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Autonomous Control, Operation, and Protection of the FREEDM System

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Abstract: This paper presents the concept of autonomous control, operation, and protection for a future distribution system named FREEDM system. The system architecture is presented first. Targeted as a grid suitable for large scale integration of distributed resources, the FREEDM System uses solid state transformers to interface the medium voltage distribution system to residential AC and DC microgrids. Innovative autonomous control, operation and protection are proposed and discussed in this paper. Simulation and experimental results are presented to verify the main concept.

I. INTRODUCTION

The Future Renewable Electric Energy Delivery and Management (FREEDM) System Center is a US National Science Foundation (NSF) generation-III Engineering Research Center (ERC) established in 2008 with its headquarters at North Carolina State University, US. The center's objective is to develop the fundamental and enabling technologies for a future power distribution system called the FREEDM system [1].

Targeted as a future grid architecture suitable for large scale plug-and-play integration of distributed resources, the proposed FREEDM system is depicted in Fig. 1 and its feasibility is based on current and future progress of power electronics technology and information technology. The medium voltage AC grid (12.45 kV) is powered by a substation Solid State Transformer (SST1) from the 69 kV transmission grid. Several distribution-level SSTs are connected to the medium voltage system and transform the 12.45 kV to the low voltage AC (120 V) and DC (380 V), both of which can then enable the residential AC microgrid (AC MG) and DC microgrid (DC MG). A solid state fault isolation device (FID) is used to isolate the malfunction areas when the system is in abnormal condition, such as single phase or three phase faults. Bidirectional communication in the SSTs and FIDs deliver the system information to the control center and take the instructions from the control center. A completely decentralized software and communication architecture is also be researched by the center[1]. In summary, the key features of this innovative FREEDM system are:

1. Ability to form plug-and-play AC and DC MG that integrate distributed renewable energy resources (DRER) and distributed energy storage devices (DESD).
2. Intelligent power management (IPM) through the use of high bandwidth SST that directly controls medium voltage and low voltage interfaces.
3. Intelligent fault management (IFM) with ultra-fast and intelligent fault isolation capability of the FID.
4. Intelligent energy management (IEM) via coordinated optimization and dispatch of distributed resources.

One major challenge for such a system is to operate each component in a distributed fashion while maintaining system stability under all operation conditions. This is the objective of the IPM and IFM control. The instructions from the control center are too slow and can only be used for system monitoring, optimization and economic operation (the IEM functions). This paper aims at providing possible solutions for a truly distributed and autonomous control, operation, and protection of the FREEDM system.

The paper is organized as following. Section II introduces the main system operation modes of the FREEDM system. In Section III, a brief introduction of SST is presented. A truly distributed and autonomous IPM control strategy is proposed in Section IV. The distributed system protection with FID is presented in Section V. Section VI concludes the paper.

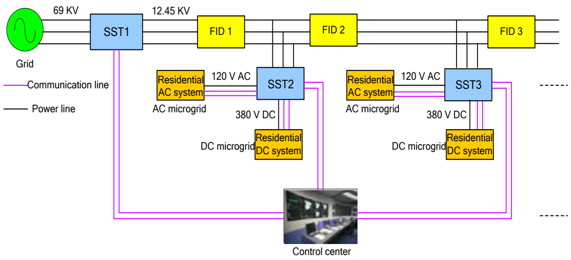


Fig. 1 FREEDM System diagram

II. MAIN OPERATION MODES OF THE FREEDM SYSTEM

Due to the use of substation and distribution level SSTs, and their ability to disable or enable any input/output interfaces under certain criteria, the FREEDM system has three main operation modes including: transmission connected mode, FREEDM system islanding (substation SST1 disconnects the FREEDM system from transmission grid), and SST islanding (SST2 or SST3 disconnects AC and DC MGs from medium voltage grid). The proposed IPM control must therefore be capable of controlling the key system parameters (i.e. voltage and frequency) in all three modes and must automatically switch between these modes. Fig. 2 depicts the three system modes and the key criteria used for transition between any two modes.

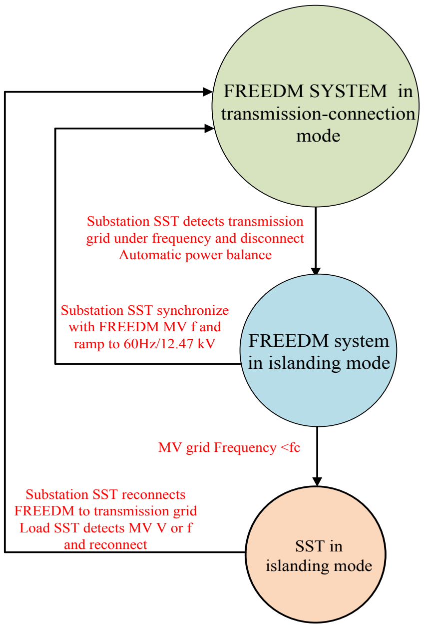
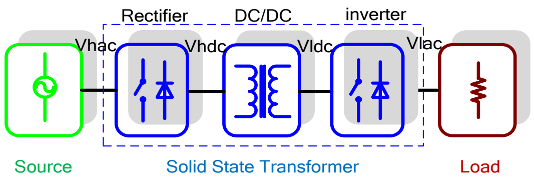


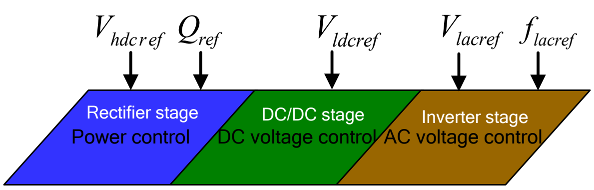
Fig .2 FREEDM System's three main modes of operation

III. SOLID STATE TRANSFORMER (SST)

SST is a power electronics conversion device with AC input and AC and DC output. Voltage transformation is achieved through a high frequency (10-20 kHz) transformer and power electronics control. A three-stage topology shown in Fig.3 (a) is typically used for the SST. The low voltage DC output can be used to form the DC MG and the low voltage AC can be used to form the AC MG. SST transfers power between its input and output. A typical internal control of the SST is shown in Fig. 3(b). The rectifier stage regulates the active power transferred, which is ensured by regulating the high voltage dc bus, as well as the reactive power supplied to the medium voltage grid. Qref can be set to zero to allow the SST to operate under unity power factor condition. The low voltage dc bus is regulated to a reference value, such as 380V, by SST's dc/dc stage and this bus is interfacing with DC MG. In addition, the inverter stage supplies regulated ac voltage for the residential AC load or AC MG [2]-[4].

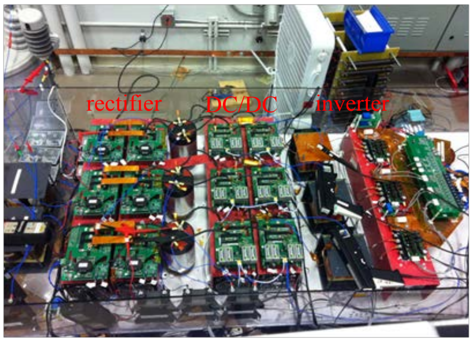


(a) Configuration of the SST

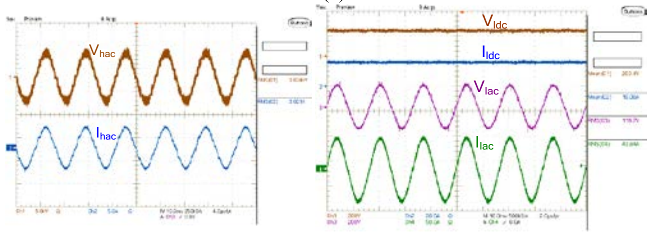


(b) typical SST control

Fig .3 Control for single SST



(a)



(b) (c)

Fig .4 SST hardware test bed and steady state operation of SST: supply power to both ac and dc port

Development of SSY relies on the progress of high voltage power semiconductor devices such as 6.5 kV Si IGBT and 15 kV SiC MOSFET. At FREEDM System center, several major efforts are underway to develop distribution class SST. Fig.4 shows a 10kVA single phase SST developed and the test result when it delivers power from a 3.6kV ac grid to 200V dc and 120V ac residential grid.

IV. AUTONOMOUS CONTROL STRATEGY FOR THE FREEDM SYSTEM

<u>SST Control Strategy:</u>

The control shown in Fig.3 is typical for a single SST operation. However, the FREEDM system involves many SSTs and three main operations modes. One of the greatest challenges is to have a control strategy that will work for all three modes and for all SSTs. More broadly, we must have a control that can maintain the system stability for the whole FREEDM system. This means the main system parameters such as voltage and frequency must be controlled at all times. There are three major devices that are responsible for the control: the substation SST, the distribution SST and DC and AC microgrid. To simplify our discussion in this paper, we will only focus on DC MG. Since voltage and frequency must be controlled with high bandwidth (<1 cycle), communication system cannot be used. A truly distributed and autonomous control must be used for all SSTs and DC MG.

In transmission grid connected mode, medium voltage grid voltage and frequency are controlled by substation SST1 and distribution SSTs (SST2 and SST3) interface medium voltage grid with low voltage AC and DC MGs. SST2 and SSt3 are not responsible for controlling the MV grid voltage and frequency, and are only responsible for controlling the DC MG voltage. Power flow under this mode of operation is not an issue as we can draw power drawn from the transmission grid or send power to transmission grid, the control of power flow in this mode can be based on consideration from economic dispatch point of view to dispatch available distributed resources. This is the function of the IEM and will not be discussed further in this paper.

When the substation SSTs detects a transmission grid failure (under frequency, Fig. 2), SST1 disconnect the FREEDM system from the transmission grid and enters the FREEDM islanding mode. Conventional power distribution system has to shut down when the transmission grid is in fault condition. While in FREEDM system, the distributed energy resources and storages in AC and DC MG may provide enough power for all loads or critical loads hence FREEDM system islanding is *physically* feasible. For this mode to be stable, system power balance must be immediately established in order to maintain the medium voltage power system stability.

When the system power is unbalanced, the MV grid frequency is abnormal (lower than 60Hz when there is a lack of power and higher than 60Hz when there is excess of power). Thus, this frequency can be used for the distribution SST to detect mode transition from grid connected to FREEDM system islanding, and adjust its control the achieve power balance. On the other hand, all power sources are connected on the low voltage DC side of the SST. Hence a novel strategy is to implement a control that relates the MV grid frequency to the low voltage DC reference. This novel control strategy, called frequency to DC voltage droop, is shown in Fig. 5. In this control strategy, once the frequency is no longer 60Hz, the low dc side voltages of SST 2 and 3 are no longer the constant values but proportional to the MV grid frequency.

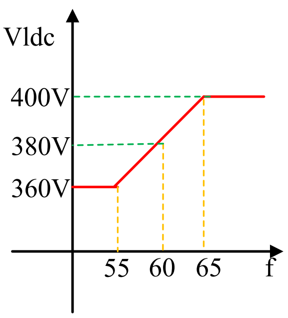


Fig .5 Frequency to DC voltage droop control of the SST

In this control, the DC bus voltage range is defined as [360, 400] and the frequency range is [55, 65]. When the freqeuncy is lower, the DC voltage is also lower, informing the DC MG devices (PV, storage, load etc) that there is a need to reduce power consumption and deliver power to the MV grid. By Figure 5 control, there is no change for SST low dc voltage control in both transmission connection mode and this FREEDM islanding mode. When the system is in the transmission connection mode, the frequency is fixed as 60 Hz and the voltage will be always controlled as 380 V. While the ac voltages at input and output side are still controlled by rectifier stage and inverter stage respectively. If the power balance will not be achieved and the MV grid frequency goes out of the range [55, 65], the SST will shut down its rectifier stage and disconnect the DC MG from the MV system, the system will enter the third operation mode: SST islanding. In this mode, the DC MG can still operate and power the load connected to the DC as well as those on the low voltage AC side. However, power balance in the low voltage DC and AC systems must also be achieved for this mode to operate.

When the transmission grid recovers, the substation SST (SST1) will start up and reconnect the FREEDM system with the transmission grid. The reconnecting strategy is straightforward since SST1 can provide the needed frequency synchronization. These are also shown in Fig.2

Autonomous DC Microgrid Control

DC MG control must be able to respond to the signal provided by the SST (Fig.5) and change its power flow to maintain system stability. A typical DC MG [5] is depicted in Fig. 6, which is consisted of renewable energy sources (PV), energy storage (battery) and load. The load is divided into the critical load and non-critical load. Critical load is always connected to the system while the non-critical load can be shed when the system power is short. Battery can be considered as the energy buffer because of its ability of charging and discharging. For high bandwidth IPM functions, the control of all DC MG resources must also be distributed and autonomous instead of hierarchical [6]-[7]. Communication ports are needed to monitor these devices for IEM functions under normal grid connected mode but will not be used for IPM functions. For example, under normal grid connection mode, the battery can be charged or discharged based on economic dispatch signals from the communication/software.

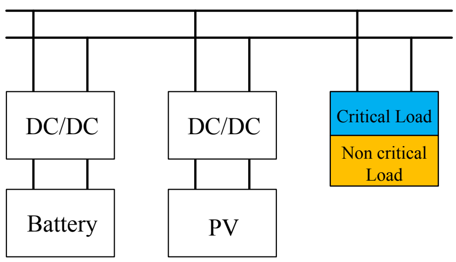


Fig .6 DC MG diagram

a. Battery control

The proposed battery control diagram is shown in Fig. 7 which can operate under all three modes. The battery's power flow is responding to SST command by a voltage to power droop control. Thus, when SST low dc voltage changes, the battery output power varies. A specified dead band area [377, 383] is defined as the area for the battery to accept the IEM instructions to operate in constant current charge or discharge mode. Also two voltage limiters are defined for the bus voltage range. The high value is 410V and the low value is 350V, which are different from the SST droop range. The more details for these two values will be discussed in following section (SST in islanding mode).

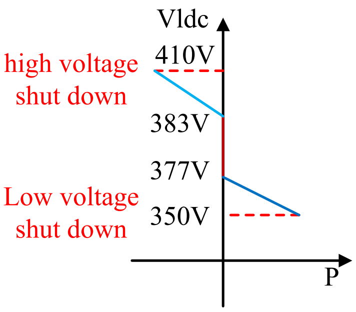


Fig .7 battery voltage droop curve

b. PV control

The PV control diagram that can work for all three modes is shown in Fig. 8, which consists of two control algorithms. When the bus voltage is less than 400V, the PV is always in MPPT. While the bus voltage is greater than 400V, PV switches to voltage control mode. Then its output power decreases to avoid the bus voltage reaching the high limiter.

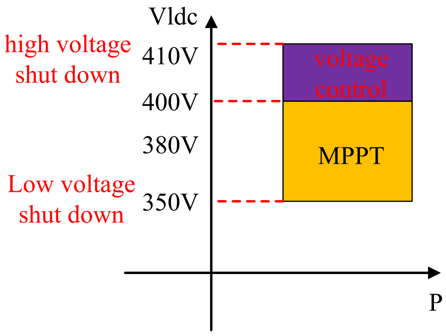


Fig .8 PV control diagram

c. Load control

Autonomous load control is needed to achieve system power balance. The load is categorized into different levels. The critical load is always connecting to the system. The non-critical load can be shed based on their predefined level and bus voltage. The load control diagram is depicted in Fig. 9.

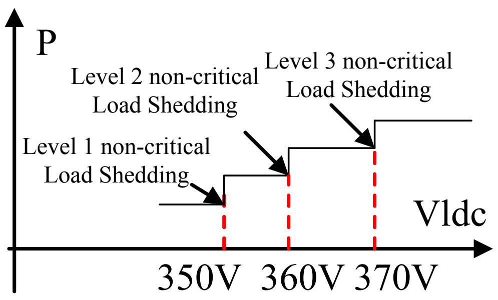


Fig .9 Load shedding control diagram

Control of SST islanding mode

When DC MG can't supply enough power to regulate the medium voltage bus, the MV frequency will keep decreasing. When it is less than 55 Hz, the SSTs enter SST islanding mode. In this mode, the rectifier and DC/DC stages of the SST will stop, then only DC MG supply the load and low voltage AC inverter stage. This is the reason why the battery droop control voltage range is greater than SST droop control range. It's easily to conclude that the control algorithm proposed for DC MG also works for this mode. When the SST detects the MV grid recovering, the rectifier and DAB stages starts and the system goes back to the FREEDM transmission grid connected mode.

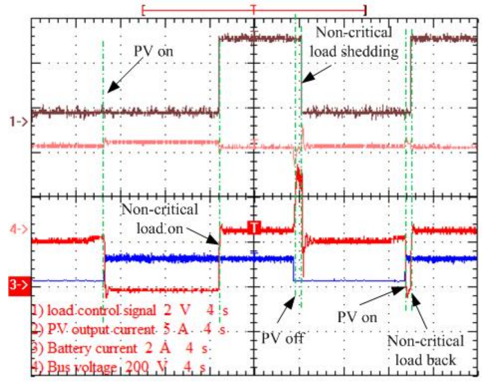


Fig. 10 Waveform for load shedding and back

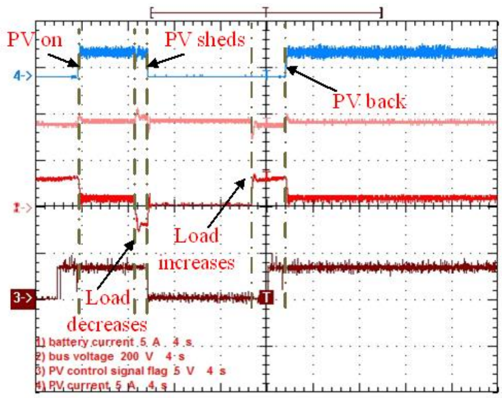


Fig. 11 Waveform for PV shedding and back

Two experiment results for load shedding and PV standby are shown in Fig. 10 and 11.The worst case for bus voltage dropping is that only battery supplies the power to the load without PV. Initially, only one battery supplies the critical load. The battery outputs power to the load. Then one PV parallels to the system and its output power is greater than load, thus the battery switches to the charging mode and bus voltage increases. Then the non-critical load connects to the system, the battery has to go back to discharge mode to output power and bus voltage droops. While the value of bus voltage is still than the threshold value for load shedding, the critical load still connects to the system. When PV has no power to the system, the battery output power increases and the bus voltage keeps decreasing. Since the time value for the bus voltage filter is 0.5 s, after 0.5 s as the bus voltage less than 365 V, the non-critical load is shedding from the system. Then bus voltage gets some recovery. When the PV is back to the system, the bus voltage increases and the battery output current decreases. Same as the load shedding, after 0.5 s as the bus voltage greater than 380 V (threshold value for load back), the non-critical load reconnects to the system. After the load back, PV output power is less than the load, so the battery is in the discharge mode.

For PV shedding case (Fig.11), initially, the battery supplies the critical load alone. Then PV panel connects to the bus and supply the power to the system. The bus voltage increases and the battery output current decreases. But the battery still output power to the load and the bus voltage is less than 380 V, so the PV is still on the MPPT mode. As the load decreases to zero, the bus voltage increases and the battery switches from discharging mode to the charging mode. Since the time value for the bus voltage filter is 0.5 s, after 0.5s as the bus voltage is greater than 395 V, the PV is in stand-alone mode and no output power to the system. Then the battery's output power is almost zero and the bus voltage is 380 V. When the load is back to system, the bus voltage decreases and the battery output current increases. Different from the PV enters to standby mode, after 1.5 s as the bus voltage is less than 375 V, the PV is back to MPPT mode from standby mode because there is about 1 s for PV module soft-start time. After the PV back, the voltage gets some recovery and the battery output current decreases.

V. AUTONOMOUS PROTECTION STRATEGY FOR FREEDM SYSTEM

A typical solid state FID structure that is used in FREEDM system is shown in Fig. 12. This FID includes four diodes to provide the bidirectional power flow and a solid-state switch for interrupting the current.

A novel autonomous fault detection and isolation algorithm is proposed based on the v-i characteristics of solid-state switches [8]. The two-piece linearized V-I characteristic of a generic solid-state switch (i.e. IGBT or MOSFET) is shown in Fig. 13. This characteristic is composed of two regions. First is the saturation region where the voltage drop across the device is very small compared to the line voltage, and this is for currents smaller than the knee point current in the characteristics. The second region is the active region where the terminal voltage of the device reached the line voltage for currents greater than the knee point current of the characteristics. The knee point current of the characteristics is controllable using the gate voltage of the device.

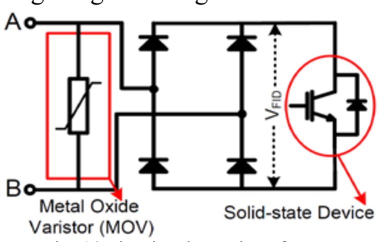


Fig. 12 circuit schematics of FID

When a fault happens in the system, the current through the FID goes beyond the knee point of the characteristics resulting in an increase in terminal voltages of the device. So, by sensing the terminal voltage of device, a fault in system can be detected.

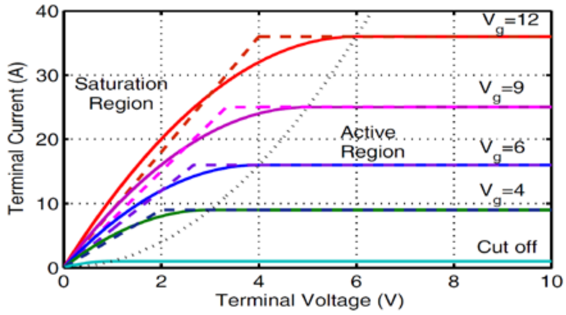


Fig. 13 two-piece linearized characteristics of an IGBT or MOSFET for different gate voltages

1). Coordination in radial systems:

A generic radial network is illustrated in Fig. 14. Optimal coordination of FIDs in such radial networks is a simple and straightforward task. Based on the minimum fault current level 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.

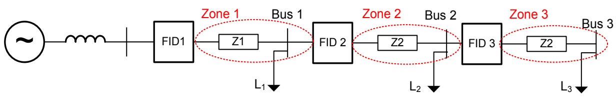


Fig. 14 Single line diagram of a radial electric network with presented FIDs as protection devices

2). Coordination in loop networks.

Since the current can flow in both directions in a loop network, the simple coordination procedure as radial networks cannot be used since it fails in the objective of providing un-interrupted current to all but fault parts of the system. So, instead of using time-inverse relays to reach maximum restoration in the system a new reclosing strategy is proposed in this paper.

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.

The reclosing procedure that is used in this paper is explained using the flowchart of Fig. 15. Fig. 16 demonstrates each step if this procedure for fault on bus number "three" of the sample loop system. Each state of the system in Fig. 17 is marked by the same letter with Fig. 16.

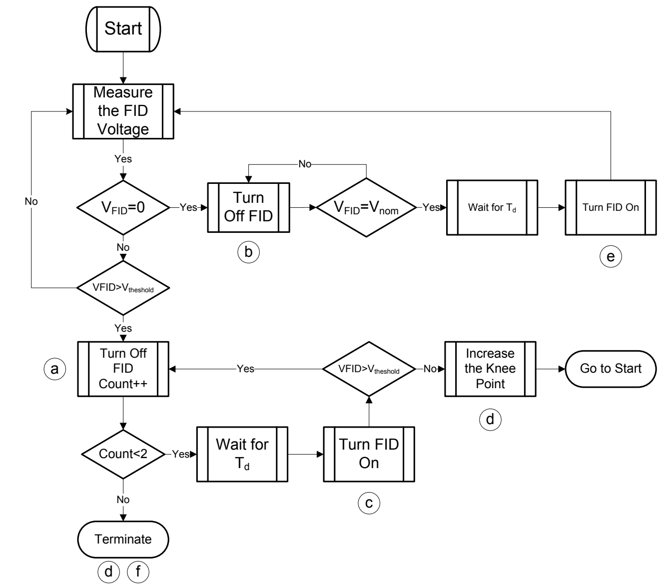


Fig. 15 Flowchart of the proposed re-closing algorithm

3). Experimental results:

The system of Fig. 15 is implemented using five FIDs as it is shown in Fig. 16. A zero impedance fault is created a bus number "three" and the results are presented in Figs. 18 and 19. Fig. 18 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 within a short time interval. As it can be seen in Fig. 18, after the re-closing moment (2), Bus 2 remains energized so, only for an interval of less than 1.5*ms* 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.

Fig. 19 demonstrates 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 41.2μs compared to 10 to 20 cycles in conventional circuit breakers.

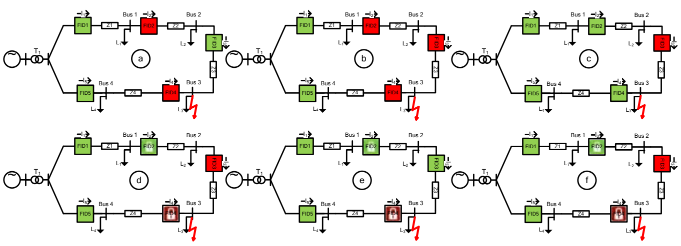


Fig. 16 implement of the proposed re-closing algorithm

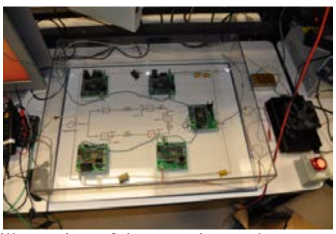


Fig. 17 illustration of the experimental setup prototype

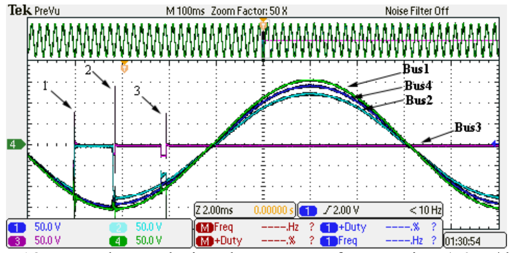


Fig. 18 Bus voltages during the process of restoration (50 V/div)

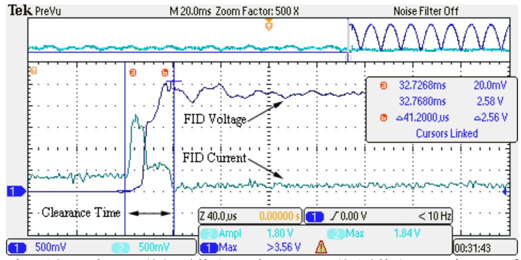


Fig. 19 Voltage (30V/div) and current (2A/div) transients of FID2 during the fault clearance process

VI. CONCLUSION

This paper presents the concept of autonomous control, operation, and protection for a future distribution system. The system architecture, which is the FREEDM system, is presented in this paper. Solid state transform is adopted to interface the distribution system to residential AC and DC micro-grid. The corresponding autonomous control structure, system operation and protection schemes are proposed. Experimental results are presented to verify the main concept of the proposed method.

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