Design of an Adaptive Protection System for Microgrids with Distributed Energy Resources in Accordance with IEC 61850-7-420

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Abstract

Distributed Energy Resources (DERs) bring many technical challenges, which can be better managed in small and more manageable networks such as microgrids. One key challenge is the protection of microgrids where bidirectional power flows, DER fault current contributions, and dynamic changes in the microgrid call for advanced protection philosophies. This paper proposes an Ethernet-based adaptive protection scheme for microgrids penetrated with DERs. The proposed ideas show how such a novel protection system can be designed and developed in accordance with the IEC 61850 standard and specifically its recent extension on DER systems. The paper demonstrates how the information data models of DERs given in the IEC 61850-7-420 standard could be used in developing such an adaptive protection system. IEC 61850-7-420-based information modelling of example DER systems is discussed. Specifics of the information exchange in the communication network and the developed central control are deliberated.

1. Introduction

Protection of DG-penetrated microgrids requires a redesign in conventional protection philosophies due to a number of concerns including the presence of bidirectional power flows and DER fault contributions [1]. A microgrid can operate in grid-connected or islanded modes, and DERs could connect or disconnect subject to the availability of the source and perhaps the generation strategy. Such dynamic changes would alter the fault current levels within a microgrid. For example, in the grid-connected mode, the utility grid and DERs all contribute to short-circuit currents whereas in the islanded mode, fault currents are smaller as microgrid DERs would be the only active sources [1]. All these demand an adaptive scheme that can respond to such dynamic changes updating protection settings as required.

Fig.1 shows the small 50Hz, 22-kV Medium Voltage (MV), and 415-V Low-Voltage (LV) distribution system at the focus of this paper. The point of common coupling to the utility is at the MV level. There are two 415V, 2MW CHP generators connected to Bus 2, which are operated at capacity. There is a 3.3kV, 1.5MVA synchronous diesel generator connected to Bus 5, which provides black start power to essential loads following a mains failure. The diesel generator is not run in parallel with the mains. There are provisions to further expand the capacity of the CHP plant by installing an additional 415V 2MW unit. A 3-Φ PV system with the total capacity of 500kW is connected to Bus 4 via Power Electronics (PE) interface at the LV level. Fig. 1 also shows the Ethernet architecture designed using IEDs, GenSet controllers and the Microgrid Protection Management Controller (MPMC). The key conceptual features of this system were reported in [2-4].

This paper highlights the design aspects of an adaptive protection scheme designed using advanced communication between intelligent devices in a microgrid network in accordance with the IEC 61850 standard. The key contribution is the discussion on the role IEC 61850-7-420 compliant data communications play in the design of such an adaptive scheme. Section (2) reviews communications-assisted, adaptive microgrid protection schemes. Section (3) presents the adaptive time-overcurrent protection theories devised in [2, 3]. A brief overview of IEC 61850-7-420 is provided in Section (4). Section (5) discusses the design aspects of the proposed adaptive protection management system with emphasis on the exchange of data amongst the various microgrid network IEDs.

2. Review of microgrid protection schemes

The work in [5] proposes a strategy for inverter-based MV microgrids and discusses various protection functions that can be implemented in modern protection relays dispersed throughout the microgrid. It is suggested in [5] that each time a fault is detected, these protection relays should communicate with a central 'microgrid protection commander' informing the commander about the fault event. The 'commander' then communicates back with the remote protection relay issuing a trip signal to that relay. This approach of communication during the presence of a fault is risky and as a major point of criticism of the suggested strategy. A differential protection-based microgrid protection system is proposed in [6]. The work is noteworthy, but communication aspects are not adequately covered and there is a very limited discussion on how the communication of data would play a role in the proposed microgrid protection scheme.

Reference [7] presents notable work on protection coordination in active distribution grids. An adaptive protection scheme is proposed, which adjusts the active setting groups of the field protection devices with respect to the network changes. A centralised controller, which performs the real–time analysis of the state of the distribution system, receives IEC 61850 compliant data from field devices and performs the necessary control function. MATLAB simulations were carried out for various possible network configurations, and IED setting groups were developed and programmed into the controller. The paper gives the details of the IEC 61850-based communications taking place for the transfer of key data and for the initiation of setting group changes.

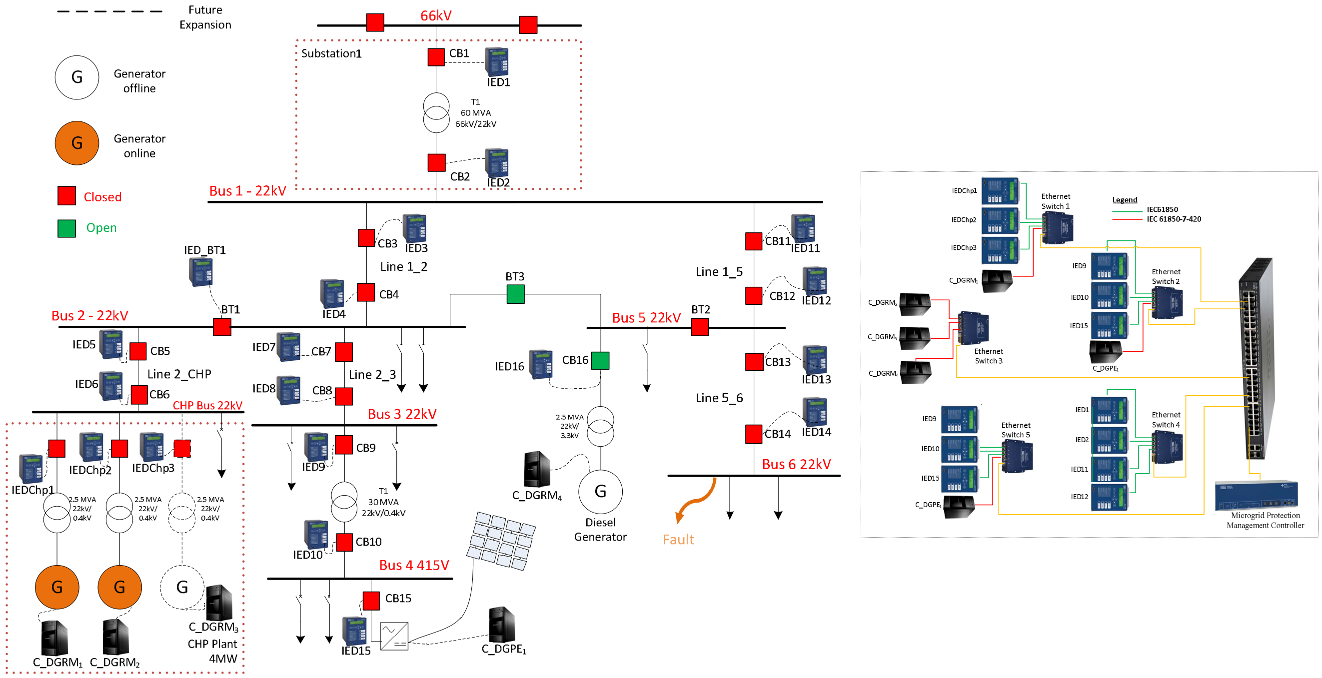

Fig. 1. Microgrid test system

The discussion in [8] takes the work presented in [7] a step further and presents the design/implementation of the proposed adaptive protection and control scheme for a Finnish pilot project. IEC 60870–5-104 was used for the data communication between the DER and central controller. While most previously published work considers data communications in protection schemes, they don't explicitly discuss what/how data needs to be communicated. The work in [7, 8] is a critical contribution that fills this gap.

3. Proposed adaptive overcurrent protection scheme

Fault currents supplied by Rotating Machine (RM) DGs were approximated to 5 times their rated currents whilst fault currents from PE-interfaced DGs were approximated to about 1.5 times their rated currents in [2, 3]. Then, the instantaneous fault current through a feeder can be calculated as in (1). The reverse fault current seen by an IED can be computed from (2).

$$
\begin{aligned}
I_{fault_r}^{forward} &= (I_{fault-grid}^{\;r} \times OperatingMode) \\
&+5\times\Sigma_{i=1}^{m}(k_{i\_r}\times I_{rated\,DG-RM_i}\times Status_{DG-RM_i}\times IM_{DG-RM_i}) \\
&+1.5\times\Sigma_{i=1}^{x}(I_{rated\,DG-PE_i}\times Status_{DG-PE_i}\times\times IM_{DG-PE_i}) \qquad (1)
\end{aligned}
$$

$$
I_{fault_r}^{reverse} = I_{fault_r}^{total} - I_{fault_r}^{forward} \qquad (2)
$$

Where $\boldsymbol{r}$ *is the relay in consideration*

$\boldsymbol{OperatingMode}$ denotes stand-alone or islanded operation. (OperatingMode =1 for grid-connected; =0 for islanded)

$\boldsymbol{I_{fault-grid}}^{r}$ is the fault current contribution of the grid seen by the i_{th} relay.

$\boldsymbol{m}$ is the total number of RM DERs in the microgrid

$\boldsymbol{x}$ is the total number of PE-Interfaced DERs in the microgrid

$\boldsymbol{k_{i\_r}}$ is the impact factor of the i_{th} RM-DER on the fault current seen by the i_{th} relay.

$\boldsymbol{I_{faultDG-PEi}}$ is the maximum fault current given by the i_{th} PE_interfaced DER

$\boldsymbol{Status_{DG-PEi}}$ is the status of the i_{th} PE-interfaced DER ($Status_{DG-PEi}$ = 1 if the DER is on; = 0 if the DER is off)

$\boldsymbol{IM_{DG-PEi}}$ = 0 if the DG-PE$_i$ does not impact the forward fault current of a feeder

$\boldsymbol{IM_{DG-RMi}}$ = 0 if the DG-RM$_i$ does not impact the forward fault current of a feeder

$\boldsymbol{I_{faultDG-RMi}}$ is the max fault current given by the i_{th} RM-DER

$\boldsymbol{Status_{DG-RMi}}$ is the status of the i_{th} RM DER ($Status_{DG-RMi}$ = 1 if the DER is on; = 0 if the DG is off or if the DG-RM$_i$ does not impact the forward fault current of a feeder)

$\boldsymbol{I_{ratedDG-RMi}}$ is the current rating of the i_{th} RM-DER

$\boldsymbol{I_{ratedDG-PEi}}$ is the current rating of the i_{th} PE-DER

4. IEC 61850-7-420

IEC 61850-7-420 [9] addresses interoperability concerns related to the monitoring/control of DER devices. The basis for the standard was that different DER communication technologies from many manufacturers resulted in technical, implementation and maintenance difficulties. IEC 61850-7-420 defines Logical Nodes (LNs) applicable to DER systems such as diesel generators, solar cells, fuel cells, and combined heat and power systems. These LNs are Object-Oriented (OO) data models that describe the processes to be implemented and controlled, e.g. the functionality of a rectifier or an inverter. The LN and data classes form the elements that allow creation of the information model of a real DER system device, e.g. the photovoltaic module. The complete behaviour of a real device can be represented with a hierarchical modelling of the data and functions in that device. This starts with the "Server' that represents the physical device, i.e. the DER Controller (DERC). Each DERC will compose a range of LDs that enable the aggregation of relevant sub-functions of that device. Fig. 2 demonstrates the information modelling of a Diesel Generation System (DGS), which consists of seven LDs and relevant LNs.

The DERES (excitation system) LD consists of two LNs (DREX and DEXC) that represent the information model of a generator excitation system. The DERGC LD aggregates all the sub-functions that relate to the information modelling of the DER generator. This includes information on the state of the generator, its ratings, and synchronisation details. The C_DGRM_4 is the SERVER and holds all this information. There will be various vendor specific communications in between this C_DGRM_4 and elements of the DGS, which is often referred to as the 'bay level' communication. The CHP information model is similar to the model shown in Fig. 2 except for the energy converter LD, which is the DERCHP LD in the case of the CHP system. The PV system information model is very different, and includes LDs describing the functionality of the PV system (ratings, array characteristics) and DER inverter/converter (nameplate data, characteristics, etc.).

IEC 61850-7-420 doesn't cover information exchange services, covered in IEC 61850-7-2 [10], on how data gets communicated using the client-server Abstract Communication Service Interface (ACSI) services, buffered reports or Generic Object Oriented Substation Events (GOOSE). This paper addresses this deficiency and demonstrates how the IEC 61850-7-2 services can also be applied in DER systems. This is a key attribute of this paper that sets it aside from similar work in the literature.

5. Microgrid Protection Management System

This section details the monitoring, decision making, and control (change settings) aspects in developing this protection scheme. Fig. 4 shows the required information exchange in developing the scheme. GOOSE messaging is widely reported in the literature. Yet, IEC 61850 information exchange is not limited to the GOOSE-based real-time exchange of time-critical information. There is a whole subset of client-server services that constitute the ACSI. MMS Read/Write Services are used in 61850 applications to read or write non real-time data, e.g. setting groups.

Fig. 5 shows the control logic developed to operate within MPMC, the brain of the scheme. MPMC extracts information received from the IEC 61850 network and maps this information onto a set of internal variables. This is called the cross mapping. This information is then used in performing the analysis required to determine the changes in the network topology (e.g. from grid-connect mode to the islanded mode). Based on this analysis, the MPMC then executes control actions and for example modifies the fault current settings of the relevant relays using the MMS Write service. As shown in Fig. 5, the operating mode is computed from the incomer CB statuses. The incomer CB statuses are cross-mapped onto Integer MPMC variables. A CB is on if its status points to the value of '2', which signifies that the CB is on. When both CBs are detected to be on, this signifies a grid-connected operation. Otherwise, the microgrid is deduced to have islanded.

Connection status of each DER is a key aspect of this scheme. For a RM-DG, its connection status is assessed from the analysis of its CB status and operational state from the GenSet controller. The '**DGEN'** LN in IEC 61850-7-420 models this information on the RM-DG operational status. In the case of the PV system, its connection status is diagnosed to be 'on' if the DC switch between the PV array and inverter, and the AC switch between the inverter and the microgrid network are both on, and the PV system controller signals that power is being delivered to the network. The **ZINV** LN models this information about the connect mode of the inverter making it available for exchange through GOOSE messaging in real-time applications.

Computation of the DER maximum fault current is carried out by acquiring the current rating of a DER and then computing the maximum fault current along the lines described in Section (2). This is based on the hypothesis that RM fault currents can be approximated to 5 times their rated currents and those of the PE-interfaced DGs to about 1.5 times their rated currents.

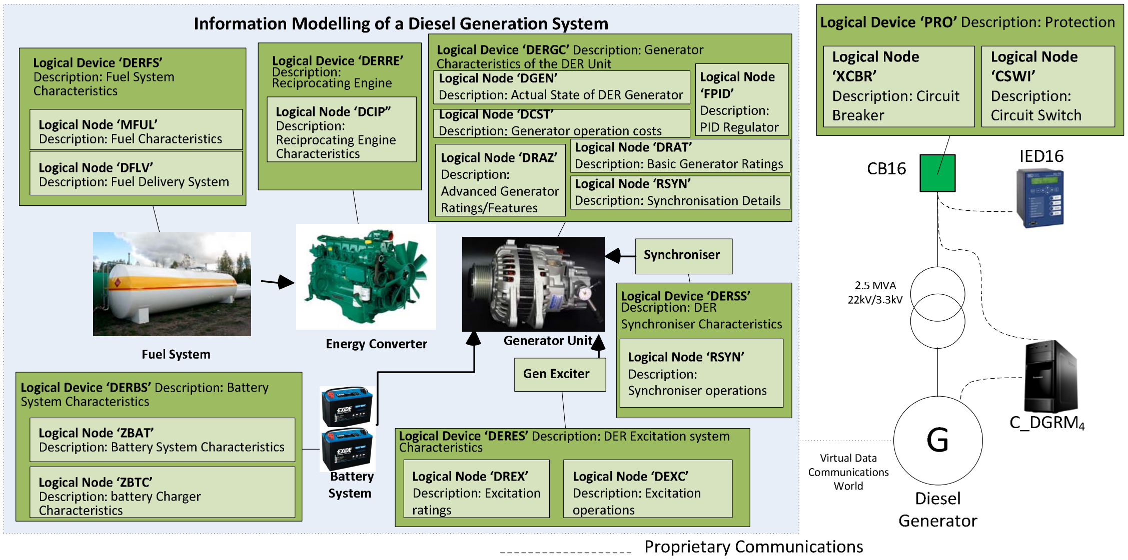

Fig. 2. IEC 61850-7-420 information modelling for the diesel generator

There are alternate approaches that can be taken. For example, the **DRAT** LN models information on the maximum fault current rating of a DER system and effectively provides this data about both an RM-DG and an inverter. Finally, the reverse and forward fault current thresholds are computed from (1) and (2). For a RM, its impact factor (k_{i_11}), connection status and the maximum fault current is considered. For a PE-interfaced DER, the computation is based on its connection STATUS and the maximum fault current BECAUSE its fault current does not vary and the impact factor doesN'T apply. The **PTOC** LN is critical as it models the directional time OC element of a protection device describing the relevant setting curve. THE IEC 61850 SetDataValues service (I.E. THE MMS Write service that it maps to) can then be used for setting the relevant parameters of the **PTOC** element as the last step in the realisation of the adaptive scheme.

The proposed scheme can modify the protection settings for each one of the three scenarios given in Section (4). Moreover, it does not require the pre-determination of protection settings for different configurations, the approach given in [7, 8], and settings are rather modified on the fly. It also does not also necessitate the use of the Setting Group Control Block (SGCB) services recommended in [7, 8], as these services are optional and not implemented in most vendor products. This aspect of the proposed scheme sets it aside from the only comparable work discussed in [7, 8].

6. Evaluating the scheme

The author is currently working towards developing a Windows-based simulation for evaluating the scheme and ideas proposed in this paper. Fig. 3 shows the concept under construction. A Substation Configuration Language (SCL) editor will be first used to create, edit, and validate IED Capability Description (ICD) files for the Servers as well as the MPMC client as a first step in the Substation Engineering process. The ICD files will be used to describe the object models of various devices within the proposed system by modelling their communication interfaces. A Windows-based IEC61850 platform will then be used to create the SERVERS and the CLIENT as shown in Fig. 3. Message traffic will be generated in accordance with Fig. 4 and ideas presented in Fig. 5 tested. The author will subsequently publish the test results.

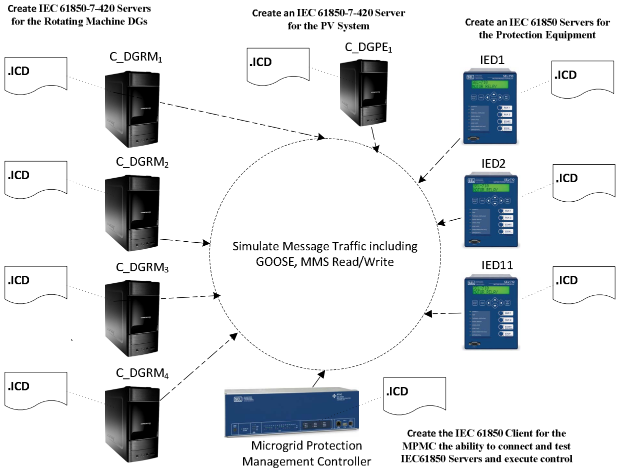

Fig.3. Evaluation platform

7. Conclusion

This paper has filled an important gap in the literature by discussing the use of IEC 61850-7-420 DER information data models in the development of an adaptive protection scheme for microgrids. The proposed protection scheme is novel and can be used to modify the protection thresholds in a microgrid network in response to dynamic changes occurring in that system.

Novel control logics have been developed and proposed for implementation in a central controller to realise the monitoring, decision making, and control aspects of the proposed adaptive scheme. The complete system design approach adopted in the presentation of the work effectively summarises and demonstrates how such a scheme can be directly applied in practice. The paper was concluded with a brief discussion on the Windows-based test platform currently being developed for evaluating the scheme.

8. References

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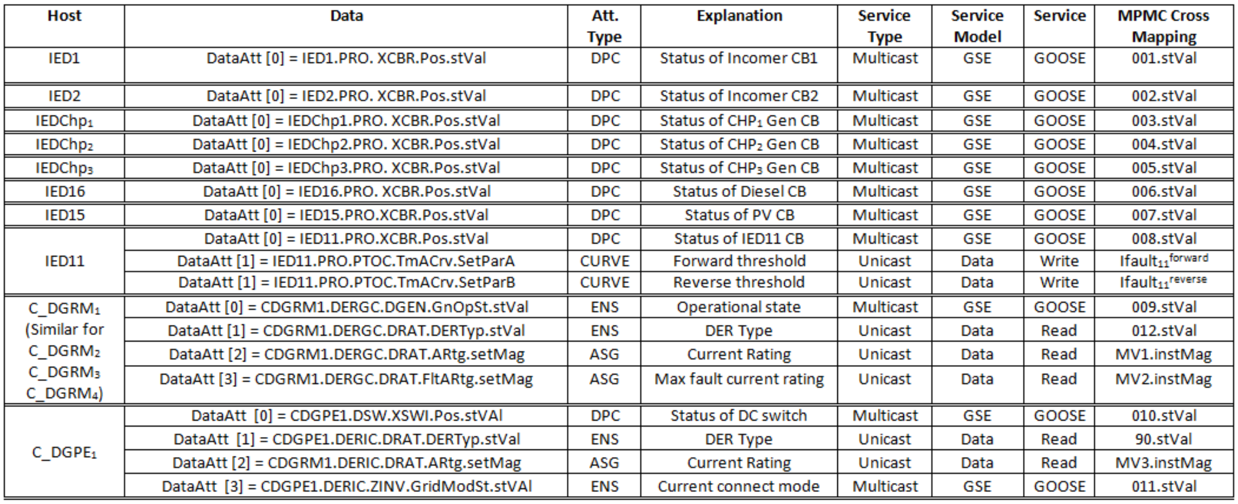

Host	Data	Att. Type	Explanation	Service Type	Service Model	Service	MPMC Cross Mapping
IED1	DataAtt [0] = IED1.PRO. XCBR.Pos.stVal	DPC	Status of Incomer CB1	Multicast	GSE	GOOSE	001.stVal
IED2	DataAtt [0] = IED2.PRO. XCBR.Pos.stVal	DPC	Status of Incomer CB2	Multicast	GSE	GOOSE	002.stVal
IEDChp$_1$	DataAtt [0] = IEDChp1.PRO. XCBR.Pos.stVal	DPC	Status of CHP$_1$ Gen CB	Multicast	GSE	GOOSE	003.stVal
IEDChp$_2$	DataAtt [0] = IEDChp2.PRO. XCBR.Pos.stVal	DPC	Status of CHP$_2$ Gen CB	Multicast	GSE	GOOSE	004.stVal
IEDChp$_3$	DataAtt [0] = IEDChp3.PRO. XCBR.Pos.stVal	DPC	Status of CHP$_3$ Gen CB	Multicast	GSE	GOOSE	005.stVal
IED16	DataAtt [0] = IED16.PRO. XCBR.Pos.stVal	DPC	Status of Diesel CB	Multicast	GSE	GOOSE	006.stVal
IED15	DataAtt [0] = IED15.PRO.XCBR.Pos.stVal	DPC	Status of PV CB	Multicast	GSE	GOOSE	007.stVal
IED11	DataAtt [0] = IED11.PRO.XCBR.Pos.stVal	DPC	Status of IED11 CB	Multicast	GSE	GOOSE	008.stVal
	DataAtt [1] = IED11.PRO.PTOC.TmACrv.SetParA	CURVE	Forward threshold	Unicast	Data	Write	$Ifault_{11}^{forward}$
	DataAtt [1] = IED11.PRO.PTOC.TmACrv.SetParB	CURVE	Reverse threshold	Unicast	Data	Write	$Ifault_{11}^{reverse}$
C_DGRM$_1$ (Similar for C_DGRM$_2$ C_DGRM$_3$ C_DGRM$_4$)	DataAtt [0] = CDGRM1.DERGC.DGEN.GnOpSt.stVal	ENS	Operational state	Multicast	GSE	GOOSE	009.stVal
	DataAtt [1] = CDGRM1.DERGC.DRAT.DERTyp.stVal	ENS	DER Type	Unicast	Data	Read	012.stVal
	DataAtt [2] = CDGRM1.DERGC.DRAT.ARtg.setMag	ASG	Current Rating	Unicast	Data	Read	MV1.instMag
	DataAtt [3] = CDGRM1.DERGC.DRAT.FltARtg.setMag	ASG	Max fault current rating	Unicast	Data	Read	MV2.instMag
C_DGPE$_1$	DataAtt [0] = CDGPE1.DSW.XSWI.Pos.stVAl	DPC	Status of DC switch	Multicast	GSE	GOOSE	010.stVal
	DataAtt [1] = CDGPE1.DERIC.DRAT.DERTyp.stVal	ENS	DER Type	Unicast	Data	Read	90.stVal
	DataAtt [2] = CDGRM1.DERIC.DRAT.ARtg.setMag	ASG	Current Rating	Unicast	Data	Read	MV3.instMag
	DataAtt [3] = CDGPE1.DERIC.ZINV.GridModSt.stVAl	ENS	Current connect mode	Multicast	GSE	GOOSE	011.stVal

Fig. 4. IEC 61850 and IEC 61850-7-420 compliant information exchange

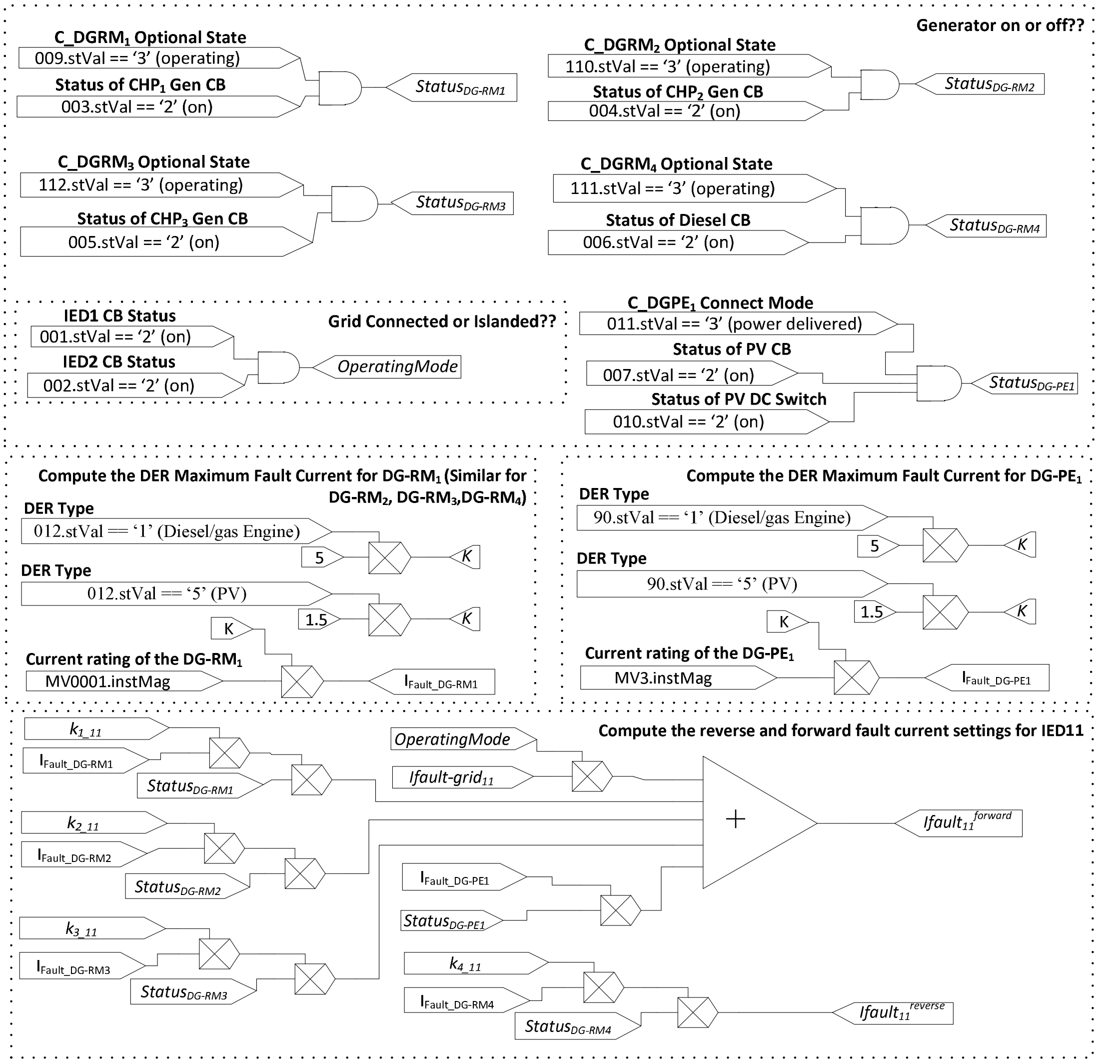

Fig. 5. Adaptive microgrid protection control logic