LC Compensators for Power Factor Correction of Nonlinear Loads

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***Abstract*—A method is presented for finding the optimum fixed LC compensator for power factor correction of nonlinear loads where both source voltage and load current harmonics are present. The LC combination is selected because pure capacitive capacitors alone would not sufficiently correct the power factor. Optimization minimizes the transmission loss, maximizes the power factor, and maximizes the efficiency. The performance of the obtained compensator is discussed by means of numerical examples.**

***Index Terms*—Harmonics, power factor, reactive power.**

NOMENCLATURE

R_{LK},X_{LK}	Load resistance and reactance at harmonic number K (in ohms).
G_{LK},B_{LK}	Load conductance and susceptance at harmonic number K (in ohms).
R_{TK},X_{TK}	Transmission system resistance and reactance at harmonic number K (in ohms).
X_L,X_C	Fundamental inductive and capacitive reactance of the compensator (in ohms).
R	Resistance of the compensator reactor (in ohms).
I_{SK}	Supply current at harmonic number K (in amps).
I_S	RMS value of supply current (in amps).
I_{lK}	Load current at harmonic number K (in amps).
I_{LK}	Load harmonic current (in amps).
I_{CK}	Capacitor current at harmonic number K (in amps).
P_L	Load power (in watts).
P_S	Supply power (in watts).
V_{LK}	Load voltage at harmonic number K (in volts).
V_{SK}	Supply voltage at harmonic number K (in volts).
V_L	RMS value of load voltage (in volts).
f_o	Frequency (in Hertz).
$\omega_o = 2\pi f_o$	rad/s.

I. INTRODUCTION

HARMONIC currents may be injected in a utility customer's supply feeder because of a resonance between the customer's capacitor-compensated load and the equivalent inductive source impedance, excited either by source harmonics generated by nonlinear loads at other system buses, or load harmonics created by the customer's nonlinear load itself, or both. In any case, excessive harmonic currents have the effect of shortening equipment life expectancy and degrading the overall power factor.

When the harmonics are clearly caused by source distortion, a first reaction might be to detune the harmonic resonance circuit by modifying the compensating capacitor value. For example, a method is presented in [1] to reduce source-generated harmonics by altering the capacitance while retaining sufficient fundamental compensation. Reference [2] showed that source generated harmonics could be reduced by using an LC compensator, while a higher maximum possible power factor can be obtained. Such a compensator may actually have a lower total volt-ampere rating than that of a pure capacitive compensator to achieve the same power factor. Furthermore, if a sufficiently complex compensation network is used, current harmonics can be completely eliminated as shown in [3].

On the other hand, if a nonlinear load generates significant harmonic currents locally, tuned filters may be installed to prevent the currents from being injected into the system. However, such filters are resorted to only for heavily nonlinear loads because of high cost. One important side effect of adding a filter is that it creates a sharp parallel resonance point at a frequency below the notch frequency [4]. This resonant frequency must be safely away from any significant harmonic. Filters are commonly tuned slightly lower than the harmonic to be filtered to provide a margin of safety in case there is some change in system parameters. If they were tuned exactly to the harmonic, changes in either capacitance or inductance with temperature or failure might shift the parallel resonance into the harmonic. This could present a situation worse than without a filter because the resonance is generally very sharp. For this reason, filters are added to the system, starting with the lowest problem harmonic. For example, installing a seventh-harmonic filter usually requires that a fifth-harmonic filter also be installed. The new parallel resonance with a seventh filter only would have been very near the fifth, which is generally disastrous.

In this paper, both the equivalent source and load are considered to generate harmonics. It is assumed that the load harmonics are not sufficiently serious to suggest tuned filters, but

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when combined with source harmonics, the use of a pure capacitive compensator would degrade power factor and overload equipment. Consequently, an LC compensator is selected. The different criteria [5] for the design of the LC compensator are discussed, taking into consideration the nonlinearity of the load by using direct polytope search method.

II. Basic Approach of Compensation

A single-phase network equivalent of the system considered is shown in Fig. 1.

The Thevenin voltage source representing the utility supply is

$$\mathrm{v_S(t)} = \sum_{\mathrm{K}} \mathrm{v_{SK}(t)} \tag{1}$$

and the Kth harmonic Thevenin source impedance is

$$\mathrm{Z_{TK}} = \mathrm{R_{TK}} + \mathrm{jX_{TK}} \tag{2}$$

where K is the order of harmonic present.

The nonlinear load is represented as a harmonic current source by

$$\mathrm{i_L(t)} = \sum_{\mathrm{K}>1} \mathrm{i_{LK}(t)} \tag{3}$$

and the Kth harmonics load admittance

$$\mathrm{Y_{LK}} = \mathrm{G_{LK}} - \mathrm{jB_{LK}} \tag{4}$$

where $\mathrm{G_{LK}}$ and $\mathrm{B_{LK}}$ are the equivalent conductance and suscpetance of the load.

Hence, the following criteria could be envisaged for optimizing the value of the compensator:

i) minimizing the transmission loss;
ii) maximizing the power factor;
iii) maximizing the transmission efficiency.

III. Economic Impact of LC Compensators versus Capacitors

Adding a reactor to detune the system can modify adverse system response to harmonics. Harmful resonance is generally between the system inductance and shunt power factor correction capacitors. The reactor must be added between the capacitor and the system. One method is to simply put a reactor in series with the capacitor to move the system resonance without actually tuning the capacitor to create a filter. Reference [6] shows that power factor for linear loads can be maximized for an LC compensator if the optimization is constrained by a given cost and that this cost may actually be lower than that for the purely capacitive compensation at the same power factor. The end product is displayed in graph form, where for any given compensator cost in Egyptian pounds (L.E.), the maximum possible power factor and corresponding LC combination can be found. Reference [7] shows that power factor can be maximized for using LC compensators for nonlinear loads if the optimization is constrained by a given cost and that this cost may actually be lower than that for the purely capacitive compensation at the same power factor, Fig. 2.

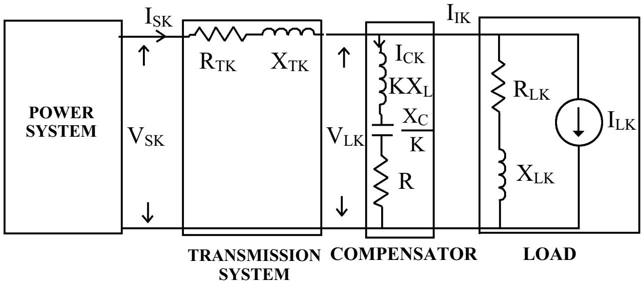

Fig. 1. Single-phase equivalent circuit for Kth harmonic with compensation.

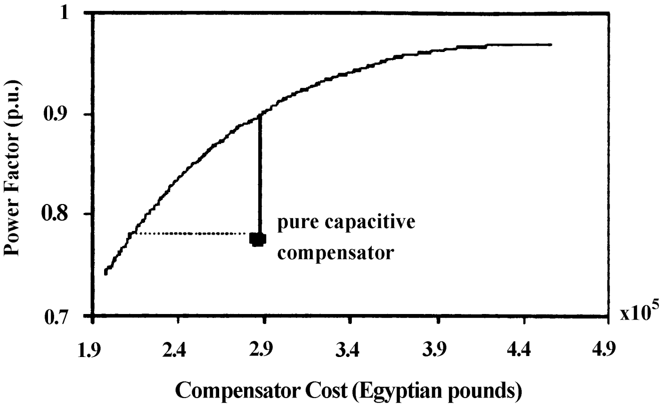

Fig. 2. Power factor versus compensator cost [7].

It is observed (Fig. 2) that the same power factor can be obtained by LC compensation at a lower cost, or the LC compensator at the same cost can achieve a higher power factor. To understand why the total volt-amperes in the two series LC elements may remain constant or even decrease as an inductance L is added, consider the case where both the capacitive and inductive reactance are increased such that $(\mathrm{X_C} - \mathrm{X_L})$ and, thus, the fundamental compensation current remains the same. At the same time, $\mathrm{X_L}$ is large enough so that the LC combination appears inductive to higher order harmonics and blocks them out. Thus, it is conceivable that a power factor may increase without a proportional increase in total volt-amperes.

IV. Objective Functions

Let $\mathrm{X_C}$ be the capacitive reactance, $\mathrm{X_L}$ be the inductive reactance, and R be the compensator resistance at the fundamental frequency.

The compensating impedance $\mathrm{Z_{CK}}$

$$\mathrm{Z_{CK}} = \mathrm{R} + \mathrm{j}\left(\mathrm{KX_L} - \frac{\mathrm{X_C}}{\mathrm{K}}\right). \tag{5}$$

Let $\mathrm{Z_{CLK}} = \mathrm{Z_{CK}}$ in parallel with $\mathrm{Z_{LK}}$, let $\mathrm{Z_{TLK}} = \mathrm{Z_{TK}}$ in parallel $\mathrm{Z_{LK}}$, and let $\mathrm{Z} = \mathrm{Z_{TK}}$ in series $\mathrm{Z_{CLK}}$.

After some complex algebraic manipulations, the expression for the Kth harmonic source current and load voltage are given by

$$\mathrm{I_{SK}} = \frac{\mathrm{V_{SK}(AR + jBR) + I_{LK}(CR)}}{\mathrm{A_{IK} + jA_{JK}}} \tag{6}$$

$$\mathrm{V_{LK}} = \frac{\mathrm{V_{SK}(CR) - I_{LK}(DR * ER)}}{\mathrm{A_{IK} + A_{JK}}} \tag{7}$$

where

$$\begin{aligned}
\mathrm{AR} &= \mathrm{R + R_{LK}}\\
\mathrm{BR} &= \left(\mathrm{X_{LK} + KX_L - \frac{X_C}{K}}\right)\\
\mathrm{CR} &= \mathrm{R_{CLK} + jX_{CLK}}\\
\mathrm{DR} &= \mathrm{R + j}\left(\mathrm{KX_L - \frac{X_C}{K}}\right)\\
\mathrm{ER} &= \mathrm{R_{TLK} + jX_{TLK}}\\
\mathrm{A_{IK}} &= \mathrm{R_{TLK} + R(R_{LK} + R_{TK})}\\
&\quad \mathrm{- (X_{LK} + X_{TK})}\left(\mathrm{KX_L - \frac{X_C}{K}}\right)\\
\mathrm{A_{JK}} &= \mathrm{X_{TLK} + R(R_{LK} + X_{TK})}\\
&\quad \mathrm{+ (R_{LK} + R_{TK})}\left(\mathrm{KX_L - \frac{X_C}{K}}\right)\\
\mathrm{R_{TLK}} &= \mathrm{R_{TK}R_{LK} - X_{TK}X_{LK}}\\
\mathrm{X_{TLK}} &= \mathrm{R_{TK}X_{LK} + X_{LK}R_{LK}}\\
\mathrm{R_{CLK}} &= \mathrm{RR_{LK} - X_{LK}}\left(\mathrm{KX_L - \frac{X_C}{K}}\right)\\
\mathrm{X_{CLK}} &= \mathrm{RX_{LK} + R_{LK}}\left(\mathrm{KX_L - \frac{X_C}{K}}\right).
\end{aligned}$$

A. *Transmission Loss*

$$\mathrm{TL} = \sum_{\mathrm{K}} \mathrm{I_{SK}^2 R_{TK}}. \tag{8}$$

B. *Power Factor*

$$\begin{aligned}
\mathrm{PF} &= \frac{\mathrm{P_L}}{\mathrm{V_L I_S}}\\
&= \frac{\sum \mathrm{G_{LK}V_{LK}^2}}{\sqrt{\sum \mathrm{I_{SK}^2 + V_{SK}^2}}.}
\end{aligned} \tag{9}$$

C. *Transmission Efficiency*

$$\begin{aligned}
\eta &= \frac{\mathrm{P_L}}{\mathrm{P_S}}\\
&= \frac{\sum \mathrm{G_{LK}V_{LK}^2}}{\sum \mathrm{I_{SK}^2 R_{TK}} + \sum \mathrm{G_{LK}V_{LK}^2}.}
\end{aligned} \tag{10}$$

V. IDENTIFICATION OF SKIN EFFECT

Skin effect is an alternating current phenomenon where the current in a conductor tends to flow more densely near the outer surface of a conductor that in the center area. Skin effect will be applied in the analysis to account for the impact on the system impedance of the frequency dependence of the resistive component of the load. At utilization voltages, such as industrial power systems, the equivalent system reactance is often dominant by the service transformer impedance [4]. For lines and cables, an estimated correction factor [8] for skin effect is applied by increasing the resistance with frequency by

$$\mathrm{R = R} * \left[1 + \frac{0.646\mathrm{K}^2}{192 + 0.518\mathrm{K}^2}\right] \text{ for lines} \tag{11}$$

or

$$\mathrm{R = R} * \left[0.187 + 0.532\mathrm{K}^{\frac{1}{2}}\right] \text{ for cables.} \tag{12}$$

For transformers, an estimated correction factor [8] for skin effect is applied by increasing the resistance with frequency by $\mathrm{K}^{1.15}$. The exception to this rule is with some transformer. Because of stray eddy current losses, the apparent resistance of large transformers may vary almost proportionately with the frequency [9]. Finally, in most power systems, one can generally assume that the resistance does not change significantly when studying the effects of harmonics less than the ninth [4].

VI. HARMONIC RESONANT CONSTRAINT

System resonant conditions are the most important factors affecting system harmonic levels. Parallel resonance is high impedance to the flow of harmonic current, while series resonance is low impedance to the flow of harmonic current [10].

It is essential to identify the value of inductor and capacitors $\mathrm{KX_L}$ and $\mathrm{X_C/K}$ that can cause resonance. By substituting for $\mathrm{Z_{CLK}}$ in terms of $\mathrm{R_{CLK}}$ and $\mathrm{X_{CLK}}$ and for $\mathrm{Z_{TK}}$ in terms or $\mathrm{R_{TK}}$ and $\mathrm{X_{TK}}$, the real and imaginary parts of the Z will be obtained. By equating the imaginary part to zero and after simplifications the following is obtained:

$$\mathrm{A_1}\left(\mathrm{KX_L - \frac{X_C}{K}}\right)^2 + \mathrm{A_2}\left(\mathrm{KX_L - \frac{X_C}{K}}\right) + \mathrm{A_3} = 0 \tag{13}$$

where

$$\begin{aligned}
\mathrm{A_1} &= \mathrm{X_{TK} + X_{LK}}\\
\mathrm{A_2} &= \mathrm{R_{LK}^2 + X_{LK}^2 + 2X_{LK}X_{TK}}\\
\mathrm{A_3} &= \mathrm{R^2X_{LK} + X_{TK}}\left[\mathrm{(R + R_{LK})^2 + X_{LK}^2}\right].
\end{aligned}$$

Solving (5) for finding $\mathrm{X_L}$ and $\mathrm{X_C}$

$$\mathrm{KX_L - \frac{X_C}{K}} = \frac{-\mathrm{A_2} \pm \sqrt{\mathrm{A_2^2 - 4A_1A_3}}}{2\mathrm{A_1}}. \tag{14}$$

By taking the solution of (14), where the square root of the discriminant is positive (the other solution corresponds to resonance between the load and the combination of the source impedance and the compensator), the results give regions where $\mathrm{X_L}$ and $\mathrm{X_C}$ prevent the occurrence of resonance.

Note that for sufficiently large load resistance and/or load reactance, (13) reduces to

$$\mathrm{KX_L} - \frac{\mathrm{X_C}}{\mathrm{K}} + \mathrm{X_{TK}} = 0 \tag{15}$$

which then represents only the resonance condition between source impedance and compensator. Note that the resonance peaks broaden for increasing variance of $\mathrm{X_{T1}}$.

VII. Formulation of the Search Algorithm

After formulating the objective function and the constraint, the problem addressed in this study becomes the following:

a) Maximizing the power factor
find $\mathrm{X_C^*}$, $\mathrm{X_L}$.*
To maximize PF
subject to $\mathrm{X_C}$, $\mathrm{X_L}$ is not part of solution of (13).

b) Minimizing the transmission loss
find $\mathrm{X_C^*}$, $\mathrm{X_L}$.*
To minimize TL
subject to $\mathrm{X_C}$, $\mathrm{X_L}$ is not part of solution of (13).

c) Maximizing the transmission efficiency
find $\mathrm{X_C^*}$, $\mathrm{X_L^*}$.
To maximize η
subject to $\mathrm{X_C}$, $\mathrm{X_L}$ is not part of solution of (13).

The direct polytope search method [11] was chosen because it requires fewer steps and function evaluations. The method assumes no smoothness. It is based on function comparison. It beings with $\mathrm{X_1 \ldots\ldots X_{n+1}}$.

At each iteration, a new point is generated to replace the worst point, which has the largest function. The new point is obtained from

$$\mathrm{X_K} = \gamma + \alpha(\gamma - \mathrm{X_j}) \tag{16}$$

where $\gamma = (1/\mathrm{n})\sum_{\mathrm{i}\neq\mathrm{j}}\mathrm{X_i}$, and $\alpha > 0$. If $\mathrm{f(X_K)} < \mathrm{f(X_j)}$, an expansion point is obtained from

$$\mathrm{X_O} = \gamma + \beta(\mathrm{X_K} - \gamma) \tag{17}$$

where $\beta > 1$. If the new point is the worst point that polytope would be constructed to get a new point. This procedure is repeated until a stopping criterion is satisfied. In the optimization process, the resistance of the compensator reactor has been neglected due to its small value with respect to its fundamental reactance [6].

VIII. Examples and Simulated Results

Four cases of an industrial plant were simulated using the optimization method. The numerical data were primarily taken from an example in [10], where the inductive three-phase load is 5100 kW. The 60-cycle supply bus voltage is 4.16 kV (line-to-line). The data are given in Table I.

We obtain the values of the three criteria using the direct polytope search method; see Table II.

TABLE I
System Parameters and Source Harmonics

Parameters & Harmonics	Case 1	Case 2	Case 3	Case 4
Short CircuitMV A	150	150	80	80
R_{T1} (Ω)	0.01154	0.01154	0.02163	0.02163
X_{T1} (Ω)	0.1154	0.1154	0.2163	0.2163
R_{L1} (Ω)	1.742	1.742	1.742	1.742
X_{L1} (Ω)	1.696	1.696	1.696	1.696
V_{S1} (kV)	2.4	2.4	2.4	2.4
V_{S3} (%V_{S1})	0	0	0	3
V_{S5} (%V_{S1})	5	7	5	5
V_{S7} (%V_{S1})	3	7	3	3
V_{S11} (%V_{S1})	2	2	2	2
V_{S13} (%V_{S1})	1	1	1	1
I_{L3} (A)	304	304	304	304
I_{L5} (A)	33	33	33	33
I_{L7} (A)	25	25	25	25
I_{L9} (A)	26	26	26	26
I_{L11} (A)	8	8	8	8
I_{L13} (A)	9	9	9	9

TABLE II
Simulated Results for the Optimization Method

Criteria	X_C (Ω)	X_L (Ω)	PF (%)	I_S (A)	η(%)	TL (kW)
Case 1						
Min. *TL*	4.06	0.45	98.85	705.12	99.66	5.74
Max. *PF*	3.84	0.40	99.01	705.34	99.66	5.74
Max. η	3.91	0.43	98.98	705.13	99.66	5.74
Case 2						
Min. *TL*	4.06	0.45	98.74	706.12	99.66	5.75
Max. *PF*	3.85	0.41	98.89	706.39	99.66	5.76
Max. η	3.91	0.43	98.87	706.13	99.66	5.75
Case 3						
Min. *TL*	4.19	0.46	95.17	700.46	99.36	10.61
Max. *PF*	3.59	0.28	97.26	706.75	99.36	10.80
Max. η	3.95	0.47	95.19	701.55	99.37	10.65
Case 4						
Min. *TL*	4.19	0.47	95.01	701.24	99.36	10.64
Max. *PF*	3.60	0.30	96.75	709.39	99.36	10.89
Max. η	3.97	0.45	95.50	702.31	99.37	10.67

Table II shows that LC compensators can achieve a higher power factor than pure capacitive compensation [5], [11] for nonlinear loads when source harmonics are present. Comparison of the results shows that a lower short-circuit capacity corresponds to a higher power factor at the same conditions. This is to be expected since with higher transmission impedance, less harmonic current will flow into the compensated load, cases 1, 3. Also it is shown that additional harmonic contents result in lower power factor. This is caused by the increase in compensated line current due to the additional harmonics; see cases 2 and 4. In practice, power dissipation of the resistance of the compensator reactor, however small, will take place. Table III shows how its value (as a percentage of its fundamental reactance) affects the solution.

The above results show that the assumption made of neglecting this resistance is a reasonable assumption because it made an error about (1%) in the results.

TABLE III
EFFECT OF THE RESISTANCE OF THE COMPENSATOR REACTOR ON THE CRITERION OF MINIMUM TRANSMISSION LOSS FOR CASE 3

R (%)	PF (%)	TL (kW)	η(%)
1.0	95.07	10.61	99.13
2.0	94.98	10.64	98.90
3.0	94.89	10.67	98.67
4.0	94.80	10.70	98.44
5.0	94.71	10.70	98.22

Based on the results and experience gained from this study, additional observations are made on the concept of power factor correction in nonsinusoidal systems.

1) The three criteria–minimization of the transmission loss, maximization of the power factor, and maximization of the transmission efficiency lead to different optimal solutions, although the corresponding performance may not be very different.
2) Passive compensator value that would produce a unity power factor is not physically realizable.
3) Neglecting the resonant phenomena in the analysis would lead to erroneous results.
4) Due to resonant conditions, an increase of shunt compensator does not necessarily produce an improved power factor operation as predicted by fundamental frequency analysis.
5) Due to the uncertainties in system parameter data, one might consider a suboptimal compensation if resonant conditions occur at various compensator values very close to the optimal values.
6) The harmonic voltage distortion generated by a nearby customer could produce, to another customer, a low power factor-operating problem of which a simple and economic solution may not be feasible.
7) The analysis is also applicable for more general loads, even if the structure is more complex than that in Fig. 1. It suffices to use suitable G_{LK} and B_{LK} characteristics.

IX. CONCLUSION

For nonlinear loads, it is necessary to use LC compensators. Such compensators have dual purposes. The first is that it acts as a compensator to improve the power factor of the nonlinear loads. Second, it acts as a filter of the harmonic load currents thus preventing the proliferation of the network with these currents. A major advantage of the LC compensator is the much higher power factor attainable (up to 98%). A model for determining an optimal LC shunt compensator value at nonsinusoidal busbars, including the three basic criteria—maximizing the power factor, minimizing the transmission loss, and maximizing the transmission efficiency—is developed. The choice of the compensator value is constrained by the values that may cause resonance. The model for the nonlinear load is a two variable problem in L (inductor) and C (capacitor) so the direct search polytope algorithm is used. Compared with pure capacitive compensation, LC compensation provides the same power factor at a lower compensator cost. The advantages of the present method include the improvement in the accuracy of the solution and in the ability of the developed algorithm to guarantee convergence to the optimal solution. Using this method, the global optimal solutions as well as the local optimums are determined. This additional information can be useful for performing a cost-benefit decision analysis before implementing the optimal LC compensator. Finally, whether or not the solution generated by this method is indeed optimal depends on the knowledge of the system configuration, operating conditions, and harmonic voltage distortion. Nevertheless, the developed method represents a useful tool for providing an optimal solution under a given situation.

Ongoing research effort consists of the modification and application of this method to take into account the manufacturer's standard values for power shunt capacitors as well as the effect of time variation of system impedance and voltage harmonics on the solution. Note that this effort is in conjunction with the concern and activities in the IEEE Power Engineering Society on harmonics and their effects on the power systems operation.

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