# A Methodology for Determining Fault Current Impact Coefficients of Distributed Energy Resources in an Adaptive Protection Scheme

Cagil OZANSOY, *Member, IEEE*

College of Engineering and Science
Victoria University, Melbourne, Australia
cagil.ozansoy@vu.edu.au

## Abstract

**The benefits of integrating Distributed Energy Resources (DERs) within power system networks outspread into social, environmental/ecological, and economical aspects. Large-scale deployment of DERs in electricity grids bring many technical challenges, which can be better managed in small and more manageable networks, such a microgrids. One such key challenge is the protection of microgrids where bidirectional power flows, fault current contributions from DERs, and dynamic changes in the microgrid necessitate advanced protection philosophies to be developed. This paper proposes a communications-based adaptive protection scheme for microgrids with DERs. A key contribution is the development of an approach for the quantitative determination of the variance in the fault current impact factors of rotating machine generators in such an adaptive scheme with increasing distance from that generator. A microgrid test system has been proposed and PSSE simulation results are presented to formulate the approach.**

## 1. Introduction

Microgrids are small distribution networks, which do not follow the conventional radial structure of large utility grids and may comprise possible generation, load, and even energy storage elements. The economic, environmental and social benefits of integrating DER technologies such as Photovoltaic (PV), wind and fuel cell systems within the grid has been clearly recognised by nations worldwide. Yet, the impacts and challenges of the integration of Distributed Generation (DG) in networks are also evident. DG offers solutions to many of the challenging electrical energy problems, including blackouts, brownouts, meeting peak load demands, reducing transmission losses, and often aids in reducing the energy costs.

When operated in a microgrid network, DERs may aid in ensuring an uninterrupted, steady supply of power to customers in the case of network disruptions or disconnections given that there is sufficient generation capacity. This is a key advantage of microgrid networks, which can operate in islanded mode by disconnecting from the utility grid. DG in small and more manageable microgrid networks is regarded as a more efficient way of tackling the power quality, protection, and control challenges concerned with the integration of DERs into the electricity grids [1]. This paper discusses one of these challenges, the protection of microgrids, in detail.

The protection of microgrids with DG is a challenge and conventional protection philosophies cannot be applied without a redesign due to a number of concerns. First, unlike the unidirectional power flow in a traditional radial grid structure, power flows are bidirectional in a microgrid due to the presence of DERs. The utility grid is no longer the only source of fault currents in a microgrid and DERs also make fault current contributions [1]. The fault current contributions of DERs depend on the DER type and show significant differences that must be carefully considered. Micro-sources such as PV and wind-turbine systems cannot usually be directly connected to the grid, and need to be interfaced via Power Electronic (PE) interfaces with in-built fault-current limitation. Such PE-interfaced DERs, for example, contribute much smaller fault currents when compared to Rotating-Machine (RM) DERs in the event of a fault.

The dynamic nature of a microgrid signifies that a microgrid can operate in two main modes, grid-connected or islanded modes, and DERs could connect or disconnect depending on the availability of the source and perhaps the generation strategy. Such dynamic changes would alter the fault current levels within a microgrid network. For example, in the grid-connected mode, the utility grid and microgrid DERs all contribute to short-circuit currents whereas in the islanded mode, the fault currents are smaller as microgrid DERs would be the only active sources [1]. All these necessitate the development of an adaptive protection scheme that can respond to such dynamic changes and update the protection settings as required.

This paper presents a case study to highlight the possible design aspects of such an adaptive protection scheme implementable using a communication network. This communication network enables advanced communication between the intelligent devices in the microgrid network in accordance with the IEC 61850 [2-4] standard. The work presented demonstrates how the previously reported theoretical protection philosophies [5, 6] can be implemented using Ethernet communication enabled Intelligent Electronic Devices (IEDs). Yet, the most significant contribution to knowledge is the development and reporting of a methodology for determining the variance in the impact factors of RM-DERs on fault currents in the network. This is one key aspect of this study separating it from similar works [7-10] in the literature.

The organisation of the paper is as follows. Section (2) presents an overview of adaptive Over-Current (OC) protection in microgrids. Section (3) introduces the case study to be analysed in this paper. Section (4) expands the adaptive time-OC protection theories devised in [5, 6]. A brief overview of the proposed communications-based protection scheme is also discussed in Section (4). Section (5) presents a methodology for determining the impact factors of RM-DERs at various bus locations within a power system network. Section (5) also demonstrates PSSE studies carried out to substantiate the diminishing fault current contribution of a DER in a power system network with increasing distance from that generator.

## 2. A review of adaptive overcurrent protection schemes for microgrids

This section presents a review of the OC protection schemes that have recently been discussed in the literature for the protection of microgrid protection systems. In [7], the authors argue that that the protection of grids is often based on OC relays with time-current discriminating capabilities. The paper argues that a single setting group for OC relays is insufficient and it is essential to take into account the grid configuration and changes in the location, type, and amount of generation. A number of case studies are presented to analyse faults occurring internal and external to a given microgrid and to further demonstrate how changes occurring in the microgrid topology and generation could impact fault currents. A novel adaptive protection scheme is then proposed, which relies on real-time measurements and data from offline short-circuit analysis to update relay settings. The paper stresses on the use of directional relays with current direction sensitivity for the practical implementation of such a scheme.

The study in [8] proposes a communication-less adaptive OC protection scheme using only local information suggesting that implementing a communications system may be costly and complex. The paper argues that OC protection schemes designed for the grid-connected mode may take longer to clear faults in the islanded mode leading to generators getting disconnected due to their UV protection schemes. The proposed scheme is, however, quite complex and requires lots of logic processing in every single relay. In the proposed scheme, an adaptive relay is primarily used to detect whether the microgrid is operating in grid-connected or islanded modes. The adaptive scheme relies on the interaction between forward and reverse relays. Forward relays are used to detect faulted sections and to do so; they are required to hold the time-OC characteristics of all the downstream relays. If a faulted section is detected, it is required to trigger a reverse relay to change its tripping characteristics. More details of the proposed scheme can be read in [8]. The proposed scheme is complex and would require substantial manual programming of each relay with algorithms and multiple settings, and cannot be used in cases when generators connect to the microgrid distribution system. Furthermore, the proposed scheme must rely on hardwired connections between reverse and forward relays even though this is not explicitly stated in the paper.

A protection strategy that does not require communications or adaptive schemes, but still based on the use of microprocessor relays is proposed in [9] for a LV microgrid. The work presented in [10] demonstrates Simulink models for simulating an adaptive relaying scheme. The method is based on OC relaying, and determination of the overall impedance of the system plays a significant role in the adaptive scheme.

## 3. Microgrid test system

Fig.1 demonstrates the microgrid test system that will be analysed in this paper. It is a small 50Hz, 22-kV Medium Voltage (MV), and 415-V Low-Voltage (LV) distribution system as shown in Fig.1. At the MV level, there is a single point of common coupling to the utility. There are two 415V 2MW CHP generators connected to Bus 2, which are operated at capacity. The CHP units also supply auxiliary loads within the CHP plant. 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 three-phase solar PV generation system with the total maximum capacity of 500kW is also connected to Bus 4 at the LV level. The PV generation system is connected to the network via PE interface. The following sections will further refer to and analyse the microgrid test system shown in Fig.1 in regards to the protection of the distribution network. The following scenarios will be examined in detail:

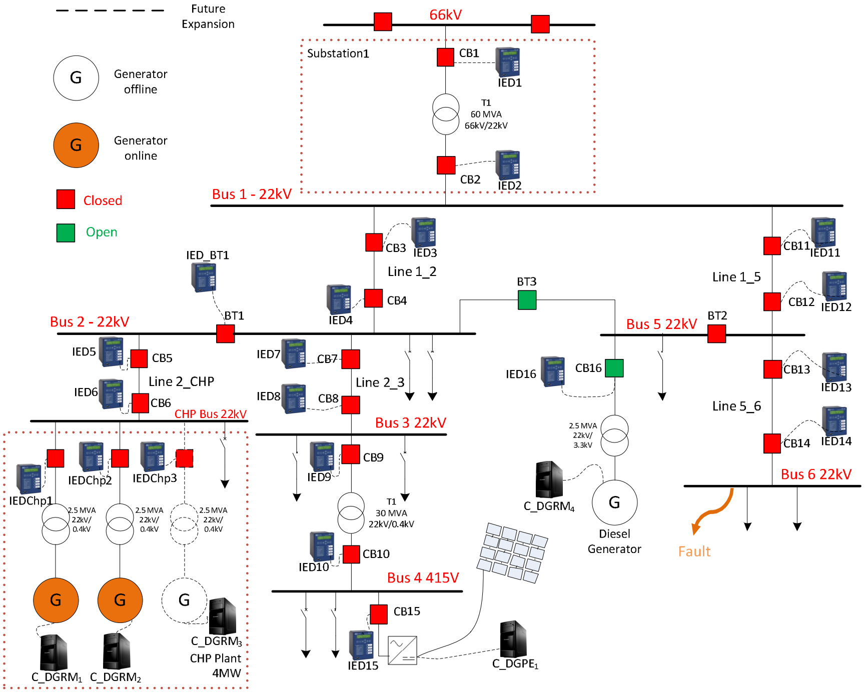

**Fig.1.** Microgrid test system

1. The microgrid is operating in grid-connected mode and the diesel generator is off.
2. The microgrid gets disconnected from the grid and the diesel generator kicks in.
3. The third Trigen unit is added to the network.

## 4. The proposed adaptive overcurrent protection scheme for microgrids

In [5, 6], the theoretical mathematical foundations of an adaptive overcurrent microgrid protection scheme were developed. It was determined that the instantaneous fault current through a feeder (also seen by a CB/Relay squad protecting that feeder) can be calculated as in (1) [5, 6].

$$I_{fault_r} = (I_{fault-grid_r} \times OperatingMode) + \Sigma_{i=1}^{m} (k_{i\_r} \times I_{fault_{DG_i}} \times Status_{DG_i}) \qquad (1)$$

It is widely known and accepted in the literature that the fault currents supplied by Rotating Machine (RM) DGs can be approximated to 5 times their rated currents. On the other hand, the fault currents provided by PE-interfaced DGs can be approximated to about 1.5 times their rated currents [5, 6]. Then, the equation given in (1) can be rewritten as in (2-3).

$$\begin{aligned} I_{fault_r^{total}} &= (I_{fault-grid^r} \times OperatingMode) \\ &+ \Sigma_{i=1}^{m} (k_{i\_r} \times I_{fault_{DG-RM_i}} \times Status_{DG-RM_i}) \\ &+ \Sigma_{i=1}^{x} (I_{fault_{DG-PE_i}} \times Status_{DG-PE_i}) \qquad (2) \end{aligned}$$

$$\begin{aligned} I_{fault_r^{forward}} &= (I_{fault-grid^r} \times OperatingMode) \\ &+ 5 \times \Sigma_{i=1}^{m} (k_{i\_r} \times I_{rated_{DG-RM_i}} \times Status_{DG-RM_i} \times IM_{DG-RM_i}) \\ &+ 1.5 \times \Sigma_{i=1}^{x} (I_{rated_{DG-PE_i}} \times Status_{DG-PE_i} \times\times IM_{DG-PE_i}) \qquad (3) \end{aligned}$$

Where ***r*** *is the relay in consideration*

***OperatingMode*** *denotes stand-alone or islanded operation. (OperatingMode =1 for grid-connected; =0 for islanded)*

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

***m*** *is the total number of RM DERs in the microgrid*

***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.*

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

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

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

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

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

$\boldsymbol{Status_{DG\text{-}RMi}}$ *is the status of the* $i_{th}$ *RM DER (*$Status_{DG\text{-}RMi}$ *= 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)*

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

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

What's proposed is indeed an Ethernet communications-based adaptive protection scheme designed conforming to the IEC 61850 [11-13] standard and specifically its recent extension, IEC 61850-7-420 [14], on DER systems [15]. Fig. 2 shows one example implementation of such a switched-Ethernet communication architecture constructed using IEDs, GenSet controllers and the Microgrid Protection Management Controller (MPMC). The MPMC acts as the brain of the proposed scheme extracting the information received from the IEC 61850 network and mapping this information onto a set of internal variables. 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 services. The key conceptual features of this system were reported in [4-6]. The communications aspects of the proposed system will be detailed in a separate paper.

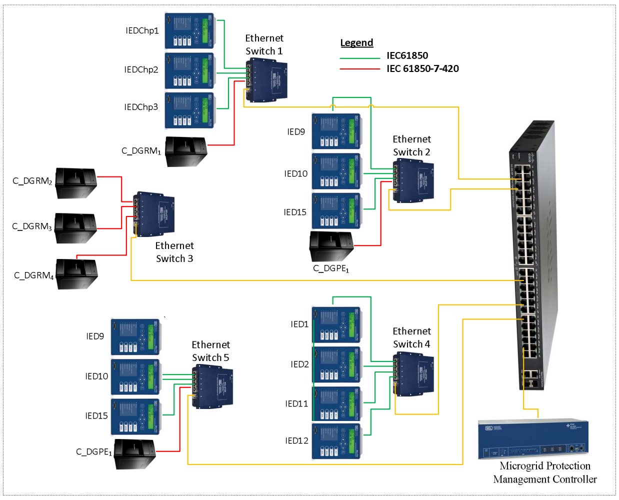

**Fig.2**. Communications for the overcurrent protection scheme

## 5. Methodology for determining the impact factors of renewable energy sources

A visual inspection is required to inspect the system to determine how the feeders are impacted for forward and reverse forward fault currents. As suggested earlier, the use of directional OC relays with current direction sensitivity is a critical aspect of implementing such an adaptive scheme. Each relay is required to have forward and reverse fault current settings. An inspection of Table 1 reveals that each feeder will be impacted by a DG either for its reverse or forward fault current setting.

**Table 1.** Reverse and forward impacts of DGs

| | *DG-RM₁* | *DG-RM₂* | *DG-RM₃* | *DG-RM₄* | *DG-PE₁* |
|---|---|---|---|---|---|
| *IEDr* | Forward | | | | |
| IED₅ | x | x | x | √ | √ |
| IED₇ | √ | √ | √ | √ | x |
| IED₁₁ | √ | √ | √ | x | √ |
| IED₁₄ | √ | √ | √ | √ | √ |
| | Reverse | | | | |
| IED₅ | √ | √ | √ | x | x |
| IED₇ | x | x | x | x | √ |
| IED₁₁ | x | x | x | √ | x |
| IED₁₄ | x | x | x | x | x |

If the total fault current seen by an IED is calculated from (2) and its forward fault current from (3), then the reverse fault current can be computed from (4).

$$I_{fault_r^{reverse}} = I_{fault_r^{total}} - I_{fault_r^{forward}} \quad (4)$$

The impact factor $k_{i\_r}$ is a value between 0 and 1, and used to calculate the fault current contribution of a RM-DER at any point within the microgrid [5, 6]. It is a well-known fact the fault current impact of a RM-DER reduces as distance from that DER increases due to the impedance of the distribution network. The fault-currents of PE-interfaced DERs do not vary with distance but with their control loops, and therefore the $k_{ir}$ factor does not apply to PE-interfaced DERs [5, 6]. The theoretical mathematical foundation for the calculation of the impact factors was developed in [6] and the complexity of a hand-calculation to determine the $k$ factors was argued in [5]. The calculation of the impact factors as well as the $I_{fault\text{-}grid}^{r}$ values is however critical for the successful implementation of the scheme proposed in this paper.

In [5], $k$ was assumed as '1' and certain other features of the proposed scheme were investigated. This paper aims to address this shortcoming of the work described earlier in [5] and proposes an offline-simulation based methodology for the determination of $k$-values. The network shown in Fig.1 has been modelled in PSSE and a three-phase short circuit analysis using the IEC 60909 fault-calculation method was carried out to determine the $k$ values. In conducting the offline analysis, the following relation given in (3) was recalled and utilised.

$$k_{i\_r} = \frac{I_{fault_r^{DG-RM_i}}}{I_{fault_{DG-RM_i}}} \quad (5)$$

Fig.3 shows a section of the PSSE slider-diagram used for the short circuit analysis. In this paper, only balanced three-phase to ground (positive sequence) faults have been considered. CBs have been modelled using the bus and breaker elements in PSSE as shown in Fig.3. Table 2 demonstrates the calculated $k$ values for the CB11 at CB11_BUS. It shows the fault currents seen by the 11th relay (IED11) under transient conditions for each individual contribution of a RM-DG. The methodology followed in determining the $Ifault_{DG\text{-}RMi}$ and $Ifault_r^{DG\text{-}RMi}$ values and in calculating the $k$-values involves determining the three-phase fault currents at the generator bus and the CB11 Bus for each generator one at a time (only one generator in service at a time). As expected, the impact of the fault contribution of a generator diminishes with distance as shown in Table 2. The relative change with distance, demonstrated in Table 3, is fairly small due to the small lengths of conductors chosen in this particular simulation case.

The $k$ values are relatively small and clearly inversely proportional to the distance. $k_{4\text{-}11}$ is the largest one since DG-$RM_4$ is the closest generator to Line1_5 and CB11.

**Table 2.** Impact factors for the 11th relay (IED11)

| $DG\text{-}RM_i$ | $Ifault_{DG\text{-}RMi}$ | $Ifault_{11}^{DG\text{-}RMi}$ *at Bus CB11_Bus* | $k_i\_11$ |
|---|---|---|---|
| $DG\text{-}RM_1$ (CHP1) | 14023 A | 261 A | 0.0186 |
| $DG\text{-}RM_2$ (CHP2) | 14023 A | 261 A | 0.0186 |
| $DG\text{-}RM_3$ (CHP3) | 14023 A | 261 A | 0.0186 |
| $DG\text{-}RM_4$ (Diesel) | 1154 A | 167.8 A | 0.145 |

**Table 3.** Variation in fault currents

| $DG\text{-}RM_i$ | $DG\text{-}RM_1$ (CHP1) | $DG\text{-}RM_4$ (Diesel) |
|---|---|---|
| *Bus CHB_Bus* | 264.8 | 166.4 |
| *Bus1* | 261.2 | 167.8 |
| *CB11_Bus* | 261.2 | 167.8 |
| Bus 5 | 260.0 | 168.3 |

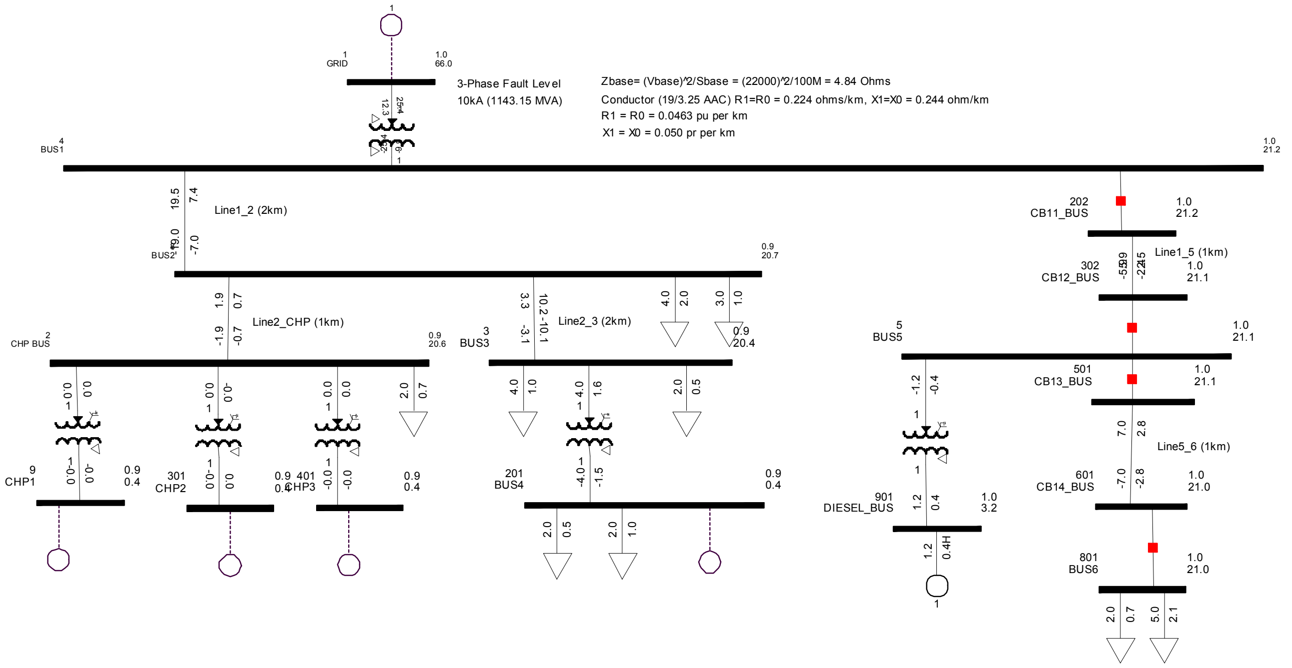

**Fig. 3.** PSSE-slider diagram

By carrying out this proposed offline simulation methodology, it is therefore possible to determine all the $\boldsymbol{k_{i\_r}}$ values, which are critical coefficients in (1-3) and which therefore play a critical part in the realisation of the proposed adaptive protection scheme. The results obtainable from an offline simulation can be saved and loaded in the MPMC, which is the brain of the system. The MPMC collates status signals, measured and sampled values, and GOOSE messages from throughout the network adjusting the $I_{fault\text{-}r}$ lookup table in its memory and updating the relay fault current pickup thresholds (when necessary in response to dynamic changes) via client-server MMS interactions. This new idea presented in this paper has complemented the earlier work discussed in [5] where the $\boldsymbol{k_{i\_r}}$ coefficients were assumed to be 1.

## 6. Conclusion

Adaptive protection schemes are unavoidable in microgrid power system networks with large penetrations of renewable energy sources. Such an adaptive protection scheme can be used to modify, on the fly, the protection thresholds in a microgrid network in response to dynamic changes occurring in that system. An IEC 61850 and IEC61850-7-420 switched based Ethernet network has been conceptually proposed in this paper as a viable implementation model of such an adaptive protection system.

In updating the protection thresholds in such a scheme, it is critical to calculate the instantaneous fault currents through a feeder (also seen by a CB/Relay squad protecting that feeder). Formulations have been provided in this paper to enable such numerical calculations in a real-time automation controller supervising the adaptive protection scheme. In the calculation of the protection thresholds, previous formulations assumed the fault-current impact factors ($\boldsymbol{k_{i\_r}}$ coefficients) of DERs to be constant throughout the system. In this new follow-up paper, an offline-simulation based methodology based on three-phase short circuit analysis using the IEC 60909 fault-calculation method is being proposed for the determination of *k*-values. This new idea will assist power system protection engineers in the development of precise protection settings. This is the key contribution in this paper separating this work from similar works in the literature.

## 7. References

[1] T. S. Ustun, C. Ozansoy, and A. Zayegh, "Recent developments in microgrids and example cases around the world—A review," *Renewable and Sustainable Energy Reviews,* vol. 15, pp. 4030-4041, 2011.

[2] International Electrotechnical Commission (IEC), "Communication networks and systems in substations – Part 7-1: Basic communication structure for substation and feeder equipment – Principles and models," in *IEC Standard IEC/TR 61850-7-1*, 1 ed. Geneva, Switzerland, 2003.

[3] International Electrotechnical Commission (IEC) TC 57, "Communication networks and systems in substations - Part 1: Introduction and overview," in *IEC Standard IEC/TR 61850-1*, 1 ed. Geneva, Switzerland, 2003.

[4] T. S. Ustun, C. Ozansoy, and A. Zayegh, "Modeling and simulation of a microgrid protection system with central protection unit," in *TENCON Spring Conference, 2013 IEEE*, 2013, pp. 5-9.

[5] T. S. Ustun, C. Ozansoy, and A. Zayegh, "Modeling of a Centralized Microgrid Protection System and Distributed Energy Resources According to IEC 61850-7-420," *Power Systems, IEEE Transactions on,* vol. 27, pp. 1560-1567, 2012.

[6] T. S. Ustun, C. Ozansoy, and A. Ustun, "Fault current coefficient and time delay assignment for microgrid protection system with central protection unit," *Power Systems, IEEE Transactions on,* vol. 28, pp. 598-606, 2013.

[7] A. Oudalov and A. Fidigatti, "Adaptive Network Protetcion in Microgrids " *International Journal of Distributed Energy Resources,* vol. 4, pp. 201 - 225, 2009.

[8] P. Mahat, C. Zhe, B. Bak-Jensen, and C. L. Bak, "A Simple Adaptive Overcurrent Protection of Distribution Systems With Distributed Generation," *Smart Grid, IEEE Transactions on,* vol. 2, pp. 428-437, 2011.

[9] M. A. Zamani, T. S. Sidhu, and A. Yazdani, "A Protection Strategy and Microprocessor-Based Relay for Low-Voltage Microgrids," *Power Delivery, IEEE Transactions on,* vol. 26, pp. 1873-1883, 2011.

[10] C. Buque, S. Chowdhury, and S. P. Chowdhury, "Modelling and simulation of adaptive frequency relaying for distributed generation," in *AFRICON, 2013*, 2013, pp. 1-5.

[11] C. R. Ozansoy, A. Zayegh, and A. Kalam, "The Real-Time Publisher/Subscriber Communication Model for Distributed Substation Systems," *Power Delivery, IEEE Transactions on,* vol. 22, pp. 1411-1423, 2007.

[12] C. R. Ozansoy, A. Zayegh, and A. Kalam, "Object Modeling of Data and DataSets in the International Standard IEC 61850," *Power Delivery, IEEE Transactions on,* vol. 24, pp. 1140-1147, 2009.

[13] C. R. Ozansoy, A. Zayegh, and A. Kalam, "The Application-View Model of the International Standard IEC 61850," *Power Delivery, IEEE Transactions on,* vol. 24, pp. 1132-1139, 2009.

[14] International Electrotechnical Commission (IEC), "Communication networks and systems for power auility automation - Part 7-420: Basic communication structure - Distributed energy resources logical nodes " in *IEC Standard IEC/TR 61850-7-420*, 1 ed. Geneva, Switzerland, 2009.

[15] T. S. Ustun, C. Ozansoy, and A. Zayegh, "Distributed Energy Resources (DER) object modeling with IEC 61850-7-420," in *Universities Power Engineering Conference (AUPEC), 2011 21st Australasian*, 2011, pp. 1-6.