Ultra Fast Protection of Radial and Looped Electric Power Grid Using a Novel Solid-State Protection Device

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***Abstract*—Exploiting the fast operation of solid-state Fault Isolation Devices (FIDs), this paper presents a novel over-current protection scheme for radial and looped electric power distribution systems. The main feature of the proposed protection scheme is that it ensures the maximum restoration of the system in less than a quarter of the electric cycle. Due to the inherent characteristics of the solid-state devices, the FID is also able to limit the fault current to the maximum allowable fault current level of the system, thus reducing the thermal and mechanical stress on transformers and other power system equipments. Using the inherent characteristics of the solid state devices, a novel fault detection criteria is also proposed that eliminates the necessity of the current sensor or transformer (CT) for detecting the over-current fault. These advantages are all achieved without requiring communication between FIDs. Performance of the FID with the proposed protection scheme is demonstrated based on an all-analog logic-level grid-voltage scale experimental setup. The experiments demonstrate the capability of the proposed protection scheme to fulfill the demands of highly inter-connected electric power distribution systems.**

I. Introduction

Conventional distribution systems, either radial or looped, rely on relays with time-inverse and directional characteristics to ensure selectivity between protection devices [1]–[3]. Reliable though, this protection takes a long time (up to 20 electric cycles), depending on the subunits belonging to the grading path, to detect and clear the fault, causing the voltage to collapse for a significant time, damaging the voltage sensitive loads and imposing a great stress on network equipments.

On the other hand, as more and more distributed generation units are being added to the today's power distribution grid, the nature of traditional radial network is changing into a active network where the power can flow in every direction. This, in turn, requires extra protection devices to be installed on the existing network which only has protective relays installed on the main feeder. Proper coordination of a large number of devices in series has also practical limitations. There are also many potential challenges when large amount of distributed generation units are integrated to a distribution system, as [4], [5]:

- Voltage regulation: control of system voltage can be difficult, especially where the generation is intermittent (i.e. solar power), so a fast fault clearance is required.
- Increased short circuit level: As the system become more and more energized with distributed resources, the short circuit level of system increases resulting in necessity of regular upgrades in switchgear and other network equipments which leads to increased cost.

FID offers considerable advantages compared to mechanical circuit breakers for meeting the demands of today's rapidly growing distributed electric power network [6]–[8]. These advantages include: shorter fault clearance time (in order of tens of microseconds), fault current limitation capability, reduced cost and extended life span. The fast operation of FID reduces the time interval over which, the load voltage is disturbed, which produces a higher voltage quality during the transients. While suppressing the instantaneous voltage drops, the fault current capacity of network equipments can be lowered using the high speed current limiting capability of FIDs.

The major drawback of present FID solutions is the necessity of a pilot protection system [9] for exploiting its the high operation speed which introduces extra cost and complexity to the protection system. Primarily, because of this disadvantage, FIDs have not been widely employed as the major protecting device in power systems.

Based on the inherent characteristics of solid state devices, this paper introduces a new criteria for detecting the over-current fault in electric distribution systems which makes the protection independent of current sensors or transformers (CTs). Using the introduced criteria and the fast operation of FIDs, a new re-closing strategy is introduced that eliminates the necessity of communication between FIDs and ensures the reliable operation of FID-based protection system in both radial and looped power systems. Current limiting is also achieved as an inherent characteristic of the protection scheme.

The rest of this paper is organized as follows: in section II, characteristics of FID and a novel fault detection criteria is introduced. In section III, coordination procedure based on the propose detection criteria is presented for both radial and looped power systems. Section IV presents experimental results and conclusions are stated in section V.

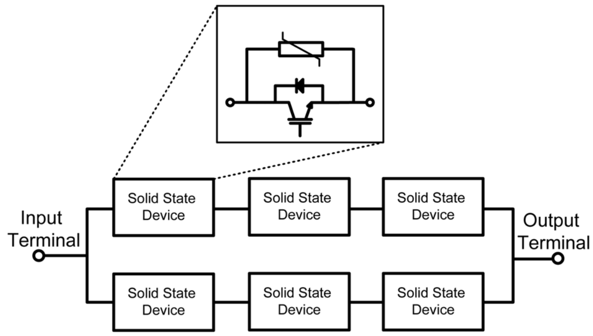

Fig. 1. Representation of a FID with a generic solid state device and MOV at the input stage.

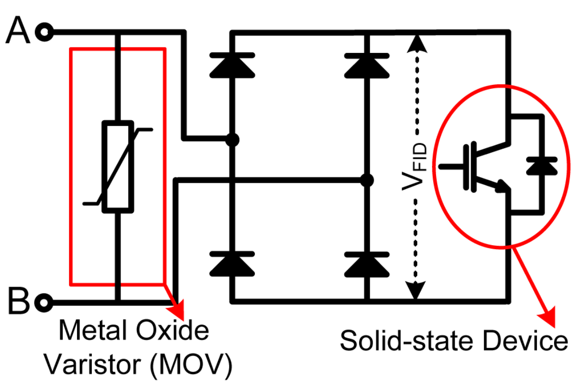

Fig. 2. Proposed FID configuration in this paper.

II. Over-Current Fault Detection Criteria

The first part of this section explains the terminal characteristics of a slid-state FID. The second part then, develops a novel fault detection criteria for FID-based protection systems.

A. FID Characteristics

FID, as it is shown in Fig. 1, is an ultra fast solid state breaker that is used to interrupt fault currents that can occur in a power system. A complete FID package usually contains a solid state switch (i.e. power MOSFET or IGBT) or an array of series and parallel connected solid state devices. Series and parallel devices are used to increase the voltage and current capability of the device. Also, since most of solid state devices have only one directional current conduction and/or voltage blocking capability, anti-parallel connection of devices with extra diodes for reverse voltage blocking should be considered for conduction in both directions. An alternative and much cheaper solution for anti-parallel connection of devices, as it is shown in Fig. 2, is using a H-bridge diode rectifier at the input stage of solid state devices. Since it is much reliable and easier to control, hereinafter in this paper, the configuration of Fig. 2 is considered as FID with diode voltage drops being neglected.

The *v-i* characteristics of a generic solid state device at its output terminals is shown in Fig. 3. For the purpose of this

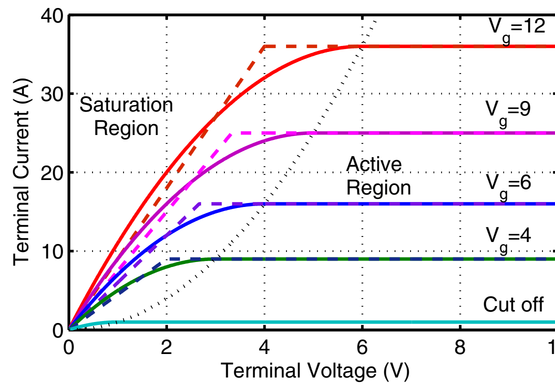

Fig. 3. Terminal characteristics of a generic solid-state device for different gate voltages.

paper, this characteristics can be estimated by its two-piece linearized model.

Safe operation of the solid state-device is only possible in the saturation region. In case of a fault in the system, the terminal current of the FID increases, resulting in the operation point of the device to move to the active region. During this condition, as it is shown in Fig. 3, the terminal voltage of the device increases dramatically causing excessive dissipation on the device, so, if proper detection and turn off measures are not considered in, permanent damage to the device will be imminent.

B. Fault Detection

The novel fault detection algorithm that is proposed in this paper is based on the characteristics of Fig. 3. As it is explained previously in this section, normal operation point of a solid-state device is in the saturation region where its terminal voltage is negligible compared to the line voltage (or equivalently, the equivalent resistance of device is very low). On the other hand, due to flow of the fault current in case of a fault on the system, the operation point moves to the active region resulting in a dramatic increase in the terminal voltage. So, by sensing the terminal voltage of the solid state device, the faulty condition in the system can be determined.

In addition to current sensor elimination, this scheme provides protection for the solid state device against over current damage. By adjusting the gate voltage also, the terminal characteristics of the solid-state device can be programmed to gain desired fault current selectivity required for proper coordination of devices.

III. Coordination Procedure

In this section, the coordination procedure for the FID-based protection system with the introduced fault detection criteria is presented for radial and looped or multi-source power systems.

A. Coordination in Radial Networks

A generic radial network is illustrated in Fig. 4. Optimal coordination of FIDs in such radial networks is a simple and straightforward task. Based on the minimum fault current level

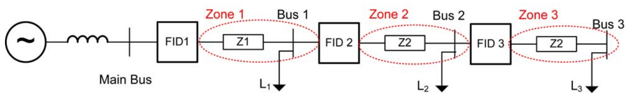

Fig. 4. Single line diagram of a radial electric network with presented FIDs as protection devices.

of each zone and maximum fault level of downstream zone, the gate voltage of solid state devices in each FID is programmed in such a way that for a fault in a specific zone, operation point of the associated FID of the zone moves to the active region so the fault can be detected. This rule implies that the gate voltage of each FID should be higher than downstream and lower than upstream FIDs. Using this coordination scheme, optimal protection of radial system is ensured in addition to limitation fault current in the system.

B. Coordination in Loop Networks

As loop distribution networks are fed from both ends and fault current can flow in both directions, the simple coordination procedure for radial networks can not be used since it fails in the objective of providing uninterrupted supply to all but faulty section of the system. So, instead of using directional and time-inverse characteristics to reach the maximum restoration of loop network, a new ultra fast re-closing strategy is proposed in this paper that ensures the optimal protection of the loop system.

The first step to use the proposed re-closing strategy is to determine the tripping fault current level of individual FIDs. This can be done by selecting the knee point current of each FID to be two times the maximum load current that can possibly flow through each FID if the loop is broken from one end. Using this scheme:

- ensures that at least one FID in each path interrupts the flow of current to the fault.
- entire feeder is able to be fed from one end.
- fault current is limited in the feeders.
- no delay is required for coordination.

Special considerations should also be taken into account if the loads permit inrush or short-term transient currents.

The manipulated re-closing strategy is explained using an example. Consider the loop feeder of Fig. 5 in which the knee point of FIDs are selected using the aforementioned strategy. Initially, for a fault on Bus 3, FID4 picks up the fault and disconnects it from one end. Moments after that, FID2 pick up and clears the fault from another end. This transition is demonstrated in Fig. 6(a), in which open FIDs are presented by green color and close ones are presented by red.

Although the fault is de-energized, Bus 2 is unnecessarily disconnected from the system. As soon as FID2 opens, the line voltage sensor that is integrated in FID3 recognized the voltage loss and trips FID3. Re-closing function of this FID is also disabled since zero voltage is determined in the line. This state of the system is shown in Fig. 6(b).

FIDs are set to re-close with a specific time delay under the condition that line voltage exists at their terminals. With

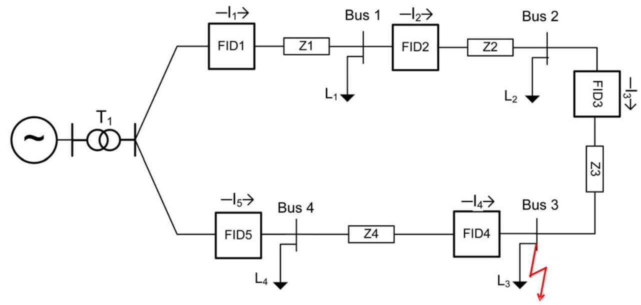

Fig. 5. Single line diagram of a loop electric network with presented FIDs as protection devices.

TABLE I
PARAMETERS OF THE EXPERIMENTAL PROTOTYPE

Parameters	Values
Solid state device type	MOSFET
MOSFET voltage rating	600 V
MOSFET current rating	20 A
Rated grid voltage	60 Hz
Rated grid frequency	60 Hz
L_1, L_2, L_4	110 W
L_3	220 W

FID2 and 4 being close again, fault current flows through FID 4 causing it to open again while FID2 remains close since no fault is detected. FIDs are also programmed to stay at the condition that comes right after the first re-closing, so FID2 and 4 are locked closed and open respectively. The above process is illustrated in Figs 6(c) and (d).

With FID2 being close, the line voltage builds up at terminals of FID3, enabling its re-closing function. After re-closing, FID3 trips again since the fault still exists on Bus 3 and it remains at the open condition. This process is illustrated in Figs. 6(e) and (f).

As it is illustrated in Fig. 6, using the aforementioned re-closing algorithm which is also presented in the flowchart of Fig. 7, the maximum restoration of the loop system is reached without adding delay to protection devices.

IV. Experimental Results

Five FID circuits have been built based on the proposed protection algorithm. Since Loop feeder is much general compared to radial feeder, only experimental results based on the loop feeder of Fig. 5 are presented in this paper.

A picture of the experimental setup is shown in Fig. 8 and characteristics of the system under experiment is presented in Table. I.

A zero impedance fault is created on Bus 3 and results are presented in Figs. 9, 10 and 11.

Fig. 9 demonstrates the bus voltages during the restoration process. At the moment that is marked by *(1)*, fault is created on the system and shortly after that, FID2 and 4 clear the fault from the system. Between the *(1)* and *(2)*, FID3 turn off due to voltage loss in the line and at *(2)*, FID2 and 4 re-close with

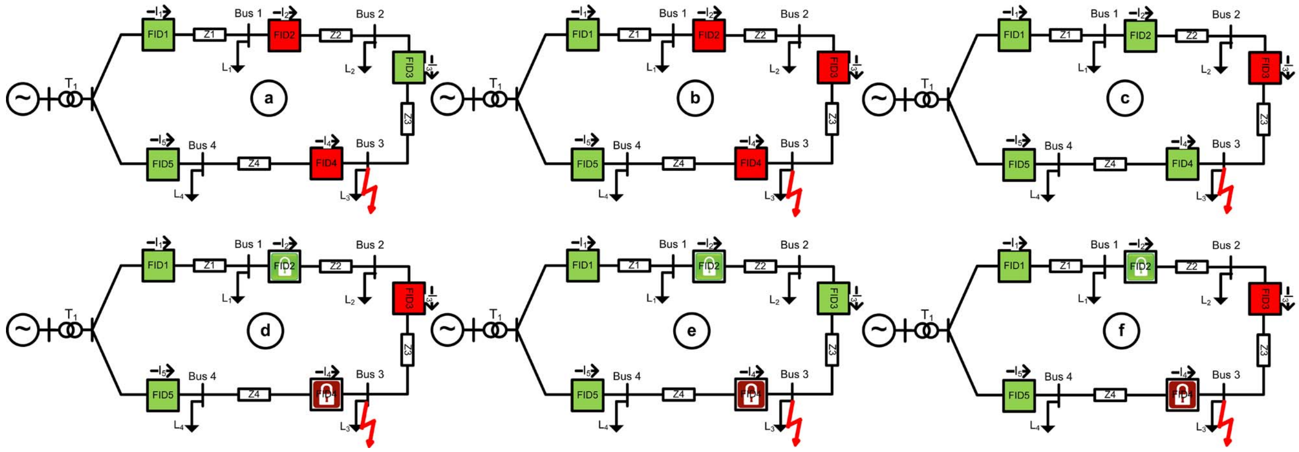

Fig. 6. Evolution of the protection system states during the procedure of fault clearance using the proposed FID.

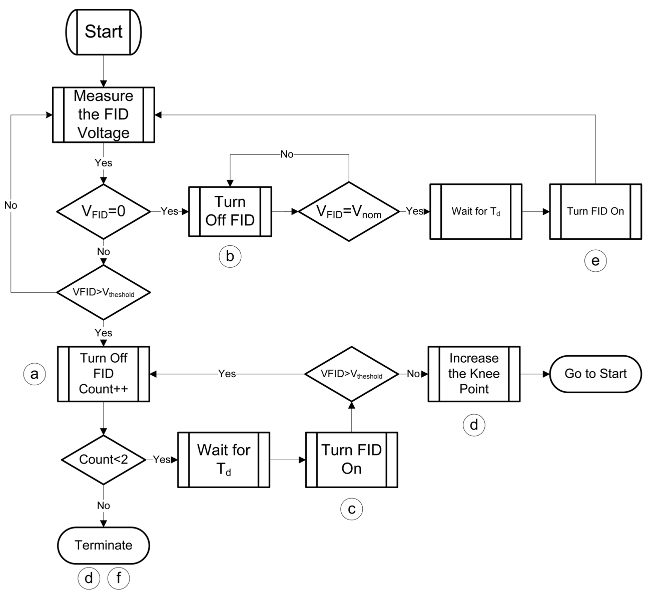

Fig. 7. Flowchart of the proposed re-closing algorithm.

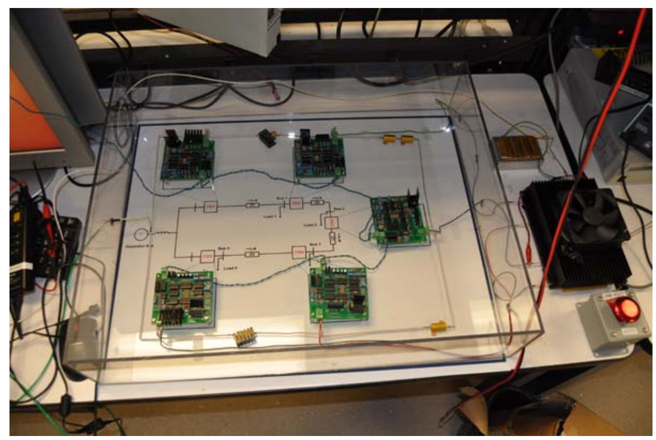

Fig. 8. Illustration of the experimental prototype.

within a short time interval. As it can be seen in Fig. 9, after the re-closing of moment *(2)*, Bus 2 remains energized so, only for an interval of less than $1.5ms$ this bus is disconnected from the supply. By re-energizing Bus 2, FID3 is able to re-close at *(3)* and due to persistence of the fault it opens and faulty section of the system is successfully disconnected from the supply.

It is visible in Fig. 9 that the entire restoration process takes no more that a quarter of a cycle and can even be shortened by reducing the time intervals between re-closings.

Fig. 10 demonstrated the voltage and current of FID2 during the fault clearance of moment *(1)*. As it is shown in this figure, the fault clearance process takes around $41.2\mu s$ compared to 10 to 20 cycles in conventional circuit breakers. The fault current limiting capability of FID is also shown in this figure. As the current through FID increases beyond its knee point, its terminal voltage also increases very fast causing the fault current to be successfully limited around two times of the maximum load current.

The voltage-current trajectory of FID2 during the turn-off process is demonstrated in Fig. 11. This figure also shows how the terminal voltage of FID increases with current to limit the fault current in the system.

V. Conclusion

This paper presents a novel over-current protection algorithm that utilizes the fast operation of FID to provide maximum restoration for the system. The main feature of the proposed algorithm is its superior fault clearance and restoration speed compared to conventional protection schemes. This protection algorithm reduces the fault clearance time to less than 50 μs and total restoration time to less than quarter of a cycle. Performance of the proposed algorithm was evaluated based on experimentation on a low voltage loop system.

The experimental results show the effectiveness of the proposed protection to successfully and rapidly clear the fault

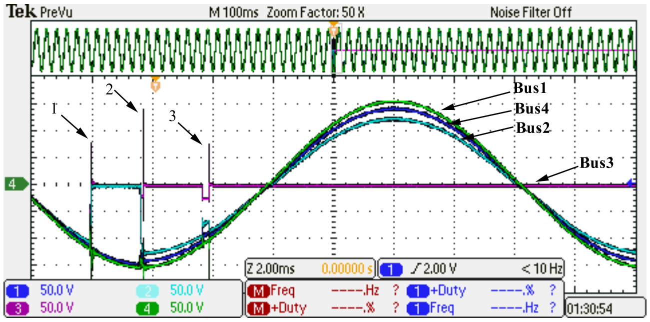

Fig. 9. Bus voltages during the process of restoration (50 V/div).

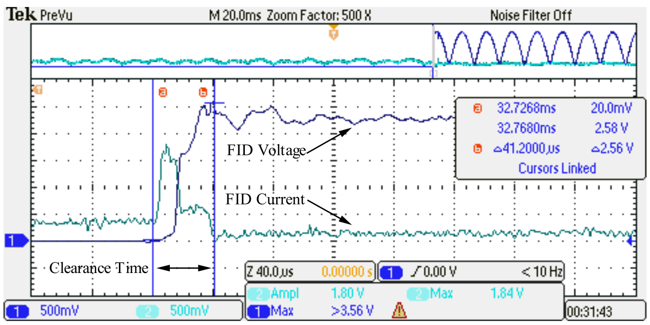

Fig. 10. Voltage (30V/div) and current (2A/div) transients of FID2 during the fault clearance process.

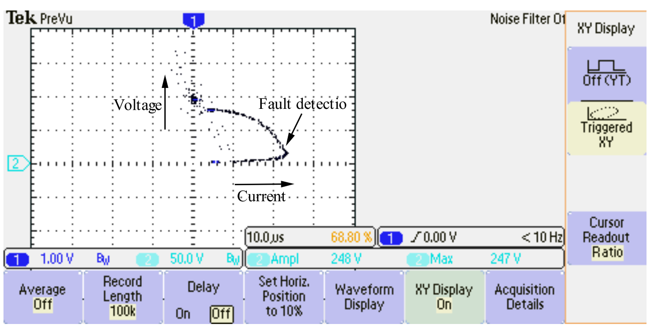

Fig. 11. Voltage-current (100 V/div-2 A/div) trajectory of FID2 during the turn-off process.

from distribution system, reach the maximum restoration of the system and limit the fault current. These advantages, in particular, increase the power quality of the supply system while reducing thermal, electrical and mechanical stresses on the network equipments.

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