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FOR SMART GRID PROOF OF CONCEPT OF A SMART FAULT CURRENT CONTROLLER WITH A SUPERCONDUCTING COIL

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Abstract — *The power grid, especially distribution grid, has been more complicated due to distributed generations (DGs) with renewable energy sources and the smart grid. The complexity changes two things in terms of a fault; higher prospective fault current and the temporal variation of sources and loads. To correspond to those remarkable changes, we propose a fault current controller (FCC) named "smart FCC." The smart FCC consists of a superconducting coil with a freewheeling diode if necessary, four thyristors, and a control unit. Smart FCC can not only limit but also control the current when a fault occurs. The smart grid technology can provide so enough information that it is possible to estimate which level of limited current should be the best in the real-time situation of the grid. Based on a real-time calculation of optimal fault current using the smart grid monitoring technologies, this new device is always ready to adjust the fault current. In this paper, we introduce a concept of the smart FCC and prove the concept. Various topologies have been proposed and simulated. Finally, a case study on a distribution class of 22.9 kV smart FCC has been conducted based on a conceptional system design.*

Index Terms*—Fault current controller, smart grid, superconducting coil.*

I. INTRODUCTION

The electrical grid has faced a challenging change, called the smart grid. Many things drive the change; the old-fashioned and aging infrastructure, the brink of being exhausted of the fossil fuel, and the explosive growth of demand for electricity. The existing grid is also becoming increasingly regionalized with more generation located remotely to close to its particular source of fuel. The grid will therefore have to mitigate in- creasing inter-regional fault current transfers and the increasing number of parallel transmission paths that will be required to allow lowest cost electricity to flow to where it is needed and to allow a smarter grid to quickly respond to disruptions of sources, transmission or local generation paths.

Distributed generation (DG) can help but is not always available when needed, and also must be redesigned. Solving this complex set of problems will require a combination of new policies and technologies. As a possible solution, the smart grid has been proposed and widely known. Although the smart grid is still a concept at the moment, the needs for new paradigm of the grid should lead to the realization of the concept. In a view of technical side, the smart grid can be implemented by fusion of the power system and the information technology (IT). The IT can not only help to upgrade of the power system but also derive the novel power equipment. To reduce the fault current, many kinds of superconducting FCLs have been researched and some of them are about to be installed on-site [1]. To reflect the paradigm shift of the power grid, from large capacity transmission to the smart grid with DGs with renewable sources, we propose a new device to control the fault current, named "smart fault current controller (FCC)." A research on a FCC was attempted in 2003 [2]. Even though the former FCC could control the fault current, a target peak current value had to be set before the installation. In addition, it is hard to change the setting value during operation. In contrast, we propose a new fault current controller combined with the smart grid technology. In this paper, we introduce a concept of the smart FCC and prove the concept based on circuit simulation.

II BACKGROUND

A. Changing Environment in Distribution Grid

In tradition, the distribution grid has one-way flow; from the transmission grid to loads. In recent years, as renewable energy sources (RESs) are getting more, RES-based DGs are becoming wide spread in some regions. The RES-based DGs have two key features; (1) an unpredictable output power in some cases such as wind and solar power and (2) some of them are combined with loads in some distribution class. The power flow should be two-way caused by these load-combined DGs, which play a role of either the load or the source. In most cases, the DGs are connecting to the transmission line so far, some load-combined DGs, such as a building with many solar cells on their roof, are also getting more. As the number of these DGs increases in a grid both transmission and distribution system [3], the prospective fault current is higher and hard to predict. This change is al- ready on-going, and will be boosted up by remarkable progress of RES technologies. As a result, the protection scheme for fault current management has been challenging.

B. Smart Grid

One of key technologies of the smart grid is a real-time monitoring of all parts of power grid based on IT. For instance, the advanced measuring infrastructure (AMI) technology let us know a real-time load capacity [4]. When the monitoring technology is applied over the grid, all information about the grid network could be obtained, which includes generating sources capacity as well as loads capacity. Then, it is possible to calculate the suitable limiting impedance at any moment

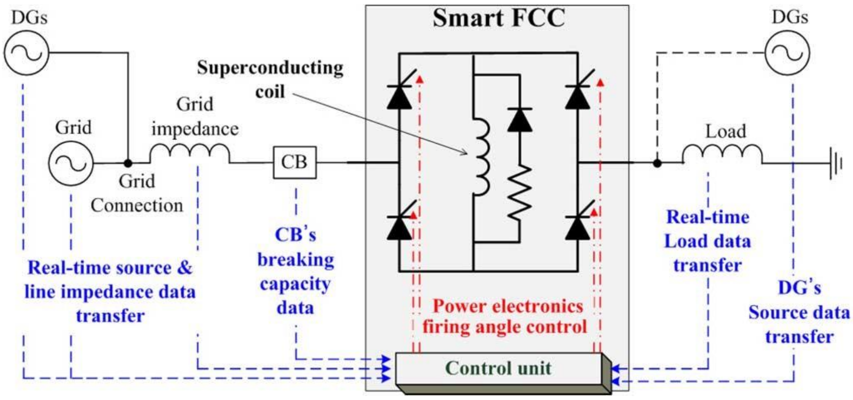

Fig.1 Schematic drawing showing the smart FCC and location in a grid with grid-connected DGs.

III CONCEPT OF SMART FCC

A. Needs

Conventional methods of dealing with high fault current, such as series reactors, introduce impedance all the time, during not only the fault but normal operation. To overcome this drawback, SFCLs are being developed. Most of SFCLs generates the resistive impedance only during a fault. The limiting impedance is mainly determined by intrinsic characteristics of superconductor. Though the superconducting to normal transition is very fast and effective, the limiting impedance cannot be adjusted once installed. In the traditional grid, there is no reason to vary the impedance. However, as mentioned in Section II-A, a new scheme of distribution grid, including DGs, needs to react instantaneously to meet the suitable fault current level. The smart FCC can not only limit but also adjust the fault current when a fault occurs.

Operational Principle: The smart FCC is based on solid- state and superconducting technology. It consists of a superconducting coil with a freewheeling diode if necessary, four thyristors, and a control unit [2]. Fig. 1 shows the schematics deployed the smart FCC and a grid.

Since the main topology is similar to a full-wave rectifier, called a bridge, the operational principle can be explained as a rectifier. The superconducting coil has no resistance and large inductance. Since the coil is a kind of energy storage, a current flowing the coil should be accumulated and then finally almost direct current (dc). It means there is no voltage drop across the coil in a normal operation. Note that the line current is ac and the coil current is dc. The dc coil current makes all thyristors turned on. Hence, the nominal ac current behave not to flow in the coil. In this case, the voltage drop is caused by just thyristors, or any other solid-state if replaced, since the coil is superconducting state and almost zero ac loss.

On the other hand, when a fault occurs, the coil current should be increased. At this time, the large inductance of the coil reduces an abrupt surge at the first swing. After the first swing of half cycle, a control unit supplies controlled gate signals to the four thyristors. These gate signal delay can adjust the fault cur- rent level. In a range of 0 to 180 degrees, the delay angle can be selected. For example, if the delay is 0 degree, this FCC operates like a bridge-type SFCL employing power diodes, so-called a dc reactor type SFCL. If the delay is 180 degrees, there is no signal to any thyristors, which means line current is cut off. Fig. 2 shows one example of fault controlling based on a simulation. These two charts are both in a case of 90 degrees delay. As shown in the charts, after the first peak, the line current was controlled by the firing angle delay.

The most important part of the smart FCC system is the control unit. All information about the grid network related to the smart FCC can be transferred to the control unit as Fig. 1. The information can be converted to an equivalent value such as Thevenin impedance and load current in the line. The control unit can calculate the optimal fault current level based on the collected data. The existing protection devices, such as over cur- rent relays and circuit breakers, should be considered when the calculation of the optimum fault level is performed. Since the generating source capacity has a temporal variation when DGs are connected to the grid, the optimum delay angle should be calculated every collection of the information. That is, real-time optimal firing angle is being calculated and ready to supply to the gate signals. When a fault occurs, the coil current should be increased. Then, the controller can recognize an event of the fault. The gate signals can be controlled based on the updated optimal firing angle delay. Fig. 3 shows the flow chart of the controlling procedure. The firing angle can be modified even during the fault in order to satisfy with the optimal fault current level by considering the interrupting duty of breakers and time delay before interruption

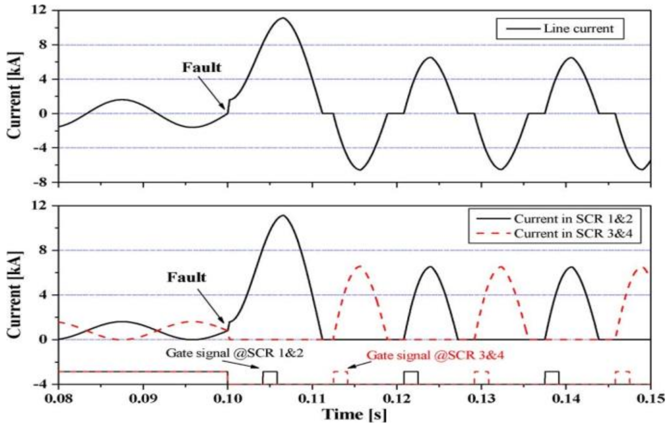

Fig. 2. Line current and thyristors current at 90 delay.

B. Features

There are some features of the smart FCC. At first, it is possible to adjust the fault current, which is the main function. Secondly, this superconducting coil is not quenched so that the recovery time can be quite short. Thirdly, existing protection coordination can be kept. There is nothing to be changed with installation of this device, because this device can fit the fault current to the existing relay setting value. Next, it can make a function of pause. If the firing angle is cut-off, the smart FCC conducts as a breaker. This is not a mechanical breaker, but the grid can re- turn once re-injecting the gate signals. This function can be help to reclosing process. Finally, it could make an improvement of power quality. Since there is a large inductance coil in it, when an unexpected happening such as voltage sag occurs, it can instantly respond like SMES.

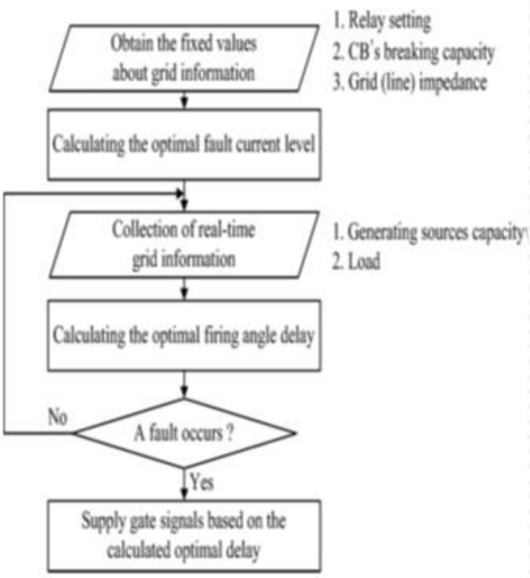

Fig.3. Flow chart of the controller operation.

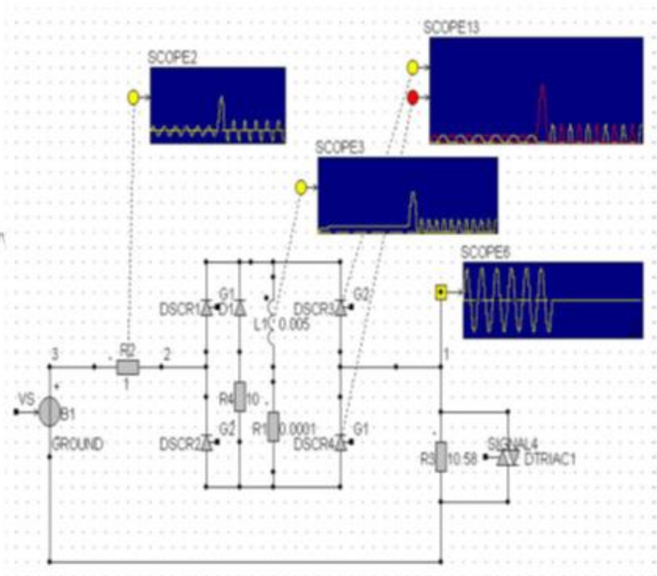

Fig.4. Simulation model of CASPOC2003.

IV PROOF-OF-CONCEPT OF SMART FCC

A. Modeling and Simulation

To simulate the proposed circuit, a commercialized circuit simulator, CASPOC2003, was used. The main variable is the firing angle in the simulation model, which can vary with 0 to 180 degrees. Fig. 4 shows a simulation model including some quick results. Table I shows some parameters to simulate.

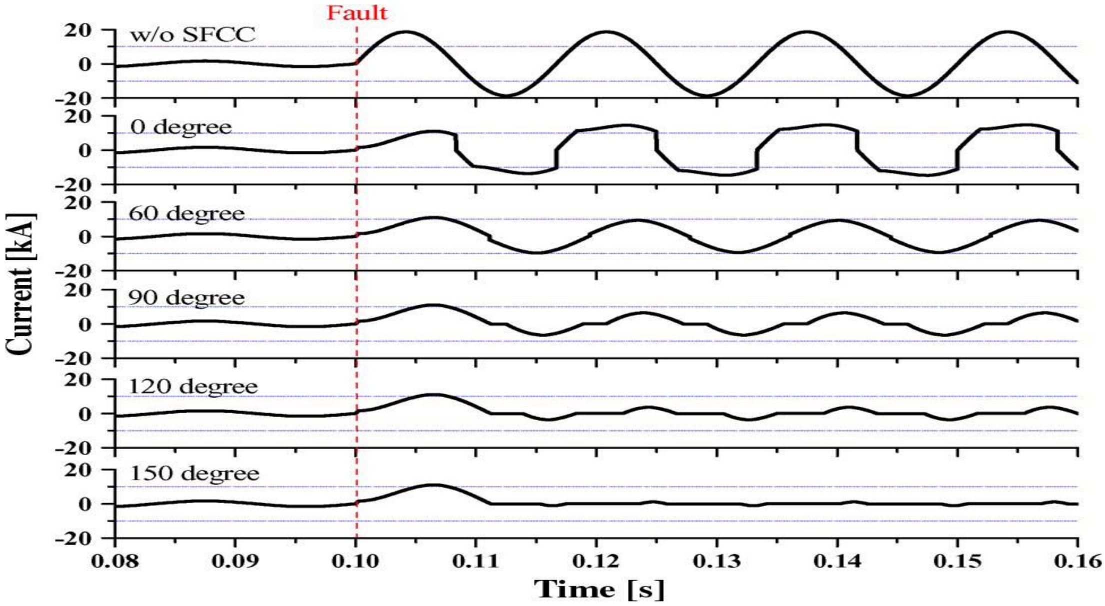

Fig. 5. Line currents with various delay angles with freewheeling

B. Proof of Controlling

Even though the control unit is supposed to calculate the optimal phase angle in real case, we vary the angle values by manual to prove a function of fault current controlling. Fig. 5 shows that the variation of delay angle can adjust the fault cur- rent to the target level.

C. Effect of Freewheeling Circuit

Since the superconducting coil is a kind of energy storage as mentioned above, a freewheeling diode and resistor can affect the current waveforms. Fig. 5 is a case with the freewheeling circuit, whereas there is no freewheeling one in Fig. 6. Other parameters are all same except the freewheeling in between two cases.

As shown in Fig. 6, the freewheeling circuit is not mandatory in terms of just current controlling. However, the super- conducting coil currents are different from each other. Fig. 7 shows the coil current of both cases. In case of no freewheeling, there is no chance to discharge the current during the fault so that the current is getting larger. In contrast, in case of with free- wheeling, the coil is charging and discharging repeatedly during the fault. Hence, after the clearance of the fault, the freewheeling case is much easier to return to the status of before the fault. In summary, a freewheeling circuit is necessary to recover the superconductor.

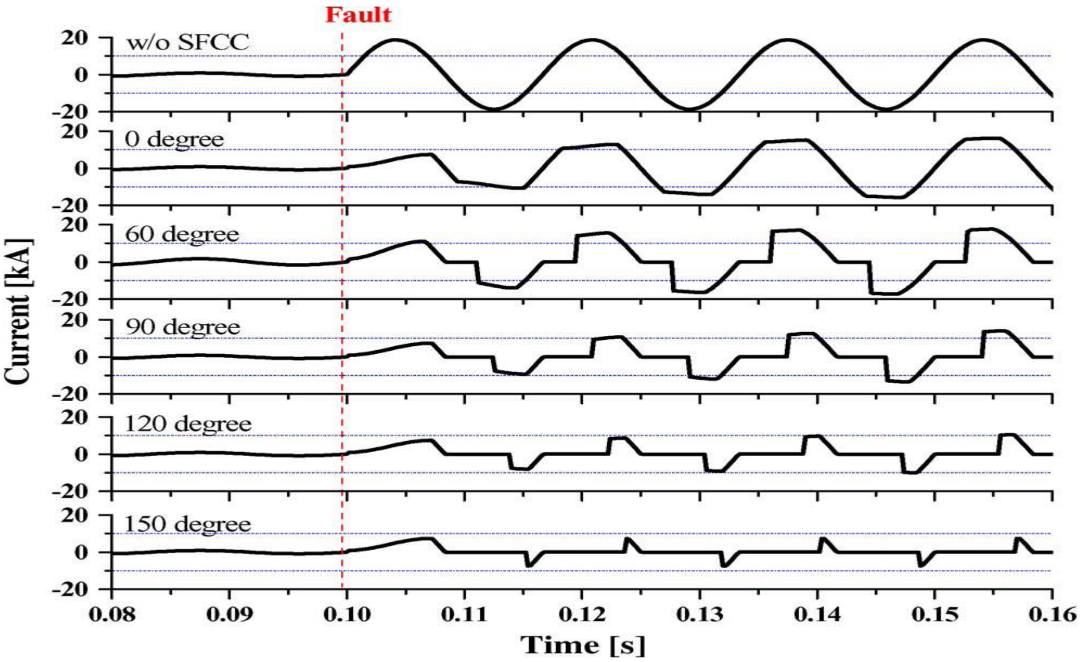

Fig. 6. Line currents with various delay angles without freewheeling.

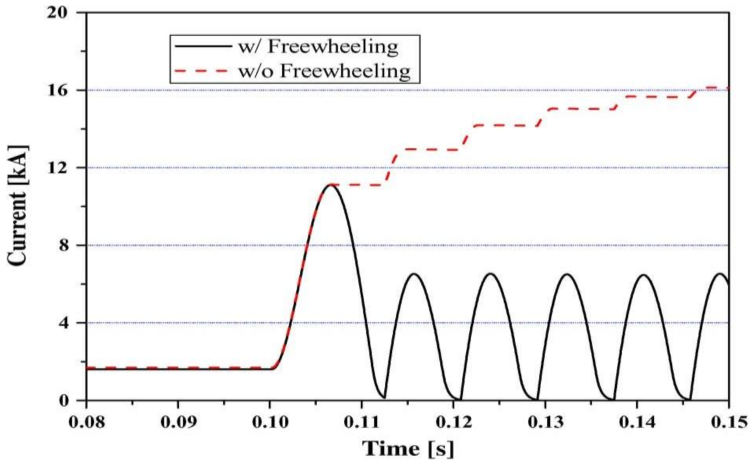

Fig. 7. Superconducting coil current in 90 degree delay case; with and without freewheeling circuit.

V CONCLUSION

As a new solution of dealing with fault currents, we proposed the smart fault current controller. Most of conventional SFCL is passive except solid state FCL, so it is hard to control the fault current. In contrast, this new device can adjust the fault current level actively. For this active controlling, the smart grid technology, especially monitoring and collecting all information about the related grid network, is collaborated with the smart FCC. Optimal phase angle delay value for the solid-state power elements, such as thyristors, is being calculated by a control unit in the smart FCC all the time during operation, even before the fault. In this paper, we proposed the concept of the smart FCC and attempted to prove the concept based on the circuit simulation. In addition, it is found that a freewheeling circuit is necessary to make instant recovery.

The actual linkage between information about a grid through the smart grid and the control unit of this device should be re- searched in the near future. In the next step, we will implement practical operation of this device and a small-scaled grid net- work with some DGs, and then prove the operation of active controlling by experiments.

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