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Research article

Comparison of resistive and inductive superconductor fault current limiters in AC and DC micro-grids

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Abstract: Superconducting Fault Current Limiters (SFCL) have been used in power systems for many years, however the best possible positioning of different SFCL still needs a lot of work. Resistive and Inductive are two types of SFCL used in power system. Function of both these current limiters is to control the fluctuations and abnormalities in the system by introducing a high impedance in it, through transforming itself from normal stage to superconducting stage. In this research, placement of resistive SFCL and inductive SFCL in AC and DC microgrids (MG) are analyses at two different positions; at the point of integration of conventional source and distributed generator (DG) and at the point where DG is added to the system. The AC and DC microgrids contains industrial and residential loads, while they use respective main wind power generation source and photo voltaic power source along with conventional power, supplied from main grid. The behavior of both types of SFCL in their grid models is analyzed through MatLab Simulations, in order to compare their effectiveness and determine best possible position to place them.

Keywords: superconducting fault current limiter; AC microgrid; DC microgrid

1. Introduction

Electrical energy utilization has increased to a large amount in past few decades due to economic growth. In annual energy outlook report of the U.S. Energy information administration,

domestic electricity demand is predicted to increase by 24% in 2035 [1]. Along with this a global electricity consumption trend is also reported to be continuously increased [2]. In order to cater this increase of electricity, along-with consideration of economy and stability of system, an interconnection between conventional power plants is established. This puts electric transmission system under tremendous burden of transmitting bulk amount of power and brings it to upper thermal limit. An increase in gap between demand and supply results in even more expansion of generation and supply system. Under these constraints, power supply is becoming more uneconomical in industrialized countries. For these reasons smart grids are proposed which consume power efficiently and use microgrid (MG) technology to utilize renewable energy resources along with conventional resources and increase the reliability of the power system [3]. The MG has the advantage that it may operate with normal interconnection, as well as in islanding mode.

Addition of DG in existing grid may result in an increase in the system fault current. These fault currents may excessively damage the network [4]. Protection against these fault currents is needed to avoid any harm to the system. Conventionally, special protection schemes, using relays and circuit breakers, are applied. However, they can affect the stability of system and increase the cost of extra equipment [5,6]. Furthermore, if fault occurs in any branch of system it may cause a blackout if protective devices are not installed properly. Fault current limiters (FCL) can be used as alternative for the conventional protection devices to reduce the fault current [7]. FCL are helpful in protection of power system by confining first peak of fault current and protect distribution and transmission lines from any stress. Under normal conditions the FCL has low impedance with low voltage drop, thus reducing any fault across it. However, during fault condition, it provides a large impedance in the path of fault current, to reduce it.

Superconductor fault current limiters (SFCL), due to their low voltage drop at normal conditions, can be effective with faster response [8]. Two types of SFCL are commonly used in MG networks i.e. Resistive SFCL (RSFCL) and Inductive SFCL (ISFCL) [9]. RSFCL is simple in design and smaller in size and easy to make but, ISFCL needs low power for cryogenic conditions. Function of both SFLCs is to control the fluctuations and abnormalities from the system by introducing high resistance in it.

Recently, there has been an increase in research on the use of SFCL in the electrical MG [10,11]. In [12] flux-coupling-type of SFCL that coordinates with directional over-current protection and differential protection is suggested for MG protection. The SFCL is applied to enhance the performance of permanent magnet synchronous generator in a wind turbine along with DC MG under fault condition in [13]. In [14], the authors have worked on the comparison of a dynamic voltage restorer (DVR) and the SFCL for low voltage ride-through capability enhancement of a 10-kV MG that has distributed photo-voltaic (PV) power generation, energy storage and loads. It was deducted that the DVR are less economical than the SFCL. In [15] the authors analyzed the effect of the RSFCL on an isolated MG with dynamic load and found that they effectively reduce the fault current and use fast response to improve its transient stability. Conventional protection devices have delay in response time which allow more than two cycles to pass through it before it get activated, however, SFCL has less response time. The MG stability improvement under fault current is also achieved, in [16], by using of SFCL and superconducting magnetic energy storage (SMES), together, through wireless network communications.

One of the contemporary topics is the analysis of efficient positioning of SFCL in a microgrid [17–19]. Through simulation studies the strategies for effective placement of SFCLs in

MG is discussed along with the transient analysis for the response of system to the faults. In [20] the authors have proposed best possible placement of SFCL at the point of integration of generating sources, for both distribution and consumption grid faults in a smart grid application. The behavior of resistive SFCL in term of temperature is used to re-model it and its performance is analyzed for appropriate location in a smart grid in [21]. In [22] the authors have proposed minimum number of SFCL for best possible locations in smart grid. To the best of authors knowledge, most of the work on fault current reduction in MG is achieved by using resistive type of SFCL. Furthermore, RSFCL is used in AC microgrid with AC and DC power source, while final power supplied to the consumers, in same network, is AC. However, comparison of RSFCL and ISFL used in a MG, especially in case of DC MG is not done.

In this paper, we have analyzed the effect of the use of SFCL in the AC and DC microgrids. Both resistive and inductive SFCLs are used for this purpose. Furthermore, the best possible position of both RSFCL and ISFCL in AC and DC MG applications, is also evaluated. We have analyzed them by using at the point of integration and at the point of DG sources which are connected with the main grid. In most of the real world MGs, only one of distribution generations i.e. either DC generation, through PV cell, or AC generation, through wind power plant, is used, along with the conventional grid. Therefore, in this research we have separately analyzed the cases of AC and DC MG for the use of SFCL. The AC and DC MG contain industrial load and residential loads which are studied through simulation work. As a result of our research in the paper we have suggested the appropriate type of SFCL which can be used in both the AC and DC MGs along-with the suitable location for their placement in the system for efficient fault current limitations.

The paper is further organized as follows; the details and specifications of AC and DC microgrids used in this research work paper and their MatLab simulations are given in the section 2. Both the MG's are separately modeled. The MatLab simulation model of the resistive and the inductive superconductor fault current limiter are also discussed in this section. The analysis for the best possible position of SFCLs in each MG along with the comparison of their effectiveness in current limiting during the occurrence of fault is given in the section 3. At the end in the section 4 further discussions about the results, suggestion for SFCL usage and possible future work is given.

2. Materials and methods

In this paper the AC and DC MGs are simulated in MatLab environment. Each of the MGs is simulated separately. Furthermore, in order to analyze the effective performance of each SFCL. The RSFCL and ISFCL are also modeled in simulation.

2.1. Microgrids

A microgrid is a group of AC or DC electric power sources operating locally, near the consumers. They may be connected to conventional power grid. However, they may be separated from it by using islanding mode. In this paper we are discussing both MG's, where the conventional power is continuously supplied to the load.

2.1.1. AC microgrids

The grid of renewable sources that produce AC power as output, such as wind power plant, which are added in existing power system, is called AC microgrid. The AC MG model used in this research is shown in Figure 1. In this MG two power sources are used; one of them is a conventional AC power plant of capacity 1000 MW and the other is a wind power plant with power capacity of 9 MW. For simulation purposes, are used just. The system provides power to industrial consumers at a voltage of 25 KV and domestic load, operating at the voltages of 400 V.
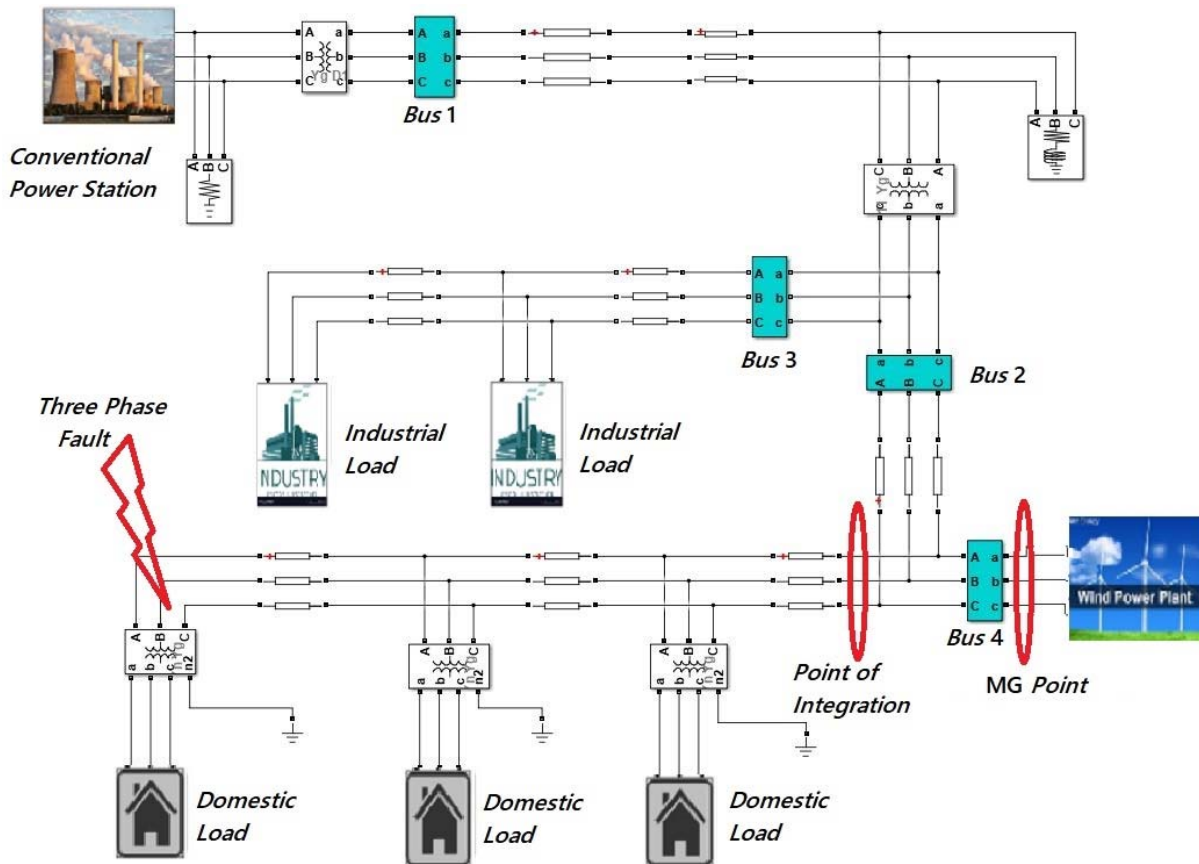

Figure 1. AC microgrid with conventional power source and distributed generation (wind power source).

Conventional power plant produces 1000 MW power at a voltage of 315 KV which is then step down to 154 KV through step down $Y - \Delta$ transformer. A 100 MW reactive load has also been attached to reduce the harmonics coming from the synchronous machine. Power, after stepping down to 154 KV, is being transported through 200 Km transmission line. A 330 MVAR reactive loads has been connected to the system for removing third harmonics and for the filtration of the MG. The 154 KV power is then stepped down to 25 KV to provide power to the two industrial consumers each of 6 MW ratings. Then, a 9 MW wind power source is connected to the 25 KV transmission line. The point of connection of wind power source, with the transmission line, is called as integration point, which is connected to three domestic power consumers (DPC), each having a power rating of 1 MW.

The integration point is at the distance of 5 Km from the first domestic power consumers (DPC). Each DPC is at also a distance of 5 Km from the neighboring consumer. Power from 25 KV bus bar line is provided to DPC after stepping down the voltage to 400 V. Voltages and current measuring blocks, in the system, are used at Bus1, Bus2, Bus3 and Bus4. Bus4 block is installed in the way of power from the wind power plant for the measurement of abnormalities created, on the MG, as a result of integration of two sources. The description and parameters of AC MG is given in Table 1.
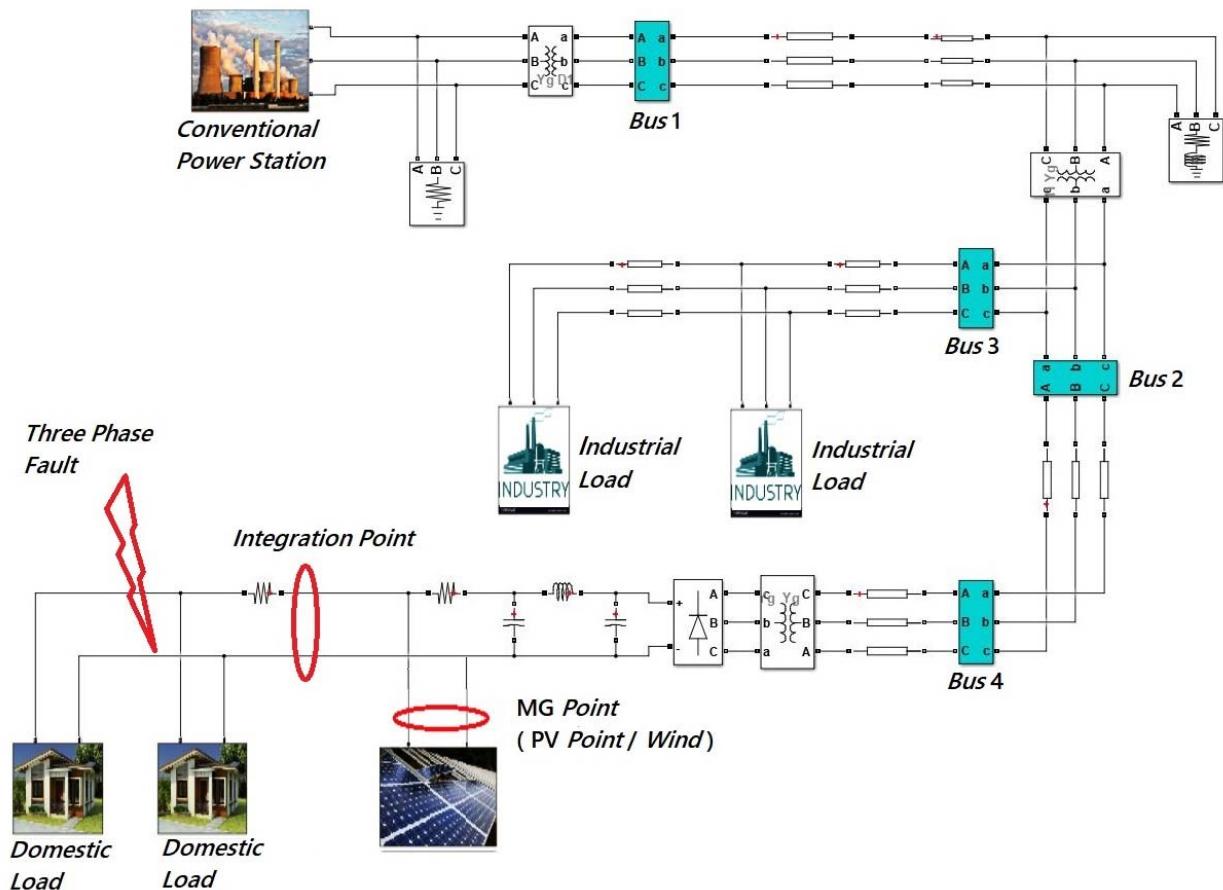

Figure 2. DC microgrid with conventional power source and distributed generation (photo-voltic source).

2.1.2. DC microgrids

A DC microgrid maintains a DC bus, which feeds DC loads connected to it, sometimes DC is converted into AC to supply AC loads. The grid of renewable sources which produce DC power as output are included in AC power source, such as PV sources. Normally renewable DC power source i.e. PV source are used as DG to reduce the number of AC to DC converters however the supply from the conventional source is converted to DC through inverters. The DC MG used in the research as shown in Figure 2. In DC MG, similar to an AC MG, there is a conventional power plant of capacity 1000 MW, suppling power to two 6 MW industrial consumers and three domestic power consumers, each having a rating of 1 MW. A 400 KW PV source at the consumers grid side is used which is installed near the load center in order to reduce the line losses through transmission lines losses.

Before connection of conventional power to the grid with the PV source power, in order to supply power to domestic load, its power is converted from AC to DC power. Therefore, the distribution of power is of DC type where, at each domestic consumer, it is converted into AC using an inverter. The description and parameters of DC MG is given in Table 1.

Table 1. Characteristic of AC and DC microgrid.

Parameters	AC Microgrid	DC Microgrid
Conventional Power	1000 MW	1000 MW
DG Power Source	Wind Power Plant	PV Power Source
DG Power Rating	9 MW	400 KW
No of Industrial Load	2	2
Ratings of Industrial Loads	5 MW	6 MW
Distance between Industrial Loads	5 Km	5 Km
No of Domestic Load	3	3
Rating of Domestic Load	1 MW	1 MW
Distance between Domestic Loads	5 Km	5 Km

2.2. SFCL model

A Fault Current Limiter (FCL) reduce fault current in case of occurrence of fault in power system. They show zero impedance during normal system operation and add a large resistance to reduce the fault current when fault occur in the system. They should have a fast response and normally operate within the first cycle of the fault current. It should have short time recovery and automatically goes back to normal state within short time. It should operate and return back to its normal state automatically. For a symmetrical three-phase fault, in order to reduce the fault, current the impedance Z_{FCL} can be given as:

$$Z_{FCL} = \frac{V_{ph}}{I_{fc}} - Z_s \tag{1}$$

where V_{ph} is phase voltage, I_{fc} is fault current and Z_s is impedance of system under fault.

A superconducting fault current limiter (SFCL) is one of most common FCL used these days. SFCL are effective current limiters, since they have low voltage drop, across them, at normal conditions. They also have quick response, during fault conditions. SFCL are used in distribution and transmission system either in AC and DC microgrid to make the system efficient and reliable with economically feasible for producers and consumers. Superconducting fault current limiters should normally operate at superconducting stage and there is no voltage drop across it. It works as an impedance during fault mitigation. It has automatic triggering, and it should quench in resistive stage automatically without any manual switching or sensors. When the fault is removed it would go back to superconducting stage again. The response of superconductor is very fast, and it also has very small recovery period. It would prevent any loss of energy and prevent any increase the temperature of cryogenics. Apart from all of these ideal SFCL should not affect the entire integrated power systems and promising in giving the excellent progress about trustworthiness.

Resistive and Inductive SFCL are used in this work to analyze and compare for suitable positioning them in AC and DC MGs at the point where they give best response. In Figure 3

schematic diagrams are given for both Resistive and Inductive SFCL. RSFCL, shown in Figure 3 a) is the simplest type of super conductor fault current limiter. It is smaller as compared to other types of SFCLs of same ratting. It has a resistor parallel to it to prevent any overvoltage. During normal conditions all the current passes through the RSFCL and in case of fault when the current exceeds through it above some critical value its resistance increases, thus limiting the current. On the other hand, saturated core SFCL, shown in Figure 3 b), consist of two iron cores, along with a DC bias coil, is used as example for ISFCL in this research work.
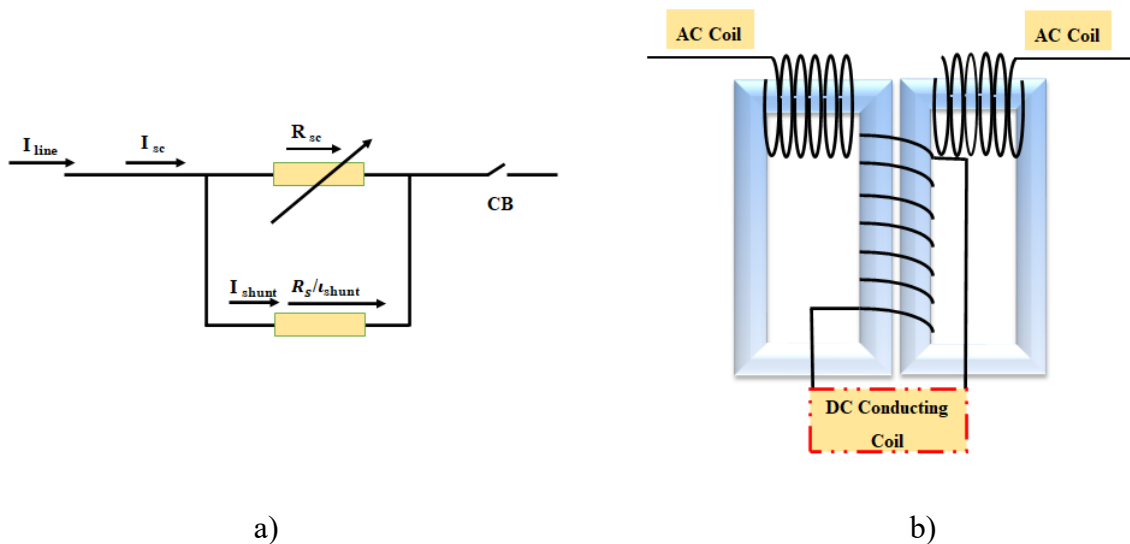

a)   b)

Figure 3. Schematic diagram of SFCL: a) RSFCL, b) ISFCL diagram.

The mathematical model of the RSFCL is given as [23]:

$$R(t) = \begin{cases} 0 & t < t_o \\ R_n \left[1 - exp^{\left(-\frac{t-t_o}{\tau}\right)}\right]^{\frac{1}{2}} & t_o \leq t < t_1 \\ & t_1 \leq t < t_2 \\ a_1(t - t_1) + b_1 & t_2 \leq t < t_3 \\ a_2(t - t_2) + b_2 & t > t_3 \\ 0 & \end{cases} \tag{2}$$

where, $R(t)$ is the instantaneous resistance of RSFCL. R_n is saturated impedance at normal temperature and τ is the time constant. While t_o is time to start quenching the fault current, t_1 is staring time of first recovery time period and t_2 is the starting period of second recovery time. Second recovery period is steeper than the first recovery period.

In Figure 4 single phase simulink models of AC RSFCL, designed by considering six fundamental parameters [17,23], is shown. The AC RSFCL model contains current measurement block, RMS, characteristic table, controlled voltage source and first order harmonic filter. The current is measured, then its RMS value is passed through a characteristic table or comparison. If the current exceeds the set-point, the resistance of SFCL's increases to some given level in a response time, already adjusted to the system. The DC RSFCL can be modeled by removing RMS block (blue) and the harmonic filter block (blue) from AC RSFCL model. The characteristics of AC/DC RSFCL is given in Table 2.

Table 2. Characteristic table of AC/DC RSFCL.

Parameters	AC RSFCL	DC RSFCL
Triggering current	550 A	900 A
Maximum resistance	90 Ω	50 Ω
Minimum resistance	0.01 Ω	0.01 Ω
Quenching time	2 ms	2 ms
Recovering time	10 ms	10 ms
Operating voltage	25 KV	0.5 KV
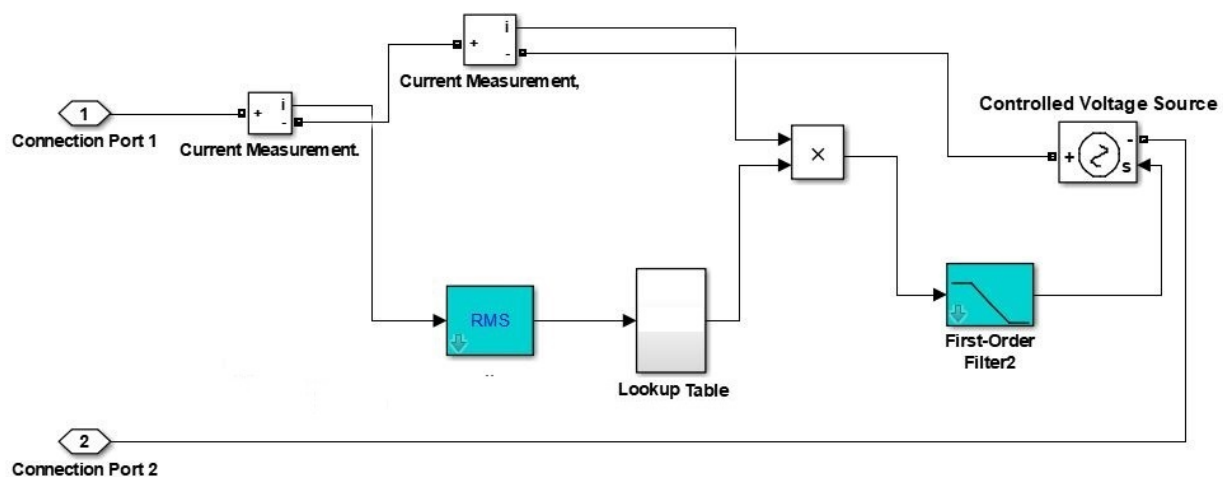
Figure 4. RSFCL simulink model [18].

In Figure 5, single phase Simulink models of AC ISFCL is given. The ISFCL is applied by using the characteristic of voltage drop in the saturated core ISFCL [24]. The saturated cores ISFCL uses a super conducting coil with highly saturated iron cores. This can be attained by a DC current that passed through a high temperature superconducting (HTS) coil to keep two iron cores saturated (for a single phase configuration). In case of occurrences of fault the current increase from normal value, the inductance of SFCL suddenly increases, and limit the current through an inductive voltage drop. The cores of the limiter changes between saturated and unsaturated states, in such condition. The electromagnetic behavior of ISFCL is found on the basis of line current i_{line} and linked flux ψ_{ISFCL} in order to determine the voltage drop given as [25]:

$$V_{ISFCL}(t) = \frac{d\psi_{ISFCL}(t)}{dt} = \frac{d\psi_{ISFCL}(t)}{di_{line}(t)} \cdot \frac{di_{line}(t)}{dt} \qquad (3)$$

Table 3. Characteristic table of AC/DC ISFCL.

Parameters	AC RSFCL	DC RSFCL
Triggering current	550 A	900 A
SFCL resistance	0.4 Ω	0.4 Ω
Operating voltage	25 KV	55 V

The ISFCL Simulink model contains current and voltage measurement units, RMS block, characteristic table and controlled current source. The product of measured line current and SFCL resistance is compared with measured voltage to get voltage drop. The voltage drop is used to get flux linkage and compared to characteristic table which generate controlled current for the system. The DC ISFCL can be modeled by eliminating RMS block (blue) from AC ISFCL model. The characteristics of AC/DC ISFCL is given in Table 3.
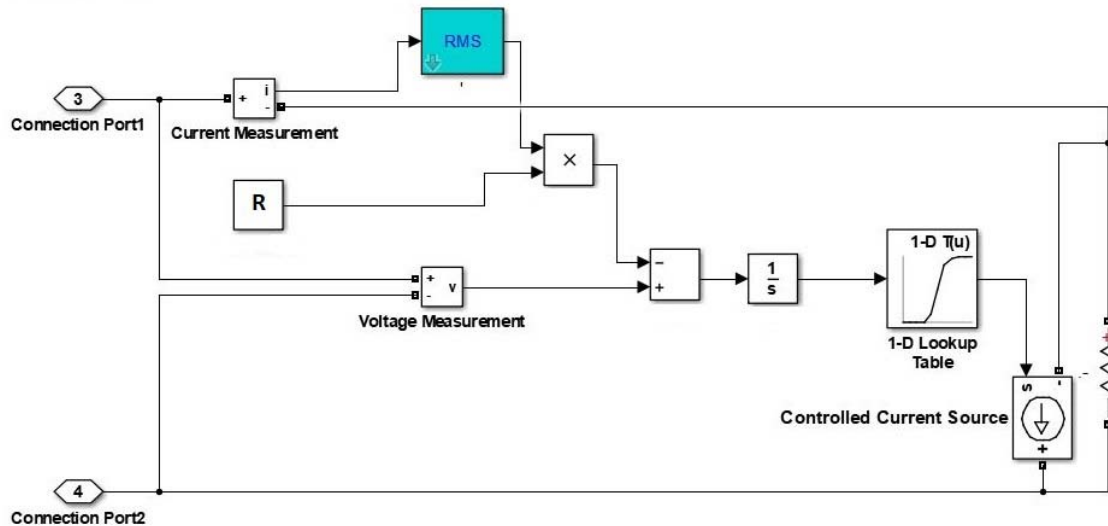

Figure 5. ISFCL simulink model [25].

3. Results

In this section resistive and inductive SFCLs are used on AC and DC MGs of section 2, to get suitable position for their placement. The fault is introduced at the domestic user's side and all the results for faults are taken at Bus4 so that the effect of usage of SFCL on MG can be analyzed. Firstly, the comparative analysis between RSFCL and ISFCL on AC MG is studied at the point of integration of two sources and at the wind power source. A fault is initialized at time instant 0.25 s, in the network.

In Figure 6 a) the results at the point of integration of two sources with RSFCL, ISFCL and without any SFCL is shown. It can be seen that RSFCL gives better results as compare to ISFCL or in configuration where SFCL is not used. Peak fault current of 1000 A flow through the network if no SFCL is used. If the ISFCL is used the fault current reduces to 550 A and for RSFCL it becomes almost equal to the normal current. In case of use of SFCL at wind power source, as shown in Figure 6 b), RSFCL gives better result. In Figure 6 c) the fault current for RSFCL for both the positions is compared and it can be observed that RSFCL is more effective if used at the point of integration of two sources. In Figure 6 d) it can be observed that fault current reduces to equal amount if ISFCL is used at the point of integration of two sources or at the wind power source. From the Figure 6 it can be observed that the RSFCL at the point of integration is most effective to be used for fault current limitation. Therefore, in AC MG system the best place to minimize the fault current is integration point and with RSFCL.
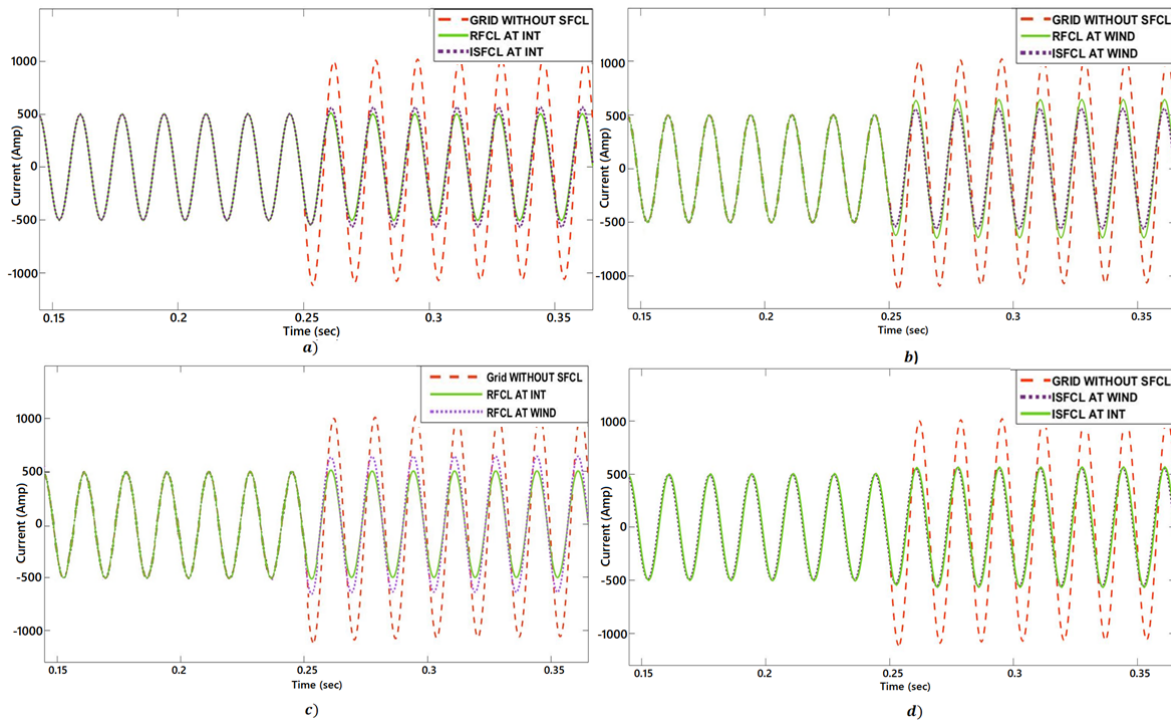
Figure 6. Effect of SFCL on AC microgrid; a) RSFCL and ISFCL at point of integration, b) RSFCL and ISFCL at wind power plant, c) RSFCL at integration point and wind power plant, d) ISFCL at integration point and wind power plant.

Figure 7. Effect of SFCL on DC microgrid; a) RSFCL and ISFCL at point of integration, b) RSFCL and ISFCL at wind power plant, c) RSFCL at integration point and wind power plant, d) ISFCL at integration point and wind power plant.
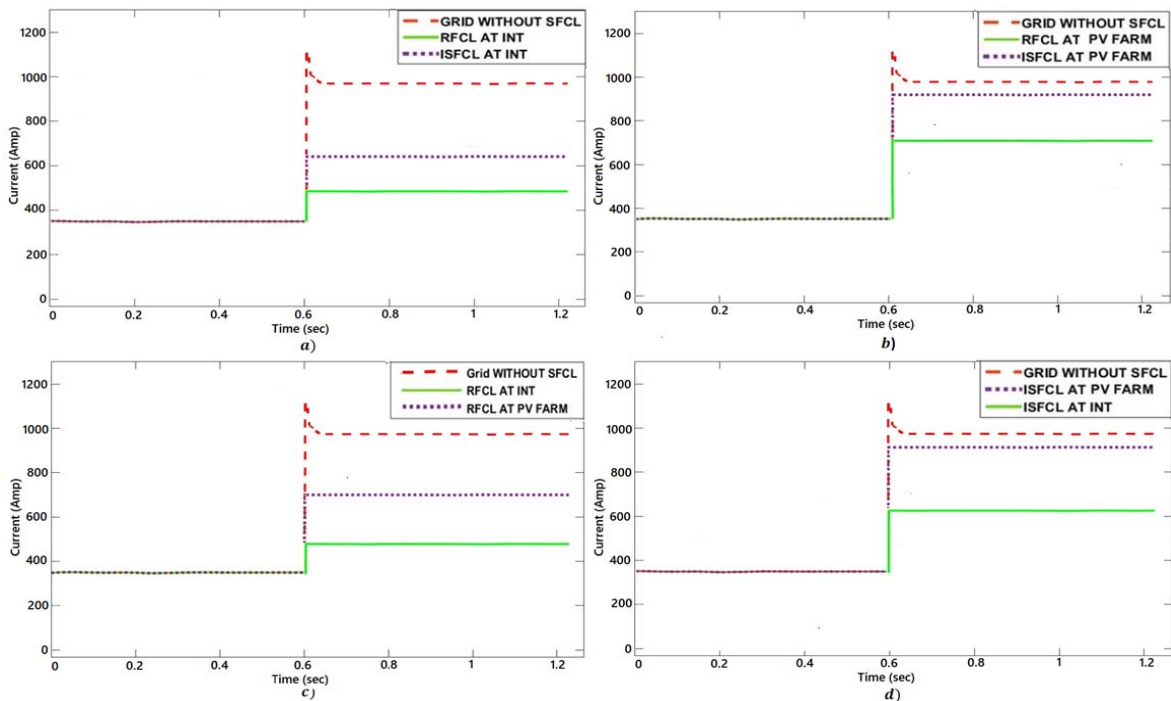
In Figure 7 we have given the results of DC MG fault current limitation with application of RSFCL and ISFCL and without use of any SFCL at the point of integration and at PV source. The power system of Figure 2 is used where power is distributed as DC. The effectiveness of SFCL is identified by initializing a fault on the domestic consumer side at the time instant 0.25 s of the simulation. In Figure 7 a) it can be observed that, after initializing a fault the RSFCL perform better than the ISFCL, at the point of integration between two sources. Similarly, at point of PV source RSFCL perform better than the ISFCL as shown in Figure 7 b). From Figure 7 c) and d) it can be observed that both RSFCL and ISFCL perform better at the point of integration. In Figure 7 c), the fault current for RSFCL for both the positions is compared. It can be seen that RSFCL is more effective if used at the point of integration of two sources. In Figure 7 d) it can be observed that fault current reduction is better for ISFCL if it is used at the point of integration of two sources.

The comparison of improvement in fault current for both the RSFCL and ISFCL is shown in Table 4. It can be deducted that the RSFCL gives batter results both in case of AC MG and DC MG as compared to the ISFCL. The RSFCL limits the fault current about 9% more than the ISFCL at the point of integration, in AC MG. On the other side for DC MG, RSFCL is 23% better than ISFCL, at the point of integration. Although, both SFCLs perform better at the point of DG source it can be observed that the positioning of SFCL at the point of integration is better. Furthermore, through all the results of Figures 6 and 7, it can be observed that both the RSFCL and ISFCL have fast response and reduce the fault current within first cycle after the time the fault occurs.

Table 4. Reduction in fault current when RSFCL and ISFCL are used in AC and DC micro-grids.

Grid	SFCL	Location	I-fault (max)	I-Improved (max)	Improvement
	Inductive	Integration Point		551 A	89.96%
AC Microgrid	Resistive	Integration Point	1026 A	504 A	98.86%
	Inductive	Wind Farm		548 A	90.53%
	Resistive	Wind Farm		680 A	65.53%
	Inductive	Integration Point		621 A	65.42%
DC Microgrid	Resistive	Integration Point	1115 A	445 A	88.74%
	Inductive	PV Farm		621 A	27.17%
	Resistive	PV Farm		702 A	54.70%

4. Conclusions

In this paper we have compared and analyzed the best position for different types of SFCL in AC and DC microgrids integrated with conventional power source. From the results of section 3 it can be concluded that the best position to control the fault current surges is the point of integration of conventional power supply and the distributed power generator. This is due to the reason that at integration point SFCLs can control the fault current coming from all sides. On the other side if it is connected at distributed generation source it can only control the fault current from DGs source and creating a negative effect on the system. This would allow the fault current to flow through the system coming from other generating sources. It can be observed that both the RSFCL and ISFCL have fast response and reduce the fault current within first cycle after the time the fault occurs. In the future the experiments on the SFCL will be conducted to get real time results.

Conflict of interest

The authors declare no conflict of interest.

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