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Impacts of Embedded Generation on Distribution Network Behavior

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ABSTRACT

This paper explores the impacts of multiple embedded generators penetration on distribution system behavior. For this rationale, a IEEE-13 bus distribution feeder was modeled and investigates by assimilating different types of embedded generation (EG) sources. Different scenarios were implemented in which WIND, SOFC FUEL CELL, SOLAR and MICRO TURBINE plants were modeled with high variability of load and generation to observe their impacts on system's protection, unsymmetrical faults also consider observing impacts effectively. To eradicate the impacts on distribution system with presence of EG's and distribution system undergone in the event of faults, in this paper primarily reverse power due to EG integration is estimated and sensed with reverse power relay, Further two types of Superconducting Fault Current Limiters Passive resonance CB (PRCB) SFCL and Inverse current injection CB (I-CB are proposed and results are compared for amended solution in mitigating fault current magnitude and over voltages, Finally penetrations levels are computed mathematically and All the modeling and simulations were carried out using MATLAB SIMULINK tool.

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1. INTRODUCTION

Embedded Generation (EG) is a small scale electricity generation nearby end-users, ranges from 10KW to 10 MW, is directly connected to distribution network (DN).penetration of EG influence the distribution system (DS) operation [1] and though the intention of EG integration in to DS are to provide sustain voltage support [2], reactive power compensation [2], reduction of losses and reliability [3], [4]. EG integration shows immense impact on grid operation [5], voltage profile [6]-[8], power quality [9], [10], grid losses [11], fault current level [12], and existing protection system [13]-[17].

From the literature, it is observed that researchers are concentrated how to provide the protection to distribution system in the event of faults through designing of protection equipment's like fuse, circuit breakers, surge arresters, surge diverters, relays and hybrid protective schemes [18]-[23] a clear research gap is identified to mitigate (solve) the negative impacts on distribution system protection with EG integration, in this paper primarily review the embedded generation benefits to the grid, grid benefits to embedded generation [24] and investigates how the embedded generation will pose impacts [25] on protection of distribution system [26] is presented in detailed.

1.1. Embedded Generation Benefits To The Grid
Reduced Transmission and Distribution losses
Potential to defer network augmentation depending on geographic location and performance during peak periods
Voltage support
Improve power system resilience
Potential emissions reduction

1.2. Grid Benefits To Embedded Generation
Provides access to upstream markets
Supports maintenance of reliability for intermittent embedded generation
Supports voltage quality important for end-use devices
Supports operating efficiency of embedded generation as output need not reflect local load
Supports start up power requirements of the customer, when peak current may increase significantly.

1.3. Considerable Impacts Of Embedded Generation
In this paper the main issues associated with the penetration of embedded generations into existing distribution systems are as follows and given in [27], [28]

a. Reverse power flow
b. Power losses
c. Voltage profile
d. Islanding operation conflicts
e. Increase in fault current
f. Power quality issues
g. Stability
h. Safe penetration limits estimation, etc. are the few performance index parameters needs to consider for analysis.

Among above identified issues during EG integration, in this paper four significant issues have been considered for analysis of distribution network. Reverse power flow, voltage profile, increase in fault current and penetration level estimation. in the event of EG integrated to DN. if local generation is exceeds the local load power flow gets reversed, this will difficult for DN protection, the detection of bidirectional power flow is essential, for this in this paper reverse power relay [29] is incorporated, it will recognizes the direction in which fault occurs, relative to the location of relay. Facilitate the solution against the protection under reach situations. as EG penetrations origin to over voltage in DN, it possess added complexity in the event of faults and EG integration reason for transitions of DN from radial to bidirectional, it brings the enhancement of fault current due to contribution from EG's, further it is severe during fault times, to protect the DN during the fault times both in voltage profile and mitigation of fault current in this paper, Previous investigations were performed initially on the Application of a Superconducting Fault Current Limiter (SFCL) for Energy Storage Protection in a Power Distribution System [30], active type SFCL is introduced [31], for mitigation of fault currents and over voltages incepted in distribution network during the faults. Further SFCL is incorporated to improve coordination between protective devices [32] and to attest the performance of SFCL Experimental investigations [33] done, the performance of SFCL being tested at various locations [34] in the power system, economical point of view tested by analyzing power dissipation [35] factor during t he operation of SFCL and later Application of Multiple Resistive SFCL 's [36] are obtained to compute the fault detection time in complex ,and practical applications issues [37] are recognized. Finally the characteristics of SFCL [38] are also presented. From the above literature, a clear research gap identified that operation of SFCL as Passive resonance CB (PRCB) SFCL and Inverse current injection CB (I-CB) could mitigate over voltage and increased fault current effectively and efficiently during the fault periods. In this paper the authors' contributions to achieve the objectives are as follows.

a. A test system is setup to identify the severe fault among symmetrical and unsymmetrical faults.
b. And least affected EG among all connected EG's for further analysis, by measuring the active and reactive power variations.
c. A methodology is developed to identify and isolate EG's at the instant of faults by designing the reverse power relay settings.
d. New techniques SFCL operated as Passive resonance CB (PRCB) SFCL and Inverse current injection CB (I-CB) are proposed to mitigate the over voltages and high fault currents caused by the EG,s penetrations and faults respectively.
e. Further simulation results from the two proposed techniques during severe fault (LLLG) with least affected EG (SOFCEG)were compared, proposed for designing of protective devices(circuit breaker)

f. Finally the different EG's penetration levels were computed with conventional mathematical formulas and analyzed.

2. PROBLEM FORMULATION

The effect of EG units on operating and planning characteristics such as voltage profile, power quality, power Losses, reliability, and protection system strongly depends on the type of EG unit. EG units can be either directly connected to the distribution grid, such as synchronous and asynchronous generators, or via a power electronic converter. In all cases, the power flows in the distribution grid as well as the mentioned characteristics are affected.

2.1. Types and Capacity of Embedded Generation

Types of Embedded Generation [39] EG's can be classified into two major parts such as inverter based EG and rotating machine EG. After the generation process inverters are usually used in EG systems, as the generated voltage may be in DC form or AC. It has to be converted first to DC then back to AC so it is required to be changed to the nominal voltage and frequency with the nominal parameters through the rectifier. Generally EG can be classified into four major types based on their terminal characteristics in terms of real and reactive power delivering capability [40]; different EG types, shown in Table 1, have been considered in this study.

Table 1. Major types of EG Based on Power Delivering Capability [41]

EG Type	Type Description	Example
Type 1	EG is capable of injecting both real and reactive power	Synchronous generators
Type 2	EG is capable of injecting real power but consuming reactive power.	Induction generators such as wind generation farms
Type 3	EG is capable of injecting real power only	PV, micro turbines, and fuel cells integrated to the main grid with converters/inverters
Type 4	EG is capable of injecting reactive power only	Synchronous compensators

The connection of a EG's to a distribution network as shown in Figure 1 will inevitably result in some local changes to the characteristics of the network The main issues are mentioned in the section (1), among listed in this paper four issues have been considered for analysis and proposed relevant solutions to protect the distribution system. Selected issues are a. Voltage profile b. Reverse power flow c. Increased fault current d. estimation of penetration levels.

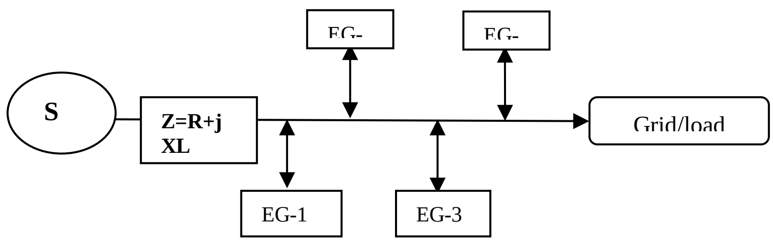

Figure 1. Single line diagram of embedded generation units interfaced power system

a. Scenario 1: voltage profile rise

The penetrations of EG in to distribution network will increase the voltage level, if this voltage is (local voltage +EG based voltage not greater than the local demand) within the permissible limits, DN can operate safely; otherwise will impose the problems on DN.

b. Scenario 2: Reverse Power Flow

In this scenario reverse power relay is proposed to protect the distribution system against the power reversals caused by the scenario1 i.e. Radial distribution networks are usually designed for unidirectional power flow, form the in feed downstream to the loads. This assumption is reflected in standard protection schemes with directional over current relays. With a generation on the distribution feeder, the load flow situation may change. If the local production exceeds the local consumption, the power flow will change the direction.

c. Scenario 3: Increase in fault current magnitude

Connection of EG to a distribution network has the effect of increasing the fault current during fault times in the network close to the point of connection. The risks when fault current levels are exceeded will cause damage and failure of the DN, with consequent risk of injury to personnel and interruption to supplies. The new fault current and setting should be calculated for the protection equipment in the system.

d. Scenario 4: Conventional approach is to estimate the penetration limits of EG

To attest the experimental results for above illustrated factors IEEE-14 bas have been considered with 4EG's (PVCELLS, MICRO TURBINE, SOFC FUEL CELL AND WIND TURBINE) in each case at selected bus no penetration levels have computed and distribution network characteristics are analyzed.

3. PROPOSED SOLUTIONS

In the process of perusal of solutions to impacts on distribution network, considering the typical distribution network shown in Figure 1, the above stated scenarios cover the most frequent changes at the instant connection of EG units and during fault times to the distribution networks, in this section the solutions are designed and discussed comprehensively.

a. Mitigation of over voltage and fault current

To maintain voltage in limits in this paper proposed Superconducting fault current limiters, For this 4 EG's are integrated in Figure 1 in to one by one and voltages are measured and recorded, to keep in permissible limits enhanced voltage due to EG's integration proposed solution have been tested and results are showing excellent . And conventional fault current limiter called Superconducting fault current limiters, employed to mitigate the fault current and protect the distribution system.

3.1. Modeling of an SFCL and Distribution Power System

a. Resistive SFCL Model:

An SFCL is one of the most promising current limiters for preventing the short-circuit current from increasing in magnitude owing to its rapid current limiting ability [42]. Many models for an SFCL have been developed, such as resistor-type, reactor-type, transformer-type, and hybrid-type SFCLs [43]. In this paper, we have modeled a resistor-type SFCL using mathematical expressive equations, which were verified by experiments and implemented using MATLAB Simulink modeling software [44]. The time evolution of the SFCL impedance RSFCL as a function of time t is given by (1), (2), and (3):

$$R_{SFCL}(t) = R_n\left[1-\exp\left(-\frac{(t-t_0)}{T_F}\right)\right]^{\frac{1}{2}} \qquad t_0 \le t < t_1 \tag{1}$$

$$R_{SFCL}(t) = a_1(t-t_1)+b_1 \qquad t_1 \le t < t_1 \tag{2}$$

and

$$R_{SFCL}(t) = a_2(t-t_2)+b_2 \qquad t \ge t_2 \tag{3}$$

b. Modeling of system voltage profile:-

Generally, a voltage magnitude at bus during fault can be calculated as (1) if fault impedance is ignored and source voltage is 1.0 [p.u].

$$\text{Vbus} = \frac{\text{ZL}}{\text{Zs} + \text{Zt} + \text{ZL}}$$

Where, Zs, Zt, and ZL are source impedance, transformer impedance, and line impedance from source to faulted location, respectively. Equation 1, also, can approximately mean the voltage magnitude at customers on all neighbor feeders of faulted feeder.

c. Voltage Variation as Application of SFCL

When SFCL is installed at the secondary side of main transformer or at the starting point of each feeder, total Impedance (denominator of (1)) is larger because of addition of impedance of SFCL in (1) and voltage sag duration is changed as the reduction of fault current.

$$\text{Vbus} = \frac{\text{ZL}}{\text{Zs+Zt+ZL}} \quad (4)$$

In addition, when SFCL is installed at the secondary side of main transformer or at the starting point of each feeder as (1) will be changed as (5) and (6), respectively.

$$\text{Vbus} = \frac{\text{ZL}}{\text{Zs+Zt+Z SFCL+ZL}} \quad (5)$$

$$\text{Vbus} = \frac{\text{ZSFCL+ZL}}{\text{Zs+Zt+Z SFCL+ZL}} \quad (6)$$

Where, ZSFCL means the impedance being saturated at normal temperature. Equations (5) and (6) represent that the SFCL should be installed the starting point of feeder based on a standpoint of only voltage sag improvement.

d. Reverse Power Flow

In this scenario reverse power relay (directional over current relay) is proposed to protect the distribution system against the power reversals caused by the scenario1 Reverse power flow is problematic if it is not considered in the protection system design. It employs the principle of actuation of the relay, when the fault current flows in to the relay in a particular direction. If the power flow is in the opposite direction, the relay will not operate. Normally the conventional over current relay (non-directional) will act for fault current in any direction. The directional over current relay will recognizes the direction in which fault occurs, relative to the location of relay.

e. Reverse power evaluation

To design reverse power relay settings for protection against the bidirectional power flows during the faults, when local voltage is exceeds the local demand. From the test system Essential data for computation is as follows

SG [kVA] rated generator apparent power

Cos (φ): rated generator power factor

In: rated current of XP2-R

Un: rated voltage of XP2-R

nI: transformation ratio of the CT

nU: transformation ratio of the VT

Connection of the reverse power relay to phase-to-phase voltage:

Conversion of the generator phase power PGS based on the CT secondary side:

$$P_{GS} = \frac{S_G \cdot \cos(\varphi)}{\sqrt{3} \cdot n_U \cdot n_I} \quad (7)$$

With the permissible generator reverse power PGS, the setting value PR is then calculated as follow

$$P_R > (\%) = \frac{\dfrac{S_G \cdot \cos(\varphi)}{\sqrt{3} \cdot n_U \cdot n_I}}{Un \cdot In} \cdot P_{RG}(\%) \quad (8)$$

Connection of the Reverse power relay to phase-to-neutral voltage, Conversion of the generator phase power PGS based on the transformer secondary side:

$$P_{GS} = \frac{S_G \cdot \cos(\varphi)}{3 \cdot n_U \cdot n_I} \quad (9)$$

With the permissible generator reverse power PGS, the setting value PR is then calculated as follows:

$$P_R > (\%) = \frac{\dfrac{S_G \cdot \cos(\varphi)}{3 \cdot n_U \cdot n_I}}{Un \cdot In} \cdot P_{RG}(\%) \quad (10)$$

f. Estimation the penetration limits of EG

To attest the experimental results for above illustrated factors IEEE-14 bas have been considered with 4EG's (PVCELLS, MICRO TURBINE, SOFC FUEL CELL AND WIND TURBINE) in each case at selected bus no penetration levels have computed and distribution network characteristics are analyzed. The effect of EG unit capacity [45], [46] can be studied by calculating the penetration level [47]-[48] of EG unit. It can be mathematically represented as the function of total complex power supplied by a EG source over complex power peak load demand.

Penetration level of EG=(Σ SEG/Σ SPEAK)*100%

Prior to implementation of proposed solutions, testing and attest the results to illustrated issues, a quick review in to the analysis of embedded generation units characteristics in both normal and abnormal conditions by measuring the active power (P) and reactive powers (Q) variations at the instant of fault times, experimental results shows all the EG's affects more to LLLG fault times and it is proposed as a severe fault, LLL, LG faults are follows the order. Table 2 shows power variations of EG's during Fault Times

Table 2. Power Variations of EG's during Fault Times

Name of EG	Active power variations (P)			Reactive power variations (Q)		
	LG	LLG	LLLG	LG	LLG	LLLG
SOLAR EG	**1.625**	5.22	9.66	5.96	**3.8**	3.875
WIND TURBINE EG	6.73	**1.21**	1.505	5.06	**3.72**	5.44
SOFC EG	4.325	11.2	**0.95**	5.2	4.96	**2.89**
MICRO TURBINE	**6.25**	8.12	6.89	6.1	4.97	**3.55**

4. RESULTS AND DISCUSSIONS

a. Bidirectional power flow–reverse power relay:-

At the instant 4 EG's are connected to distribution network and LLLG fault incepted at t=0.07 msec, due to transition of DN from radial in to network nature powers in Figure 2 gets reversed as shown in Figure 3, is computed by using Equation [3], [4].

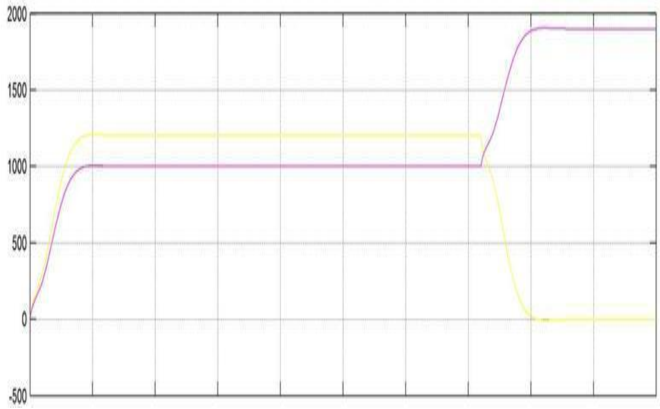

Figure 2. Active power (P) and reactive powers (Q) at Grid with EG

Reverse power relay settings are changed based on the calculated [6] % reversed power to compensate with relay to provide the protection to the DN. At the instant t=0.7 msec LLLG fault is created instantaneously powers (P & Q) gets reversed, which affects the coordination of protective devices.

To recompense the power flow direction which is shown in Figure 3, from the situation of fault affected condition in Figure 4, reverse power relay is used to compensates the reversed power directions and make facilitate the bring back the coordination among existing protective devices incorporated in DN. Compensated active and reactive powers of DN as shown in Figure 4.

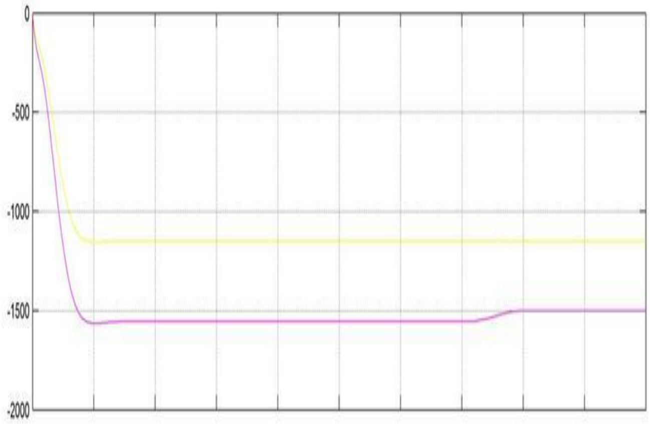

Figure 3. Reversed active power (P) and reactive powers (Q) at Grid caused by the fault

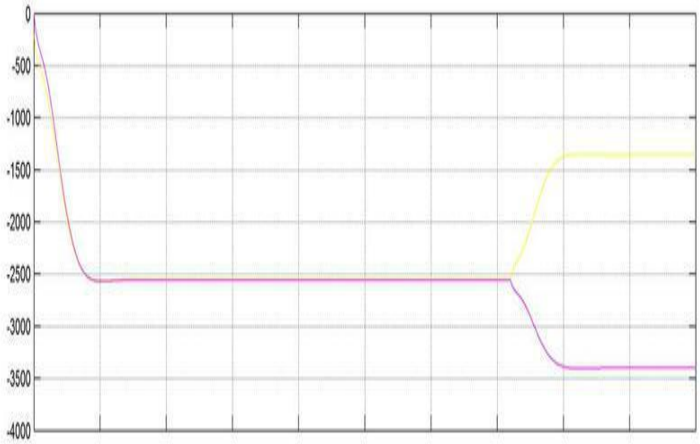

Figure 4. Compensated active power (P) and reactive powers (Q) at Grid

To facilitate the solutions to over voltages and increased fault current, in both EG's integration and fault times' short circuit studies were conducted on distribution networks framed as IEEE-14 bus comprising 4 EG's, LLLG, LLL and LG faults conditions were created using MATLAB Simulink and the effectiveness of installing SFCL to mitigate over voltage and to limit fault current was observed. Voltage profile and fault current in both cases with and without SFCL installed is compared, results are presented in Table 1.

Specifications:

a. (HTG)Generation : W_{ref}=1, P_{ref}=0.7516, V_{ref}=1, V_{stab}=11
b. Synchronous Machine : 2 MVA, 13.8 KV
c. Transformer ($25e^6$ to $6.9e^3$ Volts)
d. Magnetizing resistance and Inductance=500
e. Load (active power=$10e^6$ watts, reactive power $35e^6$ var)
f. PID controller : K_p=1, $K_{i=}$1, K_d=0.5
g. PWM IGBT Inverter
h. EGs: Solar, SOFC, Wind, MICRO turbine

Controllers used for improvement of voltage and powers are PID, FLC and Model reference adaptive controller. At the instant of LLLG fault inception in the DN, virtue of its high severity the currents in Figure 6 and voltages in Figure 5 are affected with high % compared to rest of the short circuit faults.

The consequences of unsymmetrical LLLG faults on EG connected DN is high due to net impedance offered by the EG is gets reduced in the event of LLLG fault this will increase the fault current magnitude, short circuit power factor is very low due to ratio of reactance to resistance is increases, which in turn damage to power equipment's along with protective devices.

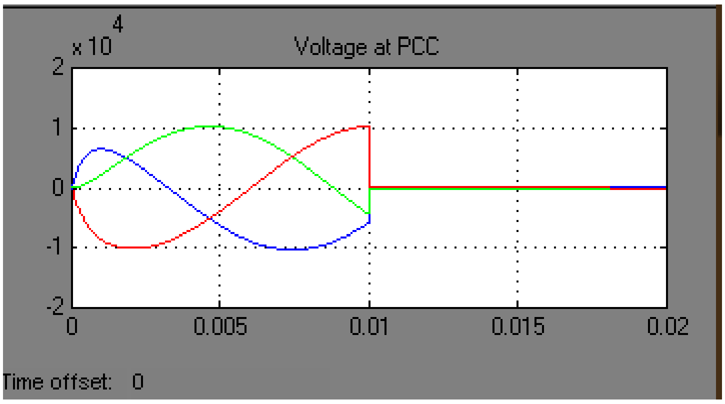

Figure 5. Voltages at PCC during LLLG fault

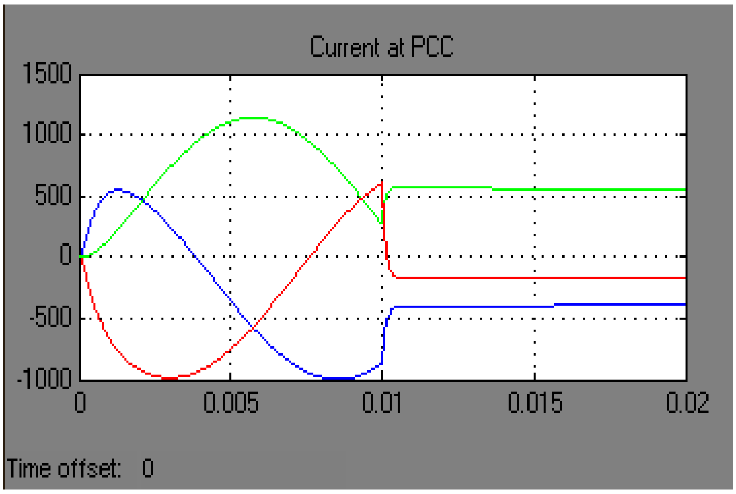

Figure 6. Currents at PCC during LLLG fault

SFCL is reduces the system impact of short circuits by limiting the magnitude of high fault currents Table 3 and it facilitates fast operation limits currents starting with the first cycle peak, introduces no steady state impedance to the grid during non-fault conditions, automatic operation requires no external controls for operation or reset, no replacement parts after fault limiting operation, modular design allows for selection of critical operating parameters. Figure 7 shows voltages at PCC during LLLG fault

Table 3. Comparison of Results

Cases	Over voltages (Volts)	Fault Current (Amps)
Without SFCL	5450	462
With SFCL	4550	361

Analysis: The application of the active SFCL into in a power distribution network with DG units is investigated. For the power frequency overvoltage caused by a fault, the active SFCL can help to reduce the overvoltage's amplitude and avoid damaging the relevant distribution equipment. The active SFCL can as well suppress the short-circuit current induced by a three-phase grounded fault effectively, and the power system's safety and reliability can be improved. Moreover, along with the decrease of the distance between the fault location and the SFCL's installation position, the current-limiting performance will increase. Figure 8 shows currents at PCC during LLLG fault.

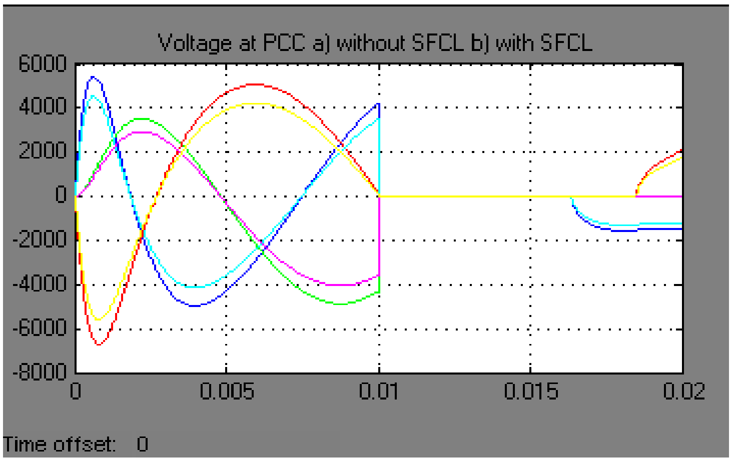

Figure 7. Voltages at PCC during LLLG fault

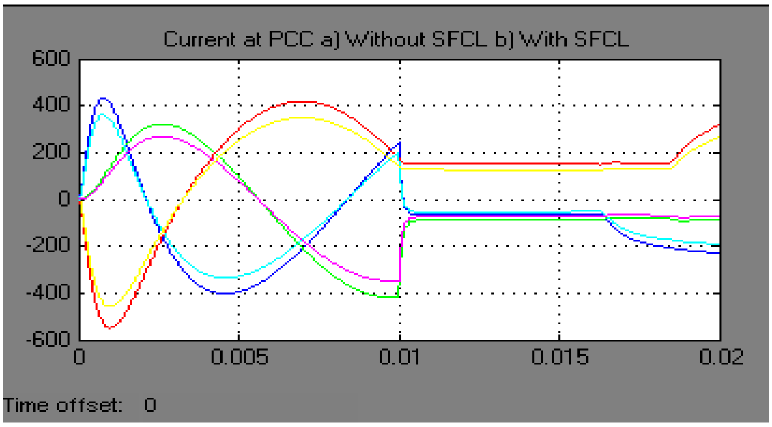

Figure 8. Currents at PCC during LLLG fault

In the event of LLLG fault in distribution network over voltages and fault currents compared with and without Passive resonance CB (PRCB) SFCL are presented and from the comparisons in Table 3 it is clearly shows with PRCB in the circuit the results are proved better. The above short circuit fault analysis is to design switchgears, specifically 3-phase fault current is to design circuit breakers and LG fault current is used to design relay settings.

Passive resonance CB (PRCB) SFCL: To dissipate the energy stress on the MCB, the secondary path with a series L-C circuit is added. When the fault occurred at 0.1 sec, MCB opens with 10 ms of delay considering opening delay, and then an arc forms across the contacts with increasing arc impedance. The DC current begins to commutate and resonate in the secondary path after the arc impedance exceeds the L-C impedance. When a DC current of the primary path meets zero crossing, a current through the MCB can be interrupted by the extinction of the arc. An additional parallel surge arrester (SA) circuit is supplemented to prevent voltage stress across the PRCB during arc extinction.

Specifications: in Table 4 the SFCL rating was 100 kV DC with a 2 kA of critical current. The maximum quenching resistance, Rm, is 10 Ω. P0 is the constant cooling power factor which depends linearly on the blow pressure p.

Table 4. Specifications of SFCL

Parameter	Value
P_o	0.393
p	70 bar
A	0.25
T	15 µsec

b. To determine the breaking capability of MCB by controlling Pc(g).

Inverse current injection CB (I-CB): This scheme is similar to PRCB. However, the pre-charged capacitor via an additional DC power source injects an inverse current into the primary path after the current commutates to secondary path. This can reduce the interruption and oscillation time when compared to that of PRCB. Before a fault, a charging switch (ACB1) and an auxiliary switch (ACB2) maintain closed state. Thereby capacitor can be charged by DC source.

When a fault occurs, after a 10 ms delay, MCB and ACB1 contacts open simultaneously. Then the high discharging inverse current from capacitor is supplied to main path. The fault current in Figure 10 is rapidly decreased and transient recovery voltage appears between the terminals of I-CB. When the voltage exceeds to the knee voltage of SA, it is triggered to restrain the voltage rise in Figure 9, and it absorbs the fault energy.

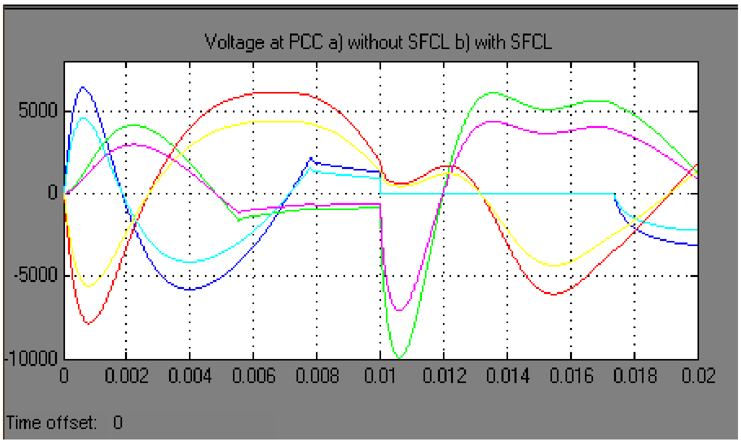

Figure 9. voltages at PCC with and without SFCL during LLLG fault

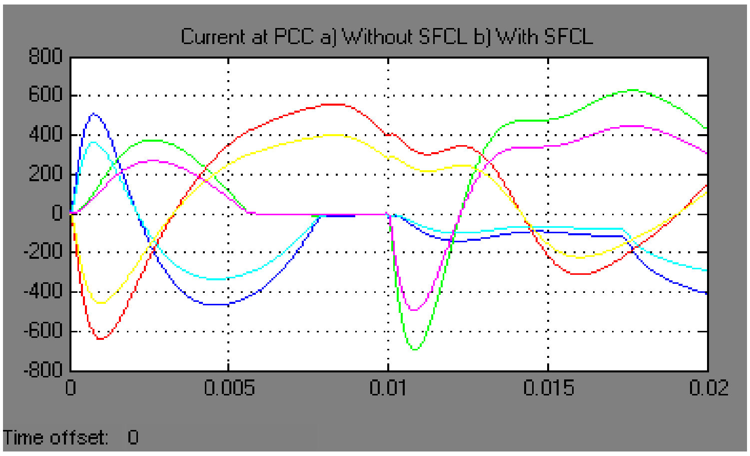

Figure 10. Currents at PCC with and without SFCL during LLLG fault

After 3 ms from the time when MCB and ACB1 were opened, ACB2 is triggered and it isolates the secondary path. This opening of ACB2 will prevent the current to flow through the secondary path which could make additional LC resonance current. Therefore, remaining fault energy is exclusively absorbed by SA. If the current reaches to zero, a residual circuit breaker (RCB) opens and the current interruption is complete. Analysis: when compared to passive resonance CB, Inverse current injection circuit breaker over voltages and fault current peak values in Table 5 are reduced.

Table 5. Comparison of Results of two SFCLs

Cases	Over voltages (Volts)	Fault Current (Amps)
Without SFCL	5450	462
With SFCL (Passive resonance CB)	4550	361
With SFCL (Inverse current injection CB)	4087	325

Finally the penetration levels of distribution network with presence of EG's mathematically represented as the function of total complex power supplied by a EG source over complex power peak load demand.

Penetration level of EG=(Σ SEG/Σ SPEAK)* 100%

5. CONCLUSIONS

The operation and performance of distribution system with presence of embedded generation is considered challenging way in current days scenarios, in this paper the negative impacts due to EG integration in to DN 's are illustrated, how the DN's are degraded by the negative impacts. To mitigate the specified impacts for this in this paper reverse power is computed and reverse power relay is proposed to identify the reverse power in the events of faults, next to mitigate the overvoltage caused by EG integration and inception faults along with the enhanced fault currents SFCL with Passive resonance CB (PRCB) and Inverse current injection CB (I-CB) modes are implemented, results are compared and Inverse current injection CB (I-CB) provides excellent results. Finally the penetrations levels are computed with mathematical formulations are proposed to compute for proper integration levels.

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