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IMPACT OF INCREASED DISTRIBUTED GENERATION ON FAULT LEVELS AND THE NETWORK EQUIPMENT

Attention towards the development of Distributed Generation (DG) is globally high. UK's concentration is to use sustainable and renewable sources to generate electricity thereby protecting the environment from getting polluted. In this paper, Distributed Generation concept is explored regarding the types, sizes, ratings, locations and benefits. It is very important to connect the developed distributed generator to the distribution network to satisfy the demand but without developing any faults and causing damage to the existing switchgear. Legal contracts that are required to be signed in order to connect the DG to the network and proper Protection Review to be followed in suppressing the faults are also mentioned. To study the impact of increased DG on fault levels, simulation approach is adopted. ETAP 7.1.0 is used to build a case study network and the results obtained are analyzed based on which critical comparison is made. The network comprises of three wind farms, each consisting of six wind turbines and a small hydroelectric plant. Various scenarios are considered and the results obtained are clearly analyzed. Protection is provided for the circuit and Star Device coordination study is performed.

Keywords: Distributed Generation, Protection Review, ETAP (Electrical Transient Analyzer Program), Star Protective Device Coordination.

1. Introduction

Global concentration on Distributed Generation (DG) is increasing. This is certain because of the increase in demand for the energy every year. The targets set by the government of Great Britain in increasing the usage of renewable sources in producing electricity and at the same time to reduce the greenhouse gases emission gave boost for the further development of DG. In order to maintain the reliability of the existing switchgear, DG is used. DG helps in maintaining the voltage levels, improving power quality and to reduce the losses in the network. Having many advantages the DG's of different types and sizes are developed to connect to the distribution networks. Distribution networks have conventional protection topologies.

The range of values or the ratings of the protective devices, lines may or may not withstand the connection of DG. Connection of DG to the distribution network meets the demand and reliability conditions along with the tendency of introducing fault currents. If the fault current increases more than the fault level design limits of the network then there is chance for the malfunctioning or damage to the equipment and loss of life and property. In order to avoid the above said disasters proper protection review should be carried out before the DG is connected to the distribution network. The conclusions of the protection review sometimes leads to the employment of cost effective and reliable methods in limiting the fault current. The focus on fault current limiters helps in the connection of Distributed Generation to the distribution networks, which eventually results in the enjoyment of advantages of DG through engineering [1, 4].

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2. DG Connectivity to the Distribution Network

Meeting the power demand is the ultimate cause for the development and usage of DG. In order to meet the power demand, DG should be connected to the distribution network. For the DG to be connected to the network there are procedures to be followed and agreements to be signed which are provided by Distribution Network Operator (DNO) and Transmission Network Operators. Connecting DG to the network should not affect the existing protection system by introducing fault current [12, 13].

3. Classification- Size of Power Station in UK and the Agreements

The range of the size of a power station or generator depends on the place the generator is situated. Three transmission owners are there across Great Britain and each of them has their own specifications in classifying the size of generators or power stations. The three transmission owners are: National Grid, Scottish Power, Scottish and Southern

Table 1: Classification of power stations:

Size	**Transmission Owner**		
	National Grid	Scottish Power	Scottish and Southern
Small	<50 MW	<30 MW	<10MW
Medium	≥50 MW and <100 MW	N/A	N/A
Large	≥100 MW	≥30MW	≥10MW

Connection and Use of System Code (CUSC) Accession Agreement: This agreement states that the owner of DG should operate following the rules mentioned in CUSC. It is a legally binding contract which mentions that the owner of the Distributed Generator should strictly follow the DNO’s licensed based code.

Bilateral Connection Agreement (BCA): This agreement is made with National Grid by the owners of DG and Distribution Network Operators (DNO) who wish to get connected directly to the National Electricity Transmission System (NETS).

Bilateral Embedded Generation Agreement (BEGA): This agreement is made between National Grid and the other party when access to the NETS is asked for. This agreement is made just for the access and not the direct connection to the NETS. It is more suitable for the owners of DG who are connected to the distribution network and willing to export the power on to NETS. It also specifies the provisions for any balancing services.

Bilateral Embedded Licence Large Power Station Agreement (BELLA): This agreement is made with the other party by National Grid whose power station can be classed as a large licence exemptible power station. This power station should be connected and be a part of DNO’s system. This agreement i.e. BELLA is only available for the owners power stations who wish to make a connection in Scotland and unavailable in England and Wales.

Construction Agreement: This agreement clearly states the rules, regulations, responsibilities, timescales, milestones and financial set outs required for the construction or modification of the direct connection to the NETS or to provide the option for the connectivity of embedded generation.

The above mentioned are all the required agreements. They vary according to the request made by the owner of that power station or Distributed Generator size and location [6, 7].

4. Protection Review

Protection review [15] must be carried out before any Distributed Generation is connected to the distribution network. Protection Review can be stated in four steps, which is followed in this paper.

Step 1: Using the technical information, the generator and its connection arrangements are modelled.

Step 2: Analysed the existing protection system.

Step 3: Determined the effects of the proposed generator connection.

Step 4: Concluded whether the Protection system meets the requirements.

5. Simulation Results and Analysis

In this paper an MV distribution network case study [11] is simulated using ETAP 7.1.0 software [16]. Increased Distributed Generation is considered in the simulation process. Three wind farms; each consisting of six wind turbines and a small hydro-electric plant comprising of three synchronous generators are used in the connection process. Different scenarios are created in the simulated circuit for the analysis purpose. Each scenario is clearly explained, simulated and analysed.

5.1. Details of DG and the Equipment Considered:

Four DG stations, i.e. three wind farms each comprising of six wind turbines and a small hydro electric plant with three synchronous generators totalling to 17.160MW capacity is connected to the busbars of the MV distribution network. Data is illustrated in appendix.

5.2 Theoretical Calculations:

IEC 60909 standards are used for calculation purpose.

1. Calculation of ZQ of the Grid

$ZQ = \frac{C*(U_{nQ})2}{S''_{KQ}} = \frac{1.1*(150*10^3)2}{3000*10^6}$; $ZQ = 8.25\Omega$

2. Calculation of ZQt

$ZQt = \frac{Z_Q}{t_r^2} = \frac{8.25}{\left(\frac{150}{21}\right)2} = 0.1617$; $XQt = 0.995*ZQt = 0.995 * 0.1617 = 0.161\Omega$; $RQt = 0.1 * XQt = 0.1 * 0.161 = 0.0161$; Therefore, $ZQt = RQ + j\,XQ = 0.0161 + j\,0.161\Omega$

3. Calculation of ZT

$ZT = \frac{U_{kr}}{100\%} * \frac{U_{rT}^2}{S_{rT}}$; Where, $Ukr = 20.5\%$, $U_{rT} = 21*103$ V, $S_{rT} = 50*106$ VA

$ZT = \frac{20.5}{100} * \frac{(21*10^3)2}{50*10^6}$; $ZT = 1.808 \cong 1.81\Omega$

4. Formula used in calculation of I''_K

$I''_K = \frac{C_{max}U_n}{\sqrt[3]{(Z_{Qt}+Z_{KT})}}$

All other calculations are performed similarly and the obtained values for the fault current contribution from the case study network are:

Table 2: Calculated results of fault current contribution by different contributors in the network.

Fault Current Contributor	**Fault Current Contribution**
Grid	6.889kA
Wind Farm 1	0.156kA
Wind Farm 2	0.605kA
Wind Farm 3	0.438kA
SHEP	0.541kA

5.3 Proposed Scenarios to Assess the Simulation:

In this paper there are 9 scenarios analysed using the case study and the related results are achieved. In this regard initially scenarios have been discussed and respective figures and tables are presented later.

Scenario1: Busbar 2 is faulted and the fault current contributions of all major blocks of the circuit are tabulated. When busbar 2 is faulted the results are obtained as shown in the table. The contributions of fault current of individual wind farms, SHEP and the grid exactly match with the results obtained through theoretical calculations in the previous section. Here the only conflict is that when the individual fault contributions are summed, it results to 8.629KA but the software results depict that the total fault current in the network is 8.604KA. The reason is that the difference in the phase angles of the individual contributor’s contribution. Though the turbines are identical their phase angles differ with each other and so same contribution of fault current cannot be expected in practical conditions. In the Fig. 1, upstream grid contributes highest fault current and next to it is the wind Farm 2. Wind Farm 1 is least fault current contributor among all. Though the size of Wind Farm 2 is less when compared with Wind Farm 3, its contribution of fault current is higher than that of Wind Farm 3. This is just because of the orientation of the phase angle at which the turbines are generating power.

Table 3: Fault current contribution when busbar 2 is faulted

Fault Current Contributor	**FaultCurrent (KA)**
Upstream Grid	6.889
Wind Farm 1	0.156
Wind Farm 2	0.605
Wind Farm 3	0.438
SHEP	0.541
Total Fault Current	8.604

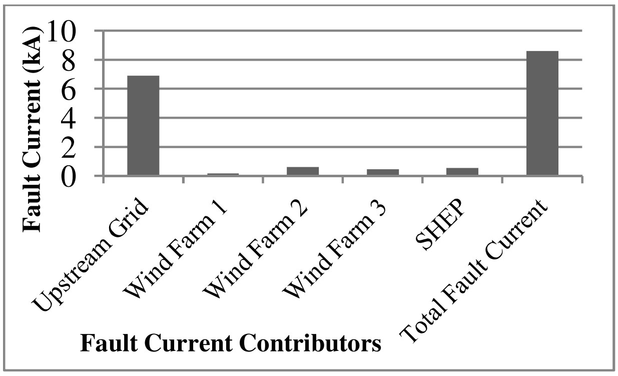


Fig. 1. Fault current contribution by fault contributors

Scenario 2: Distributed Generators are disconnected individually and the total fault current contribution is observed when busbar 2 is faulted. Here in this scenario also busbar 2 is faulted but unlike the previous scenario here the DG's are disconnected individually from the network and the total fault current is measured. Based on results Wind Farm 2 contributes more amount of fault current. That is the reason when this DG is disconnected the total fault current value came down to 8.011KA, which is least when compared with others. Wind Farm 1 contributes very less amount of fault current in the list and so the corresponding total fault current value is high when it is disconnected from the network. Wind Farm 3 and SHEP are close to each other. This can be observed in the Fig. 2.

Table 4: Total Fault current when DG 's are disconnected

Disconnected DG	**Total Fault Current (KA)**
Wind Farm 1	8.450
Wind Farm 2	8.011
Wind Farm 3	8.172
SHEP	8.064

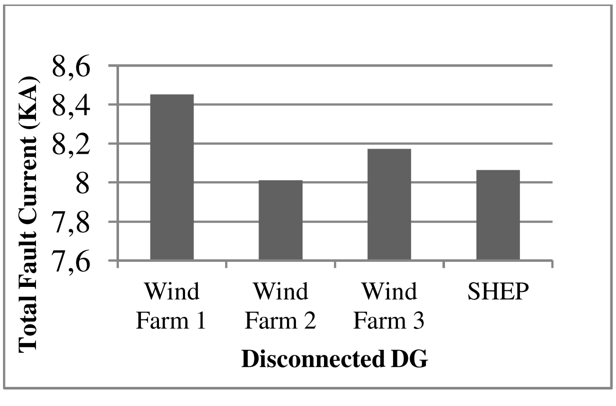


Fig. 2. Total Fault current contribution when DG's are disconnected

Scenario 3: Busbar 2 is faulted. Upstream Grid and SHEP continue to contribute fault current. In the table below the contribution of Distributed Generation i.e. each Wind Turbine generator towards total fault current as they are connected to the MV distribution network is tabulated. Contribution of Upstream Grid = 6.889KA, Contribution of SHEP = 0.541KA, Contribution of Static Loads = 0KA. This scenario is performed only to focus on the individual wind turbine fault current contribution. All the wind turbines are disconnected initially and each one is added to the network and the total and individual fault currents are observed. There are totally 18 wind turbines with 6 in each wind farm and their contribution towards fault current can be represented pictorially as below. Total fault current in the network is increasing as the wind turbines are being connected to the network one after the other. The pyramids in the figure are in increasing manner which resembles the increase in the total fault current as the turbines are connected to the network, which is totalled to 8.604KA.

Table 5: Fault Current Contribution of individual WTG's

Wind Turbine Generator Connected	**I_f contribution of Wind Farms in KA**			**Total I_f magnitude at Busbar 2 (KA)**
	1	2	3	
No WTG	0	0	0	7.427
WTG 1	0.027	0	0	7.454
WTG 2	0.054	0	0	7.480
WTG 3	0.080	0	0	7.505
WTG 4	0.106	0	0	7.531
WTG 5	0.131	0	0	7.556
WTG 6	0.156	0	0	7.580
WTG 7	0.156	0.118	0	7.697
WTG 8	0.156	0.229	0	7.805
WTG 9	0.156	0.332	0	7.907
WTG 10	0.156	0.429	0	8.001
WTG 11	0.156	0.519	0	8.089
WTG 12	0.156	0.605	0	8.172
WTG 13	0.156	0.605	0.082	8.253
WTG 14	0.156	0.605	0.159	8.330
WTG 15	0.156	0.605	0.234	8.403
WTG 16	0.156	0.605	0.305	8.473
WTG 17	0.156	0.605	0.373	8.540
WTG 18	0.156	0.605	0.438	8.604

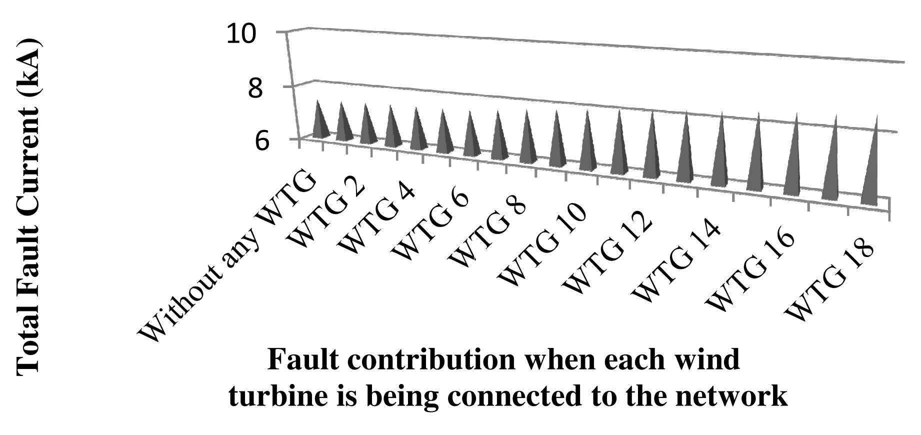


Fig.3. Total Fault current contribution when Wind Turbines are connected one after the other to the network

Scenario 4 : Bus 24 is faulted i.e. far from the connections of Distributed Generators. The contribution of farms and grid towards total fault current is tabulated. When the busbar which is far from the connection of DG's to the distribution network is faulted the observation is made. The observation made is compared with the result of scenario 1 in which the busbar which is closer to the connection of DG's is faulted. The graphical representation clearly shows that the fault current contribution is higher in SHEP when the fault occurs near to the connection of it and it is significantly low when the fault occurs far from the SHEP connection.

Table 6: Fault current contribution when fault occurs far from DG's

Fault Current Contributor	**Fault Current (KA)**
Upstream Grid	2.46
Wind Farm 1	0.056
Wind Farm 2	0.216
Wind Farm 3	0.156
SHEP	0.610
Total Fault Current	3.459

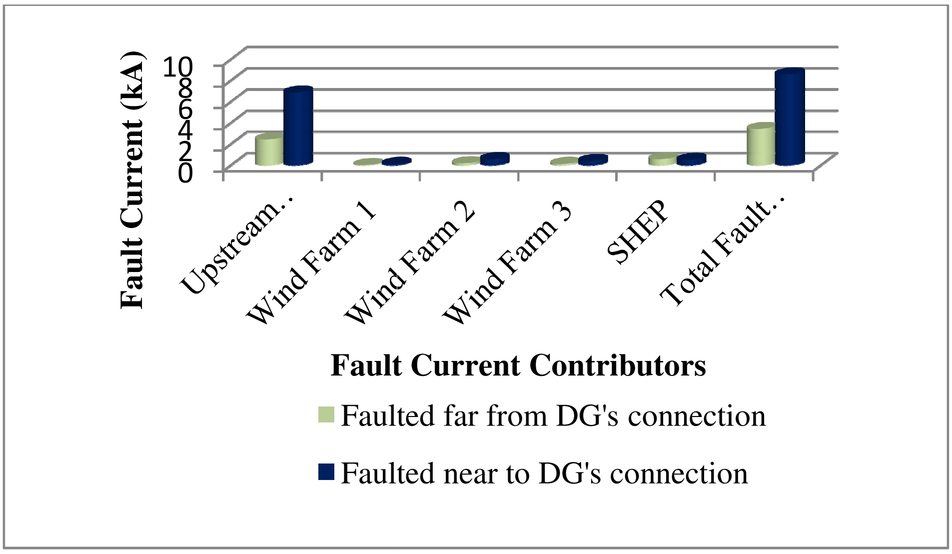


Fig.4. Comparison of fault current contribution when faulted far and near to connection of DG's to the network

Scenario 5: Static loads in the circuit are replaced with Induction Motors. In this scenario Induction motors are introduced in place of static loads with same ratings. This is done in order to analyse the fault contribution of the rotating loads if present in the network. Static loads do not contribute any fault current to the network. Always static loads cannot be expected in the network therefore rotating loads are introduced and the fault current is observed. All the Induction motors introduced are contributing equal amount of fault current which is 6.849KA. The total fault current in the circuit is increased from 8.604KA to 35.999KA on introducing Induction Motors.

Table 7: Fault current contribution of Induction Motors

Induction Motor ID	Fault Current (I_f) Contribution in KA
Mtr 4	6.849
Mtr 8	6.849
Mtr 9	6.849
Mtr 10	6.849

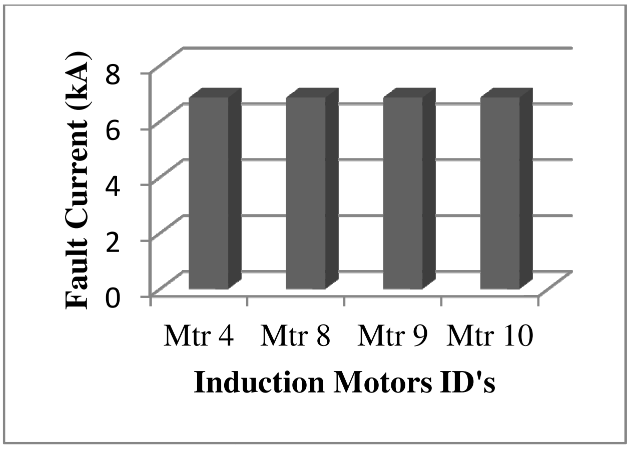


Fig.5. Fault current contribution of Induction Motors

Scenario 6: Static Loads placed in the circuit are replaced with Synchronous Motors. The replacement is clearly shown in the circuit diagram below. In this scenario Synchronous motors are introduced in place of static loads with same ratings. This is done in order to analyse the fault contribution of the rotating loads if present in the network. Static loads do not contribute any fault current to the network. Always static loads cannot be expected in the network therefore rotating loads are introduced and the fault current is observed. The observation is graphically represented with the help of Microsoft-Excel. All the Synchronous motors introduced are contributing equal amount of fault current which is 6.553KA. The total fault current in the circuit is increased from 8.604KA to 34.814KA on introducing Synchronous Motors. The fault current introduced by Synchronous motors is less when compared to Induction Motors.

Table 8: Fault current contribution of Synchronous Motors

Synchronous Motor ID	Fault Current (I_f) in KA
Syn 3	6.553
Syn 4	6.553
Syn 5	6. 553
Syn 6	6.553

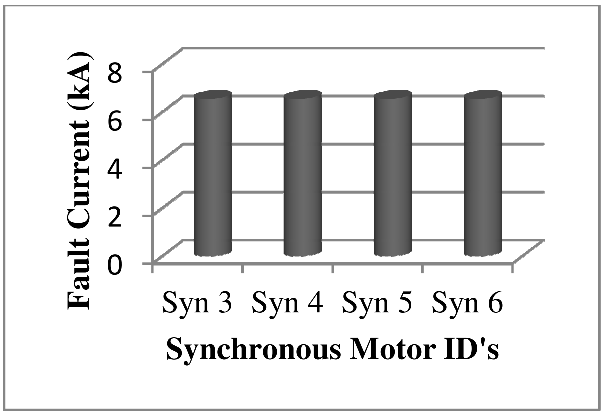


Fig.6. Fault current contribution of Induction Motors

Scenario 7: Static Loads in the circuit are replaced with Lumped Loads (80% motor and 20% static). In this scenario Lumped loads are introduced in place of static loads with same ratings. This is done in order to analyse the fault contribution of the rotating loads if present in the network. Static loads do not contribute any fault current to the network. Always static loads cannot be expected in the network therefore lumped loads are introduced and the fault current is observed. All the Lumped loads introduced are contributing equal amount of fault current which is 5.779KA. The total fault current in the circuit is increased from 8.604KA to 31.715KA on introducing Lumped loads. The fault current introduced by Lumped loads is less when compared to Induction Motors and Synchronous Motors. This is mainly because of the 20% static nature of the Lumped Loads.

Table 9: Fault Current Contribution of Lumped Loads

Lumped Load ID	Fault Current (I_f) Contribution in KA
Lump 1	5.779
Lump 2	5.779
Lump 3	5.779
Lump 4	5.779

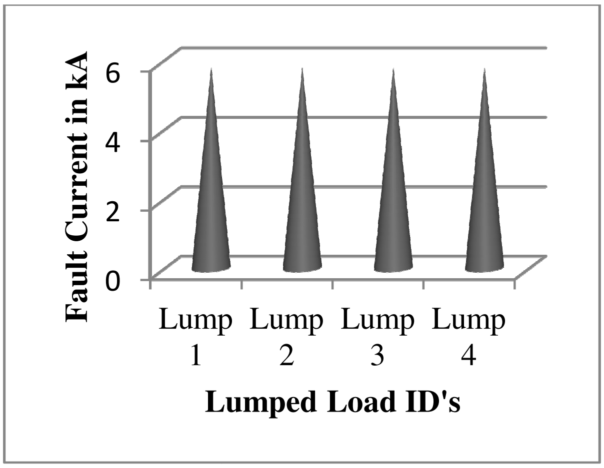


Fig.7. Fault current contribution of Lumped Loads

Scenario 8: Fault Current Limiters (FCL) [2, 3] is placed between the Wind Farms, SHEP and the faulted Busbar 2. The current limiter placed here is of 6ohms positive impedance in order to reduce the total fault current in the circuit. In this scenario fault current limiters are introduced in order to observe the effect of the FCL in limiting the fault current. There is a difference in fault current contribution i.e. when FCL is placed the contribution is less. It can be compared as below. The red cylinders in Fig.8 represent the fault current before the placement of FCL and the blue one's after the placement of FCL. Fault current limiter showed its impact in reducing the fault current.

Table 10: Fault current before and after introduction of FCL

Fault Current Contributor	**Fault Current before Current Limiter is placed (KA)**	**Fault Current after Current Limiter is placed (KA)**
Upstream Grid	6.889	6.889
Wind Farm1	0.156	0.152
Wind Farm2	0.605	0.547
Wind Farm3	0.438	0.406
SHEP	0.541	0.474
Total Fault Current	8.604	8.460

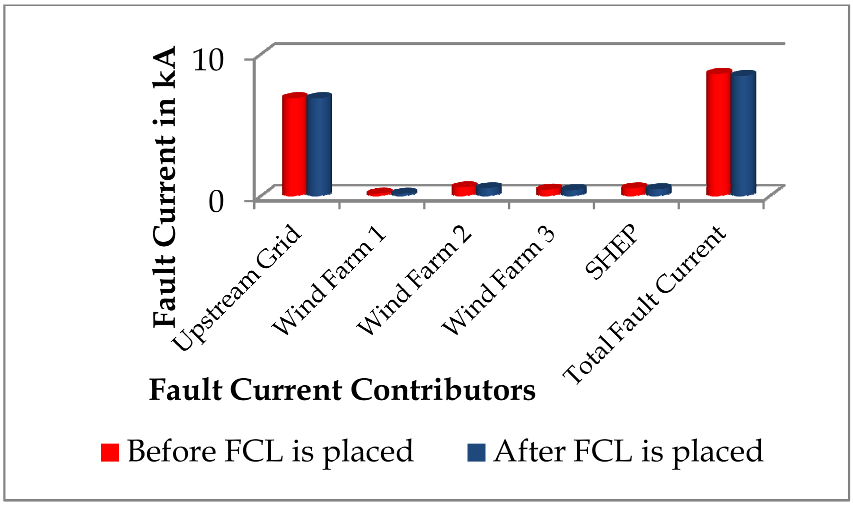


Fig.8. Fault current before and after placement of FCL

Scenario 9: Fault Current Limiters [8, 9, and 10] are introduced in the circuit and the impedance is varied to observe the contributions of fault current by the Wind Farms and SHEP towards the network. The minimum impedance of the Fault current limiter that it should possess in order to limit the fault current in the circuit is 4.3Ω. The upstream grid contribution of fault current = 6.889KA. By implementing trial and error method we found that the minimum value of impedance of the fault current limiter should be 4.3Ω in order to limit the fault current. It is then the impedance is varied in several steps and the contribution of fault current in the network by the contributors is observed and it is graphically represented as below. Increasing the impedance reduces the fault current in the network and can be clearly seen in the Fig.9 below. Wind farm 2 is contributing more amount of fault current among all the contributors as its size and the phase angle at which it is generating is more comparatively.

Table 11: Variance in Fault current of DG's on increasing the impedance

FCL Impedance	**Fault Current Contribution in KA**				
Values in Ω	Wind Farm 1	Wind Farm 2	Wind Farm 3	SHEP	Total I_f
4.3	0.155	0.590	0.429	0.506	8.560
4.4	0.155	0.587	0.428	0.504	8.554
4.5	0.155	0.584	0.426	0.502	8.547
4.6	0.155	0.582	0.425	0.500	8.541
4.7	0.155	0.579	0.423	0.498	8.535
4.8	0.155	0.576	0.422	0.496	8.529
4.9	0.154	0.574	0.421	0.494	8.523
5.0	0.154	0.571	0.419	0.492	8.517
5.1	0.154	0.569	0.418	0.490	8.511
5.2	0.154	0.566	0.417	0.488	8.505
5.3	0.154	0.564	0.415	0.486	8.500
5.4	0.153	0.561	0.414	0.485	8.494
5.5	0.153	0.559	0.413	0.483	8.488
5.6	0.153	0.556	0.411	0.481	8.482
5.7	0.153	0.554	0.410	0.479	8.477
5.8	0.153	0.552	0.409	0.477	8.471
5.9	0.153	0.549	0.407	0.476	8.466
6.0	0.152	0.547	0.406	0.474	8.460
6.1	0.152	0.545	0.405	0.472	8.455
6.2	0.152	0.542	0.403	0.470	8.449
6.3	0.152	0.540	0.402	0.468	8.444
7.0	0.151	0.524	0.394	0.457	8.407
8.0	0.149	0.504	0.382	0.441	8.358
9.0	0.147	0.485	0.371	0.426	8.311
10	0.145	0.467	0.360	0.412	8.268
11	0.144	0.450	0.350	0.399	8.228
12	0.142	0.435	0.341	0.387	8.190
13	0.141	0.421	0.332	0.376	8.154
15	0.138	0.395	0.316	0.355	8.088

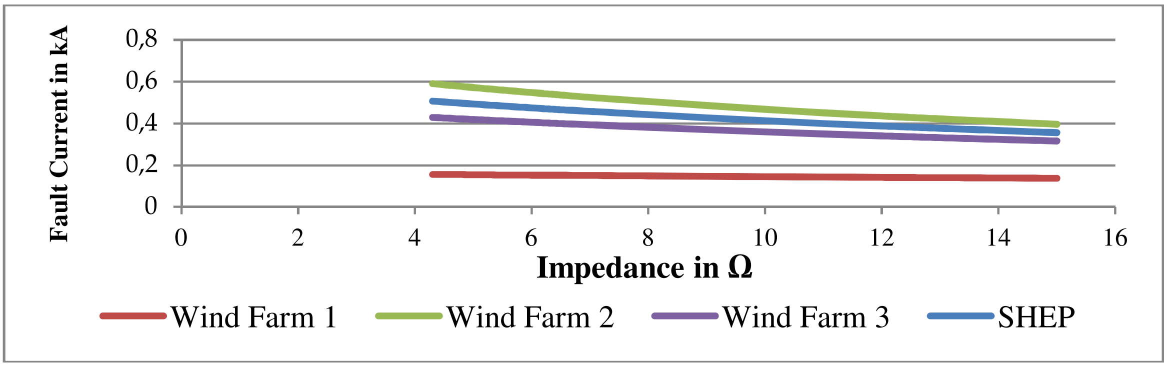


Fig. 9. Variation of fault current on increasing the value of impedance

6.ProtectionTopology

As protection is very important for the network in order to safeguard the equipment in the network and at the same time the life of people working on the network, a strategy to introduce protective devices in the simulated network is implemented. *Protective Devices Used:*

Fuse: These are introduced between the bus-bar and the loads. Fuse is selected from the library available in the ETAP software. Various technical values associated with the Fuse used are presented in Appendix

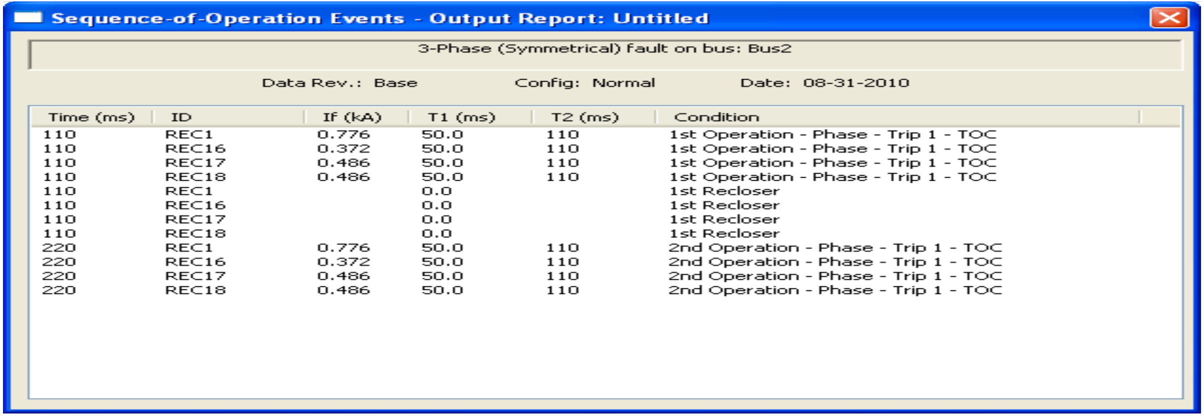
Recloser: Reclosers are introduced between the DG's and the main. They are introduced along the transmission lines to safeguard the equipment from the fault currents. Specifications of the Recloser are mentioned below in Appendix.

Circuit Breaker: Low voltage and high voltage circuit breakers are introduced for protection. LV circuit breakers are introduced at the Wind turbines and the HV circuit breakers are introduced at the transformers where the voltage is stepped up. Specifications are as below in Appendix. Similarly LV Circuit Breaker specifications are selected based on the kV ratings of the busbar to which they are connected i.e. 0.4 kV and 0.69 KV. For the HVCB which is placed near the network transformer it is selected based on the busbar rating which is 20kV.

Relays: Over current relay is used at the small hydroelectric plant. It is used for the protection at the connection of the transformer and the busbar present in that plant. Potential and current transformers are introduced along with the over current relay.

7. Star- Protective Device Coordination Study

This is extraordinary feature present in ETAP 7.1.0 with the help of which exact coordination of protective devices is performed. The values of the protective devices can be exactly set i.e. to increase or decrease the given initial readings by performing this analysis. When the Run/Update Short Circuit kA option is selected it gives the current and voltage values at all the busbars in the circuit. On inserting the fault i.e. selecting the option "Fault insertion (PD Sequence-of-Operation" in any part of the circuit, it gives the operation of the protective devices that are getting active. It also gives out the time at which the particular protective device is operated



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                         3-Phase (Symmetrical) fault on bus: Bus2

              Data Rev.:  Base          Config:  Normal          Date:  08-31-2010

Time (ms)   ID            If (kA)   T1 (ms)    T2 (ms)    Condition
110         REC1          0.776     50.0       110        1st Operation - Phase - Trip 1 - TOC
110         REC16         0.372     50.0       110        1st Operation - Phase - Trip 1 - TOC
110         REC17         0.486     50.0       110        1st Operation - Phase - Trip 1 - TOC
110         REC18         0.486     50.0       110        1st Operation - Phase - Trip 1 - TOC
110         REC1                    0.0                   1st Recloser
110         REC16                   0.0                   1st Recloser
110         REC17                   0.0                   1st Recloser
110         REC18                   0.0                   1st Recloser
220         REC1          0.776     50.0       110        2nd Operation - Phase - Trip 1 - TOC
220         REC16         0.372     50.0       110        2nd Operation - Phase - Trip 1 - TOC
220         REC17         0.486     50.0       110        2nd Operation - Phase - Trip 1 - TOC
220         REC18         0.486     50.0       110        2nd Operation - Phase - Trip 1 - TOC
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Fig. 10. Sequence of operation of protective devices

The sequence of operation and the time at which the device got operated is observed by clicking on the sequence viewer. With the help of this study it is sometimes observed that when the fault is introduced at one of the DG plants the recloser present at the network transformer is being operated and so the continuity of supply is getting disturbed. Hence the specifications of the protective devices present near the DG plant where the fault is introduced is studied carefully and are adjusted such that only the recloser present near the fault gets operated and the remaining circuit operates smoothly without any interruption in the power supply. Through this Star device coordination study any issues related to design can be known quickly and the system reliability and the stability can be increased and the financial savings for the distribution network operator can be increased.

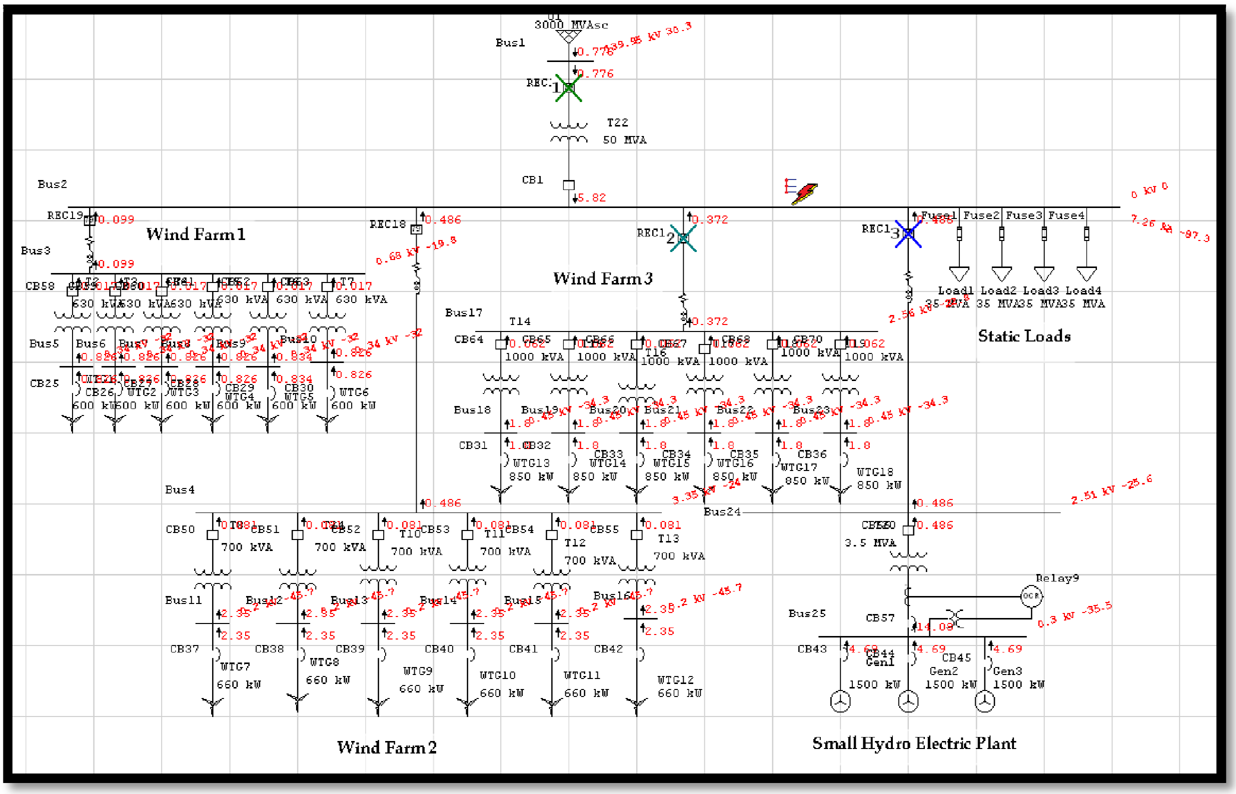

Fig.11. Total circuit on performing Star device coordination in ETAP 7.1.0

8. Conclusions

On connecting a Distributed Generator to the distribution network the fault levels definitely increase to certain extent. The rise in fault levels depends on the size of the DG connected. If the DG is of very small size, its influence on the fault levels is negligible but when the increased DG is considered it has a significant influence in the rise of fault levels in the network. This increased fault current is to be limited using the fault current limiting methods. The magnitude of the fault current is not just the important aspect to be focussed, direction of the fault current travel should also be limited. Control over the direction of the fault current is possible only if the existing protection scheme on the network effectively works. This protection topology is discussed. Protection scheme can be effectively improvised by the star device coordination study using ETAP 7.1.0 software which is clearly stated in this paper. *Impact on Busbars:* The high fault currents that arise when the increased DG is connected to the network, results in the increase of thermal and mechanical stresses on the busbars and the conductors available. By introducing additional insulators these stresses can be minimised. *Impact on Circuit Breakers:* Circuit Breakers interrupt the supply of current if it is too high but it has its own limit to interrupt. If the generated fault current is excessive then existing circuit breakers are to be replaced with the ones with higher ratings. *Impact on Protection and Metering:* Current transformers and relays play vital role in protecting the network. Sometimes due to heavy rise in the fault level there is chance for the current transformers to reach a state of saturation. During these times relays can be accommodated to reduce the effect of fault current on CT's. Relays also sometimes encounter the situations of Under-Reaching and Over-Reaching of relays [15]. In order to overcome all these situations Star protective device coordination study should be performed and incorporating additional relays sometimes rectifies the problem. *Impact on Grounding Grids:* If the fault currents are generated in excess then the damage to the grounding system is done, this results in the operation failure, decreased safety. If this type of situations arises then remodelling the grounding system is required [5]. *Impact on transformers:* Increase in fault levels increase the thermal and mechanical stresses in a transformer resulting in the failure of the transformer. Hence Protection Review should be clearly followed by taking into consideration the mechanical and thermal stress during the design of protection to the network.

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