Towards a Self-Healing Electric Grid With Superconducting Fault Current Controllers

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***Abstract*—Uncertainty and complexity due to expanded adoption of renewable energy resources, distributed energy resources as well as expanded electric transportation and dynamic demand response technologies in the power industry present significant challenges in grid operations. It is thus required to develop smart protection and control actions for ensuring highly reliable and healthy electric power infrastructure by increasing resiliency against component failures or natural disasters, i.e. self-healing ability. This paper, in particular focuses on the self-healing in the context of grid protection using smart superconducting fault current controller (Smart FCC). A systematic framework and technological requirements are presented for realizing the envisioned self-healing protection capability using Smart FCC while minimizing the electric loss near zero through superconducting coil. Illustrative examples, modeling and simulation studies demonstrate the validity and efficacy of the proposed framework and envisioned technology.**

***Index Terms*—DG, fault current, power fluctuation compensation, protection, self-healing, smart FCC, smart grid.**

I. Introduction

UNCERTAINTY due to expanded adoption of renewable energy resources, distributed generation (DG), and steadily increasing but dynamically controllable loads in the power industry present significant challenges in grid operations. A variety of advanced power devices, including power electronics-based controllers and advanced IT-based protection schemes, have been actively researched and deployed in the electric power grid for ensuring highly reliable and healthy electric power infrastructure. These control and protection schemes increase resiliency against grid components' failures, i.e., self-healing ability and thus build the envisioned "Smartness" into the grid to cope with those emerging challenges, which is named smart grid. Smart grid may be defined as the overlaying of a unified communications and control system on the existing power delivery infrastructure. Its advanced two-way communications allows the information exchange necessary to monitor operating status of the components, faults and power quality, enhancing the energy efficiency and the customer service in a variety of ways.

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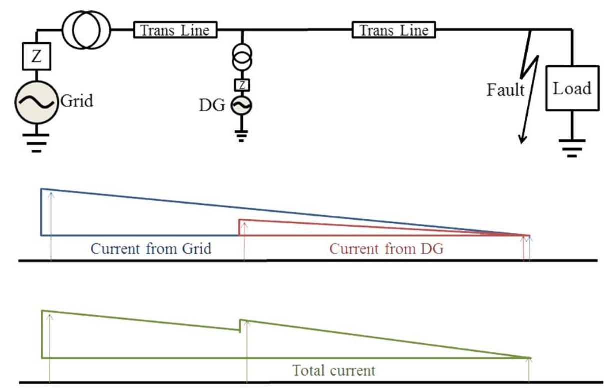

Fig. 1. Impact of DG on the increase of fault current level.

As briefly stated earlier, DG is one of the key components of smart grid for increasing energy efficiency and power system reliability. Integration of multiple DGs, however, may lead to critical challenges in coordinating various protection devices because fault current levels may increase or dynamically change depending on the sizes, types and locations of DGs, variable generation in nature. Modern grid has been faced with the increasing fault current levels along with increasing power capacity along with load growth which brings the reinforcement of the system equipment, leading to lower impedance [1]. Increasing DGs surely complicates the situation, potentially threatening the system security.

Fig. 1 illustrates fundamentals of DG's contribution to the increasing fault current level. When grid-connected DG runs, not only the fault current from the power grid to the fault location but also fault current from DG flows to the fault area. Increased fault current levels may cause problems, in particular when the fault current level exceeds the interrupting ratings of the multiple protection devices. Then, the pre-established coordination between the protection devices may possibly be lost and the reclosers or fuses on the feeders may not function in the designed sequence. It is worth noting that Fault Current Limiter (FCL) has been actively investigated as an attractive solution to regulating the fault current levels and maintaining the aforementioned protection coordination. However, functionalities of FCL are limited in that it operates in a predetermined way (determined in the planning stage for possible operating scenarios), and excessive limitation can delay the operation of the circuit breaker connected in series, and thus affect the protection coordination. The upshot could be catastrophic failure not uncommonly reported these days [2]. More adaptive and intelligent protection scheme is desired.

Motivated by the aforementioned efforts, this paper is focused on improving the self-healing capability of the smart grid with high penetrations of variable DG using Smart fault cur-

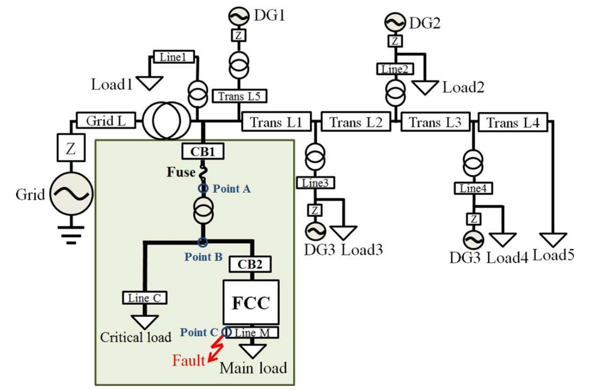

Fig. 2. Distribution system with DGs: a test system for demonstrating the performance of Smart FCC in maintaining the protection coordination.

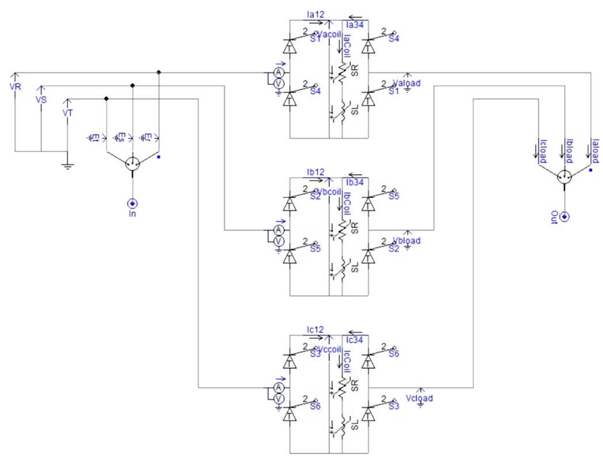

Fig. 3. PSCAD/EMTDC model of a three-phase Smart FCC.

rent controller (Smart FCC), conceptually proven in our earlier work [2]. It takes advantage of the controllability of power electronics reinforced by the superior property of superconducting coil, i.e., very large lossless DC current densities. Smart FCC, employing a full bridge thyristor rectifier, can regulate the fault current level to a reference value by changing the firing angle of the thyristors [2], [3]. We present practical control schemes for Smart FCC against operating scenarios of the future distribution system with high penetrations of DGs, and demonstrate its validity and effectiveness in keeping the grid security and saving critical loads potentially lost due to lost coordination without Smart FCC, i.e., improved self-healing capability.

This paper is organized as follows: In Section II, a test system and its PSCAD model for demonstrating the proposed control scheme for Smart FCC is discussed. Specifications of model parameters are included. Section III presents efficient method for calculating the firing angles to properly control the fault current levels. Simulation studies for various operating scenarios are presented in Section IV followed by analysis of time current characteristic curve (TCC curve) in Section V. Discussion and conclusions are provided in Section VI.

II. Modeling and Simulation

A real distribution system model is adapted to a benchmark system with high penetrations of variable DGs. It consists of 4 DGs and 7 loads as depicted in Fig. 2. It is assumed that faults frequently occur near bus to the considerable loads, named main

TABLE I
Parameters in the Distribution System

Name	Parameters	Name	Parameters
Grid	345 kV	Main Load	4 MVA 0.98 pu
DG1	22.9 kV	Critical Load	1 MVA 0.97 pu
DG2	22.9 kV	Load1	1 MVA 0.97 pu
DG3	22.9 kV	Load2	8 MVA 0.96 pu
DG4	22.9 kV	Load3	11 MVA 0.95 pu
CB1	560 A	Load4	3 MVA 0.95 pu
CB2	560 A	Load5	15 MVA 0.95 pu
Fuse	140 K	Superconductor	1.0+j1.508 Ω
Grid line	0.24+j0.9 Ω		
Transmission line	0.1819+j0.3912 Ω/km	Transformer from grid	345 kV/154 kV 300 MVA
Distribution line	0.0736+j0.1277 Ω/km	Transformer	154 kV/22.9 kV 10-20 MVA

load in Fig. 2 and Smart FCC is connected to the main load. There is also critical load, say, delicate industrial plant nearby the main load. With increasing DGs, the distribution system experiences increase of fault current levels and coordination of the existing protection devices are lost. As discussed in Section I, unexpected higher fault current may flow to the fault area point C from the each variable DG, which could adversely impact the previously well-coordinated protection operation[1]. Smart FCC is deployed as an effective and adaptive solution to the challenges in coordinating protection devices. Intelligent electronic devices (IEDs) for monitoring the real-time operating states should be useful for accurately determining the reference limitation levels online, i.e., firing angles for Smart FCC. Accurate knowledge of the target system obtained via thorough planning Studies should also be helpful in validating the reference values.

Three-phase fault condition and synchronized closing and opening of protective devices operating are assumed. Parameters of the system components are presented in Tables I and II. As quenched on high current, superconductors in Smart FCC are considered as rheostats to presume that it quenches in 0.007 s after a fault happens at 0.5 s from zero impedance with superconducting state. Smart FCC is a resistive type as shown in Fig. 3.

III. Determination of Firing Angle

As the Smart FCC contains power electronics device, output voltage and current are related with firing angles, important factors for operating the solid-state devices accurately. Fig. 4 presents how fault current level changes with the firing angle on the Point B split for main and critical loads in Fig. 2. The fault current level on the y-axis is normalized by the maximum allowable fault current, a priori knowledge of the system given the available generation and system impedance. When a fault occurs, DC filtered current of the first half peak which is the same as fault current without the Smart FCC is extracted to calculate the firing angle that controls that fault current level to

[1]Protection coordination may be considered perfect for all other operating conditions except for the cases occurred due to variable DGs. This is the pitfall of the existing deterministic protection scheme that relies on predetermined operating scenarios. It motivates the development of adaptive protection schemes against increasing uncertainty and complexity of the smart grid.

TABLE II
LINE DISTANCE

Name	Parameters	Name	Parameters
Trans line 1	1 km	Distb Line1	1 km
Trans line 2	2.7 km	Distb Line2	2 km
Trans line 3	1.6 km	Distb Line3	3.1 km
Trans line 4	6.1 km	Distb Line4	1.7 km
Trans line 5	2 km	Distb LineM	2.3 km
Fault location	0.3 km from FCC	Distb LineC	1 km

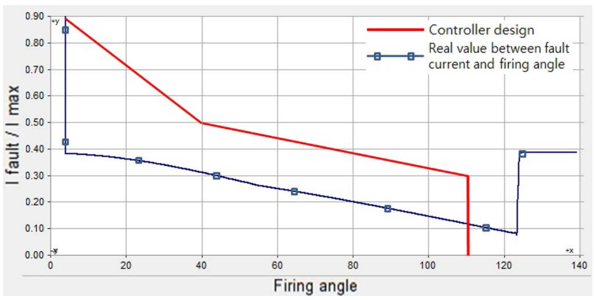

Fig. 4. Determination of firing angle with reference to the fault current level.

the desired level without disrupting the well-established protection coordination. Using the measured peak value may be a good option at this stage. However, once the online grid information such as operating status of DGs and line configuration is informed, Thevenin equivalent circuit based calculation for important lines may also be possible. This can be used preventively as real-time contingency analysis is conducted for transmission system.

Graphs in Fig. 4 indicate the relation between firing angle and controlled fault current in P.U. with reference to the maximum fault current. Blue line with square marks is actual trace of fault current in the system as the firing angle increases. It should be noticed that tolerance for error has to be considered when designing the controller as presented by the red solid line in Fig. 4. Since high fault impedance doesn't break protection coordination, it can be used for finding the operating point when protection coordination gets lost. Prior knowledge of this operating point is critical for maintain the protection coordination.

IV. Protection Coordination

When installing protection device, engineers need to evaluate harmonious operation with other protections. Loads could suffer from unexpected outage, causing huge financial loss otherwise. Hence protection coordination is essential for protection to design power system. When fault occurs on the low voltage side in Fig. 2, well-designed protection coordination must work in the following order; first downstream current breaker CB2, which does not affect load of another lower voltage side. Secondly, when CB2 did not run properly, upstream current breaker CB1 have to act faster than fuse. Fuse is the last option to cut off under the fuse-saving scheme.

A. Well-Coordinated Protection Devices

As can be seen in Fig. 5, CB2 operates faster than fuse or CB1 with the fault at the location point C, 0.3 km from the FCC, due to well-coordinated protection. As clarified in Fig. 6, CB1 must trip quicker before the fuse melts between CB1 and the point A in Fig. 2.

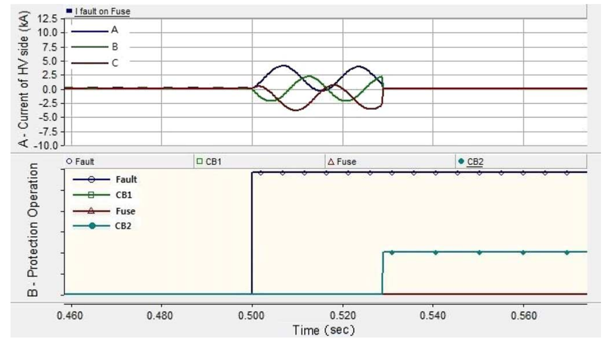

Fig. 5. When a line fault occurs on the point C without DGs (A) high voltage side fault current (B) CB2 operates faster than other protection devices.

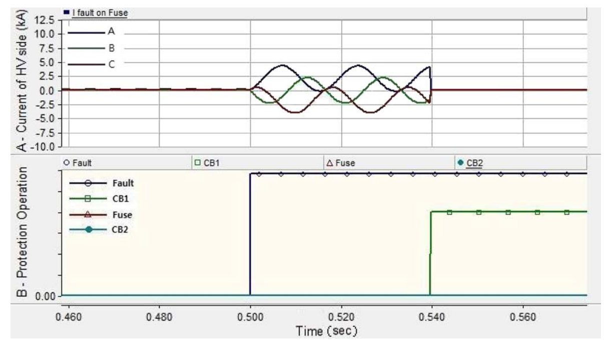

Fig. 6. When a line fault occurs on the point A without DGs (A) high voltage side fault current (B) CB1 operates faster than other protection devices.

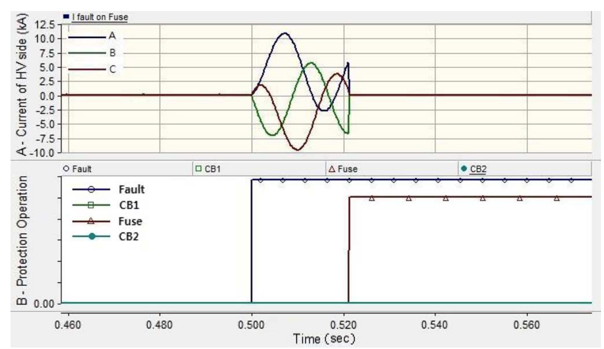

Fig. 7. When a line fault occurs on the point C with DGs (A) high voltage side fault current which is higher than that without DGs, (B) fuse operates faster than other protection devices, which breaks protection coordination.

B. DGs Breaking Protection Coordination

High penetration level of grid connected DGs should result in larger fault current level and may destroy the harmony of fitly coordinated protective gears, hence collapse coordination, for example, by blowing the fuse faster than other CBs. This causes nuisance tripping of the critical loads located downstream from the fuse. Technically, huge financial loss or damage to the equipment sensitive to power quality may occur. As shown in Fig. 7, fuse breaks the fault current faster than other protective devices, and as a result of this phenomenon, a critical load would be disconnected. This occurs when studies for coordinating protection devices unfortunately didn't consider the high currents

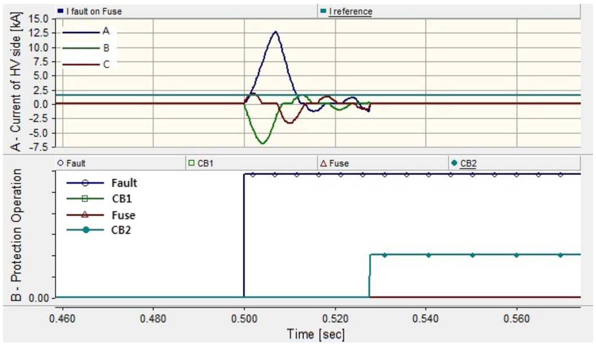

Fig. 8. When a line fault occurs on the point C with DGs; (A) high voltage side fault current controlled by the Smart FCC, (B) CB2 operates faster than other protection devices, which is proper operation of protection devices.

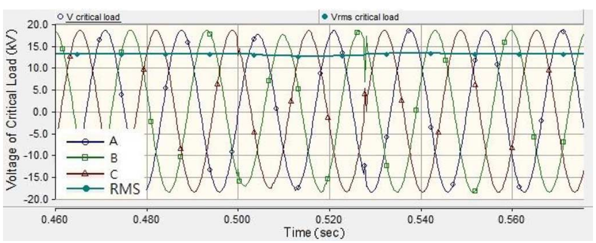

Fig. 9. Voltage and current waveforms of the critical load bus.

form the variable DGs. The protection devices apparently seem to be well-coordinated but this is not the case for the case as discussed above and illustrated in Fig. 7. Smart FCC can effectively prevent this situation as detailed in the following sub-sections.

C. Deployment of Smart FCC

After deploying the Smart FCC, the utility can prevent breakdown of the coordination. The Smart FCC regulates the fault current to the point to make protection devices operate properly and maintain the protection integrity. The Smart FCC controller calculates firing angle and controls fault current under the reference value, therefore protection devices operate as designed (see Fig. 8).

As clarified in Fig. 9, voltage-sensitive critical loads survive the fault because CB2 operates faster than the fuse due to Smart FCC operates properly and the impact is minimal. Although little distortion accompanies with voltage waveforms, critical load would not be affected by the voltage sag according to CBEMA or ITI curve [4] because voltage P.U. is between 1 and 0.9 for 0.3 second after the fault. Unless the FCC is installed, voltage would drop down around 0 P.U, so all of electrical devices in critical load zone would be lost due to the blown fuse.

V. Analysis in TCC Curve

To find and evaluate controlled fault current level, analysis in TCC curve is desired to be conducted because it allows for determining exact operating point as presented in Fig. 10. Low voltage side fault without DG occurs around point A, and it is quite safe level to keep the coordination. However, when

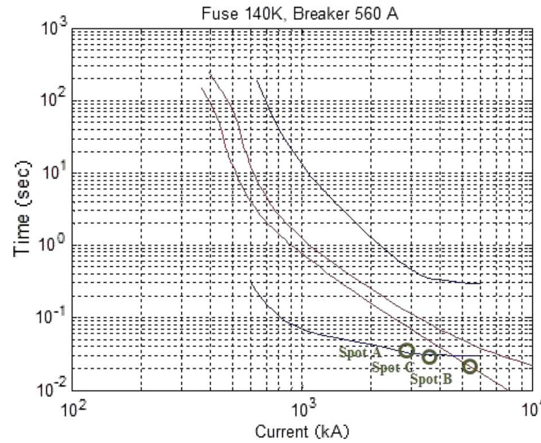

Fig. 10. Operating points on the TCC (Time Current Characteristic) curve.

DGs are connected to the grid, the fault current would be increased and protection coordination would be lost as indicated in point B. the Smart FCC can be a solution to move the operating point B to point C by controlling the fault current to an appropriate level.

VI. Discussion and Conclusion

Increasing fault current levels in electric grid has become an ever increasing problem for utilities. High penetration of DGs in the smart grid system may also change the fault current level dynamically, which may ruin the protection coordination scheme and cause catastrophic failure of the system.

Unlike the exiting current limiter, the proposed Smart FCC can control fault current to the desired levels. Thus, it helps avoid any malfunction of the existing protection devices and keep the system integrity. Self-healing of the future smart grid through Smart FCCs may be fully realized when the envisioned ICTs (Information and Communication Technologies) are fully implemented. This is because the system operators should be able to monitor the grid status accurately and make informed-decisions promptly for ensuring the system security by taking advantage of the advancing ICTs. They should be informed on the adequate fault current levels at the critical locations where Smart FCCs are deployed, and updated with the proper firing angle online. When a fault occurs, firing angle gate signals are promptly applied to the relevant Smart FCC and the fault current is regulated to the target value. Finally, the system integrity is maintained.

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