Adaptive Protection Algorithms for Smart Distribution Systems: Hardware-in-the-loop Testing and Validation

S. Grillo, M. Bertolo
Politecnico di Milano
p.za Leonardo da Vinci, 32
I-20133 Milano, Italy
mario.bertolo@mail.polimi.it
samuele.grillo@polimi.it

E. Ragaini
ABB
via Pescaria, 5
I-24123, Bergamo, Italy
enrico.ragaini@it.abb.com

Abstract— **Renewable energy sources are a great challenge for the future. Our ability to abandon the dependence on traditional sources strictly depends on them. The exploitation of these sources could be performed through an efficient integration of distributed generation units (solar, wind, etc.,) in electrical grids. This process has raised several issues in the global operation of the entire system. One of these issues is related to the possible failure of protection devices in case of fault, jeopardizing the safety of users and equipment. In this paper new methods and algorithms, which could coordinate intelligent protection devices in a smart grid scenario, are presented. The effectiveness of these new protection methodologies was assessed using a simulation of a distribution system (equipped with a distributed generation unit) in a "hardware-in-the-loop" setup. The protection methods were implemented in the simulation and exploited to efficiently protect the system during fault events.**

Index Terms—**distribution system, distributed generation, hardware in the loop, protection devices, protection methods, short-circuit current.**

I. Introduction

Nowadays communities strictly depend on a secure and reliable supply of energy. Modern society is in continuous development and evolution and its requirements are becoming increasingly demanding, needing the availability of an efficient, secure and reliable electrical network. Considering this social contest, several investments and technological innovations will be required aimed to improve and strengthen electrical infrastructure and to tackle these new requirements [1]. With a view to reduce CO_2 emission increasing the production of energy from renewable energy source (RES) and to integrate different kind of distributed generation (DG) units, electric distribution networks (DNs) are evolving towards a smart distribution system paradigm. This new pattern includes a wide range of new technologies, such as communication infrastructure, intelligent electronic devices (IEDs), SCADA systems, etc., able to integrate and coordinate this new kind of distributed power sources and to efficiently manage them for a better use of electrical energy [2]. By introducing these new kind of technologies in electrical systems, traditional protection schemes for distribution systems could not operate in an appropriate way. For this reason, new methods, algorithms and technologies are required so as not to compromise the correct operation of the protection system. Concerning the development of new apparatus and equipment, the adaptive settings of protection devices were developed in the 1980's thanks to the increase of computer-based technologies, allowing the possibility to change relays attributes and obtaining IEDs able to perform logical computation and data processing. In the new smart grid scenario, relays whose settings can be changed and managed in response to grid operational state transitions could be an optimal and powerful key to success [3]. Some of the protection methods present in literature propose different kind of solutions, maintaining a similar structure from a constructive point of view [4]–[6]. In fact, it is assumed that an effective microgrid central controller (MGCC) with communication, data acquisition and automation systems is available to perform several control functions and is in direct communication with IEDs on site (i.e., digital relays). In the previous methods the MGCC has to coordinate protection devices during fault events, identifying the faulted point based on fault current direction [4], [5] with a very limited time action, thus needing a very reliable, fast and faultless communication system. In [4] for example (Fig 1), once a fault is detected, the service is interrupted and the faulted point is located in the branch between two adjacent protection devices which sensed the fault current with opposite direction [4]. With the proposed methods, the control center coordinates IEDs based on the short circuit level of the grid and on the topological structure of the network, adapting protection devices' current thresholds for every possible situation and having an adequate time interval to make the appropriate computations and to exchange information with protection devices. This paper describes the implementation of a hardware-in-the-loop (HIL) setup composed by software and hardware components realized at the Corporate Research Center of ABB in Baden-Dättwil (CH). The main goal of this setup is to test new methods for the control and the management of protection devices with real ABB hardware devices, test them and give an idea on how they could be used in future implementation of smart grid management systems.

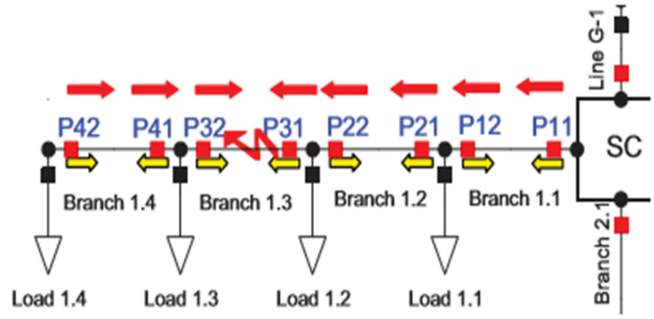

Fig. 1 Fault protection scheme.

The document is structured as follows: Section II describes the protection methods developed and tested. Section III describes the HIL setup. In Section IV simulation results are reported and commented. Finally, in Section V conclusions are drawn.

II. Protection Algorithms

Two adaptive protection algorithms are presented in the present Section. As above mentioned, these methods are based on the analysis of the topological structure of the network and on the level of the power sources connected to it before the fault, making protection devices suitable for each situation in case of fault and avoiding that a short circuit current could compromise the entire electrical system and equipment. The first is based on the use of the impedance matrix (*Z* matrix) while the second is based on the division of the network in controlled areas.

A. Protection method based on impedance matrix

The impedance matrix is closely related to the topological structure of the network and to the power source directly connected to it [7]. In fact, it is computed based on the utility grid, line impedances and on the DG units connected to the power system [7]. In this proposed algorithm, the matrix is computed in the MGCC and, when a power source is connected to or disconnected from the grid, the matrix changes accordingly and also the value of the short circuit current in case of fault [8]. Once this change is detected and the new value of the potential fault current is computed, the MGCC can send an adaptive order to all protection devices and make them ready for the new situation. Relying on this concept, a flowchart (like the one shown in Fig. 2) can be developed for the adaptive protection method.

B. Protection method based on "Area Concept"

With this algorithm, DN is divided in protection areas. Each of them includes a busbar, a protection device and a local logic controller (LLC). Following a connection/disconnection of any kind of DG unit to the busbar, the LLC re-calculates the short circuit level of its own area and, based on the current level, the protection settings of devices are adapted accordingly [9]. Each LLC is in direct communication with nearby controllers, which receive this new value through a communication channel and, if needed, adapt their protection devices following the new situation. The short circuit level in each protection area is computed exploiting the so-called "MVA method" for fault analysis [9], [10]. MVA values for each component are evaluated with the following formulas:

$$\text{utilitygrid} \rightarrow \frac{V^2_{\text{line-to-line}}}{X_{\text{grid}}} \tag{1a}$$

$$\text{transformer} \rightarrow MVA_{\text{trafo}} = \frac{MVA_{\text{rated}}}{X_{\text{trafopu}}} \tag{1b}$$

$$\text{generator} \rightarrow MVA_{\text{gen}} = \frac{MVA_{\text{rated}}}{X''_{\text{genpu}}} \tag{1c}$$

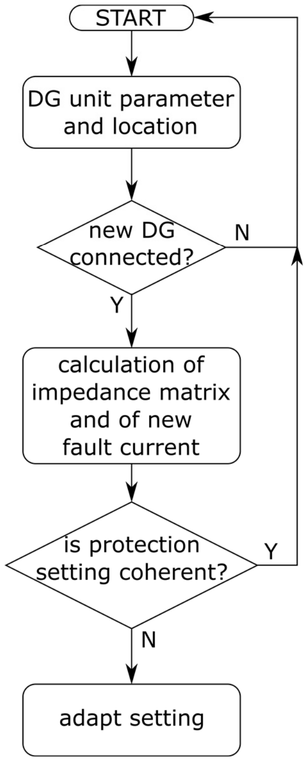

Fig. 2 Flowchart of the adaptive algorithm.

Once the new values are obtained for each network component, the total amount of the short circuit level of the system is calculated combining different elements as:

$$\text{series comp.} \rightarrow \text{MVA}_{1,2} = \frac{\text{MVA}_1 \times \text{MVA}_2}{\text{MVA}_1 + \text{MVA}_2} \tag{2a}$$

$$\text{parallel comp.} \rightarrow \text{MVA}_{1,2} = \text{MVA}_1 + \text{MVA}_2. \tag{2b}$$

With this method, it is possible to provide a decentralized protection of active DN (see Fig. 3) without the need to know the complete system topology, diminishing the burden on communication infrastructure and allowing protection system adaptation after connection/disconnection of new DG unit.

Fig. 4 and Fig. 5 present the flowcharts of the algorithms.

III. Hardware-in-the-loop setup

The developed setup has the purpose to test the adaptive protection methods previously described, running different simulations of an LV electric power system (with loads and a DG unit) in a LabVIEW environment and, at the same time, performing a digital-to-analog conversion of the simulations values and use them as input for real protection devices. These

IEDs are in direct communication with LabVIEW through a Modbus TCP/IP communication channel and the network topology simulated by the software can be updated based on protection relays status (OPEN/CLOSED). When the configuration changes, the analog values used to feed protection

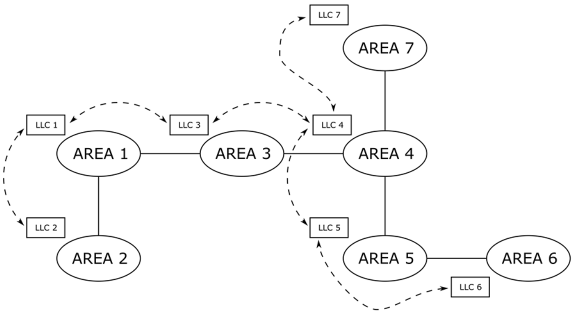

Fig. 3 Example of communication between protection areas.

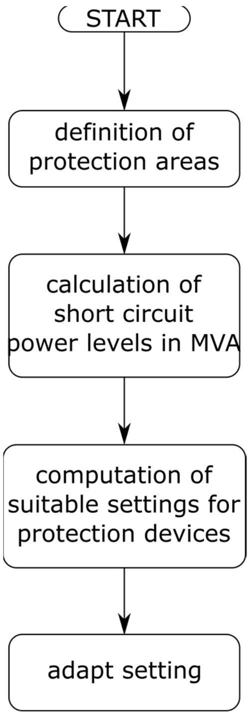

Fig. 4 Flowchart of the adaptive algorithm (off-line phase)

devices change accordingly, creating in this way the "hardware-in-the-loop setup" composed by a hardware component (protection devices) and a software component (LabVIEW).

A. Software component

The structure of the software allows to program the entire simulation of an LV system (see Fig. 6) in different subparts and to coordinate their relative inputs and outputs. The programmed subsystems are:

- synchronous generator subsystem, to perform a real-time behavior of the DG unit;
- power flow subsystem, to compute bus voltages and branch currents;
- short-circuit subsystem, to compute and simulate short circuit currents in case of fault.

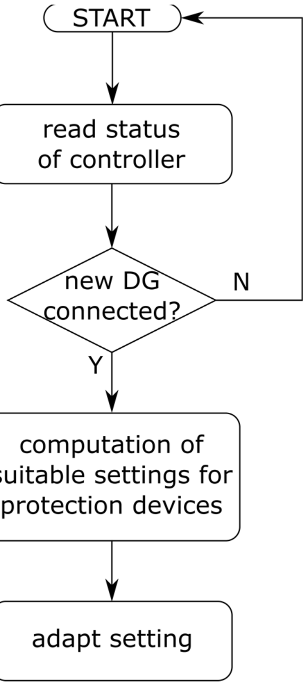

Fig. 5 Flowchart of the adaptive algorithm (on-line phase)

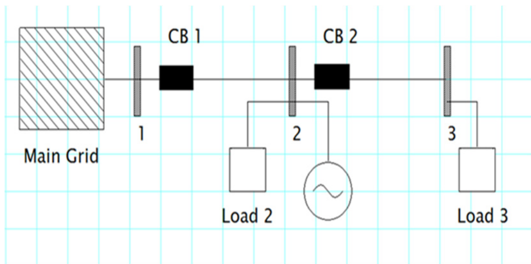

Fig. 6 Low voltage network simulated in LabVIEW.

Fig. 7 shows the final layout of the control panel, through which it is possible to set generator and loads input values. By taking the output of the generator subsystem and using it as input for the power flow subsystem, it is possible to obtain the real-time voltage and current profile of the entire network. Consequently, bus voltages are used as input for the short circuit current subsystem, which, in turn, produces as output bus voltages and branch currents in the system in case of a three-phase fault in bus 3.

B. Hardware component

Once the software component of the simulation is completed, the last step for the realization of the setup is the coordination with the hardware part. Three devices have been used to this aim:

- a function generator, to convert digital values of the simulation in analog values;

- two IED protection relays Emax 2.

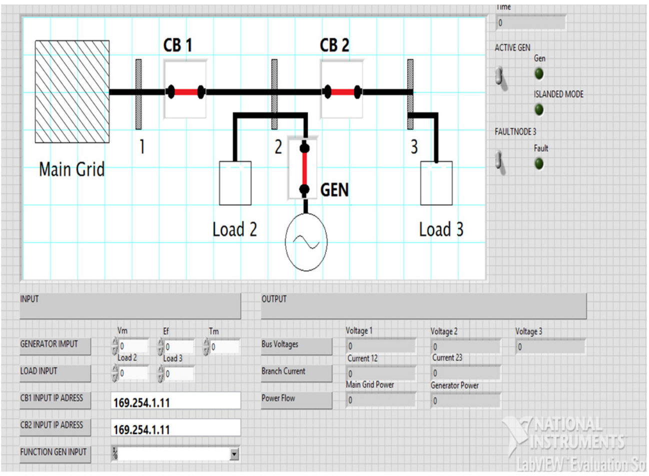

Fig. 7 Simulation control system layout.

The function generator is interfaced with LabVIEW and is programmed in order to simulate an analog value corresponding to the simulated value of the branch current and transmit this value to the protection relay. When, in case of fault, the current simulated is too high for relay threshold settings, the device trips and isolates the branch. Fig. 8 shows the final layout of the hardware-in-the-loop setup.

IV. Implementation of Protection Algorithms and Simulation Results

A. *Impedacne Matrix method*

In the developed simulation there are the pre-computed values of the impedance matrix for each mode of operation of the power system (grid-connected, grid-connected with DG, island mode). Basically, the software computes the short circuit current that could flow in the branch during a fault based on the present value of the matrix. Every time a variation of this matrix occurs (i.e., a modification of the topology or of the devices connected to the grid) a "write command" through Modbus TCP/IP channel is sent to IEDs in order to adapt protection settings, thus achieving a dynamic adaptation. Referring to the simulated power system topology shown in Fig. 6, the software keeps under control the fault current that could flow in the branch between Bus 2 and Bus 3. When, for instance, the power system is disconnected from the utility grid switching to the islanded operation with only the generator as power source, the fault current that could flow in branch 2-3 is considerably reduced, and the software will send a change order to CB2. Considering the graphs shown in Fig. 9 and in Fig. 10, it is possible to see that after a simulation of a three phase fault in bus 3, protection device CB2 has always a protection setting coherent with the fault current: in the first case, the LV system is connected to the main grid and the protection tripping time is 0,3 s; in the second case, even if the potentially fault current is significantly reduced due to the switching to the island operation mode, tripping time is still of the same order of magnitude (0,35 s), and the adaptation of the protection system is properly obtained.

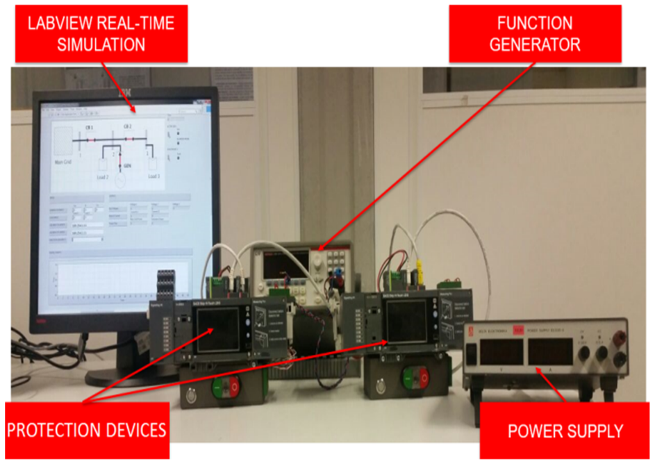

Fig. 8 Hardware-in-the-loop setup implementation.

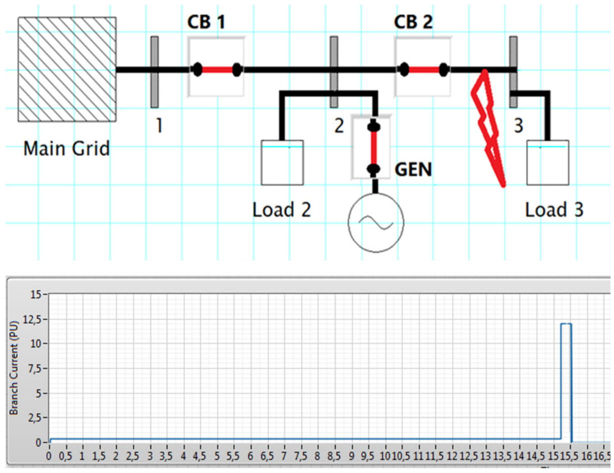

Fig. 9 Simulation results with impedacne matrix algorithm (grid connected mode).

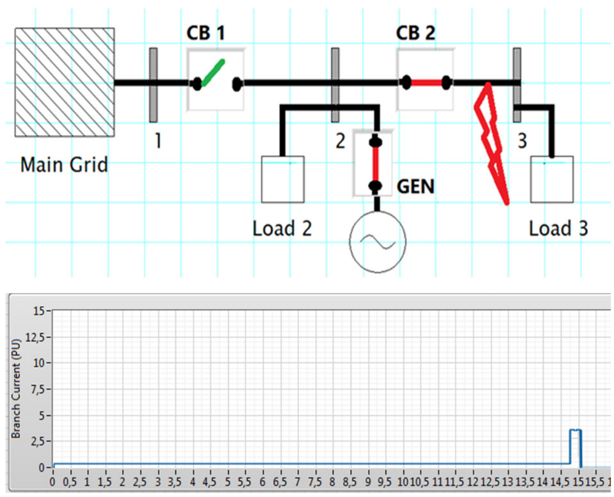

Fig. 10 Simulation results with impedacne matrix algorithm (island mode)

B. Area concept method

When analyzing the algorithm based on the area concept, the power system shown in Fig. 11 is used. The system is divided in two areas with their own LLCs. Considering AREA 1, every

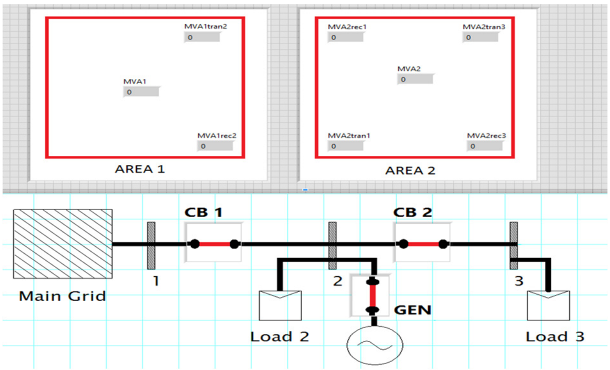

Fig. 11 Area concept.

time the system is connected/disconnected from the grid (CB1 CLOSE/OPEN), the LLC updates the value of the short circuit level (MVA1) of its own area and transfers it to AREA 2 (MVA1tran2). At the same time, it receives the short circuit level computed by the LLC in AREA 2 (MVA1rec2). In the same way, in AREA 2 (the area in which the DG unit is present) the LLC updates its own short circuit level (MVA 2) when generator in connected/disconnected to/from the grid (CBgen CLOSE/OPEN) and receives the information sent by AREA 1 (MVA2rec1). The values received (MVA2rec1) are added to its own value and sent back to hypothetical nearby areas. With this procedure, every area is updated every time there is a short circuit level variation and protection devices are kept with appropriate settings. In Fig. 12 and Fig. 13 the numerical results of the simulations of the two protection methods are reported. Like in the previous case, it is possible to see that in case of fault, the short circuit current is interrupted in a suitable time both in case of grid connected mode ($0,3\ s$) and in case of island mode ($0,35\ s$).

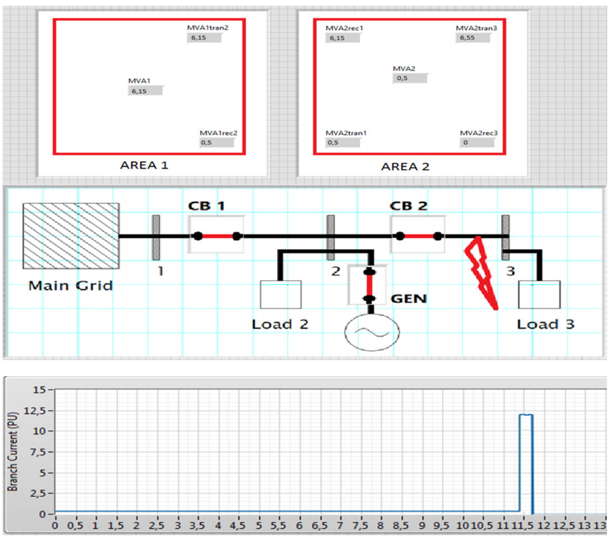

Fig. 12 Simulation results with Area concept algorithm (grid connected mode)

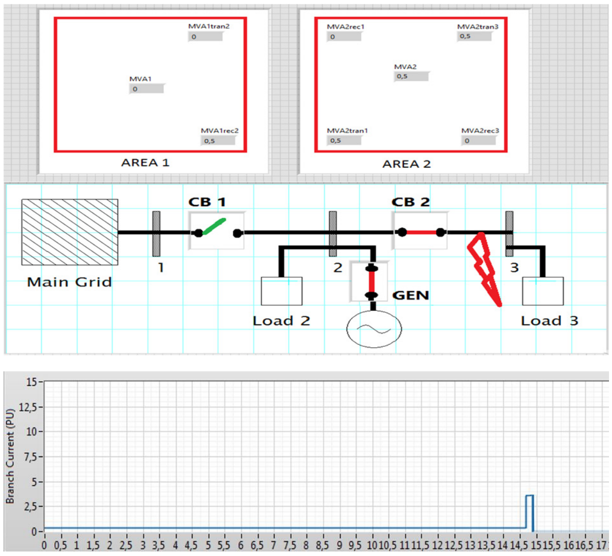

Fig. 13 Simulation results with Area concept algorithm (island mode)

V. Conclusion

This article shows new methods that could be implemented to obtain an adaptive behavior of the protection devices in a smart grid environment, giving a comprehensive description of them, highlighting the effective aspects of these new processes and testing their efficiency in the HIL setup. Future works could be done implementing the protection algorithms developed and their efficiency in a more complex environment, obtained by adding other components that are becoming increasingly important in the smart grid scenario, such as energy storage, solar panels, wind turbines, electrical vehicles and their recharge stations, etc. Pros and cons of the two adaptive methods analyzed are reported in Tab. I.

TABLE I. Pros and cons of protection algorithms.

Method	Pros	Cons
Impedance Matrix method	Simple; Local logic controller is not needed; Exploits impedance matrix which can be used also for other purpose (bus voltages, currents, etc.).	Difficult to be implemented in large network.
Area concept method	Low computational burden; Scalable; The division of the network in areas could simplify the approach.	Needs the presence of local logic controller; Complex communication infrastructure among areas.

Finally, as far as SCADA systems are progressively improving their tools, computational power and applications (topological representation of the network, data acquisition from network devices, calculation and representation of power supply state of each network element, etc.), it would be possible to achieve a real demonstration of these protection methods also in a real distribution system (pilot projects), testing their efficiency also in the field.

References

[1] N. Hatziargyriou *et al.*, *Microgrids: architectures and control*. Wiley Online Library, 2014.

[2] R. Morello, S. C. Mukhopadhyay, Z. Liu, D. Slomovitz, and S. R. Samantaray, "Advances on Sensing Technologies for Smart Cities and Power Grids: A Review," *IEEE Sensors J.*, vol. 17, no. 23, pp. 7596-7610, Dec. 2017.

[3] S. Voima, H. Laaksonen, and K. Kauhaniemi, "Adaptive protection scheme for smart grids," in *12th IET International Conference on Developments in Power System Protection*, 2014.

[4] S. Conti, L. Raffa, and U. Vagliasindi, "Innovative solutions for protection schemes in autonomous MV micro-grids," in *International Conference on Clean Electrical Power*, 2009, pp. 647–654.

[5] Y. Xu, Y. Ping, Z. Qunru, L. Peng, and L. Jinyong, "Strategy research of low voltage photovoltaic microgrid protection," in *IEEE PES Asia-Pacific Power and Energy Engineering Conference*, 2014, pp. 1–6.

[6] K. Vijitha, M. Selvan, and P. Raja, "Short circuit analysis and adaptive zonal protection of distribution system with distributed generators," in *IEEE International Conference on Energy, Power and Environment: Towards Sustainable Growth*, 2015, pp. 1–6.

[7] J. J. Grainger and W. D. Stevenson, *Power system analysis*. McGraw-Hill Education, 1994.

[8] H. H. Zeineldin, "Optimal Allocation of Distributed Generation to Minimize Relay Operating Times," in *IET International Conference on Developments in Power Systems Protection*. 2012.

[9] A. Oudalov, A. Fidigatti, D. Ishchenko, E. Ragaini, J. Stoupis, and L. Milani, "Adaptive Protection For Distribution Grid Based On Area Concept," U.S. Patent 20 160 190790A1, Apr. 30, 2014.

[10] M. Bredice, "An IEC61850 based protection system for microgrids," Master's thesis, Politecnico di Milano, 2012.