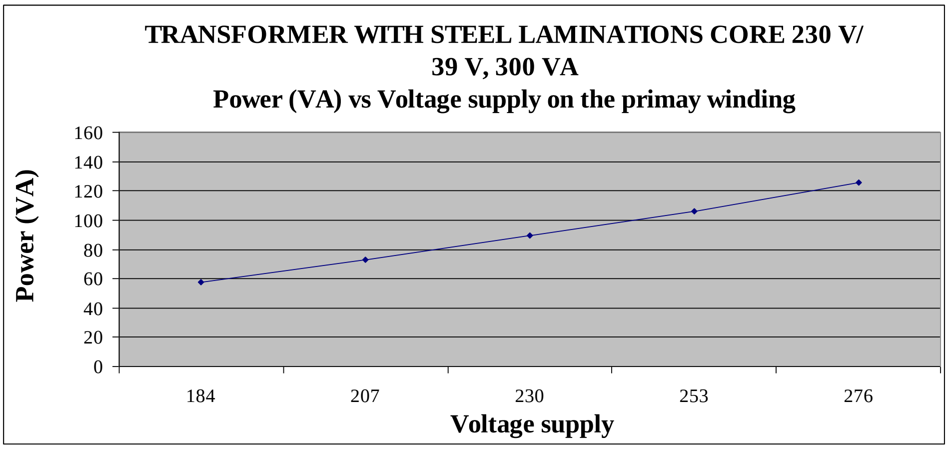

Figure I.5: Power (VA) vs Voltage supply variation on the primary winding of the transformer.

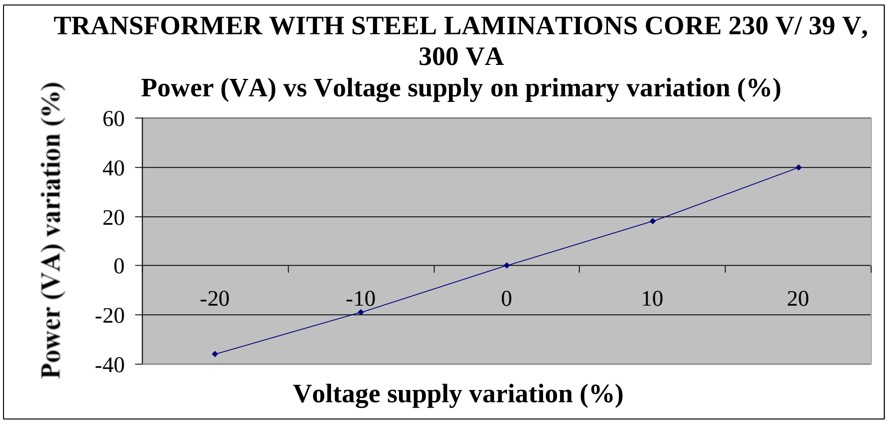

Figure I.6: In percentage, power (VA) vs mains variation on the primary winding of the transformer.

Table I.3: Experiment results variations of power (VA) and variation of the mains nominal voltage supply by ±20%.

V_{rms} variation (%)	VA variation (%)
20	40
10	18
0	0
-10	-19
-20	-36