# Bidirectional Non-Superconducting Fault Current Limiter (BNSFCL) for Smart Grid Applications

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**Fault current limiters (FCLs) are proposed widely in literature for improving different characteristics of electric power system. Solving protection problems in smart distribution networks in presence of distributed generation (DG) is an example for the applications of FCLs discussed in recent papers. Voltage sag during faults is a power quality (PQ) concern in the power system. In this paper, it is shown that in smart distribution networks including microgrids, FCL can effectively alleviate this problem, according to the fault location. Therefore, a bidirectional non-superconducting fault current limiter (BNSFCL) is presented in this research, so that the bidirectional fault suppression has become available. Analytical analysis and simulations are provided to validate the effectiveness of the BNSFCL topology. Results show that by using proposed structure in distribution networks with microgrids, both protection and PQ status are enhanced, i.e. the BNSFCL prevents deep voltage sag and protection mis-coordination. The proposed topology can be applied in smart grid architecture _where the bidirectional current flow has made conventional protection schemes useless_ effectively and can have acceptance for implementation as one of the future power system components.**

***Keywords:*** *Bidirectional non-superconducting fault current limiter (BNSFCL), Microgrid, Power quality (PQ), Voltage sag*

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## Nomenclature

| | |
|---|---|
| $V_{PCC}$ | Voltage of point of common coupling |
| $V_G$ | Generated voltage of power plant |
| $V_{DG}$ | Generated voltage of DG unit |
| $R_d$ | Resistance of the copper-coil magnet |
| $L_d$ | Inductance of the copper-coil magnet |
| $Z_{L1}$ , $Z_{L2}$ , $Z_{L3}$ | The equivalent impedance for loads 1to3 |
| $Z_{T1}$ , $Z_{T2}$ , $Z_{T3}$ | Short-circuit impedance of transformer |
| $Z_F$ | Fault impedance |
| $Z_Q$ , $Z_G$ | Equivalent impedance |
| $Z_{DG}$ | Impedance of DG unit |
| $Z_{Line}$ | Transmission Line impedance |
| $Z_{BNSFCL}$ | Impedance of FCL structure |
| $I_{mU}$ | Maximum permissible current for upstream |
| $I_{mD}$ | Maximum permissible current for microgrid |
| $I_{up}$ | Measured upstream current |
| $I_{down}$ | Measured microgrid current |

## 1. Introduction

Distribution networks supply the electricity based on strict power quality (PQ) standards. While power reliability (PR) concentrates on blackouts, PQ explains other characteristics of delivered energy that directly affects the operation of grid utilities and consumers. Transients, voltage imbalances and harmonic distortion are regarded as examples of such characteristics. PQ study is the measurement, analysis and improvement of bus voltage to keep it in a sine state with nominal voltage and frequency. Other definition describes PQ as ways to avoid any change in voltage and frequency or in current that leads to a deficiency or mal-operation in utilities [1].

Most of the end users in the smart grid architecture are not connected to high voltage (HV) network directly. On the contrary, they face to a secondary low voltage (LV) distribution network called microgrid. A microgrid is a LV network including loads and several distributed generation (DG) units connected to it [2 and 3]. The main disadvantage of DG is producing fault current that are more than the breaking capacity of circuit breakers (CBs) and fuses. Furthermore, the fault current produced by DG unit are also causing problems in protection coordination and relay mal-operation that must be suppressed efficiently. Each microgrid may contain one or some critical loads that are sensitive to the characteristics of delivered power, thus PQ at the sensitive load bus (SLB) in a microgrid is regarded as an important concern and the voltage quality of DG terminal must be enhanced. Voltage sag is one of the PQ top concerns in a grid. There are several reasons that lead to a voltage sag. Short circuit occurrence is one of the main reasons that cause voltage sag in the point of common coupling (PCC). In this case, electricity grid faces to an increment in current rate. During fault, the voltage sag is proportional to short-circuit current. Therefore, fault current limitation will cause voltage sag compensation. PCC is known as one of the hotspots in distribution network. As discussed, a fault in the microgrid leads to the sharp current increment and thus deep voltage sag at PCC.

One way to improve both the efficiency and PQ of the distribution network is automatic voltage control (AVC). AVC is monitoring voltage levels within the LV network intelligently to maintain the voltage level within preset limits by adjusting the control factors. Controllable FCL can be used as one of the AVC devices. FCL technology improves grid smartness. In many papers, implementation of fault current limiter (FCL) is described as a PQ enhancement method [4 and 5]. In [6], a solid-state fault current limiter named TBSSFCL is proposed for radial distribution networks, but has limited application and bulk structure. A bridge type solid-state fault current limiter (BSSFCL) is presented in [7] which is based on a series reactor, but has low efficiency due to the high conduction loss of the switching components. In [8], a non-superconducting fault current limiter (NSFCL) is discussed, but has complicated design considerations and controller scheme. A multilevel non-superconducting FCL is presented in [9], but high number of components increases its weight and volume and it is not an economic choice for low and medium power applications. In [10], a new structure for FCL, based on the system impedance named IBFCL is proposed that has a complicated control strategy. A capacitor based FCL (CBFCL) is presented in [11] which is rather a complicated device with too many components. Besides the fact that FCLs play a critical role in reducing short circuit currents, they also help coordination of relays that is comprehensively studied in [12]. A new NSFCL is proposed in [13] which is applicable for a wide range of fault currents, but has too many components and is not suitable for bidirectional fault suppression. In [14], authors present a bridge-type FCL for energy management in AC/DC microgrids. Besides its relatively simple structure, bidirectional fault current limitation is not possible which might lead to some protection problems.

In this paper effect of FCL on PQ during a fault condition is studied. FCL proposed here is a bidirectional non-superconducting fault current limiter (BNSFCL) as an interface between main grid and the microgrid. Considering a fault in microgrid or main grid, it is shown that using BNSFCL not only helps to reduce fault current optimally, but also enhances PCC voltage profile and protection coordination status. Rest of the paper is organized as follows: Proposed BNSFCL topology and its control strategy are discussed in section 2. A brief comparison study with other FCL topologies is conducted and the results are presented in section 3. Detailed voltage sag analysis in the sample power system is presented in section 4. In section 5, protection coordination in sample power system is studied and finally in section 6, simulation results are given to validate the study.

## 2. BNSFCL Topology and Analysis

FCL topologies are either bidirectional or unidirectional depending on their current limiting direction. In the case study presented in this paper, a bidirectional structure for FCL is implemented i.e. in the case of a short-circuit fault in microgrid or main grid, FCL actively suppresses fault current amplitude. Besides, due to the bidirectional current flow between interconnected microgrids and the upstream network, conventional protection methods _which are only capable of the unidirectional protection_ will not be effective. Using superconducting fault current limiters (SFCLs) is regarded as a good way to control fault currents because of their low losses during normal operation, but SFCL technology is not mature enough and it is available with high costs. Using a non-superconducting coil instead of a superconducting one makes the structure simpler and cheaper. Power loss of non-superconducting coil is negligible and it is capable enough. Combination of these theories leads to the topology introduced in this paper, BNSFCL which is shown in Fig.1.

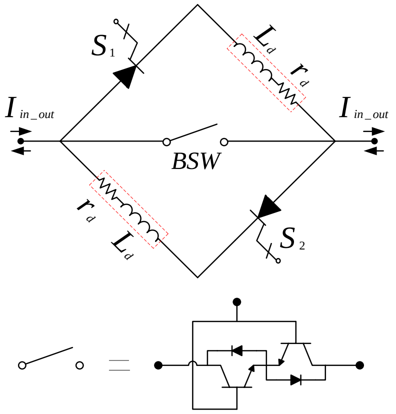


**Fig. 1.** Proposed BNSFCL circuit

The circuit is simple and is composed of three main components that are described as follows:

- A bidirectional semiconductor power switch that is composed of two high power IGBTs and their diodes.
- Two non-superconductor (copper coil) magnets that are modeled by a resistor and an inductor.
- Because of the ability of GTOs to work properly with high current and voltage ratings, two GTOs are used in fault current limitation paths in series with two dc reactors.

Most of the previously introduced structures for this application have too many components with complicated control strategies. This new topology with its simple circuit provides a more capable control strategy in comparison with the previous structures.

### 2.1. Operation principles

This structure is installed between the main grid and microgrid and limits the contribution of the microgrid during a fault in upstream or vice versa. Different modes of BNSFCL operation are presented in Fig. 2. An advantage that can be mentioned for the BNSFCL is its normal operation mode (Fig. 2c). In this mode, only a negligible voltage drop on the bidirectional switch exists, but in previous topologies in literature, current limiting inductance is always in the current path that leads to efficiency reduction of FCL due to high losses. In case of fault in main grid inserting an additional FCL in the DG's feeder will help the BNSFCL to complete its duties and in case of fault in microgrid, the conventional FCL – like the one introduced in [15] – limits excessive fault current contribution of the new installed DG unit and does not lead to a considerable voltage sag at PCC.

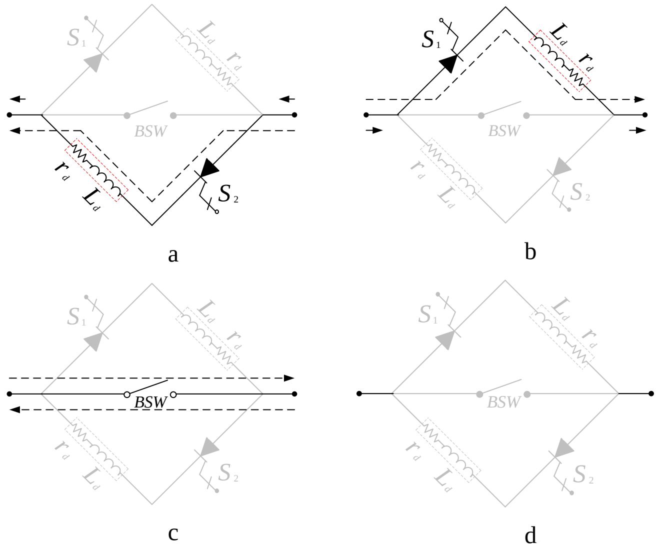


**Fig. 2.** BNSFCL operation modes a: fault in microgrid, b: fault in upstream, c: normal operation (no fault) d: fault in upstream and microgrid at the same time

### 2.2. Control strategy

Based on the operation principle of the BNSFCL, the proposed control strategy flowchart is presented in Fig.3a. First, data from upstream and downstream current sensors are given to the control unit. When the fault detected by comparing the sample current with maximum permissible current limit, pulses are generated and sent to the proper switches. Simple diagram of control unit composed of logic circuits is shown in Fig.3b.

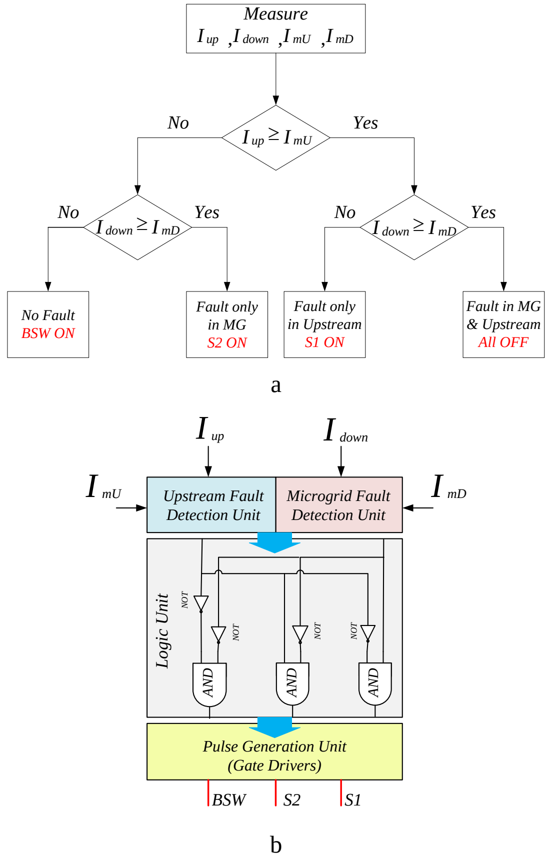


**Fig. 3.** a: control flowchart b: controller diagram

### 2.3. Efficiency study

BNSFCL is an additional component that is added to the smart grid to improve its functionality during faulty conditions, but as any power electronics interface, the proposed BNSFCL causes power loss that reduces overall efficiency of power grid. The loss of BNSFCL topology can be neglected due to its beneficial function. There are two major factors that are responsible for losses:

- Conduction loss of semiconductor components
- Loss of the current limiting copper coil

Switching loss is not considered due to the low switching frequency. $I$ is the current that passes through the topology. When the BNSFCL is active, i.e. it is limiting the current flow from the upstream to the microgrid or vice versa, the voltage drop across the current path is as follows:

$$V_{drop\ 1} = r_{s1\ or\ s2} I + Z_d I \qquad (1)$$

Where $r_{s1\ or\ s2}$ is the internal resistance of switches $S_1$ or $S_2$ and $Z_d$ is the equivalent impedance of copper coil. During no fault condition, a bidirectional switch is active in the BNSFCL topology which causes a drop in this mode as follows:

$$V_{drop\ 2} = r_{IGBT1\ or\ IGBT2} I + V_{D1\ or\ D2} \qquad (2)$$

Where $r_{IGBT1\ or\ IGBT2}$ and $V_{D1\ or\ D2}$ are the internal resistance of one of the IGBTs in BSW and voltage drop through the diodes of BSW, respectively.

Considering $P_{out}$ as the power at the output terminal of topology, the efficiency of BNSFCL topology in different modes can be presented as following equations:

$$\eta_{faulty} = \frac{P_{out}}{P_{out} + V_{drop1} I} \qquad (3)$$

$$\eta_{no\ fault} = \frac{P_{out}}{P_{out} + V_{drop2} I} \qquad (4)$$

### 3. Comparison Study

Various FCL topologies are discussed in literature including superconducting and non-superconducting structures [6-11]. Although these FCLs are introduced to improve different characteristics of power systems, all of them pursue one aim which is to minimize the negative effects of fault on power system components. In this section, a brief comparison between the BNSFCL and other FCL types discussed in the introduction is presented. Number of components, modularity, bidirectional functionality and multilevel capability are the factors considered in this study. Considering single-phase type for all topologies, results are presented in Table 1.

**Table 1.** Comparison of FCL topologies

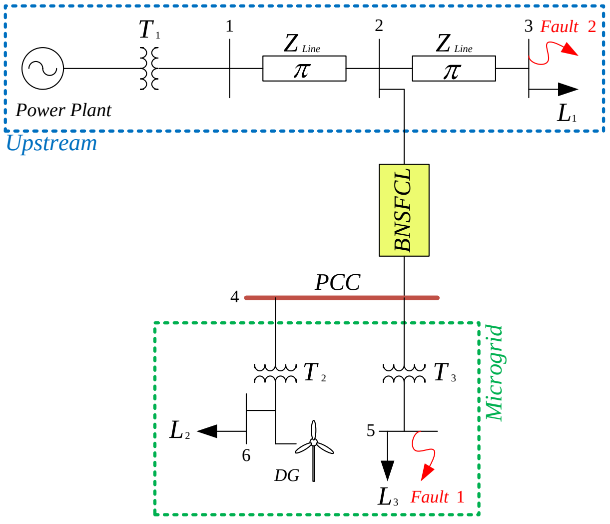
| Topology | Diodes | Power Switch | Copper Coil | Resistance | Transformer | Modularity | Bidirectional Function | Others |
|---|---|---|---|---|---|---|---|---|
| Proposed | 2 | 4 | 2 | × | × | ✓ | ✓ | Multilevel Capability |
| [6] | 0 | 2 | 1 | × | 1 | × | ✓ | - |
| [7] | 2 | 4 | 1 | × | × | × | × | - |
| [8] | 6 | 1 | 1 | 1 | 1 | × | × | - |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| [9] | 8 | 4 | 1 | 4 | 2 | × | × | Multilevel Capability |
| [10] | 0 | 5 | 0 | 4 | × | × | × | Multilevel Capability |
| [11] | 4 | 4 | 1 | 1 | 1 | × | × | 1 capacitor & 1 dc bus |

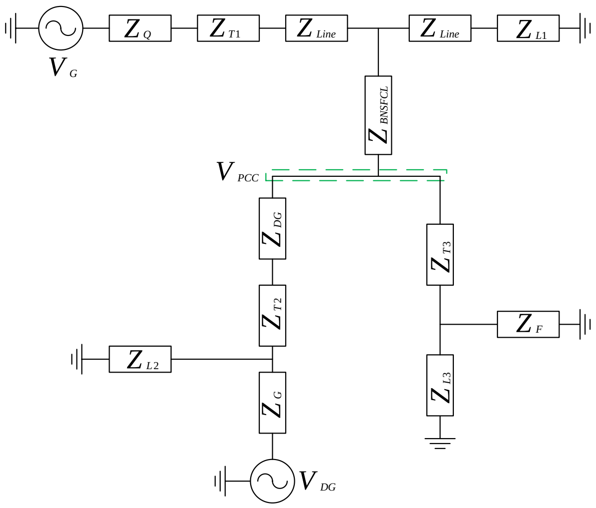
To recapitulate, the proposed BNSFCL provides interesting characteristics such as modularity, bidirectional function and multilevel capability with a simple power circuit and feasible control strategy. Unlike most of the FCLs in literature, current limiting component is not always in current path and enters the structure only in faulty conditions.

## 4. Voltage Sag Study

A power system that consists of the main transformer, lines and protective devices such as a CB, an automatic re-closer (RC) to protect the power system, and a BNSFCL to decrease the fault current is shown in Fig.4a. The microgrid is integrated with DGs. In this network, fault condition is studied in two upstream and downstream parts. To study the effect of BNSFCL in different fault conditions in a distribution network including microgrid, equivalent circuit of the power system is used in this part. Fig.4b shows the impedance diagram of the power system. This figure shows a substation with only one microgrid. However, proposed analysis can be extended to any number of feeders and microgrids. It is to be mentioned that the microgrid supplies a sensitive load. To calculate the voltage sag, the simple voltage divider method is used. All impedances used in analysis and calculations are presented in the Appendix.



a



b

**Fig. 4.** a: Medium Voltage (MV) distribution network connected to a microgrid, b: Impedance equivalent circuit of power system

Fig.5 is the simplified equivalent circuit for Fig.4b. From Fig.5a, in the normal state, the voltage magnitude in the substation PCC can be expressed as follows:

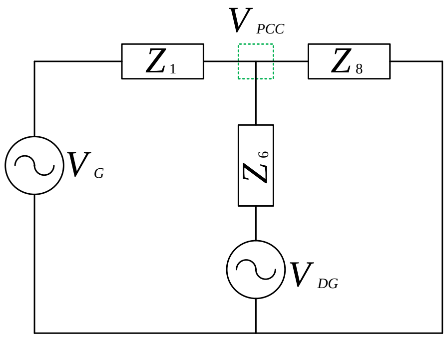
$$V_{PCC} = \frac{\frac{V_{DG}}{Z_6}+\frac{V_G}{Z_1}}{\frac{1}{Z_{eq4}}} \qquad \textbf{(5)}$$

With a fault in the bus 5, the voltage sag occurs in the substation PCC. The positive-sequence equivalent circuits of such a system implemented with BNSFCL and without it are shown in Fig.5b and 5c, respectively. The voltage of substation PCC using BNSFCL can be expressed as follows:

$$V_{PCC} = \frac{\frac{V_{DG}}{Z_{eq1}\,Z_6}+\frac{V_G}{Z_{FCL}\,Z_1}}{\frac{1}{Z_{eq1}\,Z_{eq2}}-\left(\frac{1}{Z_{FCL}}\right)^2} \qquad \textbf{(6)}$$

Also the PCC voltage when there is no BNSFCL implemented in the system is expressed as the following equation:

$$V_{PCC} = \frac{\frac{V_{DG}}{Z_6}+\frac{V_G}{Z_1}}{\frac{1}{Z_{eq3}}} = Z_{eq3}\left(\frac{V_G}{Z_1}+\frac{V_{DG}}{Z_6}\right) \qquad \textbf{(7)}$$



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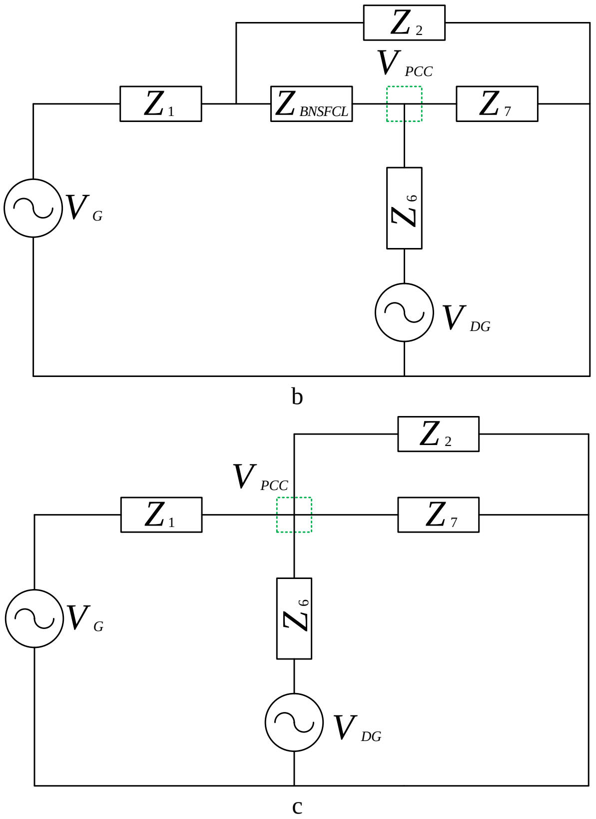

**Fig. 5.** Simplified circuit a: in normal state, b: BNSFCL included under fault, c: without BNSFCL under fault

In the three-phase fault condition (that is a balanced fault) $Z_F$ is equal to zero. Equation (5) shows the PCC voltage in a normal state. Consequently, a comparison of (6) with (7) shows that the voltage sag occurs in the fault interval, respectively. So, the sensitive load experiences worse conditions. To have a more clear comparison between three analyzed states, Fig.6 is presented that depicts PCC voltage based on variations of generated powers (using system parameters). This figure clearly shows that by using BNSFCL in faulty condition, PCC voltage profile is enhanced efficiently.

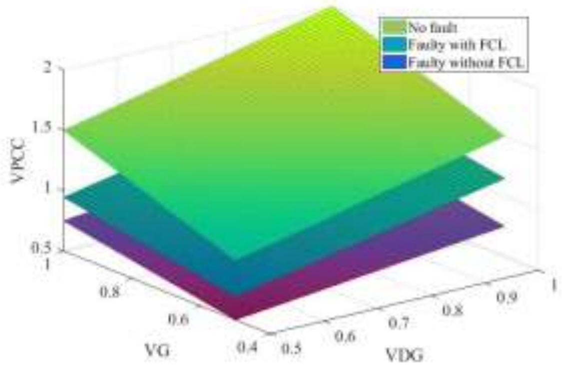

**Fig. 6.** PCC voltage of the three analyzed states

## 5. Protection Co-ordination in The Sample Power System

A protection coordination system generally consists of a re-closer, which interrupts the current for a short period of time, and a fuse, which permanently blocks the current [16]. Two conditions are studied in this paper, network with and without BNSFCL.

- If power system consists of no BNSFCL and DG unit, operation of re-closer is faster than fuse under protection coordination, but when fault current increases due to the implementation of DG, the fuse melts before the re-closer operates, that results in a violation of protection coordination. This causes complete blackout to critical loads (L1) – i.e. reliability problem– which may lead to significant economic loss.
- Considering a BNSFCL implemented to the system under the same grid conditions, the BNSFCL monitors any fault current level in real time. Consequently, the current level decreases to a specified level which leads to a successful protection coordination, so instead of blowing a fuse, the re-closer successfully interrupts the current for a short period of time and a fuse-saving scheme maintains protection coordination.

Figure7 shows the main grid part of the studied power system that is implemented with protection devices such as over current relays (OCRs), fuse and re-closer. Results will be presented in the next section.

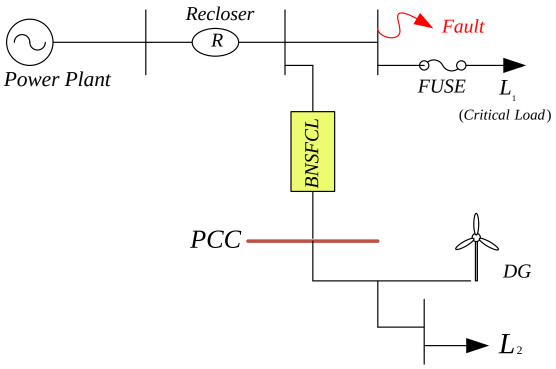

**Fig. 7.** Sample grid with protection devices

## 6. Simulation Verification

Analytical analysis and simulation results using MATLAB/Simulink software are presented to validate the effectiveness of the FCL structure. Power system specifications and parameter settings are shown in Table 2. The simulation results, shown in the following figures, are obtained for two different fault locations, where a three phase short circuit to ground occurs at points F1 and F2 (shown in Fig. 4a). Protection coordination results are also presented.

**Table 2.** Network and BNSFCL data

| Network components | Data |
|---|---|
| Power plant | 6 kV , S=100 MVA , R/Z=0.045 |
| $T_1$ | 6/20 kV , S=50 MVA |
| $T_2$ | 0.69/20 kV , S=2 MVA |
| $T_3$ | 20/0.4 kV , S=1.5 MVA |
| DG Unit | 690 V , PF=0.9 lag |
| $L_1$ | Non-rotating Load: S=20 MVA , PF=0.94 |
| $L_2$ & $L_3$ | Non-rotating Loads: S=1.2 MVA , PF=0.95 |
| $Z_{Line}$ | Overhead line: R=2.75Ω , XL=4.15Ω |
| $R_d$ | 0.01 Ω |

Analyzing the operation of FCL is an important issue in power system protection studies. Pulses for switching the BNSFCL are shown in Fig.8. It is to be mentioned that FCL is practically inactive when there is no fault in the grid.

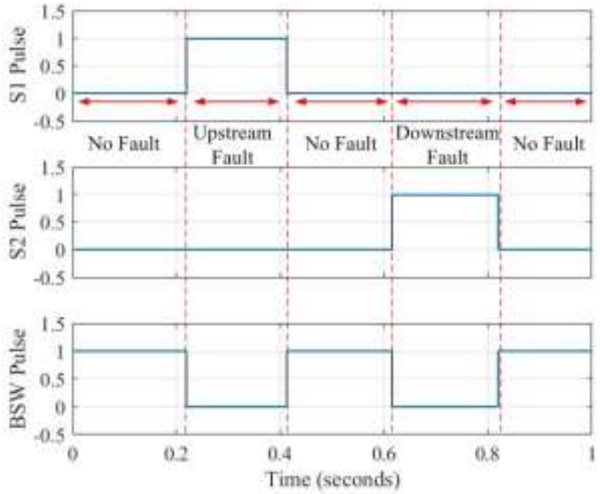

**Fig. 8.** Pulses sent to BNSFCL switches

BNSFCL suppresses high fault current caused by a downstream fault, effectively. This fact is shown in Fig.9. As discussed before, the BNSFCL can also be regarded as an efficient device for preventing deep voltage sag in the microgrid during fault in the main grid. This is the undeniable capability of the proposed structure which limits the fault current drawn from the microgrid, so a less sever voltage sag will be seen by loads in the microgrid. Simulation result is shown in Fig.10 that is highly compatible with analysis presented in section 4. In case of fault occurrence in the main grid, there is an undeniable difference between fault currents with and without BNSFCL. This fact is shown in Fig.11.

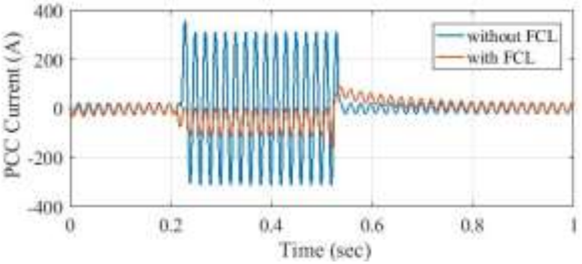

**Fig. 9.** PCC current during a microgrid fault

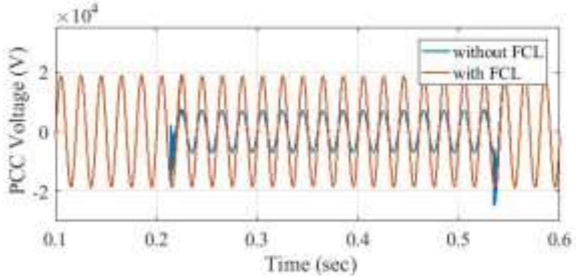

**Fig. 10.** PCC voltage enhancement using BNSFCL during a fault in upstream

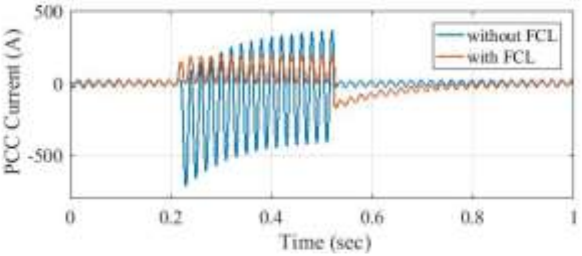

**Fig. 11.** PCC current during a upstream fault

For coordination between re-closers and fuse, the re-closer must protect the fuse from temporary faults and fuse must operate for permanent faults. This requires that the re-closer's fast curve stays below to the minimum melting (MM) curve of the fuse [17-19]. Time-Current curves are presented as following in Fig.12. Fault current through the re-closer is different from the fault current passing through the fuse, so the fault current seen by fuse is likely to be higher than the fault current seen by re-closer, as shown in Fig.12, fuse may operate before re-closer and every temporary fault changes to permanent blackouts. As described in section 5, by implementing the BNSFCL and therefore limiting the fault current, re-closer operates before fuse and guarantees the protection coordination.

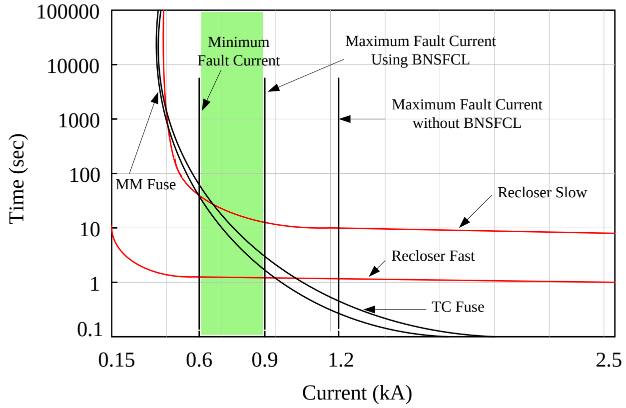

**Fig. 12.** Curves of fuse (MM & TC) and re-closer (slow & fast) for protection coordination

## 6. Conclusion

In this paper, a bidirectional controllable fault current limiter named BNSFCL was introduced. Voltage sag and fault current limiting operations were analysed. The proposed BNSFCL was installed between the main grid and microgrid and efficiently limited the contribution of the downstream network during upstream fault condition and vice versa. Also it enhanced PCC voltage profile in upstream fault conditions. This topology has low initial costs because of cancelling out superconductor technology. By using semiconductor switches, the proposed BNSFCL has high speed. Besides, by using efficient control strategy, the proposed BNSFCL can preserve the coordination protection of the upstream OCRs, i.e. re-closer operates before fuse and prevents permanent blackouts. Unlike other FCLs in papers, BNSFCL provides interesting characteristics such as modularity, bidirectional function and multilevel capability that enhance its flexibility. In general, this type of FCL, with the flexible and capable characteristics and low cost, is useful for power quality and protection coordination enhancement and can have acceptable market in the near future. Our next study will be conducted on the detailed analysis of a modular multilevel BNSFCL based on the topology presented in this paper. Experimental validation will also be provided in our next paper.

## Appendix

All impedances used in analysis and calculations are presented as follows:

$Z_1 = Z_Q + Z_{T1} + Z_{Line}$

$Z_2 = Z_{Line} + Z_{L1}$

$Z_3 = Z_{DG} + Z_{T2}$

$Z_4 = Z_{L3} \parallel Z_F$

$Z_5$: Using Thevenan & Northon principles

$Z_6 = Z_3 + Z_5$

$Z_7 = Z_{T3} + Z_4$

$$\frac{1}{Z_{eq1}} = \frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_{FCL}}$$

$$\frac{1}{Z_{eq2}} = \frac{1}{Z_6} + \frac{1}{Z_7} + \frac{1}{Z_{FCL}}$$

$$\frac{1}{Z_{eq3}} = \frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_6} + \frac{1}{Z_7}$$

$$\frac{1}{Z_{eq4}} = \frac{1}{Z_1} + \frac{1}{Z_6} + \frac{1}{Z_2} + \frac{1}{Z_{T3}+Z_{L3}}$$

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