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Standard-based Engineering and Distributed Execution Framework for Intelligent Fault Management for FREEDM System

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***Abstract* - This paper proposes standards' based software and communication platform for implementation of distributed grid intelligence in FREEDM system. This enables system level design for distributed application and consistent mapping to the interfacing hardware. The system becomes scalable, re-configurable and easily maintainable. Applying IEC 61499 standard for distributed and embedded applications and IEC 61850 standard for communication in substation, multi-agent design can be systematically introduced to power system automation. With this approach distributed grid intelligence nodes become intelligent, independent and interactive agents, with vendor independent software and unified communication. This concept is illustrated on an example of distributed intelligent fault management system, and verified through simulation.**

Keywords: FREEDM, IEC 61850, IEC 61499, intelligent fault management, protection, GreenHub, distributed intelligence

I. Introduction

A. *Energy Internet*

To reflect the need for the smart and robust electrical grid, the Future Renewable Electric Energy Delivery and Management (FREEDM) centre has developed "Energy Internet" concept, the vision for the future power system, and is proving this by building the real-life prototype FREEDM system [1].

Energy Internet has three key elements: plug and play interface (like a RJ45 Ethernet), an energy router that manages energy flows to the right place and an open-standard operating environment [1].

The plug-and-play interface is the universal electrical interface, allowing distributed generation (DRER), battery (DESD) and loads connect seamlessly into the electrical network. This can be achieved by utilising advanced power electronics technologies and materials. This plug-and-play interface must also contain open-standard-based communication interface, so that the device plugged into the grid is instantly recognised. FREEDM defines that the communication standard must be able to describe loads, storage devices and generating units.

The second feature is the energy router. FREEDM proposes IEM devices, which understands the above protocol and recognise and manages all the devices. These devices are connected to the low voltage bus of the IEM. IEM is based on Solid-state Transformer (SST) device which performs physical power and energy control and voltage step-down function, DGI software and communication interface.

The third feature is the operating environment, which in FREEDM system is DGI – Distributed Grid Intelligence. DGI controls the FREEDM system. DGI is distributed across the IEM and IFM devices, therefore each IEM and IFM runs a portion of DGI. Through collaborative multi-agent behavior of IEMs and IFMs, GDI provides a smart optimal operation of FREEDM system by executing power balancing, fault isolation and other control algorithms.

Fig. 1 shows the FREEDM system control architecture. First level is the user level, where residential and industrial generation, batteries and loads are connected to the electrical grid. The second level of the control is SST level, where IEM is regulating and managing the power and energy through SST and its capabilities. The third level of the hierarchy is FREEDM system level, here where the controls are implemented as DGI environment system and resides in each IEM and IFM devices. There are two controls at this level – IEM and IFM. Multiple such FREEDM systems which form large regional grids are coordinated at the 4th level.

B. *Challenges*

Several challenges of the FREEDM system development have been outlined in [1].

The challenge with the first key technology – plug and play interface – is lack of communication standard, which unifies communication in the power system domain and defines self-awareness of the devices in the grid. Development of this standard will lead to plug-and-play protocol for the Energy

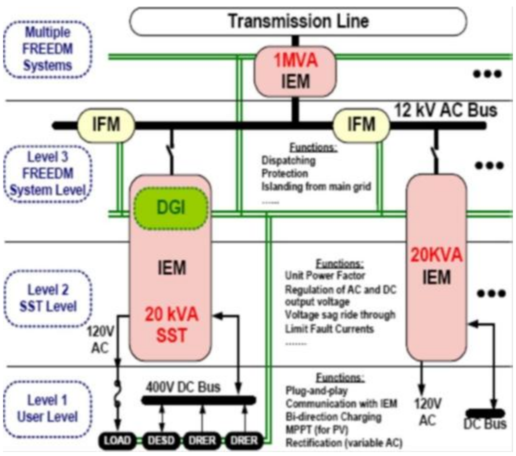

Fig. 1. Control Schematic of FREEDM system [1].

Internet [1].

For the second and third key aspects, the are two main challenges regarding IEM identified by the FREEDM centre: 1) the recognition and integration of DRERs, DSEDs and load (plug and play capability) and 2) the development of intelligent power and energy management schemes (DGI).

FREEDM centre envisions that the major challenge will be implementing system controls in a distributed manner across multiple different execution platforms (i.e. IEM and IFM). Solution to the above problem, FREEDM expects to be the development of an open-source-standard-based software and communication platform to implement DGI [1].

In this paper we propose a cyber-physical approach to FREEDM centre's solution. We propose an open-standard based framework for power grid distributed control implementation.

Solution to the two other challenges is outside of the scope of this paper. The integration of the DRER, DESD and load with IEM is to be solved and implemented on a physical level, where these devices are connected through ac or dc port (similar to "USB" port on a computer system).

Development of the actual control algorithms and schemes to be implemented is in power system domain and out of scope of this paper.

C. Paper structure

Next section outlines the contribution of this paper. IFM concept and FREEDM system novel protection are introduced in section 2. Section 3 shows development of IFM and FREEDM control system using our approach: mapping FREEDM protection system to LNs and modelling it using intelligent logical node (iLN). Also the section demonstrates a system level modelling for IFM FREEDM protection. Section 4 presents the co-simulation environment developed and simulation results.

II. Contribution of this paper

A. Contribution to FREEDM system

This paper proposes the solution to the major challenge described above: implementation of control in a distributed manner. Our approach is to combine capabilities provided by two international standards: IEC 61850 and IEC 61499, which will provide an open-standard-based software and communication protocol.

The IEC 61850 protocol provides communication interface between devices, ensuring interoperability, unified communication protocol and standardised data modelling (structure) [2]. It enables self-awareness of the devices and automation functions. The standard promotes and encourages hardware independent system design. IEC 61499 is an industrial standard for distributed systems design; it is a programming language based on event-driven Function Blocks architecture [3]. Execution of a function block is invoked by an event to perform designed algorithm. IEC 61499 is particularly designed for developing distributed applications; it enables system level design and hardware independence at the development stage. It promotes modularity, re-configurability and re-usability of the design [3]. Function blocks are convenient and natural way to design multi-agent systems (MAS).

Implementation of power system standard by means of function blocks brings together the benefits of these advanced technologies [4, 5]. Moreover it brings possibility to implement MAS in power system domain [5-7], i.e. possibility to implement DGI which is distributed multi-agent system composing of IEM and IFM agents closely interacting with each other to achieve optimal operation of the electrical grid. The proposed approach enables plug-and-play feature by providing standardised communication protocol designed specifically for power system domain and function block platform for designing modular, re-usable and reconfigurable systems.

Thus, the proposed approach attempts to solve the major challenges defined in FREEDM system:

- the implementation of all controls in a distributed manner across IEM and IFM devices;
- the recognition of DRERs, DSEDs and load (i.e. plug and play capability), this includes an open standard based communication interface.

B. Contribution to IFM project

The decision what software and hardware platform to use for implementation of IFM and IEM has not been made [1]. This has been subject to availability of advanced technologies including software that allows implementation of control algorithm in a distributed manner and hardware with the required performance and capability. Currently control algorithms for DGI (IEM and IFM) are simulated using high level programming languages and running on PC [8, 9]. Particularly, IFM protection algorithm has been implemented using LabView and running on a PC [8]. This is because FREEDM centre has yet to define a suitable software and communication platform to implement IFM DGI.

Contribution of this paper to the IFM project is implementation of IFM using proposed approach, thus enable real-world realization of IFM (DGI). Interoperability, provided by 61850 communication protocol, ensures seamless interface between AMU (analogue merging unit) sending the samples and IED or PC making decisions based on received samples, regardless of the media used (Ethernet or fiber optic) [6]. Currently the whole IFM system needs to be simulated, then, after it has been proved, the algorithms need to be re-written for the hardware platforms to be used in real system. The proposed approach allows design of the control, simulation and validation of the system while using a single tool chain. After the control logic has been validated, it can be directly distributed across available devices and executed [3]. Both IEC 61499 and IEC 61850 ensure hardware independent design and interoperability between devices from different vendors [2, 3, 10].

Work undertaken within the scope of this project: 1) The given simulation of IFM concept includes simulation of the real-world and control algorithm (IFM algorithm): separation of the control and simulation parts has been carried out and a definite picture of the model and control acquired; 2) implementation of the IFM algorithm using state of the art technologies such as IEC 61850, that enables FREEDM system and IFM in this project with standardised communication protocol, and IEC 61499, which allowed implementation of DGI in a distributed manner and enables FREEDM system with MAS capabilities; 3) developedsystem is validated using the co-simulation environment; 4) the system level design has been distributed across multiple devices and executed.

III. Intelligent Fault Management

FREEDM project has proposed a novel protection scheme, which is faster than conventional protection [8]. The main concept is to divide the system into zones, using FID – fault isolation devices (new generation circuit breakers). Thus FID is at the borders of each section. The FREEDM protection strategy is shown on Fig. 2. The protection scheme is divided into three zones and an overall zone 0. Zone 0 protection is a backup protection for overall system. At each zone AMU is placed at the terminal of distribution line and the feeder of the load to measure current, digitize and transfer the sensed

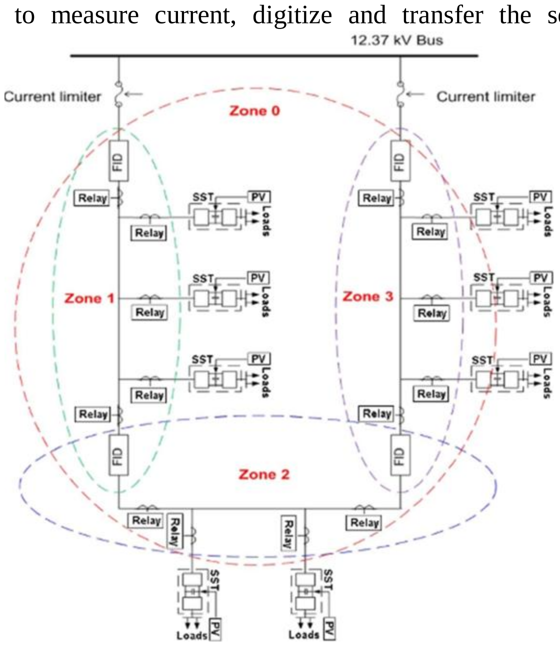

Fig. 2. FREEDM protection for FREEDM loop. Division on zones [8].

values to IFM. Each zone has an IFM which runs the protection algorithms and incorporates DGI – distributed grid intelligence. The overall protection scheme consists of primary and secondary protection.

Primary protection used is the differential scheme: if the sum of current in a zone equals zero, it indicates either there is no fault or fault is outside the zone of that IFM. In case the sum of the currents within a zone is not zero then the fault is within the zone and IFM makes decisions to trip the FIDs at the border of the faulty section. GPS time stamps are attached to each samples sent from AMU to ensure accuracy of the protection algorithm. IFM collects the sampled values from AMUs with similar time stamps and sums up these values to check if it is zero. If the sum is not zero, it holds the value and counts next coming data. If the sum is not zero for all next 10 samples, then IFM makes decision that there is a fault within the zone. IFM sends a trip signal to FIDs on the border of the zone to isolate the faulty section. In case of zero sum for any of the next 10 samples, IFM concludes that there is no fault in the zone, and resets the counter. This protection algorithm mostly relies on working of IFM, which in this case can be a computer or digital relay.

The secondary protection for this system is overcurrent protection. In this case IFM examines each incoming current sample; then compares against pre-set current value, which can be 3-5 times of the rated current. If the received sample is larger than the given set value, IFM starts counting and evaluating next 15-20 samples and if all the samples are greater than pre-set value, IFM issues the trip signal to the FID. Otherwise, IFM re-sets the counter and start evaluating forthcoming samples.

Zone 0 protection is differential protection described above, the current from zone 1, 2, 3 are evaluated at the central IFM, and in case of fault, trip is sent to corresponding FID.

FREEDM centre has prototyped this algorithm using LabView. Fig. 3 demonstrates the developed model [8]. The model includes three-terminal section, including two lines and a load. The 3 signal generators represent current at the terminal sections. Sampler is a model of AMU, samples the current and passes it to algorithm units. The differential and overcurrent units are placed in parallel.

IV. Cyber-physical approach for implementation of IFM nodes (DGI)

A. iLN mapping

The control algorithm consists of differential and overcurrent protection. IEC 61850 models these functions as PDIF and PIOC Logical Nodes [2]. In the protection scheme IFM sends trip signal to CB, therefore the control system should have CB model. According to the standard, CB is modelled as XCBR LN. Thus PDIF LN or PIOC LN issues

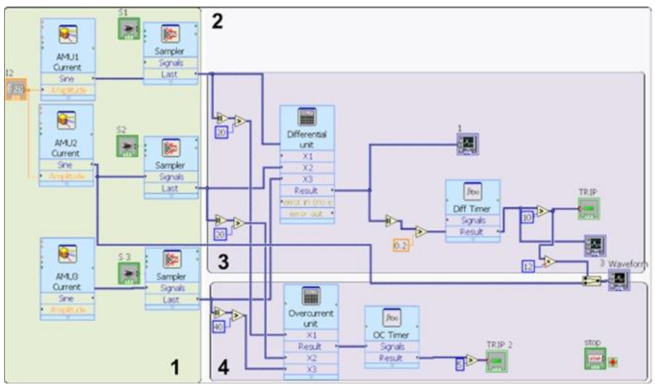

Fig. 3. Mapping control algorithms to the corresponding iLN.

trip signal to XCBR LN.

Fig. 3 shows the mapping given system simulation model to the iLNs. The real world part of the simulation, i.e. the utility model, is modelled and simulated in Matlab. The hardware parts (Fig .3, 1) of the control system shown – AMU and samplers – are decided to be moved into Matlab as they do not perform any intelligent tasks. The intelligent logical nodes are to be iPDIF and iPIOC; they will execute differential and overcurrent protection algorithms correspondingly. In the Fig. 3, Part 3 represents the differential protection and it is assigned to the iPDIF iLN, part 4 – is overcurrent protection and it is assigned to iPIOC iLN.

Thus control parts and the model (simulation) of real world is separated and a distinct picture of the control system acquired. Fig. 4 shows the Green Hub Matlab model and the corresponding protection system mapped to IEC 61850 and implemented in IEC 61499, following the rules defined in [4,

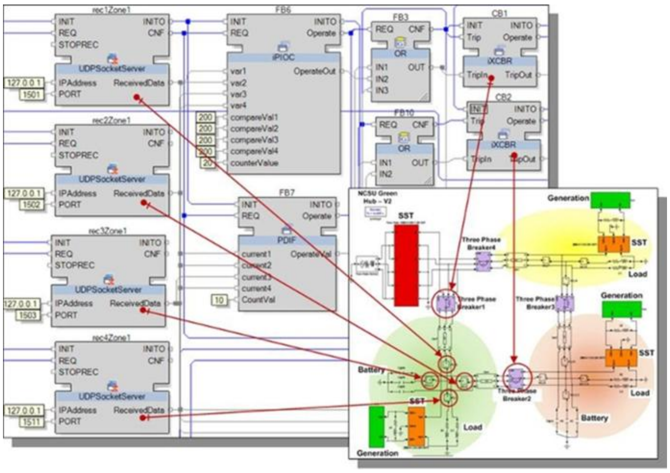

Fig. 4. Control system for one zone of the Green Hub system.

7].

For simplicity, only one zone is exemplified in Fig. 4. The control system consists of FBs – LN from the developed LN library. There is a direct relation (mapping) between equipment and automation functions used in the Green hub system and corresponding FBs (iLNs) in the control model: circuit breaker – iXCBR, receiver of digitalized current samples – UDPSocketServer, differential protection – iPDIF and overcurrent protection – iPIOC.

B. *Developing protection algorithms within the iLN*

The system is modelled as the following set of iLNs:

iPDIF consists of intelligence (logic), which performs the differential protection algorithm (user defined behaviour of this FB), and database – PDIF LN [7]. DB is the collection of mandatory and optional data according to IEC 61850 [2], and performing standard services over the data [10]. Fig. 5 demonstrates iPDIF.

DifferentialUnit4 function block is summing 4 input currents, allowing a configurable restraint ratio and number of consecutive instances where summed current is not zero . In this case restraint ratio is taken from iPDIF database, and the number of instances is set to 10. This LN performs the same task as part 3 in Fig. 4, including timer and comparison element. Fig. 6 demonstrates internals of the

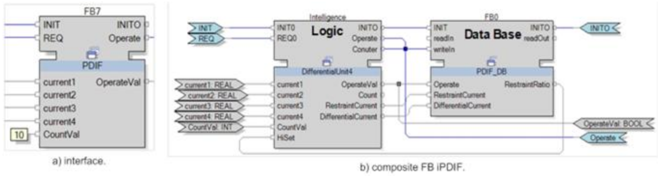

Fig. 5. Differential protection Logical Node – iPDIF.

DifferentialUnit4 block.

"Sum4" block calculates the sum of the incoming current samples, then it outputs sum, average current and ratio current to "compare" block. This block outputs signal Boolean "true" in case the sum is not zero (5% tolerance is considered). "counter" block counts how many input signals with value "true" was received and trips the circuit breaker ("operate" signal) if the number reaches "compareValue" (in this case

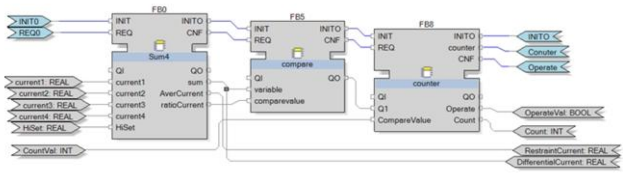

Fig. 6. Logic block of iPDIF iLN.

10). Values of restraint, differential current and "operate" data are written into database and kept updated.

iPIOC is designed in a similar manner to an iPDIF. It can handle up to 4 current inputs. If either of them exceeds the pre-set value for 15-20 samples, iPIOC iLN will initiate trip signal to iXCBR.

"OvercurrentProtection" block performs the same algorithm simulated in part 4 in Fig. 3. Each "overcurrentUnit" block compares the input current with pre-set "CompareValue", and if number of fault current samples configured "CounterVal", the block issues "OperateVal" signal. "OR" block monitors the zone, if one of the overcurrent units senses fault, it will send trip to iXCBR.

C. *System level design: Distribution of the control logic*

The advantages of the function blocks architecture are the intuitive visual design and the ease of distribution. Now, having a full library of necessary standard iLN, it is easy to implement a given protection/control system. Given protection system is implemented by dragging and dropping necessary iLN, following the topology of the system. Consequently there are three zones in the control model. Each zone has same control/protection scheme, therefore iLNs used in all zones for the same function are the instances of the same iLN. For example, iPDIF1 in zone 1 and iPDIF2 in zone 2 are the instances of same iPDIF FB. Thus the IEC 61499 architecture provides code re-usability. Fig. 7 presents FB control model. In the right bottom corner the Matlab model of

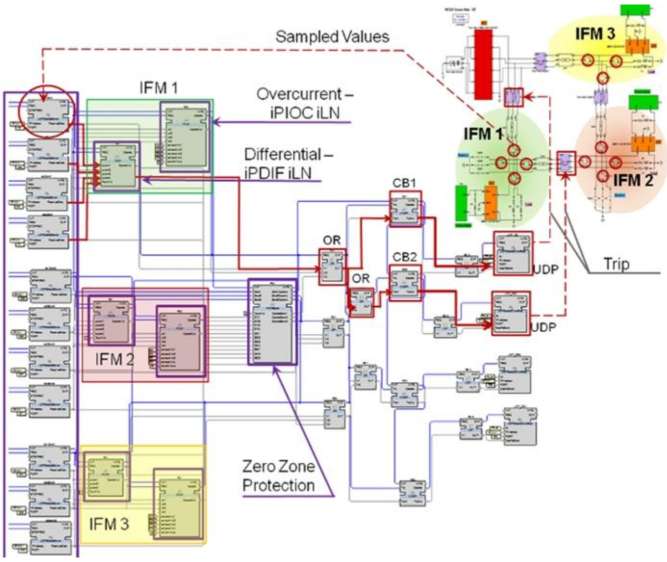

Fig. 7. System level design of the FREEDM protection scheme.

Green hub is presented, which was provided by FREEDM centre project partners. Current is measured at the given points and transmitted to FB model through UDP sockets. There is one FB to one UDP socket.

DGI in form of IFM is distributed across all zones, each zone runs portion of DGI: there is an IFM for every zone. The processed current is fed to differential protection unit within the IFM – iPDIF. Each zone has the instance of the iPDIF FB. iPDIF, estimates the given samples, and in case of fault decides to initiate Operate (Trip) signal to circuit breaker – CB – iXCBR. As in our case 2 zones are sharing a CB, therefore trip signal goes to "OR" FB first (Fig. 7). XCBR sends trip signal through UDP to Simulink model of circuit breaker.

Same flow of data and signals applies to secondary protection. iPIOC accounts for the secondary overcurrent protection.

Zero zone protection is one for the whole system – and it performs backup protection. Zero zone protection is implemented as differential protection as well – iPDIFZone0.

Each IFM comprising of iPDIF and iPIOC - is placed within each zone. They are agents performing local decision making and contributing into Distributed Grid Intelligence for protection/control of the overall electrical grid.

Each function is implemented as a module, so the design is tidy, easy to follow, maintain, re-use and re-configure the system.

Fig. 7 demonstrates a system level design of protection/control system for given Green hub model. At this stage the design is purely hardware independent. The implementation of the protection scheme can reside in a single IED/PLC/PC (i.e. physical device) or be distributed across four devices according to the topology of the grid. In this case the communication between the physical devices is using IEC 61850 protocol. Trip signals from control device to primary equipment circuit breaker are sent by means of GOOSE messages, current samples from AMU to IFM control device using the "sampled values" concept [10]. The

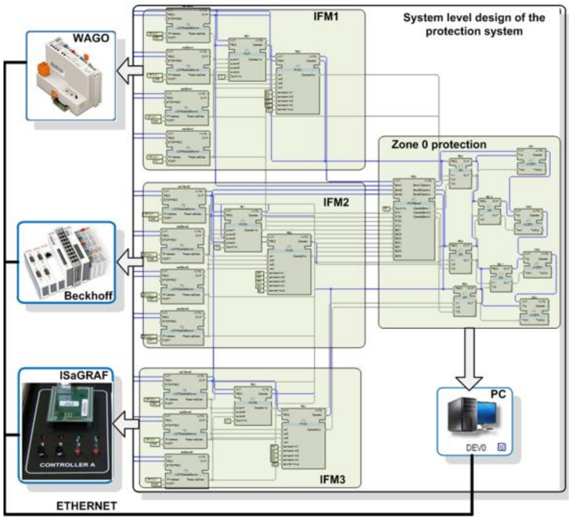

Fig. 8. Control system distribution, mapping to available hardware.

communication between control devices follows client-server protocol defined in IEC 61850 [10].

Fig. 8 shows distribution of the DGI control logic over physical devices.

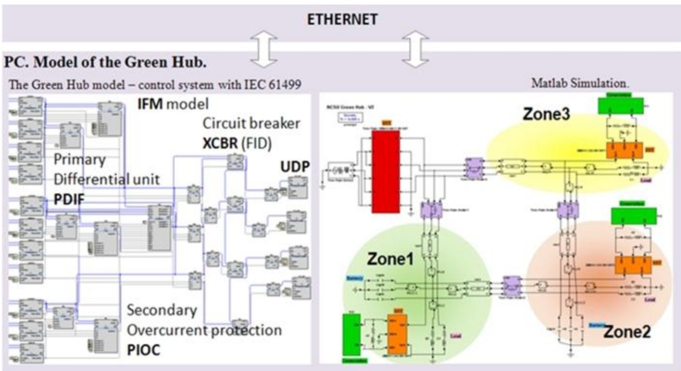

Fig. 9. Developed co-simulation environment.

V. SIMULATION AND RESULTS

Implemented control system is validated using developed co-simulation environment. Fig. 9 illustrates the concept of the simulation method.

The given Matlab model of GreenHub system runs in parallel with implemented protection scheme for that system. Sampled current values from Matlab and trip commands from the FB control model are sent by UDP. This is the same approach as used in FLISR multi-agent system [7]. Function block control model is developed using nxtControl 1.4 development tool [11].

The fault is simulated to occur in zone 3, where IFM 3 is operating. All IFM agents are constantly monitoring current within assigned zones. IFM 3 will notice that the current is out of balance, when sum of the current samples is not equal to zero. It starts counting the number of consecutive instances where summed current is not zero. Once the number reaches pre-set value, in this case 10, IFM sends the trip signal to XCBRs 3 and 4, which will isolate the faulty zone by tripping (Fig. 10). Fault is simulated at approximately 0.18 seconds. IFM has isolated the fault at approximately 0.2 seconds. This is simulation time and does not correspond to real time due to

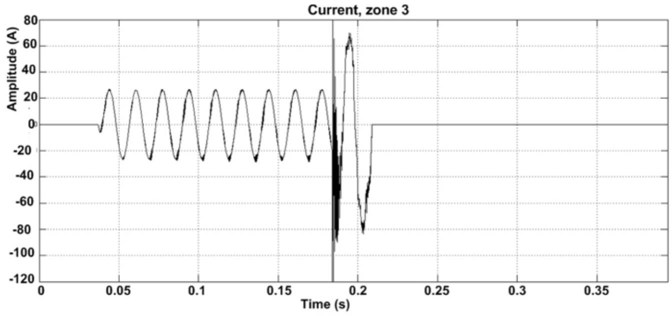

Fig. 10. Current on the load in zone 3.

computational overhead. This timing limitation of the simulation software Simulink is being investigated.

The other IFMs will sense the fault in the overall system and sum of the currents in the zone is no longer zero, however, since the result does not exceed the differential slope, these IFMs do not trip. Thus selectivity of the protection scheme is ensured. After isolating the faulty zone, the current within the non-faulty zones return back to steady state and normal operation (Fig. 11).

CONCLUSION

This paper presents a cyber-physical approach to implement DGI for FREEDM system. The approach is based on two standards IEC 61499 and IEC 61850. Combination of these brings together benefits of distributed systems and unified communication protocol. This approach enables and enhances power system with multi-agent technology and its advantages. Developed IFM control system is directly executable on available hardware supporting IEC 61499 and IEC 61850. There is no overhead of re-implementing validated algorithm to specifically adapt to the capability of selected hardware.

Immediate future work is defined to implement IEM nodes, demonstrate the power balancing scheme for FREEDM system. Here agents are interactive and make collaborative

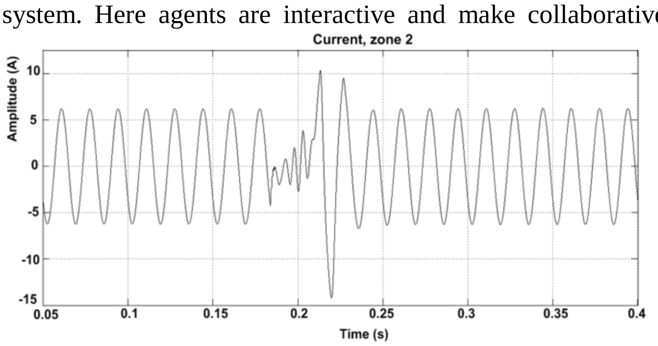

Fig. 11. Current on the load in zone 2.

decisions. This use case will demonstrate multi-agent capability of the proposed approach – iLNs, and communication facilities offered by IEC 61850.

VI. ACKNOWLEDGEMENTS

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