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DEVELOPMENT OF CO-SIMULATION PLATFORMS FOR STATIC AND DYNAMIC ANALYSIS OF SMART DISTRIBUTION NETWORKS

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To my family

and friends

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LIST OF ABBREVIATIONS

3GPP	Third Generation Partnership Project
AD	Active demand
ADM	Active Distribution Management
ADSL	Asymmetric Digital Subscriber Line
AI	Artificial Intelligence
AP	Access Point
API	Application Programming Interface
ARD	Automatic Reclosing Device
AS	Automatic Sectionalizer
BER	Bit Error Rate
BS	Base Station
CA	Carrier Aggregation
CAPEX	Capital Expenditures
CDMA	Code Division Multiple Access
CHP	Combined Heat and Power
CIM	Common Information Model
CN	Core Network
CPS	Cyber-Physical System
CVC	Coordinated Voltage Control
D2D	Device to Device
DC	Direct Current
DE	Differential Equation
DER	Distributed Energy Resources
DG	Distributed Generation
DL	Download
DMS	Distribution Management System
DPU	Data Processing Unit
DSI	Demand Side Integration
DSL	Digital Subscriber Line
DSM	Demand Side Management
DSO	Distribution System Operator
EDGE	Enhanced Data rates for GSM Evolution
EMI	Electromagnetic Interference
EMT	Electro Magnetic Transient
eNB	Evolved Node B

List of Abbreviations

EPC	Evolved Packet Core
ESM	Energy Storage Management
e-UTRAN	Evolved Universal Terrestrial Radio Access Network
FDD	Frequency Division Duplex
FDM	Frequency Division Multiplexing
FEL	Future Event List
Fi-Wi	Fiber-Wireless Network
GC	Generation Curtailment
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
GUI	Graphical User Interface
HAN	Home Area Network
HFR	Hourly Failure Rate
HIL	Hardware In the Loop
HLA	High Level Architecture
HSPA	High Speed Packet Access
HSS	Home Subscriber Server
HV	High Voltage
HVDC	High Voltage Direct Current
ICT	Information and Communication Technology
IDE	Integrated Development Environment
IED	Intelligent Electronic Device
IoT	Internet of Things
IP	Internet Protocol
ITM	Irregular Terrain Model
ITU	International Telecommunication Union
LAN	Local Area Network
LF	Load Flow
LOM	Loss of Mains
LOS	Line of Sight
LP	Linear Programming
LTE	Long Term Evolution
LTE-A	LTE Advanced
LV	Low Voltage
M2M	Machine to Machine
MAC	Media Access Control
MAS	Multi-Agent System
MBB	Mobile BroadBand

ME	Mobile Equipment
MILP	Mixed-Integer linear Programming
MME	Mobility Management Entity
MO	Multi-Objective
MTBF	Mean Time Between Failures
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
MV	Medium Voltage
NAN	Neighborhood Area Network
NB-IoT	Narrowband Internet of Things
NLP	Non Linear Programming
OF	Objective Function
OFDM	Orthogonal Frequency Division Multiplexing
OLTC	On Load Tap Changer
OPF	Optimal Power Flow
PDCP	Packet Data Control Protocol
PDN	Packet Data Network
PEV	Plug-in Electric Vehicles
PFC	Power Flow Controller
P-GW	PDN Gateway
PLC	Power Line Carrier
PRNG	Pseudo Random Number Generator
PV	Photovoltaic
QoS	Quality of Service
RES	Renewable Energy Sources
RFI	Radio Frequency Interference
RLC	Radio Link Control
RMS	Root Mean Square
RNC	Radio Network Control
RPC	Reactive Power Compensation
RRC	Radio Resource Control
RTI	Run-Time Infrastructure
SCADA	Supervisory Control And Data Acquisition
SDN	Smart Distribution Network
SG	Smart Grid
S-GW	Serving Gateway
SPS	Special Protection Scheme
SSS	Smart Secondary Substation

SS	Substation
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
UDP	User Datagram Protocol
UE	User Equipment
UICC	Universal Integrated Circuit Card
UL	Upload
UMTS	Universal Mobile Telecommunications System
USIM	Universal Subscriber Identity Module
V2G	Vehicle to Grid
V2V	Vehicle to Vehicle
VPP	Virtual Power Plant
VTB	Virtual Test Bed
WAMC	Wide Area Monitoring and Control
WAMPAC	Wide Area Monitoring, Protection and Control
WAMS	Wide Area Monitoring System
WDM	Wavelength division multiplexing
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network

ABSTRACT

The development of the future energy system in accordance with the smart grid paradigm requires a radical change in the management of the electricity distribution network, which needs to become increasingly intelligent and adaptive. Smart distribution networks (SDN) will have systems in place to control a combination of distributed energy resources, and distribution system operators will be able to manage the electricity flows using a flexible network topology. The transition towards SDN involves software, automation and control systems, to ensure that the power distribution network not only remains within its operating limits (e.g. node voltages and branch currents within the acceptable thresholds), but also that it is operated in an optimal way. The SDN operation requires the extensive use of information and communication technology (ICT) and innovative control systems in order to enable the active management of DERs and expected growing number of electric vehicles.

In SDN context, therefore, the ICT is not a simple add-on of the electrical system, but its availability and efficiency are essential to the operation of the entire power distribution system. In fact, the electric system will be managed and controlled through the communication network, which must guarantee a bidirectional exchange of large amount of data creating a keen interdependence between electric system and ICT system.

The theme of the joint simulation of the electrical system and the communication infrastructure is becoming increasingly important in the scientific research on power systems. For planning the evolution towards the implementation of SDN, appropriate computing tools (not yet available among commercial software) should be developed to take into account the reciprocal interdependencies among the two systems. The co-simulation is the most common method for studying SDNs as a cyber-physical system (CPS), since it permits simulating each subsystem (electrical and ICT) simultaneously, and has represented the focus of this Ph. D. work.

In this thesis different simulators specifically developed for co-simulation of smart distribution network analysis have been developed. They permit analyzing the slow dynamic operation of smart distribution networks (e.g. optimal power and reactive flow management, voltage regulation) as well the fast dynamic operation (e.g. fault management and reconfiguration). Different case studies have been investigated in order to show the effectiveness of the co-simulation platform features in analyzing the behavior of the smart distribution network in terms of capabilities, performances and reliability.

INTRODUCTION

The development of the future energy system in accordance with the smart grid (SG) paradigm requires a radical change in the management of the electricity distribution network, which needs to become intelligent and adaptive. Smart distribution networks (SDN) will have systems in place to control a combination of distributed energy resources (DERs), and distribution system operators (DSOs) have the possibility of managing the electricity flows using a flexible network topology [1]. The transition towards SDN involves software, automation and controls, to ensure that the power distribution network not only remains within its operating limits (e.g. node voltages and branch currents within the acceptable thresholds), but it is also operated in an optimal way.

In SDN context, therefore, Information and Communication Technologies (ICT) are not a simple add-on of the electrical system, but its availability and efficiency is essential to the operation of the entire power distribution system. In fact, the electric system will be managed and controlled through the ICT network, which will allow a bidirectional exchange of large amount of data creating a keen interdependence between electric system and ICT system. In the ICT system, the communication between the SDN components is characterized by non-idealities such as latencies and packet losses that may reflect upon the power system operation; furthermore, many components (antennas, routers, modems, etc.) are subjected to faults and malfunctioning, that may cause system reliability reduction, or service interruption [2].

For analyzing different issues related to SDN implementations it is necessary to develop new software tools that take into account the interdependences among ICT system and power system.

At the time of this writing, very often each system is simulated separately, assuming when simulating each system that the other works perfectly. Simulations capturing the operation and interactions of both systems will likely be needed to fully assess the potential reliability benefits and impacts of ICT in SDN operation.

On the other hand, the co-simulation approach is a frequently used method for studying SDNs as a cyber-physical system, since it permits simulating each subsystem (electrical and ICT) with a simulator specifically developed for that purpose. Typical benefits are stronger consistence of simulation with the real system, and the minimization of investment and time required for a prototypic result when compared to other approaches.

The focus of this work is the development of co-simulation tools, suitable for analyzing the performances of the communication technologies for smart grid applications, as well as the complete behavior of the operation of a modern power distribution network designed and managed according to a possible implementation of the smart grid concept.

The thesis will be organized as follows.

In Chapter §1 the scenario on which this research developed will be shown highlighting the reasons that oriented the study on co-simulation, and the goals pursued. The research will be collocated in the scientific background analyzing similar works that have been published in the scientific literature.

In Chapter §2 a survey on the communication technologies will be given. More details will be provided about Long Term Evolution (LTE) technology, which in the last period receives a wide recognition as one of the most interesting technologies for smart grid application. Afterward, an analysis on the different solutions for modelling the ICT system for co-simulation and similar studies is presented.

In Chapter §3 an investigation on the strategies adopted in the operation for smart grids is presented, both for normal conditions such as voltage regulation and congestion avoidance, and for abnormal conditions such as short circuits location and extinction. Then, the most recent techniques that lean towards decentralized control are presented, and a comparison with the traditional centralized strategies will be described.

In Chapter §4, the co-simulation tool is presented. The progress in the co-simulation software development, concurrently with the evolution of the research during the 3 years period of doctorate, has originated two main version releases. The first version is purposely developed for analyzing the slow dynamic operation of Smart Distribution Networks. The second version is more oriented on fast dynamic operation. Both versions will be presented and analyzed in detail showing the capabilities and the usefulness in smart grid simulation.

In Chapter §5, different case studies will be presented, that focus on both slow and fast dynamic operation of smart distribution systems. The results will be discussed, and considerations upon the different technologies analyzed with the co-simulation tool will be presented.

In Chapter §6 the final considerations on the research conducted and direction for further work are summarized.

CHAPTER I

1. CO-SIMULATION IN SMART GRID STUDY

1.1 Introduction to ICT integration on distribution networks

The push towards a more sustainable conception of technological development in the energy field has driven the commitment of governments in the direction of exploiting renewable energy sources (RES) for energy production. The liberalization of the electricity market and the incentives under the commitments set out in the Kyoto Protocol (United Nations Framework Convention on Climate Change [3]) with the signing of binding targets to be achieved by 2020 has driven the development of a large number of distributed generation (DG) plants for the exploitation of RES, of various types and sizes, located both on public and private buildings as well as in rural agricultural areas or industrial zones.

Directive 2009/28/EC assigned to Italy the task of covering a portion of gross final energy consumption - through production by RES - for a value of at least 17 % by 2020 [4]. This goal, according to the latest statistics, has already been reached in 2014 [5].

The smart grid is a recent paradigm associated with electrical power systems, which involves the integration of computer networks, control and telecommunication systems, generally referred to as information and communication technologies (ICT), to the electrical system, which can bring benefits to the electrical system in terms of global efficiency, power control and management, peak shaving, network operation when unforeseen events (failures and malfunctions) occur, and can therefore contribute to improving the integration of electric grids with DG [6]

The smart distribution network, a smart grid declination oriented to the power distribution at the medium voltage (MV) and low voltage (LV) level, if properly exploited, is able to bring power generation near to end customers, potentially contributing to reducing power dissipation in the distribution network [7]. More specifically, a SDN can be considered as a distribution network capable of intelligently controlling all available distributed energy resources in order to ensure the supply of electricity efficiently, sustainably and safely, pursuing the following functionalities:

- integration of distributed generation from RES and energy storage systems, both stationary and mobile;
- optimization in exploitation of existent infrastructure and deferment of new investment on physical power network;
- minimization of overhead and maintenance costs;
- high service reliability and power quality;
- strong resistance against attack on information system.

In the SDN, flexible network topologies confer distribution system operators (DSOs) the possibility of managing the electricity flows [1], and intelligent control systems are settled in order to address the following aspects of power management and planning:

- Protection systems: intelligent protection systems will have to rapidly act in order to solve network contingencies, like short circuits, overvoltage, and will have to work with bi-directional energy flows and with high harmonic distortion, caused by widespread presence of electronic devices both in demand side (e.g. power electronic devices for electrical drives) and in generation side (e.g. inverters dc/ac).
- Active and reactive power regulation systems: these systems will have to control voltage levels and active and reactive power flows, in order to ensure reliability and continuity of service [8].

- Frequency regulation systems: frequency control has always been widely employed at high voltage (HV) level, but nowadays a growing number of systems for frequency control are being adopted even in distribution networks. New markets are opening on generation dispatching, load shedding and demand response, which promote interest in developing new techniques for monitoring and controlling frequency in low voltage networks [9].
- Network planning: since new methods for controlling and managing the network are adopted, it will also influence network planning, which will require probabilistic approaches and multi-objective optimization [10].

In SDN context, therefore, ICT is not a simple add-on of the electrical system, but its availability and efficiency are essential to the operation of the entire power distribution system. In fact, the pervasive presence of intelligent control systems will cause a large volume of data packets that will be exchanged within the SDN system, creating a keen interdependence between electric system and ICT system.

In order to guarantee an efficient operation of the network, it is important to reach a deep understanding of smart grids communication processes, and accordingly to identify what ICT choices are best suited to ensure the quality and robustness in the information exchange required by smart grids. In the ICT system, the communication between the SDN components is characterized by non-idealities such as latencies and packet losses that may reflect upon the power system operation; furthermore, many components (antennas, routers, modems, etc.) are subjected to faults and malfunctioning, that may cause system reliability reduction, or service interruption [2]. Therefore, the choice and planning of the communication technology and infrastructure is a crucial aspect, since it must be capable of hosting this large amount of data, and guaranteeing a reliable and fast communication. In addition, it must guarantee high robustness against possible cyber-attacks.

This study is characterized by an interdisciplinary nature, as it involves the analysis of electrical networks and ICT networks in a joint and integrated way [11]. More specifically, it is necessary to develop new software tools that take into account the interdependences among ICT system and power system, to fully assess the potential reliability benefits and impacts of ICT in SDN operation. The co-simulation is the most common method for studying SDNs as a cyber-physical system, since it permits simulating each subsystem (electrical and ICT) with a simulator specifically developed for that purpose. A comparison of different approaches for smart grid simulation is presented in the next sections, which highlight the main benefits of co-simulation when compared to other techniques.

1.2 Joint simulation of electric and ICT systems

The Smart Grid concept applied to distribution networks represents one of the new engineering systems that combine physical systems with information, communication and other advanced technologies, forming in a holistic view a new peculiar complex system, which is included in the family of cyber-physical systems (CPS). CPSs are generally defined as engineering systems in which there is a synergistic interaction between physical hardware and computational components (software). The salient feature of CPS is that the functionality of these systems derives from the intense interaction between the physical and computational components of the system. CPS concept does not simply imply the union, but the intersection of the physical and cyber system. Embedded computational devices monitor and control the physical system typically with a feedback loop in such a way that physical processes affect the cyber processes, and vice versa [12].

In the case of SDNs, the physical system (the electric distribution network) strongly relies on the ICT to implement smart control capabilities. In their interaction, the two systems must be synchronized, and they must provide fast real-time responses also when sub-optimal conditions in the transmission of the signals occur, or when the data that lead the control and operation of the physical system are affected by uncertainties or sub-optimal conditions. The use of ICT systems also increases the risk of failure in the SDN as whole CPS, and introduces delays and latencies that may affect the performances in the operation of the network.

When analyzing the SDN with simulation tools, it is therefore necessary to simultaneously simulate the complex system in order to verify the true reliability of the SDN, and this requires analyzing all possible interdependencies between the electrical systems and the ICTs, especially in relation to the impact that delays, failures and malfunctions in the ICT system may have on the complete system. Ultimately, instruments for the integrated simulation of the CPS are indispensable in order to govern the dynamics of the physical system and the communication system. In this work these tools are referred as *joint simulation tools*, since they allow simulating in an integrated way both domains that constitute the CPS.

1.2.1 Dynamics in electric system and co-simulation

Smart Grid implementation relies on dynamic interactions between both cyber and physical systems through communication network where the timely delivery of a coordinated information stream is fundamental for the proper management of the network, both in normal and emergency conditions [13]. Centralized or decentralized distribution management systems (DMS) can be adopted, and, depending on the response time, they can be classified into slow dynamics operation and fast dynamics operation.

Depending on how rapid electric phenomena evolve after contingency, in the Figure 1 different Smart Grid management actions are ordered in a progressive sequence; the classification is also summarized in Table 1.

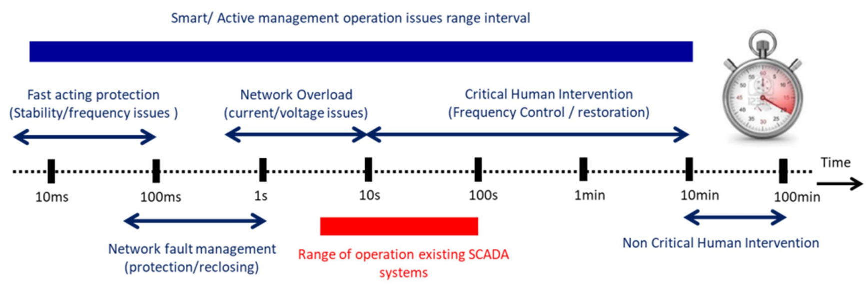

Figure 1. Smart/ Active management operation issues range interval

Table 1. Power system phenomena and relative control operation time

Power system phenomena		Time span
fast	Fast acting protection	10ms -100ms
	Network fault management	100ms -1s
slow	Network overload (current/voltage)	1s - 10s
	Frequency control	10s -10 min

These different scenarios may require different co-simulation tools characteristics, because of their different dynamics, and then, it is clear the importance of choosing different ICT network for different smart grids applications.

When studying a fast dynamics operation system, latencies become the main aspect in co-simulation results. The co-simulator must evaluate the whole chain of latencies (intelligent electronic devices (IED) physical quantity sampling, signal transmission to DMS, DMS analysis and decision, signal transmission to actuator, actuator intervention), and compare the result with the admissible phenomenon duration. In fast dynamics operation (e.g. network failure management and reconfiguration) intervention should be completed before 100ms÷1s. Also, co-simulator should evaluate the correct operation of ICT system, because a failure of ICT would bring into a black-out of the whole SDN.

When studying a slow dynamics operation system, a temporary failure of ICT should not compromise the operation of electric system, neither are latencies as important as in fast dynamics operation systems; nevertheless, co-simulation is important for supporting decision when planning SDNs, verifying correct operation of the network, conducting studies about stability with probabilistic methods (e.g. Monte Carlo studies).

1.2.2 Joint simulation classification

For integrated simulation of CPS systems, three concepts are generally applied: comprehensive simulation, co-simulation and hardware in the loop.

In *comprehensive simulation* (Figure 2a) the analysis of power system and communication network are integrated in the same environment. The challenge is to bring together both system models and solving routines, which leads either to integrate power systems simulation techniques into a communication network simulator or vice versa.[7] An advantage of this approach is that there is no need for time synchronization as both models are acting in the same environment sharing the same time management framework.

The *co-simulation* approach (Figure 2b) usually involves the integration of two or more simulators to capture the cyber physical interdependency of a system. In co-simulation, each domain of the CPS is analyzed by its own dedicated simulator, and the elaborations are brought together by appropriately designed run-time infrastructure (RTI) that coordinates the synchronization of the different subsystems. The main advantage of co-simulation is that there is no need of implementing new models, since each domain is analyzed by a specialized dedicated software. It also allows to obtain a bigger accuracy in the results, since the models are validated by the software releasers[14].

The *Hardware In the Loop* (HIL) approach (Figure 2c) is often used in power systems studies for testing control and protection strategies[15], where software simulators and hardware components are integrated in a real test bed. HIL is cited in this list because many scientific works in literature adopt this approach for studying the interactions between ICT and distribution networks in smart grid scenarios, although it cannot be considered a pure joint simulation of smart grids, since it involves real hardware devices being part of the simulation. The main advantage of the HIL approach is the perfect correspondence of the joint simulation of the CPS with a real system, but it often engages larger investment costs and longer simulation time, that precludes its utilization for long time span analysis.

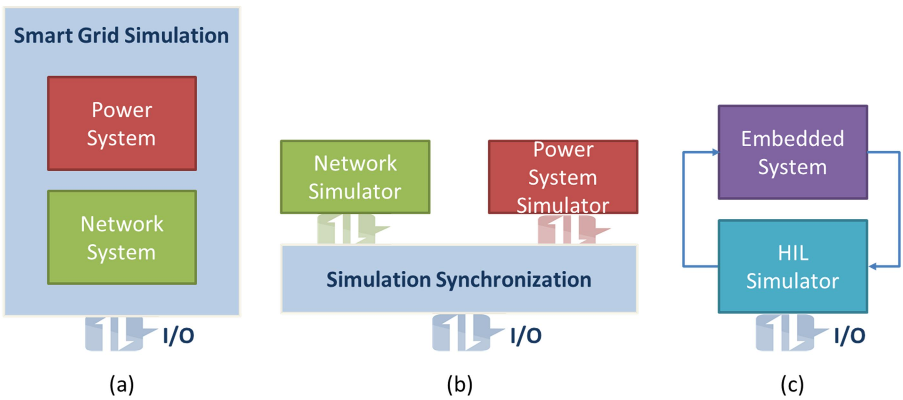

Figure 2. Schematic representation of: Comprehensive simulation (a); Co-Simulation (b); Hardware in The Loop (c)

1.2.3 Time synchronization

One main aspect that has to be analysed when developing a co-simulation tool is the synchronization between the two pieces of software (power system simulator and ICT simulator) that are included into the co-simulator. Traditionally, electrical systems simulators are based on the resolution of algebraic and differential equations in order to obtain currents and voltages evolution over time, while the ICT systems simulators adopt an event based approach.

Regarding the electrical system, state variables vary in the continuous time domain. If the case of interest is grasping the dynamics of the system, the evolution of the electrical system variables is described by differential equations (DE) that can be resolved in closed or numerical form. Differential equations are discretized based on the time interval considered in the simulation (time step), and the value of the state variable at the next simulation step is obtained from the value calculated in the previous step. On the other hand, if the case of interest is upon variables that are stable in the long term, therefore making negligible the fast transients, the evolution of electrical system over time is well represented as a sequence of steady state solutions performed with algebraic calculations such as load flows (LF). In Figure 3 it is shown a classic flow diagram for simulating the evolution of an electrical system over time.

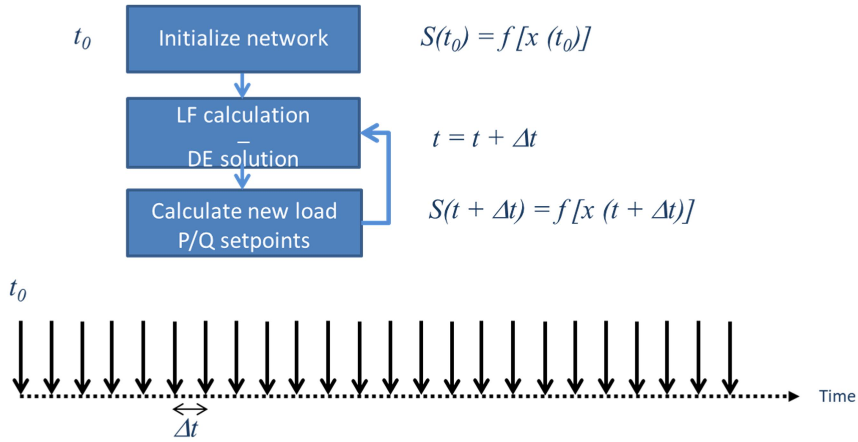

Figure 3. Power network simulation

The simulation starts by solving an initial power flow that calculates the starting state variables of the electrical system: $x=\{\theta,\mathrm{V}\}$ represents the set of voltage values (in phase and module) calculated for each node of the network, and $S=\{P,\mathrm{Q}\}$ is the set of active and reactive powers in the nodes of the network. The simulation of the system advances over time considering discrete intervals of time Δt, where each Δt corresponds to the resolution step of the differential equations in the time domain, or to a load flow execution if steady state solutions are analyzed.

In the case of the communication system, occurrences of events are usually distributed unevenly over time. For this reason the communication system simulators are provided with a scheduler that records the state of the system over time and stores an event list.

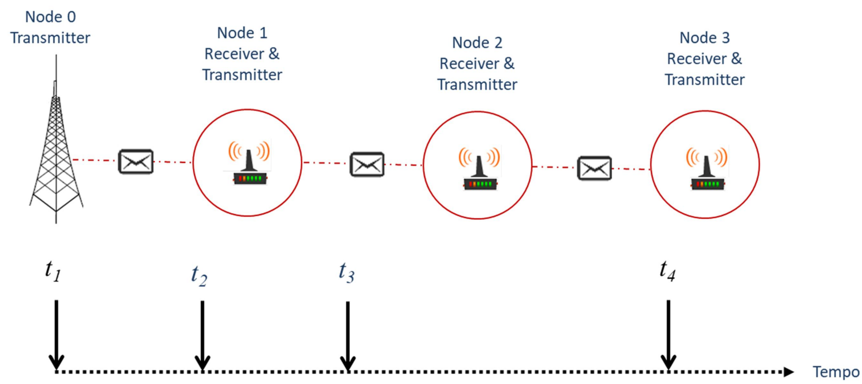

Figure 4. Communication system simulation

At the beginning of the simulation, the scheduler initializes the state of the system and the event list, which is a queue that stores events with date and time in chronological order. The scheduler considers the event at the top of the list and sorts the processes according to the chronological sequence, then establishes the next simulation interval time in function of the next event in the list. Therefore, the interval time between two sequential simulation processes is not a constant quantity, but it is variable during the whole simulation duration.

Figure 4 shows an example of dynamics in a telecommunications network, where the signal passes through several nodes in the telecommunication network. When the simulation starts, node 0 sends a packet to node 3 through node 1 and 2. The first event in the list is "node 0 sends a packet to node 1" at time t_1 with its timestamp. The reception event at node 2 is based on the properties of the communication medium at instant t_2. The second event "node 1 receives a packet from node 0" will be created and placed in the event list. The simulation will then continue this mode until the stop criterion is satisfied when node 3 correctly receives the packet transmitted by node 0.

Since the time management of electrical systems simulations and communication system simulations are so different, in co-simulation software the synchronization method is of crucial importance. Traditionally, two main techniques for synchronizing these two simulations are used in co-simulation platforms: time-stepped synchronization and event-driven synchronization.

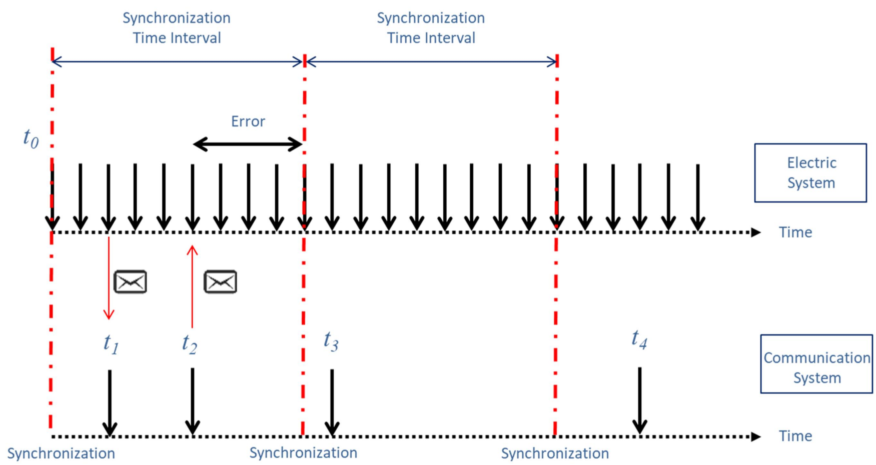

Figure 5. Co-simulation with time-stepped synchronization

Time-stepped co-simulators set a constant synchronization interval, after which power system and ICT simulations pause in order to exchange data and synchronize the time evolution of the co-simulation. It is the simplest synchronization technique to be implemented, but it can easily lead to errors if the synchronization interval is not short enough. In Figure 5, the upper axis represents the simulation process of the electric power system and the lower axis of the simulation of the telecommunication network. When the co-simulation starts, the two processes run independently of each other until the synchronization step, represented by the dashed red line. It is at this moment that the two processes pause and the exchange of information occurs. This synchronization method can easily lead to errors in the simulation if the synchronization interval is not adequate to the dynamics that characterize both domains of the CPS, and lead to delays that do not exist in the real system.

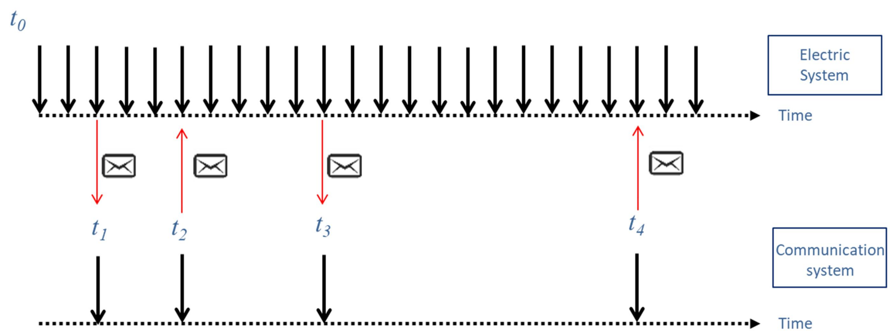

Figure 6. Co-simulation with event-driven synchronization

In event-driven co-simulators each power system simulation cycle is regarded as a discrete event (Figure 6). A co-simulation manager determines what power system events determine an ICT system call, then simulation stops and simulators update their data. Since there is not a fixed time step, because the sequence of simulations depends on the sequence of events, synchronization errors are minimized, as well as the duration of the whole simulation.

1.3 Related works

The simplest way to conduct these studies is to directly evaluate the performance of the communication network with dedicated network simulators.

Some examples of smart grid studies conducted according to this philosophy are [15]–[17], which analyze the performance of ICT infrastructures individually, making a posteriori an analysis of the correspondence of the results obtained with the specific performance required by the smart grids. However, this approach ignores the combined behavior of the SDN in terms of Cyber-Physical System.

Realizing a new simulator that can simulate both (electrical and ICT) domains of the SDN would be a complicated and challenging process. The most common choice is the use of the co-simulation approach, which integrates the most popular ICT and electrical simulators through integration frameworks.

Table 2. Selection of significant works on co-simulation (adapted from [19])

Name / Authors	Power System simulator	Communication system simulator	Type of Synchronization	Target
EPOCHS [20]	PSCAD / EMTDC e PSLF	ns-2	Time stepped	WAMS / WAMPAC
ADEVS [21]	ADEVS	ns-2	DEVS	WAMS / Load Frequency Control
Godfrey [22]	OpenDSS	ns-2	Time stepped	Active P/Q control
PowerNet [23]	Modelica	ns-2	Time stepped	Small power systems
VPNET [24]	VTB	OPNET	Time stepped	Small power systems
GECO [25]	PSLF	ns-2	Event driven	WAMS
Levesque[26]	OpenDSS	OMNeT++	Event driven	
Muller [27]	DIgSILENT PowerFactory	OPNET	Event driven	WAMPAC
Bottura [28]	EMTP-RV	OPNET	Time stepped	WAMS
SCORE [29]	SCORE	CORE	Time stepped	
INSPIRE[14]	DIgSILENT PowerFactory	OPNET	Time stepped	WAMPAC

Various solutions for realizing a co-simulation tool may be found in the Literature, that differ for the targeted field in the research on the smart grids, and consequently in architectural choices, e.g., software components, time synchronization strategy, and scalability. In Table 2 a selection of works that present an analysis of smart grids bases on co-simulation tools is reported.

The first pioneering work, aimed at a joint simulation of the electrical system and the ICT system, presents EPOCHS (Electric Power and

Communication Synchronizing Simulator) simulator [20]. It was developed with the integration of three different commercial software: PSCAD/EMTDC and GE Power Systems Loadflow Software (PSLF) simulating the power grid, and ns-2, which simulates the telecommunication network. PSCAD/EMTDC is dedicated to simulating electromagnetic transients, whilst PSLFs to simulate the electrical system for long-term scenarios.

The user interacts with the EPOCHS system through agent based modeling system, in order to simplify the model implementation and minimize the differences between the simulation environment and the real counterparty. The three simulators are combined with HLA (High Level Architecture) architecture. HLA is an IEEE standard, promoted by the US Defense Modeling and Simulation Office (DMSO), recommended by NATO in its Modeling and Simulation Master Plan, which is used in several simulation fields. This architecture main objectives are the interoperability between simulators and the reusability of simulation components. In this architecture the dedicated simulators are called *federates*, whose simulations are combined by a Run Time Infrastructure (RTI). RTI acts as a common interface layer between individual user-generated agents and simulators, and allow information exchange between individual federates of the co-simulator. Synchronization is performed with a time-stepped model, i.e. each component performs its simulation for a pre-set time, after which the simulations pauses, the RTI analyzes the data exchanged, defines the new stop time based on the received information and restarts the simulation. The disadvantage of this method is the discretization of the axis of time, entrusted to the user's choice, who must choose between two compromises. On the one hand a very dense discretization involves long simulation times; conversely, discretization that is not accurate enough may cause errors in the results obtained. Another decision given to the user is the accurate choice of the type of simulation that is intended to be made, because PSLF, PSCAD/EMTDC and NS2 can hardly operate simultaneously. Indeed, the difference in the time scale that characterizes electromagnetic simulations (PSCAD/EMTDC) and electromechanical simulations (PSLF) makes it virtually impossible to contemplate these aspects simultaneously in a single simulation.

The developed simulator is applied to a case study of the implementation of an agent-based Special Protection Scheme (SPS), where individual agents are interconnected with a telecommunications system. The proposed SPS system is simulated on a network of 145 bus and 50 generators obtained by modifying the IEEE 50-generator test-case network. The SPS system must intervene quickly and reliably to solve electromechanical instability phenomena. Independent agents are associated with SPS elements, generators, and loads. Specifically, the controller associated with the SPS communicates with the generator and load agents in order to collect different information including the status of the connection, active power, frequency and its variations. Agents associated with loads and generators send the data to the SPS controller, in order to command loads and generators in case of instability with interventions of generation dispatching and load shedding. The case study shows the ability of the control system to keep the system stable considering packet losses in the communication system.

A work similar to EPOCHS is presented in [21], where the authors use a different synchronization methodology of the two simulation systems. The electrical system is modeled with the discrete event system specification (DEVS) formalism, which is a modular framework for modeling and analyzing systems represented as a succession of discrete events, integrated with ns-2 for simulating the communication system. The power system, implicitly continuous, is represented through a DEVS-based formalism. In particular, modeling of the electrical system takes place through ADEVS, a C

++ library for the construction of discrete event simulations according to DEVS formalism. Models developed with ADEVS find integration with NS2 using the Application Programming Interface (API) provided with ADEVS. Since the DEVS formalism was developed for discrete type systems of general type and not specifically for electrical systems, it is necessary to develop a specific model for each element of the system that is included in the electric network. Therefore, in this co-simulator the use of flexibility has been penalized, and this also goes against the propensity to use common software already mastered by electrical system researchers. The co-simulation system is tested on a network obtained by modifying the IEEE-14 bus test network. The generators are modeled through the differential equations of the dynamic model of the synchronous machines, while the power grid is solved through a DC power flow. The co-simulation system is used to analyze the response of the network contingency control system, considering a variable throughput in the communication system.

Godfrey et al. in [22] present a co-simulation environment that adopts OpenDSS software for simulating the power grid, and NS2 software for the communications network simulation (Figure 7).

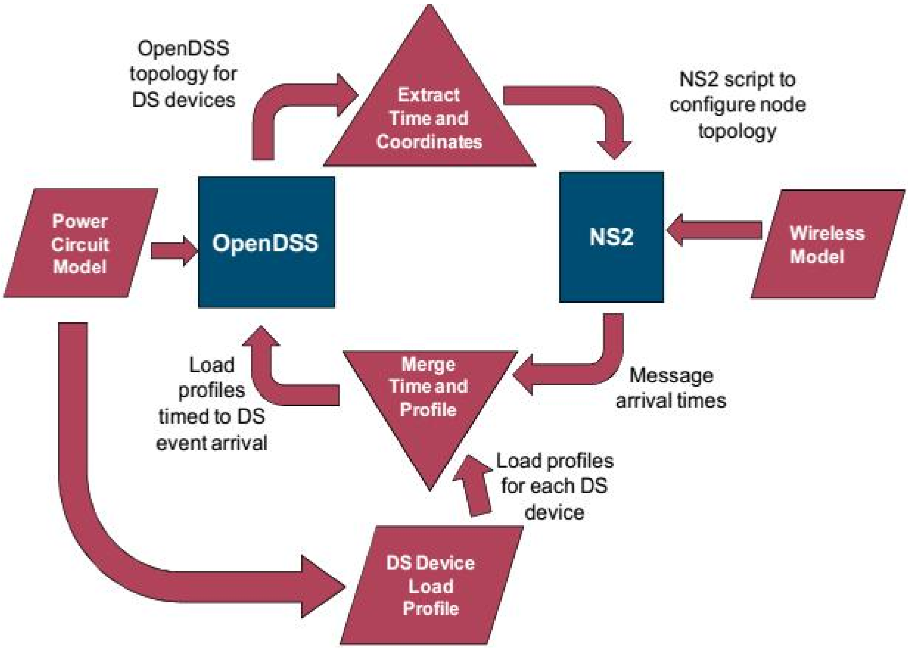

Figure 7. Architecture of co-simulator proposed by Godfrey et al. [22]

In this work, the co-simulation system is used to analyze the phenomenon of power reduction in a large photovoltaic generation plant caused by the transit of clouds that cause a shading on the panels. To compensate for the reduction in generation, distributed storage is deployed, and a DMS is charged to keep the balance between generation and load in the network considered. ns-2 is used to simulate the messages transmission to the storage unit that is assumed to give an instant response. Both ns-2 and OpenDSS operate by reading text-based scripts, so communication between these two systems is done through proper processing of their outputs, which are cyclically reinterpreted to become inputs of the complementary simulation system. More in detail, OpenDSS provides ns-2 information such as the time when the cloud transient begins, and the node topology; ns-2 instead delivers the time where corrections are effective as a result of the delays introduced by the communications system. The synchronization management is time-stepped, since voltage detection occurs as a result of repeated load flow calculations with predefined intervals of one second.

Al-Hammouri in [23] proposes a co-simulation environment called PowerNet. It combines the ns-2 network simulator with a power network simulator developed with Modelica. This co-simulator benefits from the large number of models of electrical systems available in Modelica libraries, along with the communication protocols available in ns-2. The co-simulation is entirely driven by ns-2, which is charged of sampling voltages and currents from the electrical devices modeled in Modelica, with a pre-set time interval. This platform is tested with a simple electrical system consisting of a generator and a load. Measurement systems are located at the ends of the transmission line connecting generator and load and are able to detect eventual faults on the line by measuring voltages and currents, opening the end switches if necessary. Communication can be subject to delays or jitter, introducing an element of randomness in the effectiveness of voltage regulation. In particular, the experiment demonstrates that the control system becomes unstable if the signal transmission channel uses 80% of the available bandwidth. The disadvantages in adopting a similar co-simulator framework are that using a general purpose simulator such as Modelica for modeling the electrical system makes this platform unsuitable for the more complex smart grid studies. A similar approach is adopted in [24] that is based on the software Virtual Test Bed (VTB) for the power system simulation and OPNET for the representation of the communication network.

In [25] a co-simulator was developed under the name of Global Event-Driven Co-Simulation (GECO), realized with PSLF and ns-2. GECO is characterized by different event-driven synchronous management. A global scheduler is designed to coordinate the events of the two software tools that form the co-simulator. In more details, the NS2 establishes a sequence of

PSLF power network simulation cycles, and interprets the output quantities. These events are analyzed by NS2, which is enabled to suspend PSLF and simultaneously simulate the telecommunications network. This involves minimizing co-simulation errors, since the discretization of the time axis is associated with events, and not with a time interval defined a priori.

The co-simulation software is used to conduct a study on the operation of agent-based backup protections. The network test used is a New England network consisting of 39 buses. There are 10 generators and 34 transmission lines, for a total of 68 distance relays. These relays are connected to each other by a telecommunications infrastructure modeled in ns-2. Two connection schemes are discussed: a supervisory system (master to slave) and an ad-hoc (peer to peer) system. Comparative simulations are conducted with GECO software and demonstrate the advantages of the ad-hoc method, which yields considerably lower intervention time than the supervisory method, due to the reduced distances within which the information packets are transmitted.

A similar approach is adopted by Lévesque et al. in [26]. The dedicated simulators included in the developed co-simulator are OpenDSS for the power system and OMNeT++ for the ICT system. In this work OMNeT++ is not only the simulation environment of the telecommunications system, but it is also used to implement the system coordinator, which manages the load variations through a traffic generator, monitors the electrical quantities, and deals with calling OpenDSS wherever there are load variations. The co-simulator is used to examine a voltage control algorithm in a network that is interconnected with electrical vehicles (PEVs). The co-simulator is tested on the IEEE 13-nodes radial network. Each node supplies 19 residential customers, some of which are assigned a PEV. The power system can interact through a Fi-Wi (Fiber-Wireless Network) infrastructure, which allows performing multiple network operations, such as controlling the PEV response when there are critical voltage fluctuations. This experiment was conducted on the co-simulator developed, comparing the results obtained when there are two different types of sensors: rate-based or agent-based, where the first send the measurements to the DMS with a constant data rate, while the seconds send measurements only when there is a specific event, such as exceeding a threshold. The co-simulation demonstrates that event-based sensors behave better than rate-based sensors, which only give good results at a high number of messages per second but on the other hand causing an excessive use of the communication network, twice greater than with event-based sensors.

In Muller et al. [27] is presented a hybrid simulator that takes into account various standards such as IEEE 1516-2000 (HLA), IEC 61850, OPC, and CIM, used by different research areas, with the aim of developing a highly flexible simulation environment, which allows developing applications close to industrial development. The simulator is based on HLA (High Level Architecture) software architecture, similar to the one adopted in EPOCHS. The representation of the Smart Grid in this work is divided into three levels of control: the bay-level, where the measurements are handled and the dynamics of the electrical system are analyzed inside the electrical substation (measurements, actuators, etc.); a substation level, where simulation of data exchange and processing takes place between the different bay levels that make up the substation; Finally the wide area level, through which substations can communicate with the control center that collects data and performs optimizations through system management tools. This architecture aims at creating a simulation environment as close as possible to the real architecture of real smart grids. The simulation at the bay-level is done with the DIgSILENT PowerFactory software, with a 10ms time-step. Every 10ms simulated data is sent to a server, made with MatrikonOPC Server. At the substation level there is a Data Processing Unit (DPU) registered as *federate* within the HLA architecture. The substation functions are integrated as DPU modules (e.g. decentralized protection, control systems, etc.), which can be implemented with external tools such as MATLAB or agent systems. The substation node equipment is identified by a Common Information Model (CIM) model. Wide Area communication is made with the OPNET simulator. The system control and management is realized through a JAVA instance, which is initialized and registered as an HLA *federate*. What is most peculiar of this architecture is its compliance with precise standards, which makes this system suitable for both a simulation environment and easy reproduction in a real test-bed.

This simulator is tested on the IEEE 39-bus 10-machine system, extended with three PFC (Power Flow Controllers) and a High Voltage Direct Current (HVDC) line. A disconnection of a branch of the meshed network, that causes overloads in the remaining healthy lines, is analyzed. The experiment shows that there is a considerable delay associated with the first PFC call, due to the time needed to initialize the data link, which essentially causes the failure of the first attempt by the controller. Subsequently, more calls are required, that produce a total time of almost 50 seconds before the overload is managed by the control systems. Ultimately, such a simulator appears as a useful tool for planning and testing different architectures for a real implementation of a SG.

An exhaustive survey on the various scientific works that propose co-simulation for smart grid studies is reported by the IEEE Task Force on interfacing techniques for Simulation Tools [19]. The article also shows some application-oriented examples that exploit the power of a co-simulation approach for smart grid investigations. The studies are conducted with two of the most interesting co-simulation software, INSPIRE [14] and GECO[25], and demonstrate the effectiveness of co-simulation approach in smart grid applications with highly crucial ICT impact, for example in the sensitiveness of state estimation algorithms to cyber-attacks in the ICT infrastructure, and in the evaluation of communication technology performances in smart grid operation.

An alternative approach is the comprehensive simulation, which combines power system and communication network simulation in one environment. In this case, the main concept is to bring together both system models and solving routines which leads either to integrate power systems simulation techniques into a communication network simulator or vice versa. A comprehensive simulation approach has been adopted for instance in [30] where the authors present a modular simulation environment based on OMNeT++, exploiting the existing models for the communication network but purposely developing extra models for the electrical network. Another example of comprehensive simulation approach is presented in [29]. The implemented system goes under the name of SCORE (Smart-grid Common Open Research Emulator), and is peculiar for implementing ICT system, power system, and integration framework in the same environment. This environment is based on the CORE platform, a US Naval Research Laboratory telecommunications network emulator. The SCORE system consists of several modules: a Graphical User Interface (GUI), a Service Layer, a Communication Module, and a Power Module (Figure 8). The user interacts with the GUI, which activates a python script responsible for creating emulation sessions, node instances, and power lines and communication connections. The core of the software is represented by the Communication Module and the Power Module. The first uses the protocols natively contained in the CORE platform. Each node instantiated is characterized by an ISO/OSI stack. Statistical measures such as bandwidth, loss rate, error rate, and noise level are measured on each node. The Power Module receives the network topology from the Communication Module, and updates it to each modification occurring due to the iterations between the nodes. Since SCORE is designed to work in real time, the power network calculations are performed with a DC Power Flow.

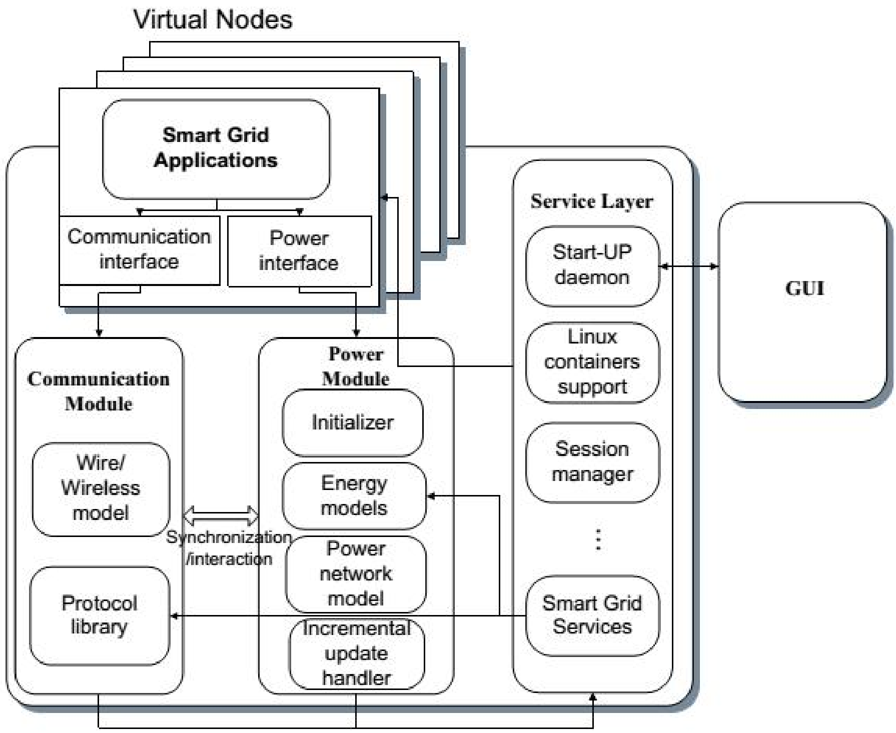

Figure 8. Architecture of SCORE comprehensive simulator [29]

The simulator is tested on a simple net consisting of a line with five domestic customers. The purpose is to test the reaction of the residential load to the demand response logic. Within each domestic premises there are loads that can be flexibly operated, fixed loads, generating plants from renewable sources and storage systems. Each node is connected to the rest through a wireless connection, simulated with ideal features. The simulation shows the behavior of the domestic customers that dynamically adapts the load profiles to variable energy prices.

A classification of different fields of application of the co-simulation/HIL approach is illustrated in [31]. Three macro-areas are identified:

- Wide area monitoring and control (WAMC)
- Optimization and control in distribution networks
- Integration of distributed generation.

In these fields of application, the co-simulation approach allows emphasizing several critical aspects related to the interaction between the electrical system and ICT for smart grid operation, in particular:

- Impact of latencies on the correct operation of the electrical system [28], [32]
- Use of artificial intelligence in the management of smart grid [33], [34]

Effect of cyber-attack on smart grid management algorithms [34]–[37]

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CHAPTER II

2. COMMUNICATION TECHNOLOGIES FOR SMART GRIDS

2.1 Introduction

The smart grid concept relies on a flexible communication architecture that allows power network devices such as sensors, smart meters, IEDs, circuit protection devices, to exchange information data in order to achieve an efficient operation of the power network. A wide range of communication technologies, both wired and wireless, is nowadays available for building the communication infrastructure that will support the smart grid data exchange. Each technology is characterized by peculiar features, for example data rate, coverage, installation and maintenance costs, reliability, exposure to cyber-attacks, etc. The technology choice is therefore crucial. In the following sections, the most acknowledged technologies for smart grid applications are expounded in brief.

2.2 Wireless technologies

Wireless technologies are offered as key candidates in building the Smart Grid communications network for a range of benefits ranging from low installation costs to ease of deployment. On the other hand, some of the disadvantages in using this technology, ranging from sensitivity to electromagnetic disturbance, distance coverage, data security and privacy, should be mentioned. Table 3 shows the characteristics of the most important wireless technologies within SG.

Table 3. Wireless technologies for Smart Grid applications

		Data Rate *(Mbps)*	Frequency *(GHz)*	Bandwidth *(MHz)*	Coverage *(km)*
Wi-Fi		600 for 802.11n	2.4 – 5.8	20, 40	1km for 802.11p
ZigBee		0.250	2.4	0.600, 2, 5	1.5km LOS
WiMAX		300	2.3, 2.5, 3.5	1.25, 5, 10, 20	50
Mobile	GPRS	0.170	0.9, 1.8	0.200	1÷10
	3G	56 in HSPA+	1.8, 2.5	5, 20	1÷10
	LTE	1000 for LTE-A	0.7, 0.8, 0.9, 1.8, 2.6	5, 20	1÷10

2.2.1 Wi-Fi

With Wi-Fi systems it is normally indicated the technology that allows the interconnection of network devices in a Wireless Local Area Network (WLAN), according to the IEEE 802.11 standard. This technology has reached an astounding success, especially with the 802.11g and 802.11b versions, that exploit the unlicensed frequency bands at 2.4GHz and 5GHz and guarantee 54Mbps in downlink with 100 m of coverage. The most recent releases aim at extending these limits. In particular, the release 802.11n declare a downlink data rate of 600 Mbps, meanwhile the 802.11p extends the coverage distance up to 1 km. The potential of this architecture widens through the use of repeaters or by interfacing the WLAN with a cellular network, therefore forming a hybrid architecture, where Wi-Fi performs the packet deliverance in a Neighborhood Area Network (NAN) or Home Area Network (HAN) domain [39]

2.2.2 ZigBee

ZigBee and 6LoWPAN are two technologies based on the IEEE 802.15.4 standard. This standard is designed for a small data traffic networking. The strength of this standard is the low energy consumption, which makes it particularly suitable for the implementation of Wireless Personal Area Network (WPAN). 6LoWPAN represents an evolution of ZigBee as it enables IPv6 traffic. ZigBee technology is the ideal solution for building automation, due to its low cost and low energy consumption, as well as its open protocol and flexibility in a wireless network. For this set of reasons, it is widely preferred to Bluetooth technology, with much higher power consumption. The low consumption of ZigBee is achieved by very small duty cycles, less than 5% [40]. ZigBee can be activated (i.e. switching from standby mode to active mode) in less than 15 ms, the latencies introduced are therefore very low. The coverage that can be reached is about 50 m, a sufficient distance for creating a meshed network in HAN.

2.2.3 WiMAX

WiMAX is a wireless technology that is based on the IEEE 802.16 standard. WiMAX provides coverage up to 50 km with data rate of 75 Mbps for fixed connections. The second release of WiMAX (IEEE 802.16m) improves the performances both in downlink and uplink, and bring data rate up to 300 Mbps and 200 Mbps, respectively [41]. For fixed communication, the bandwidth ranges from 3.5 GHz to 5.8 GHz. This frequency range, being below 10 GHz, allows penetration of obstacles in data transmission between two points that are not in line of sight, an aspect which is very important for the realization of a wireless backbone.

2.2.4 Mobile communication systems

Mobile communication systems are based on the concept of mobile network, which is a distributed radio network distributed in cells, each served by a fixed station called Base Station or Access Point. They represent a good choice in establishing communication between smart meters and utilities, or in general communication between distant nodes. Being able to exploit existing infrastructures is one of the key advantages of adopting this technology for the implementation of a Smart Grid, since it reduces costs and time of realization. This technology was originally designed for voice traffic through GSM service, of which GPRS and EDGE services are an evolution for allowing data traffic. Third generation mobile communications (3G) technologies, such as UMTS and HSPA, and fourth generation, such as LTE, complement this data-oriented development. LTE technology has reduced latency times to the order of 5 ÷ 10 ms. The global diffusion of LTE technologies among the mobile users devices has nowadays relegated WiMAX to a position of second choice technology for both generic and industrial infrastructures.

2.2.5 Satellite, microwave and optical communication

In this family are grouped those technologies that assume a secondary role in the chance of use on SG applications; however, they may be interesting in marginal situations.

Satellite communication can be a good alternative to a cost-effective ad-hoc network where there is no existing communication infrastructure. It provides global coverage and fast and cost-effective installation for those remote areas that are hard to reach from a wired or wireless access points. Satellite communication is also very useful when a reliable backup solution is needed, for example in case of failures along the mainstream communication medium. However, it is important to notice the weaknesses of this technology. Satellite technology suffers signal transmission delays much higher than wired or radio waves. A second aspect is the strong influence that weather conditions have on attenuation of the signal. These factors strongly limit the potential of this technology in SG. [42]

Microwave technology is used in point-to-point communications, due to short wavelengths that allow directional antenna transmission, increasing bandwidth and reliability. An analogous system is the utilization of light as a transmitting signal on free space. Both technologies allow the deployment of a backbone to an SG. However, there are serious problems due to strong sensitivity towards barriers and obstacles, as the signal is transmitted only on a perpendicular path, and on environmental conditions.

2.3 Wired technologies

The first man-made communications systems used copper cables to transmit analogue, later digital, signals. Even today, despite the advent of wireless communication, wired technology is widely used in a variety of fields, because it is still seen as the safest and most reliable system for transmitting information between two points. Wired technologies can be grouped into three main families:

- Copper cable communication systems;
- Fiber optic communication systems;
- Powerline communication systems.

2.3.1 Copper cable communication systems

Using telephone cables as a means of transmitting information is a low-cost solution, due to the widespread diffusion of this medium in the territory. The twisted pair, made up of two pairs of twisted copper cables, also allows a high data rate. ADSL technology provides downlink speeds of the order of several dozen Mbps while about 1 Mbps in uplink. However, the speed of a DSL data transmission depends heavily on the user distance from the station where the signal modulation occurs. In addition, in order to have a large and efficient coverage, it is necessary to constantly invest in new cable installation and in the maintenance of existing infrastructures.

2.3.2 Fiber optic communication systems

The introduction of fiber optic in communication systems, which dates back to the 1960s, offers several advantages over wired copper communication. It presents a greater bandwidth, as well as a substantial immunity to electromagnetic interference (EMI) and radio waves interference (RFI), making fiber optic the ideal communication medium in high-voltage operating environments such as in substations [39] The reduced attenuation of the signal strength results in a lower number of repeaters compared with the copper cable, with a total radius of coverage ranging from 100 to 1000 km (copper needs a repeater every 2 km). The biggest advantage, however, is determined by the data rate capability. Currently, fiber systems provide data rates up to 10 Gbps for single-wavelength transmissions, and 40 to 1600 Gbps when using WDM transmission, and a very low Bit Error Rate (BER) of the order of 10^{-15} . The disadvantage of the optical fiber is determined by the high installation costs.

2.3.3 Powerline communication systems

Powerline communication systems, often referred to as Power Line Carrier (PLC), consist of data transmission through the conductors normally used for power transmission and distribution. This is a technology that dates back to the 1950s, but it is only in recent years, with the increasing importance of ICT systems in the power grids, that this technology has gained interest. It is primarily due to the widespread presence of a data transmission medium that does not entail any additional cost, since it consists of the power line itself. In terms of bandwidth, recent improvements in PLC technology have brought transmission capacity at 45 Mbps. Although this high potential is acknowledged, its implementation is accompanied by many doubts. The electric line is in fact a complex medium, characterized by disturbances such as noise, electromagnetic interference and frequent impedance variations, making it unsuitable for data transmission. The presence of a high noise level involves a high BER, which therefore reduces performance and reliability. There are also security-related issues, since unshielded conductors for intercepting sensitive data are quite straightforward when compared to the copper pair or the fiber optic cable. Finally, it should be noted that communication between two points is interrupted by the operation of a switch or disconnector. For all these reasons, it can be considered that PLC technology, although usable for limited data traffic, is not sufficiently suited as a data transmission medium in a SG, requiring an advanced performance level that the PLC cannot currently guarantee.

2.4 LTE

With the recent enhancements in wireless solutions that guarantee a performing and reliable communication at low cost, a strong interest is upon the possibility of exploiting the last generation communication systems for supporting the transition of distribution network towards a Smart Grid scenario. However, which one communication technology solutions is the best fit to support SG applications is still not clear, even though LTE technology is considered one of the most promising ones [43]. LTE, with its widespread distribution, broad coverage, high throughput, device to device (D2D) capability, despite not being originally designed for smart grid applications, represents a valuable candidate for the usage in a SG communication system [44].

Cellular networks operating in licensed bands constitute a promising technology for Smart Grid applications. LTE is a mature and stable technology, and the most recent LTE-Advanced release provides the users with performances that are comparable with the most advanced wired DSL technology. Moreover, it is an ever upgrading technology, and the upcoming 5G version of the cellular technology promises to introduce interesting features that will increase performances and possibilities. The main features that enable LTE as a strong candidate for supporting Smart Grid communication are [44]:

- Use of licensed bands: the communication network is robust against cyber-attacks and possible stealing of confidential data, and permits a better handing of interferences if compared with technologies that operate on license-free bands.
- Mature and ubiquitous coverage: the communication network span over vast areas, thus permits to integrate even remote endpoints to the main power grid.
- High performance: high data rate, low latency, and high system reliability enable critical automation tasks within the distribution grid that are often associated with demanding QoS requirements, such as severe time constraints.
- Third-party operation: it relieves DSOs from having to run and maintain a dedicated communication infrastructure.

2.4.1 LTE Characteristics

The spreading of mobile telecommunication devices has stimulated a committed research over existing communication technologies. GSM, GPRS, EDGE, UMTS are part of this continuous evolution that has led to LTE, which represents one of the fourth generation mobile technologies (4G).

According to the ITU, fourth generation technologies requires certain characteristics to be complied with, among others: [45]

- Ability to inter-work with other radio technologies.
- High quality of service
- Data rate of 100 Mbps in motion and 1Gbps with fixed installations
- Sharing of network resources, allowing multiple users per cell.
- Scalable bandwidth from 1.4 to 20 MHz.
- Packet switching IP networks
- Connection spectral efficiency of 15 bps/Hz in downlink and 6.75 bps/Hz in uplink.
- Operating modes: TDD and FDD.

LTE is the technology that currently most efficiently meets all these requirements.

LTE is an evolution of GSM and UMTS technologies that was developed in late 2009, with the aim of increasing the capability of hosting an ever growing data traffic over mobile devices, along with the data rate, in order to provide a faster data transmission. With the possibilities provided by today's hardware and the increase in the computational power available in each telecommunications device, the increase in the data rate is easily attainable through the use of broadband carriers.

However, the increased bandwidth utilization has a price: a reduced minimum distance between the modulated symbols increases noise and interference sensitivity. Accordingly, adaptive modulation and coding and other link adaption strategies can be used to decide when to use a low modulation order or a higher order. By applying these methods of adaptation, LTE is able to significantly improve data throughput and reliability achievable in a communication connection. [46]

2.4.2 Elements of LTE architecture

The components that form an LTE network have specific functions similar to their predecessors in earlier technologies, but nevertheless, considerable change is introduced in the network architecture, which can be considered as a simplification of UMTS.

The LTE terminal is named User equipment (UE). The UE is constituted by two parts: the Mobile Equipment (ME) and the Universal Subscriber Identity Module (USIM). The ME is the real terminal that contains the hardware and software that implement the LTE capabilities (management of radio resources, communication, mobility management, security etc.). The USIM consists of an integrated circuit called UICC that contains all the information about the user, network, and services supported.

The LTE access network, also known as e-UTRAN, consists of a single element, the so-called evolved Node B (eNB), which includes all those features that in UMTS were managed separately from Node B and radio network control (RNC). In fact, since in LTE all data is directed on packet switching protocols, the core network is unique, without distinction between circuit switching and packet switching domains. The access network manages all operations related to the transmission of signals on the radio channel and consists of the following main features: radio resource management, header compression, connectivity to the EPC, network authentication and data encryption. This function is responsible for compressing the header of IP packets so as to reduce reporting traffic as much as possible. This feature is very important especially for small packages, such as VoIP packages.

The eNB is formed by physical layer, MAC, RLC (Radio Link Control) and PDCP (Packet Data Control Protocol), which contain the user plane functions such as header interpretation and encryption, along with the RRC (Radio Resource Control) that is responsible for access control, scheduling, encryption and decryption of user plane data. The simplified structure of the LTE access network reduces the interaction between the layers of the protocol stack, decreasing the latency and the amount of signaling data.

The *core network* (CN) takes care of data transfer and external packet networks. The main logical nodes that form the CN are (Figure 9):

- Mobility Management Entity (MME): This is the primary key node for the access to the core network. It is responsible for providing subscriber authentication, roaming and handover to other networks. It also tracks the location of the mobile terminal, manages paging operations, and deals with the assignment of temporary identities to individual UE.
- Home Subscriber Server (HSS): It constitutes the database for a given user, responsible for subscription, identification, registration and authentication encryption.
- Serving Gateway (S-GW): This is the interface with the e-UTRAN access network and other 3GPP networks. It deals with the mobility management of a mobile terminal that moves from one eNB to another. It also stores an UE's packets in idle state and manages the download of packages during paging operations needed to re-establish a connection between the UE and CN.
- PDN Gateway (P-GW): It deals with the allocation of IP addresses to the UE and the management of information flows, on the basis of specific QoS. In addition, it performs as an interface with external packet networks (not 3GPP).

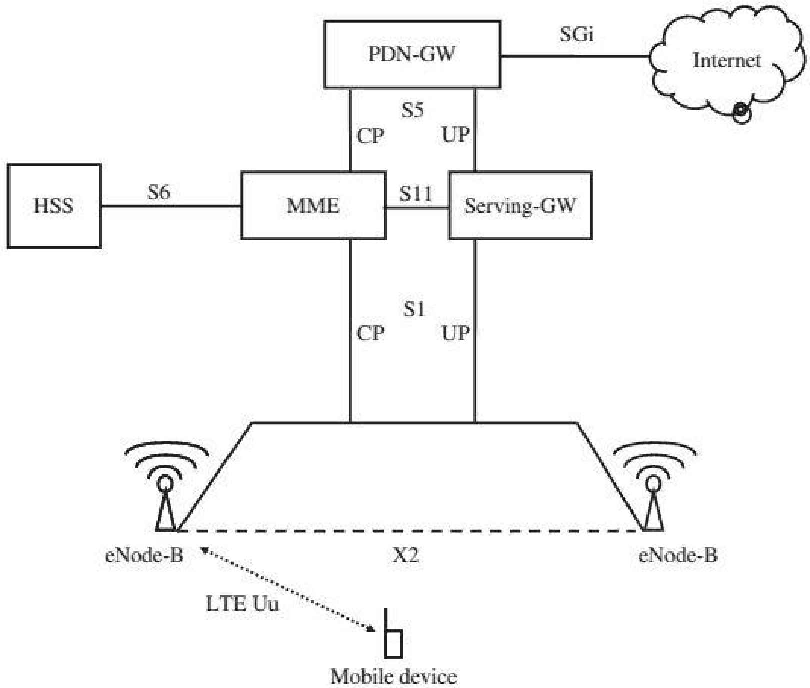


Figure 9. Main components of LTE core network[47]

2.4.3 LTE performances

LTE can be seen as an overall improvement of the 3G cellular system, which includes a series of new services and functionalities, which objective is, as in any technological evolution, to provide the system with better global performance.

In Table 4 the performance of the first Release of LTE are compared to previous systems.

Table 4. Evolution of 3GPP standards [48]

	Data Rate	Key features	Release date
GSM	DL: 9.6 kbps UL: 9.6 kbps	Digital, TDMA	1991
GPRS	DL: 14.4 – 115.2 kbps UL: 14.4 – 115.2 kbps	TDMA, GMSK, convolutional coding	1999
UMTS (Release 99)	DL: 384 kbps UL: 384 kbps	WCDMA, turbo coding	March 2000
UMTS (Release 4)	DL: 384 kbps UL: 384 kbps	Higher chip rate than release 99	March 2001
HSDPA (Release 5)	DL: up to 14 Mbps UL: 384 kbps	HARQ, fast scheduling, channel quality feedback, AMC	June 2002
HSUPA (Release 6)	DL: up to 14 Mbps UL: up to 5 Mbps	MBMS, integration with Wi-Fi	March 2005
HSPA+ (Release 7)	DL: up to 28 Mbps UL: up to 11.5 Mbps	MIMO, higher order modulation, latency reduction	December 2007
LTE (Release 8 and 9)	DL: 140 Mbps (10 MHz) / 300 Mbps (20 MHz) UL: 25 Mbps (10 MHz) / 75 Mbps (20 MHz)	OFDMA, dual carrier HSPA, SON, femtocell	December 2008 (Rel. 8) December 2009 (Rel. 9)

Key-enabling technology that distinguishes LTE from the previous 3GPP standards is the utilization of Orthogonal Frequency Division Multiplexing (OFDM) as radio channel interface, instead of Code Division Multiple Access (CDMA) that was used in the previous technologies. The OFDM technique is primarily based on the known technique of FDM (Frequency Division Multiplexing), in which the different flows of information are assigned a separate parallel frequency channels. The advantage of many slower parallel data streams is that the individual steps of the transmission process can be slow enough to avoid the problems related to the multipath transmission on the quick data streams. The broader bandwidth available for the LTE carriers, the higher the number of subcarriers used.[49]

In March 2011 has been published the Release 10 of 3GPP, which introduces LTE-Advanced (LTE-A). The LTE-Advanced technology is currently at an early stage of development. It represents the evolution of LTE, notably improving the transmission speed. It has seen the need to use techniques, such as Coordinated Multiple Point Transmission and Reception (CoMP) and Carrier Aggregation (CA) in order to improve the whole system, maintaining the initial structure of its bases with which it was created.

Despite LTE not being fully developed, the industry of cellular communications is working for a further enhancement of the standard towards what is commonly referred as 5th Generation technology (5G).

Table 5. Main features of different LTE Releases [50]

LTE	Rel. 8	Supporting both frequency division duplex (FDD) and time division duplex (TDD)
		Scalable frequency spectrum in six different bandwidths: 1.4, 3, 5, 10, 15 and 20 MHz
		OFDM
		Supporting up to four-layer spatial multiplexing with Single-User MIMO
		Achieving 300 Mbps in DL and 75 Mbps in UL
		User-plane latency of less than 20 ms
	Rel. 9	Multicast and broadcast functionality
LTE-A	Rel. 10	Carrier aggregation to utilize up to 100 MHz bandwidth
		Supporting up to eight-layer spatial multiplexing with SU-MIMO
		Enhanced Multi-User MIMO
		Extended and more flexible reference signal
		Relaying functionality
		Peak data rate beyond 1 Gbps in DL and 500 Mbps in UL
	Rel. 11	Coordinated multipoint (CoMP) transmission and reception
		Enhanced support for Heterogeneous Network (HetNet)

The main requirement of 5G technologies is to increase the capacity in order to extend the utilization of the network to non-mobile-broadband application. Non-mobile broadband applications refer to the massive machine-type communication, exemplified by sensor networks in agriculture, traffic monitoring, and remote management of utility equipment in buildings. Machine-to-machine (M2M), Vehicle-to-Vehicle (V2V), Narrowband Internet of Things applications (NB-IoT) differ from the typical mobile broadband applications requirements (Internet access with high data rate) and are mainly characterized for power-efficient low-datarate communication. LTE successor has therefore to host a wide variety of network-connected devices, each one with its own specific requirements, and flexibility has to be the first design specification from the radio interface to the core network.[49], [51]

2.5 Communication technologies modelling in co-simulation

Smart Grid co-simulators may be characterized by a different level of detail in modelling the components and the protocols that form the ICT chain through which the information is exchanged between the Smart Grid devices.

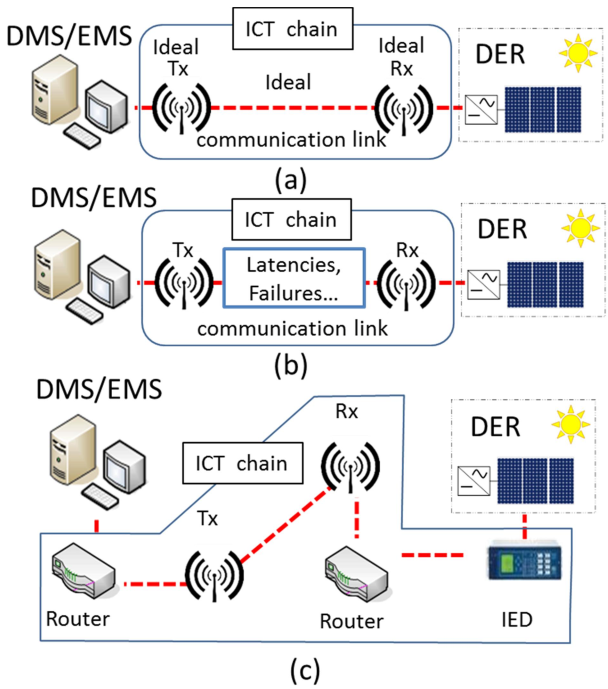


Figure 10. Modelling of ICT chain: (a) ideal ICT, (b) real ICT with black box communication link, (c) detailed ICT model

The detail of the ICT chain model may be divided in three levels as depicted in Figure 10:

(a) ideal communication link and transmitting/receiving devices,

(b) real transmitting/receiving devices with black box communication network model,

(c) detailed ICT network model [7]

In the case (a) the ICT network is considered as ideal, information traffic between source (DMS) and destination (DER) occurs without any error or delay. A co-simulation study in this case allows verifying the correctness and the efficiency of the control algorithms in ideal conditions.

In case (b) ICT network is modeled by a black box. Transmission medium and ICT devices are modeled by means of reliability parameters, and the information delivery is defined by a constant delay determined by the site and weather conditions (presence of clouds, rain, obstacles, etc.), or by reliability parameters. A study of co-simulation with a black-box ICT modeling is useful to demonstrate the robustness of the smart grid in conditions of non-delivery of the control signals, and make a planning study concerning redundancy of ICT channels, or redundancy of active resources that can provide for any lack of communication.

The third case (c) is a more detailed modeling of the ICT network. The communication network is defined by the parameters of links and network devices (antennas, routers, switches, etc.). This modeling allows the highest degree of detail and consistence of simulation to reality, allowing greater trustworthiness of results and an easier examination on any weaknesses in the ICT structure. In case of wireless communication systems and RES production subject to weather condition (e.g. solar resource) a further detail can be included considering the influence of meteorological conditions on power production and signal transmission.

The choice between these three levels on ICT modelling is made according to the degree of detail required by the simulation. A severe level of detail may in some cases be unnecessary and require long time execution in the simulation. For example, in the case of simulations oriented towards a reliability characterization of the ICT infrastructure, (e.g. with a Monte Carlo method) a detailed characterization of the ICT network is unnecessary for the stochastic results of the Monte Carlo method, and the ICT devices are described as a black box. It allows to exploit the simpler characterization of the ICT network and make the simulation faster.[52]

2.6 Weather condition in wireless communication modelling

In case of wireless communication, in order to obtain a detailed characterization of the performance in signal transmission it is necessary to take into account the weather conditions. The variability of psychrometric quantities such as temperature, relative humidity, atmospheric pressure, as well as ground type (flat, hills, etc.), affect the attenuation of the signal transmitted between antennas, particularly for long-range transmissions (WiMAX), more sensitive to weather conditions.

On the other hand, the presence of random phenomena such as atmospheric precipitation leads to a significant increase in the signal attenuation even on short-range transmissions (for example in Wi-Fi or LTE transmission), whilst characteristics such as soil morphology have a smaller impact.

The Longley Rice Irregular Terrain Model (ITM) is a method proposed by the National Telecommunication and Information Administration (NTIA), which is based on the studies proposed in the 1970 by Hufford, Longley and Rice ([53], [54]) for the planning of analogue TV broadcasting systems in the USA. The Longley Rice ITM model provides a good estimation of the average attenuation on an irregular ground on a point-to-point transmission in a frequency range between 40 MHz and 100 GHz. This model is based on experimental data recorded on a measurement campaign that considers variable settings in terms of distance between the terminals (1 to 2000 km) and antennas height (0.5 to 3000 m). It also takes into account Earth curvature, soil properties and climatic conditions.

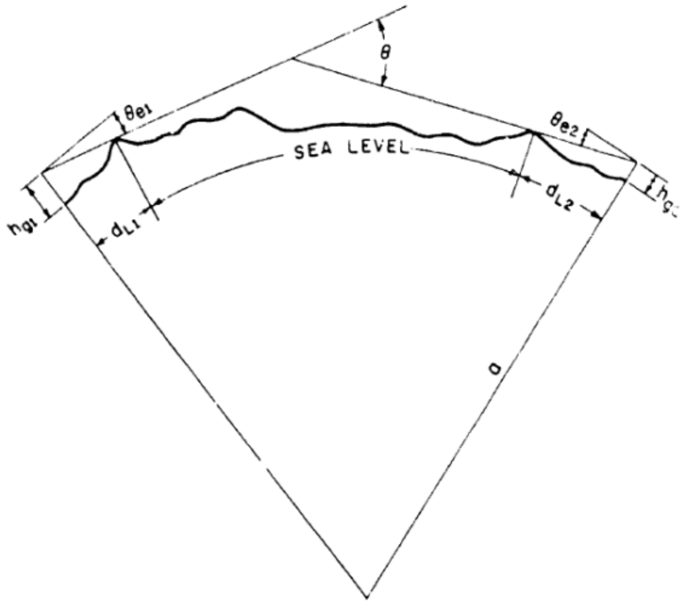


Figure 11. Descriptive variables of site geomorphology [54]

This model, given a perfect characterization of the topographic features of the site, provides an accurate description and modeling of the communication site, and allows calculating the transmission attenuation taking also the presence of elements that obstruct the transmission path.

The description of the geomorphology of the site is given by means the variables reported in Figure 11. The figure highlights the horizons d_{L1} and d_{L2}, the horizon elevation angle θ_{e1} and θ_{e2}, and the angular distance, which is function of the angle θ between the horizons of the transmitting and receiving antennas. Once the site is characterized on the basis of the parameters described, the model calculates the reference attenuation A_{ref}, which represents the average attenuation on free space. The reference attenuation is a continuous function which, given the site where the radio transmission occurs, mainly depends on the distance between the antennas; the attenuation profile over the distance can be divided in three regions: visibility region, diffraction region and scattering region (Figure 12).

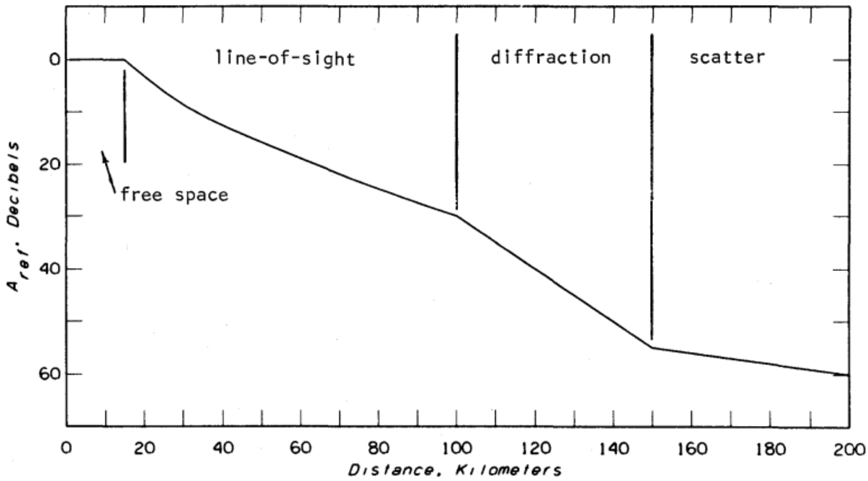


Figure 12. Typical reference attenuation in relation to distance [54]

The visibility region includes the area on which the earth convexity does not obstruct the transmission through direct radio waves; therefore in this case the field is not restricted by the presumed presence of obstacles such as hills or the like. In this region, the reference attenuation assumes a profile that combines a linear and logarithmic function over the distance. The diffraction region follows, where there is a steep increase in attenuation; this increase finally reduces its slope in the following region of scattering.

In calculations, the model considers the physical laws of surface reflection, atmospheric refraction, diffraction in atmosphere and around objects and tropospheric scattering. The model also combines these results with empirical relationships obtained from experimental measures. This combination makes the Longley-Rice model a semi-empirical model that, on the one hand, maintains a bond with the canonical laws of physics, and on the other hand observes a strong correspondence of results with the actual physical behavior of the phenomena. The reference attenuation is a figure that well represents the behavior that is expected from a signal propagation phenomenon. However, an estimation based on the exclusive knowledge of the descriptive parameters of the site may be too generalized. In order to reach a higher degree of compliance with reality, the Longley-Rice model provides a number of statistical correlations that better evaluate the forecast based on the knowledge of detail information. From a mathematical point of view this is expressed through a first definition of a quantity defined by (2.1):

$$A^{'} = A_{ref} - V_{05} - Y_T - Y_L - Y_S \qquad \textbf{(2.1)}$$

where the parameters V_{05}, Y_T, Y_L and Y_S are statistical parameters expressing respectively the seasonal variations of the surface refractiveness of the ground, the variability of the instant of observation, variability of the paths of transmission and a factor of global randomness of site conditions. Starting with the calculated value of *A'* the actual attenuation of the Longley-Rice is calculated with (2.2):

$$A_{LR} = \begin{cases} A^{'} & \text{if } A^{'} \geq 0 \\ \dfrac{A^{'}\left(29 - A^{'}\right)}{29 - 10A^{'}} & \text{otherwise} \end{cases} \qquad \textbf{(2.2)}$$

Finally it has been observed that Longley-Rice's model is based on long-term forecasts. For a thorough description of the influence of weather conditions on signal transmission in a smart grid, however, circumstantial events such as rainfall are also relevant.

For this reason an additive term has been introduced, based on the ITU recommendation ITU-R P.838-3 "Specific attenuation model for rain for use in prediction methods" [55], in order to estimate the additional attenuation given by the rainfall assessed during the simulation. The attenuation is calculated using the following expression (2.3):

$$\gamma_R = kR^{\alpha} \qquad \textbf{(2.3)}$$

Where γ_R is the specific attenuation in [dB/km], R is the rainfall rate in [mm/h], and k and α are two coefficients that are function of frequency and polarization type.

The overall attenuation is given by (2.4):

$$A_{TOT} = A_{LR} + \gamma_R d \qquad \textbf{(2.4)}$$

The Longley-Rice model is valid for signals transmitted for distances ranging from 1 km to 2000 km, so the results can be unrealistic if the model is applied to signals transmitted within 1 km of distance.

In this case for estimating the average attenuation of the signal under standard conditions (no rainfall) the Two Ray Ground Model has been adopted, while rain attenuation was evaluated separately according to the criteria proposed by ITU-R P.838-3.

The Two Ray Ground Model calculates the power received at a distance d from the transmitting antenna with the formula (2.5):

$$P_r(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4 L} \qquad \textbf{(2.5)}$$

Where P_t is the power of the transmitted signal, G_t and G_r are the gains of the transmitting and receiving antennas, L is a loss factor unrelated to propagation and h_t and h_r are the heights of the transmitting and receiving antennas respectively. Therefore, the signal attenuation in the case of short range wireless transmission is calculated by (2.6):

$$A_{TOT} = A_{TRG} + \gamma_R d \qquad \textbf{(2.6)}$$

Where A_{TRG} is the attenuation calculated with the Two Ray Ground method, and the second addend is the rain attenuation.

CHAPTER III

3. ACTIVE MANAGEMENT ON SMART DISTRIBUTION NETWORKS

3.1 Introduction

On Chapter §1 a short review on latest scenarios about the evolution of towards the smart grid paradigm has been given. A growing interest upon a reduced environmental impact of energy utilization and a favorable regulatory and financial stimulation towards RES has brought to a dispersed installation of small DG power plants on distribution networks.

The inclusion of a large number of DG plants brings both benefits and open technical issues that will be discussed in details in this chapter. Then, the management system implemented in the co-simulator will be presented.

3.2 Benefits and open issues for distributed generation

The adoption of distributed generation conveys to the electrical system a set of economical, technical and environmental benefits [56].

From an economical point of view, the main benefits that can be indicated are:

- DG allows DSO postponing CAPital Expenditures (CAPEX) caused by the load growth, since the energy provided by the DG partially sustains the load connected to the distribution network; [10], [57]
- The dispersion of DG on the distribution network provides it with more flexibility, due to the decentralization of power flow. It brings beneficial effects to energy prices; [56]

- DG from Renewable Energy Sources reduces the fossil-fuel-fired power plants energy share injected in the distribution network, which causes, due to a demand decrease, in an energy price decline; [58]
- Energy sources differentiation brings more stability to the energy prices, when compared with a narrow set of volatile sources of energy supply. [59]

A positive impact on the distribution network in terms of system support benefits from the distributed generation can be observed:

- DG, if correctly planned, allows reducing power line losses, due to the shortening path between power injection and utilization, and refining voltage profiles along the feeders; [60]
- Distributed generation can provides ancillary services, such as peak load shaving, rotating reserve, that enhance the operational capabilities of the network; [61]
- By providing backup services when system faults occur, distributed generation can increase the quality and continuity of service of the distribution network. [61]

Finally, the leading contribution of RES power plants in the distributed generation, along with storage capabilities and high efficiency energy plants like combined heat and power (CHP) plant, represents a fundamental tool for mitigating the environmental footprint of energy consumption and production.[58]

These benefits related to the distributed generation are accompanied with technical issues that are still open [61]:

- *Voltage rise.* The installation of generation plants on weakly interconnected distribution networks, for example in rural areas, characterized by long line branches and low load, may bring irregular voltage profiles and overvoltage contingencies;

- *Power Quality*. The increased penetration of non-conventional types of electricity generators, often connected through power electronic interface, can cause transient voltage variations and harmonic distortion of the network voltage. These could determine thermal stress (due to the increased losses, if the DG placement is not optimal, and the presence of the triple harmonics in neutral current, even for a balanced source), insulation stress (that leads to reduced life time of the insulators). Another issue is the load disruption, which usually occurs with sensitive loads that are designed to operate under nearly pure sinusoidal voltage, or with the loads that depend on the zero crossing of the wave (e.g., communication equipment and the electronic clocks); [62]
- *Inversion of power flow*. Electric power systems were natively designed considering a unidirectional power flow, from high voltage to low voltage substations. The increased amount of distributed generation power plants may cause a power flow inversion in some portions of the distribution network, or even a power flow inversion from distribution to transmission network. It leads to many technical issues to distribution network devices (on transformers, voltage profiles, loss-of-mains protections, etc.);
- *Protection devices*. Distributed generation flows can reduce the effectiveness of protection equipment. Customers wanting to operate in 'islanding' mode during an outage must take into account important technical (for instance the capability to provide their own ancillary services) and safety considerations, such that no power is supplied to the grid during the time of the outage. Once the distribution grid is back into operation, the distributed generation unit must be resynchronized with the grid voltage. [61]

In order to exploit the benefits provided by the DG, it is necessary to find intelligent solutions that allow solving these open issues. The acknowledged solution key for this problem consists on increasing the monitoring, control and regulation capacity. The smart grid paradigm consists in providing operation procedures that allow:[6]

- Maintaining a high grade of reliability of the electric system;
- Increasing distributed generation and load management;
- Promoting high efficiency on the energy consumption and the involvement of the customers on the energy market, for example with Vehicle to Grid (V2G) and Demand Response services.

The SDN entails applying this paradigm on distribution networks. With Active Distribution Management (ADM) techniques it is possible to exploit a high penetration of small size generation plants on distribution networks, both from renewable energy sources and not-renewable energy sources, in order to guarantee high quality of service (QoS) according to the regulatory framework and international standards [63].

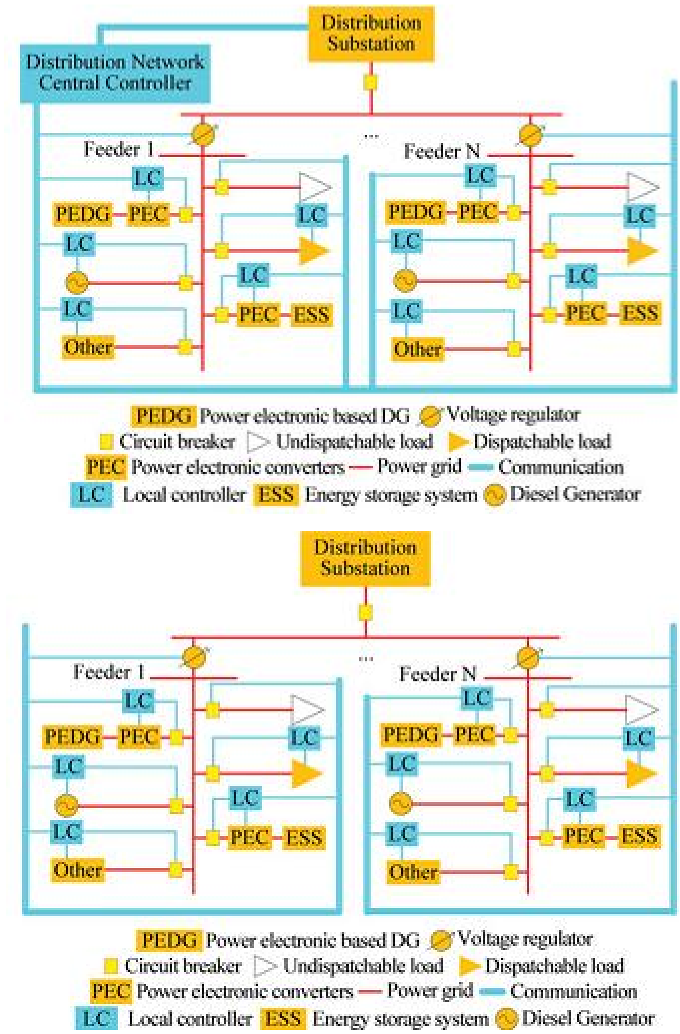
3.3 Active Distribution Management

Active Distribution Management frameworks can be classified in three categories: centralized, decentralized and hierarchical [64].

- *Centralized management framework*. On centralized frameworks, voltage and power measures are sent from the measurement points to a distribution network central controller, which is in charge of distribution network operation: active power dispatching and reactive regulation on the DG units, along with control intervention on network devices. This management framework, that resembles the SCADA system in transmission networks, is not indicated for distribution network with wide participation of DG, due to the high traffic volume necessary to control the high number of units and the high computational effort to process the data.

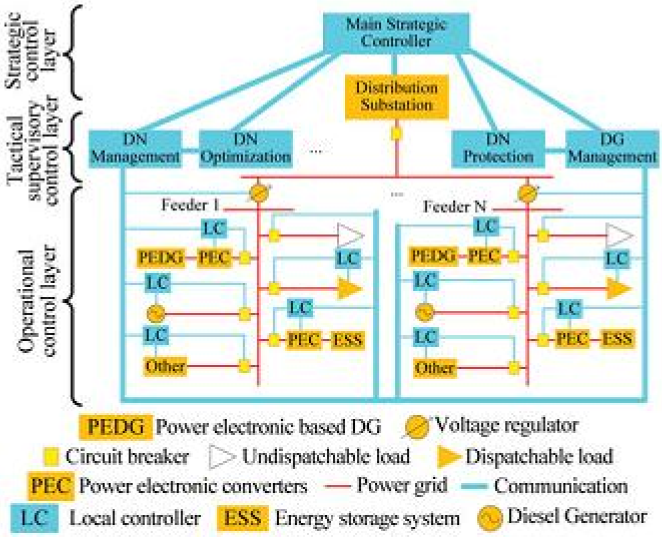
- *Decentralized management framework.* In this framework solution, each network device is provided with an autonomous artificial intelligence (AI). Operation is executed according to the information obtained with local measurements combined with the information shared by the neighbor devices. In this case, the network can be represented as a Multi-Agent System (MAS), where each network device is associated with a correspondent autonomous agent. MAS can be used for several power engineering applications, as they have peculiar characteristics that are well suited for some issues such as distributed control [65]. This solution allows reducing considerably the complexity of the system. In fact, in a future smart grid the number of sensors and controllable appliances will increase considerably; it requires a control architecture able to manage a large and composite system: a decentralization of the problem is one of the most promising methods for decreasing the complexity of the grid management [66]. Moreover, a growing interest in the research on smart grids is focused on the application of microgrids and virtual power plants (VPP) paradigms, which inherently apply a segmentation and decentralization of the power system control. MAS architecture therefore better suits a SDN implementation, which is natively characterized by a distributed attribute. [67]
- *Hierarchical Management Framework.* This framework consists on combining centralized and decentralized control through a multi-layer structure. At the highest layer, the controller is charged with control, supervision, operation and monitoring function, by aggregating all the information acquired from the lower layers. At mid-level, the

controllers coordinate the orders coming from the high level, in order to generate the optimal set points for the controllers at the lowest level. An example that adopts this framework is the microgrid concept. [68]



(a)

(b)



(c)

Figure 13. Active Management Frameworks: (a) centralized; (b) decentralized; (c) hierarchical [64]

3.3.1 Active Distribution Management techniques

Originally, distribution networks were designed according to the so-called "fit and forget" policy, which implies the planning of the distribution system in order to meet technical constraints in the most onerous conditions (e.g. full generation/minimum load or no generation/full load) even if such situation have a small probability of occurrence [57]. Active Distribution Management (ADM) provides alternative ways to solve the most common technical issues with so-called *no-network* solutions, that means avoiding or postponing physical interventions on the distribution network like line or transformer refurbishment. Traditional refurbishment investments will always be needed at some point in the planning horizon, but ADM has the potential to cope with many network issues in the short to mid-terms. [69].

Many techniques of ADM are proposed in the literature. They can be classified in the following categories [63]

- *Coordinated Voltage Control (CVC)*. It consists in minimizing the voltage variation at some pilot buses by using a multi-objective (MO) approach. Main objectives are: [70]
    - minimization of voltage deviation at pilot buses;
    - minimization of reactive power production ratio deviation;
    - and minimization of generators voltage deviation.
- *Reactive Power Compensation (RPC).* It consists on absorbing or injecting reactive power at the point of DG connection to mitigate voltage rise or fall. [71]
- *Generation Curtailment (GC)*. It consists on reducing the active power injected in the network by the DG units. [72] It implies that some producible energy is not delivered, so it can be considered an undesired effect of ADM.
- *Energy Storage Management (ESM).* The energy storage management is one of the key technologies for ADM. It allows storing the energy when congestion or overvoltage conditions occur, and injecting it during load peaks. [73]
- *Demand Side Management (DSM).* Demand-side management refers to the different initiatives intended to modify the time pattern and magnitude of the demand, introducing advanced mechanisms for encouraging the demand-side to participate actively in the network optimization process. Therefore, demand-side users are equipped with a control device, commonly known as smart meter, which communicates with the supply-side and manages their energy demand. [74]

3.3.2 Protection schemes for distribution network

With the spreading of ICT in power systems, and with the recent enhancements in wireless solutions that guarantee a performing and reliable communication at low cost, a strong interest is upon the possibility of exploiting the last generation technologies for implementing the communication layer that supports the distribution network management.

Currently, at the distribution level, due to the number of points to control and budget restrictions, SCADA are typically not cost effective at the substation level and rarely at the feeder level, and the majority of the distribution networks is not extensively monitored or controlled [75]. Traditional substation is organized according to the scheme in Figure 14. Each power line is equipped with automatic sectionalizer (AS) used in conjunction with source-side protection devices, such as reclosers or circuit breakers, positioned at the origin of the MV distribution line, to automatically isolate faulted sections of electrical distribution systems with support of SCADA systems. The power to operate the control circuitry and the mechanism is obtained from the line through the sensing-current transformers. No auxiliary power supply, external connections, or external equipment is required. The automatic sectionalizer, when the source-side protective device opens to de-energize the circuit, permits to disconnect a portion of the distribution system or a single MV user (typically passive). Sectionalizers are the most economical method of improving service continuity on distribution lines equipped with reclosers or reclosing circuit breakers.

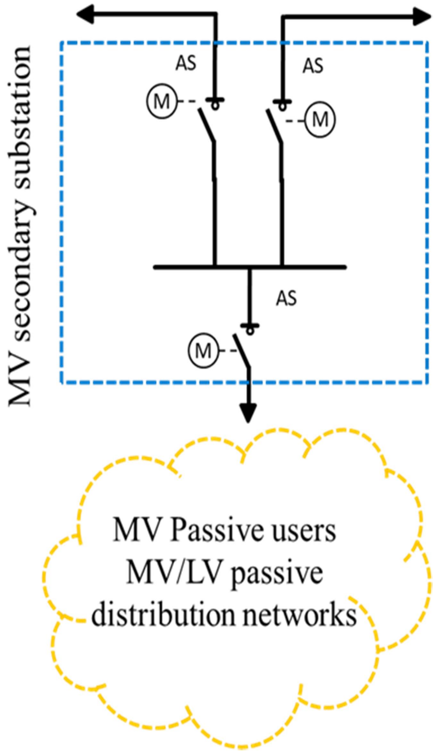


Figure 14. Schematic representation of a traditional secondary substation with automatic sectionalizers

In the future, SG operation will need more pervasive and real-time control of each network component, which will have to be equipped with smart meters and communication devices as well as with new sophisticated control and protection devices. For instance, secondary substations are getting more and more strategic in MV and LV networks to achieve service quality improvement due to their key role in power flow monitoring, distributed generation management and network automation and control. Many distributors are developing a significant activity of refurbishment of secondary substations whit new solutions for technological improvement of MV and LV equipment, MV/LV transformers, protection system, remote control devices and auxiliary components. The goals of distributors involve the exploration of existing functionalities of apparatus, to create a new SSS model with reliable power components, high performance protection schemes, efficient flow monitoring system and trusty communication infrastructures, thus optimizing the overall control of distribution network in order to:

- manage energy flows and voltage profiles according to load and DER needs,
- ensure fast reconfiguration after a failure,
- identify and pursue efficiency opportunities.

With these goals in mind all devices and their features must be integrated into a global architecture of MV and LV network control, communicating according to a centralized or decentralized logic that relies on information exchange and allows a reliable operation on them. According to this view a possible configuration of a SSS as the one depicted in Figure 15.

Currently, MV distribution networks are mainly operated with a radial arrangement. The protection is delegated to overcurrent elements based on the coordination of fuses, overcurrent relays, reclosers and sectionalisers extending along the length of supply feeders [76]. The low degree of reliability obtainable with radial network can be improved by adding emergency ties, which provide alternative routes for power supply in case of outages or scheduled interruptions.

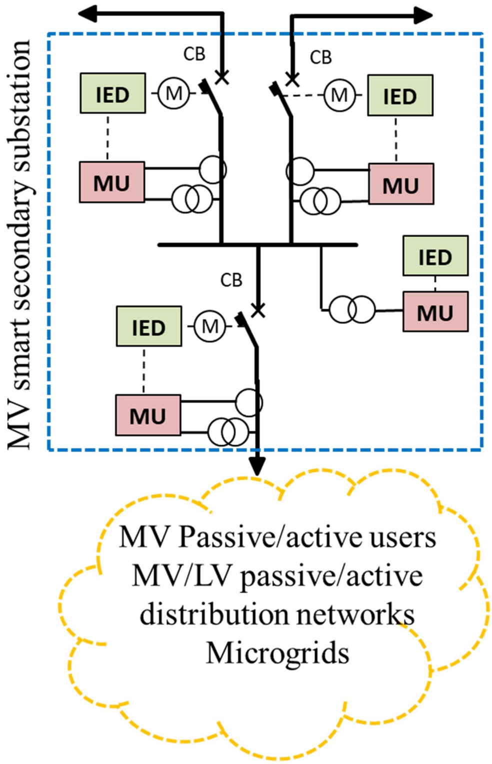


Figure 15. Schematic representation of Smart Secondary Substation

The impedance within feeders between relaying points allows coordination to be achieved as the fault level reduces down its length. As the power flow is unidirectional, this coordination is relatively easy to achieve because faults further down the feeder have lower fault current because of the higher impedance between source and fault. Relay used on radial feeders are usually supplied with both inverse-time and instantaneous elements. Inverse-time elements operate in a time that is inversely proportional to the fault current and provide the advantage of shortened tripping times for high fault currents. Instantaneous elements operate with little or no time delay when the current reaches a pre-set value. They are used to reduce operating time for severe faults and to avoid any potential loss of coordination between successive relays. [76] (Figure 16)

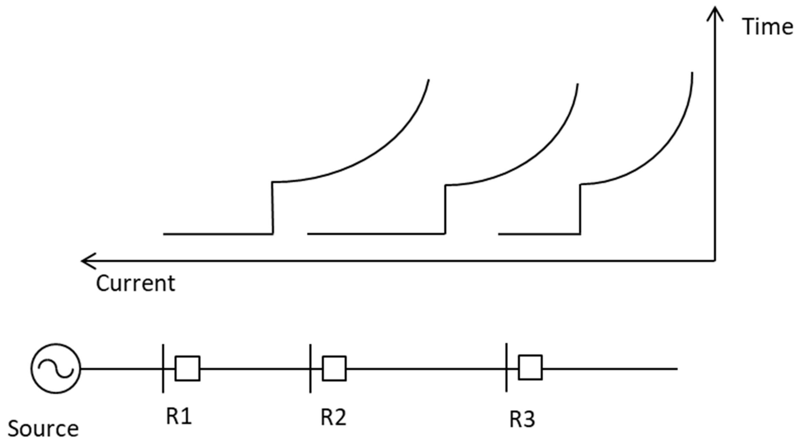


Figure 16. Relay current-time characteristics in radial feeder

In order to ensure coordination, the curves of any two consecutive relays are spaced such that two different operating times correspond to the same fault level. The difference between these two times is termed the discrimination margin and is usually within the range of 250ms to 400ms, depending on the device technology.

Regions with a high percentage of DG may be operated semi-autonomously as microgrids, resulting in a cellular structure with a high degree of fragmentation and need of coordination. Distribution operators require DG units to be equipped with additional protective devices, called Loss-Of-Main (LOM) protection, that are required to disconnect the generator from the network when the feeder protections trip during abnormal system conditions. In general, the presence of DG can cause various problems on the network operation during faults. Conflicts between DG and protections schemes are typically due to [77]:

- Unforeseen increase in short circuit currents;
- Lack of coordination in the protection system;
- Ineffectiveness of line reclosing after a fault using the automatic reclosing device (ARD) and difficult lines back-feeding;

- undesired islanding and untimely tripping of generators interface protections.

The radial operation, despite the easy operation requirements, represents an obstacle for DG proliferation. Operating the distribution system as a meshed network can present itself as a valuable solution to mitigate the negative effects of DGs in the system as well as to exploit the benefits. [78]

Meshed networks have many advantages if compared with radial schemes: a reduction of power losses, a better voltage profile, a greater flexibility and ability to cope with the load growth and an improvement of Power Quality due to the fault level increase at each bus.

On the other hand, without careful planning strategies, the adoption of a meshed scheme also presents some drawbacks, like a more complex planning and operation and a rising of short circuit current in each node, which could imply the substitution of the existing circuit breakers. [79]

For these reasons, a reconfiguration scheme that can switch between radial and meshed scheme can be a perfect compromise between these two schemes, enabling to exploit the advantages of both schemes.

Many experimental projects in European Union are focused on finding new solutions for the operation of the distribution network in order to deal with the augmented complexity associated with the Distributed Generation.

GRID4EU is a joint FP7 project composed by 27 partners from 12 EU Member States, including six European DSOs. Nice Grid is one of the six demonstration projects that are part of the GRID4EU initiative, a smart grid demonstration project led by the French DSO ERDF and developed with nine partners: EDF, GE Grid Solutions, SAFT, RTE, ARMINES, SOCOMEC, NKE, NETSEENERGY and DAIKIN. [80] The project is designed to test an innovative coordinated architecture for medium- and low-voltage distribution networks with high concentration of photovoltaic (PV) generators combined with smart end-users whose installation are capable of managing optimally their electrical needs.

Among the operation functionalities designed in this project:

- Management of a massive distributed PV generation and its impacts on the distribution grid regarding the maintenance of the voltage within the normative tolerance range around the nominal value [81]
- Microgrid operation in islanded mode. The goal is to show that a specific network area can operate independently and can be disconnected from the electrical network. Two types of microgrid operation are tested: scheduled islanding and unforeseen islanding [82]

The Italian Distribution System Operator Enel Distribuzione is also actively involved in the implementation of the Smart Grid concept with several ongoing experimental projects. One of them, called ScheMa Project, tests the performance of MV network portions in closed ring operation using an innovative control and fault detection system. This control system exploit a communication network realized with optic fiber that allows a data exchange of measurements and control signals between automated substations [83]. The automated substations along the loop line are equipped with circuit breakers (CBs): each line stretch between adjacent automated SS is therefore individually protected and switched if needed [84].

In order to reduce as much as possible communication latencies between the devices installed in automated secondary substations and in primary substation, these will be linked with an optic fiber to be installed along the MV lines. The optic cable is laid in special ducts along underground network, and exploiting existing supports for overhead networks, along with the substitution of existing conductors with another one having built in optic fiber.

A total length of about 40 km of optic fiber infrastructure has been installed in the test bed.

3.4 The proposed Active Management

3.4.1 The Distribution Management System

For the active management of the distributed energy resources, a centralized Distribution Management System is included in the co-simulation platform. The DMS optimizes an objective function that is the sum of the operational expenditures related to the active management of the distribution system by making all technical constraints (e.g., line thermal limits, nodal voltage, reserve, etc.) complied with. The economical optimization is based on price signals that guide the participation of DER in Volt/VAR regulation as well as the bids from active demand.

The DMS may choose in general the following operation optimization options (Figure 17):

- Optimization of the On Load Tap Changer (OLTC) position;
- Active power generation curtailment (GC): this option can be useful to face overvoltage conditions. The use of suitable price signals limits its usage to RES;
- Extra dispatching of active power from programmable generators, particularly effective as remedial action against voltage drop;
- Volt/VAR regulation with DG;
- Demand Side Integration (DSI), to involve customers that participate to Active Demand (AD) programs in the active management of the network, including the payback effect;
- Energy losses minimization to improve the total energy efficiency;
- Storage devices charge and discharge used for load levelling and voltage regulation.

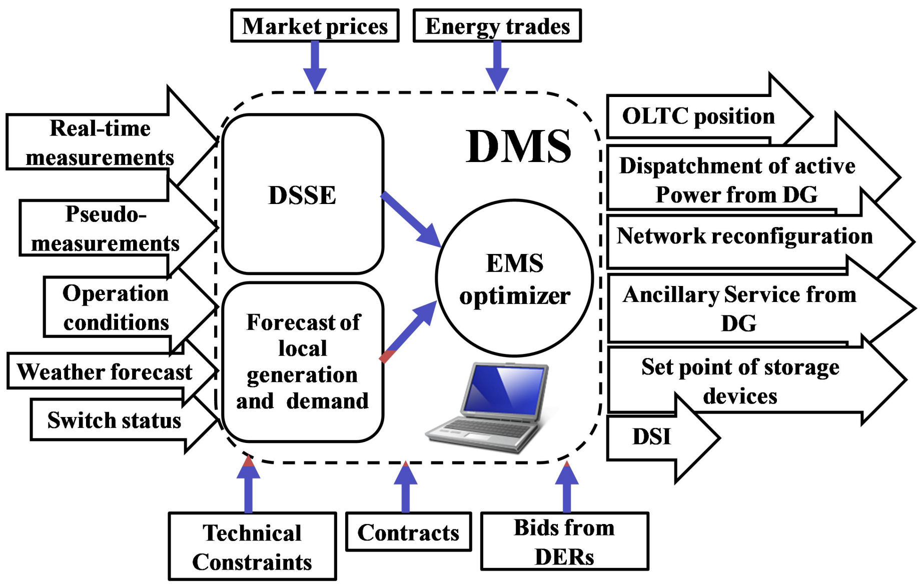


Figure 17. The architecture of the centralized DMS

The OPF can be solved with several techniques as non-linear programming (NLP), linear programming (LP) or mixed-integer linear programming (MILP). An optimal power flow for real time application requires speed, reliability and ability to handle many different operating constraints. NLP calculations risk being computationally burdensome and slow in convergence, therefore is not considered an efficient solution for real time application [85]. On the other hand, the application of the revised simplex method proves to be computationally efficient, accurate, and particularly suited to large and sparse LP problems [86]. For that reason, in the proposed application the MILP has been used, where the integer constraints is used to properly model the constraint related to the OLTC position [87].

The Objective Function (OF) to be minimized by the network operator is the sum of the costs of i_{th} active management resource alternatives C_i, i.e. the cost for changing the scheduled DG active power production, generally cost for curtailment (C_{P_DG}), the cost of reactive support (C_{VAR}), the cost of demand side integration (C_{AD}), the cost of energy storage operation (C_{DES}). Furthermore, the cost of energy losses minimization C_{losses} can be included in the OF if the improvement of the efficiency of power delivery is a task that DSOs have to pursue [96].

$$\min \mathrm{J} = \min \left\{ \sum_i C_i = C_{losses} + C_{P\_GD} + C_{VAR} + C_{AD} + C_{DES} \right\} \qquad \textbf{(3.1)}$$

The optimization problem is subject to a set of technical constraints, which are expressed as linearized equality and inequality constraints:

- $2 \cdot N_{bus}$ of equality equations, which represent the active and reactive power flow balance in the nodes;
- $2 \cdot N_{bus}$ of inequality equations, which correspond to the node voltage constraints;
- $2 \cdot N_{seg\_DG}$ constraints of inequality, which represent the capability curves of each generator. The parameter N_{seg_DG} is equal to the number of segments used to approximate the capability curve of the generators
- N_{seg_Br} constraints of inequality, which represent the thermal limits of the cables. The approach used is similar to the formulation of the capability curve of the generators, namely the thermal limit of the lines is approximated by a piecewise linear approximation, whose internal surface represents the allowable operating area;
- $4 \cdot N_{seg\_DES}$ constraints of inequality, which represent the technical limits of the storage systems. The formulation is similar to the approach followed for the generators and lines constraints.

3.4.2 The proposed protection scheme

The protection management with automation schemes is designed to keep power interruptions to a minimum time. The operation of the breakers is highly time critical, since it is necessary to guarantee an instantaneous trigger on the breakers in order to assure an efficient intervention during or after a fault extinction. The implementation of such systems requires a robust Smart Grid infrastructure, which allows defining the area of the fault and interrupting the power flow. At the same time, it is necessary to minimize the disconnection of loads and guarantee that the fault may not be fed by RESs.

Many solutions for the implementation of new protection schemes in distribution network are recently proposed. The growing complexity of the distribution network, due to the dispersed generation plants and the possibility of closed-loop operation, causes the necessity of proposing innovative schemes that strongly rely on communication networks [84], [88].

The performance of the communication system is therefore a crucial issue for the protection of distribution networks. Compared to wired solutions, such as PLC or Fiber Optics, wireless technologies offer many benefits for smart grid applications. They provide communication abilities with lower cost of equipment and installation, quicker deployment, a wired spread access and greater flexibility[89]. In the case of LTE, the technology is subjected to an ever going process of upgrading, which promises to increase its capacity in order to face with the growing request of mobile broadband applications and the densification of last generation devices that request internet access and M2M connectivity. Wide adoption, clear definition of the standard, low latencies, high throughput and low cost of deployment and management make LTE one of the most interesting candidates for the utilization in a Smart Grid context.

In the protection scheme proposed in the co-simulation platform, the communication is provided by an LTE architecture, where the Smart Secondary Substations are connected to the communication network through a LTE user equipment (UE).

Each substation is equipped with two measurement units, each appointed at detecting fault currents in the opposite directions. Conventionally, the reference positive current direction is from the feeder to the bus (Figure 18)

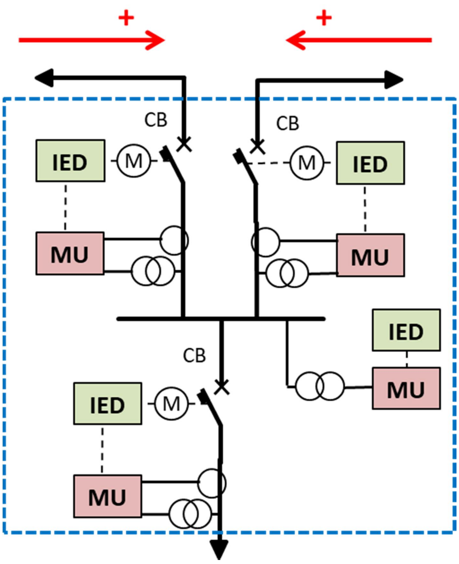


Figure 18. Conventional positive current direction in fault detection

For implementing a logic selectivity protection scheme, it is useful to derive the sequence components of the currents at each branch. Compared with the ordinary line currents in time domain, sequence components allow representing currents with a simple set of phasors, which can be easily handled for realizing an assessment of fault location and implementing the logic selectivity.

The set of three line currents are converted into their sequence components by applying the Fortescue theorem:

$$\begin{bmatrix} \overline{I}_1 \\ \overline{I}_2 \\ \overline{I}_0 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & \overline{a} & \overline{a}^2 \\ 1 & \overline{a}^2 & \overline{a} \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} \overline{I}_a \\ \overline{I}_b \\ \overline{I}_c \end{bmatrix} \qquad (3.2)$$

where $\overline{I}_a$, $\overline{I}_b$ and $\overline{I}_c$ are the current phasors measured on the three phases, and $\overline{a}$ is a complex parameter:

$$\begin{aligned} \overline{a} &= e^{j\frac{2\pi}{3}} && = -\frac{1}{2} + j\frac{\sqrt{3}}{2} \\ \overline{a}^2 &= e^{j\frac{4\pi}{3}} = e^{-j\frac{2\pi}{3}} && = -\frac{1}{2} - j\frac{\sqrt{3}}{2} \\ \overline{a}^3 &= 1 \end{aligned} \qquad (3.3)$$

The three components variables $\overline{I}_1$, $\overline{I}_2$ and $\overline{I}_0$ are the positive, negative and zero sequence, respectively.

If we consider a network powered by a symmetric ternary of voltages, the relations between currents and voltages for each sequence are:

$$\begin{cases} \overline{E}_{g1} - \overline{Z}_1 \overline{I}_1 = \overline{E}_1 \\ -\overline{Z}_2 \overline{I}_2 = \overline{E}_2 \\ -\overline{Z}_0 \overline{I}_0 = \overline{E}_0 \end{cases} \qquad (3.4)$$

that can be represented with the equivalent circuits shown in Figure 19.

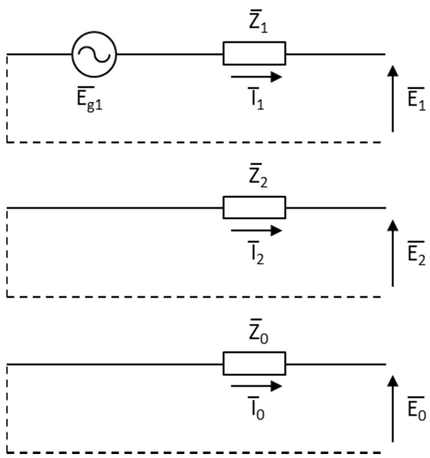
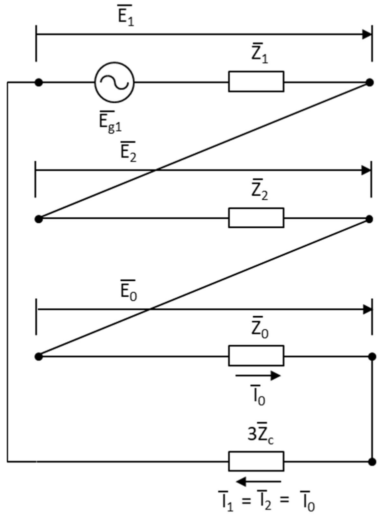


Figure 19. Equivalent circuits for positive, negative and zero sequence.

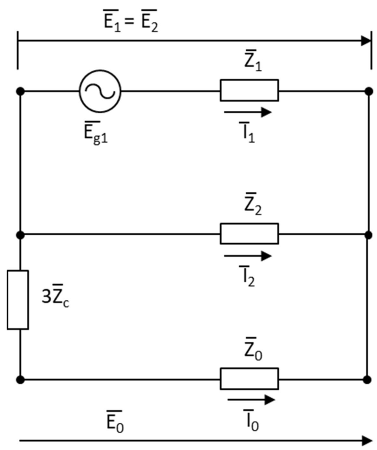
The relations in (3.4) represent a system of 3 equations with 6 variables. For the solution, three more equations are given by the fault type. Four main faults are analyzed, that are summarized on Figure 20:

Single phase short circuit



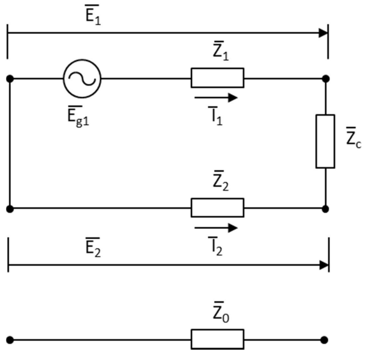
$$I_{sc} = \frac{3E_{g1}}{\left|Z_1 + Z_2 + Z_0 + 3Z_c\right|}$$

Two phase short circuit to ground



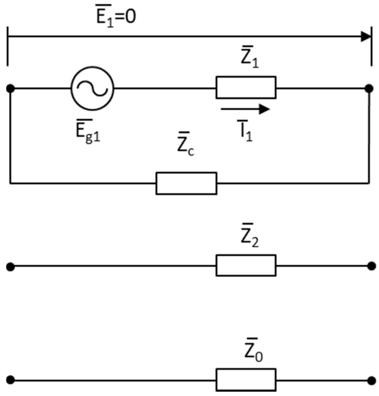
$$I_{ground} = \frac{3E_{g1}\left|Z_2\right|}{\left|Z_1 \times Z_2\left(Z_1 + Z_2\right) \times \left(Z_0 + 3Z_c\right)\right|}$$

Two phase short circuit clear of ground



$$I_{sc} = \frac{\sqrt{3}E_{g1}}{|Z_1 + Z_2 + Z_0|}$$

Three phase short circuit



$$I_{sc} = \frac{E_{g1}}{|Z_1 + Z_c|}$$

Figure 20. Summary formulae for different short circuit faults

The different fault conditions can be classified in terms of the sequence components that are involved, as summarized in Table 6.

Table 6. Fault classification in terms of sequence components

Type of Fault	Sequence components		
	Positive	*Negative*	*Zero*
Single phase short circuit	YES	YES	YES
Two phase short circuit to ground	YES	YES	NO
Two phase short circuit clear of ground	YES	YES	YES
Three phase short circuit	YES	NO	NO

Three phase short circuit is the simplest fault to be handled. Fault currents constitute a balanced ternary of currents, and present an angle shift given by the fault impedance angle ($Z_c >> Z_1$). In the following examples three phase short circuits are examined.

If we consider distribution network lines in underground cable, where resistance is usually greater than the inductive reactance ($R >> X$), the operating characteristic of the directional criteria for a three phase short circuit fault is formulated as shown in Figure 21.

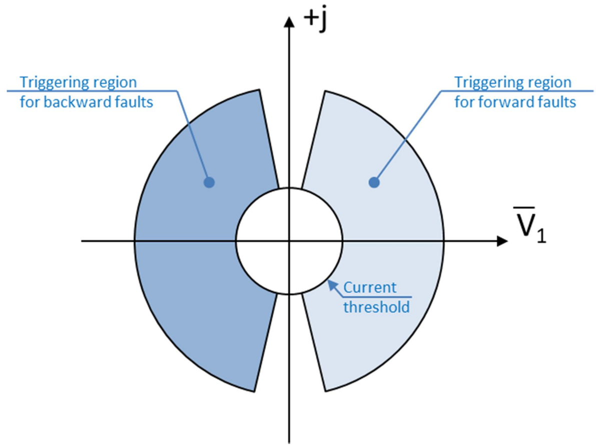


Figure 21. Operating characteristic of the directional criteria for three phase short circuit faults

A short circuit threshold is set. When current exceeds this threshold, the IED is triggered to send to the neighboring SSS the local positive sequence current measurement and the angle measurement between the positive sequence voltage and current. This scheme, which configures a decentralized architecture, avoids the utilization of the centralized DMS, and provides the network with more flexibility and rapidity of intervention [90].

The logic that manages the intervention on the breakers differs according to the network configuration, whether it is meshed or radial.

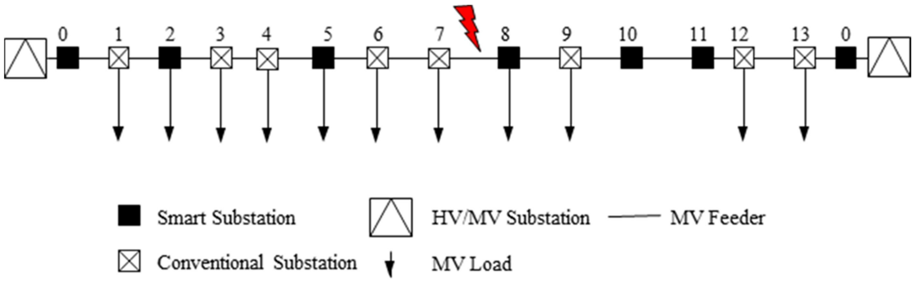
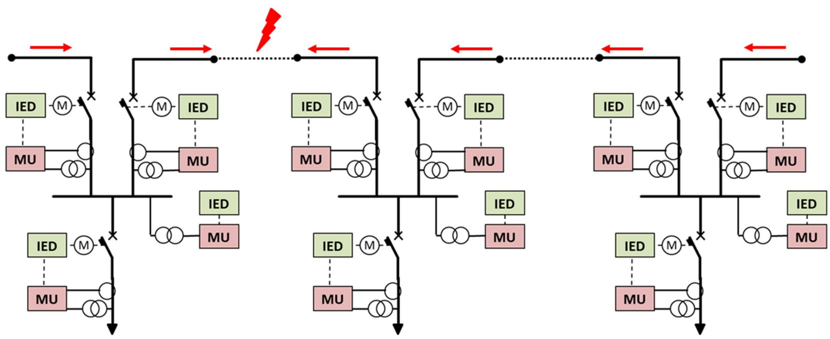


Figure 22. Meshed - Closed loop MV network

An example of meshed – closed loop network is graphically represented on Figure 22. A three phase short circuit is located between nodes 7 and 8. Since the network is fed by both extremes of the line, the fault current will flow from both HV/MV substations. Each smart secondary substation (represented in the figure with a black square) will compare the direction of the current measured by its MU with the information received by the neighbor SSS. If the fault is located on the branch that links two nodes, the current direction will be opposite (Figure 23). This condition requires the opening of both breakers.



5		8		10	
In	Out	In	Out	In	Out
+	-	-	+	-	+

Figure 23. Current direction during three phase short circuit condition

On the other hand, if the network is managed in radial configuration (Figure 24), if no distributed generation plants are present, the fault will be fed by one HV/MV substation. In this case, the nodes that are located afterwards the fault will not detect any fault, therefore the SSS at node 7 will not receive any data packet from the following SSS. This fault condition is univocal, and characterizes the fault localization. Whether a reclosing branch is present in the known topology of each SSS, the IED will be alerted for reconfiguring the network in order to minimize the impact of the fault.

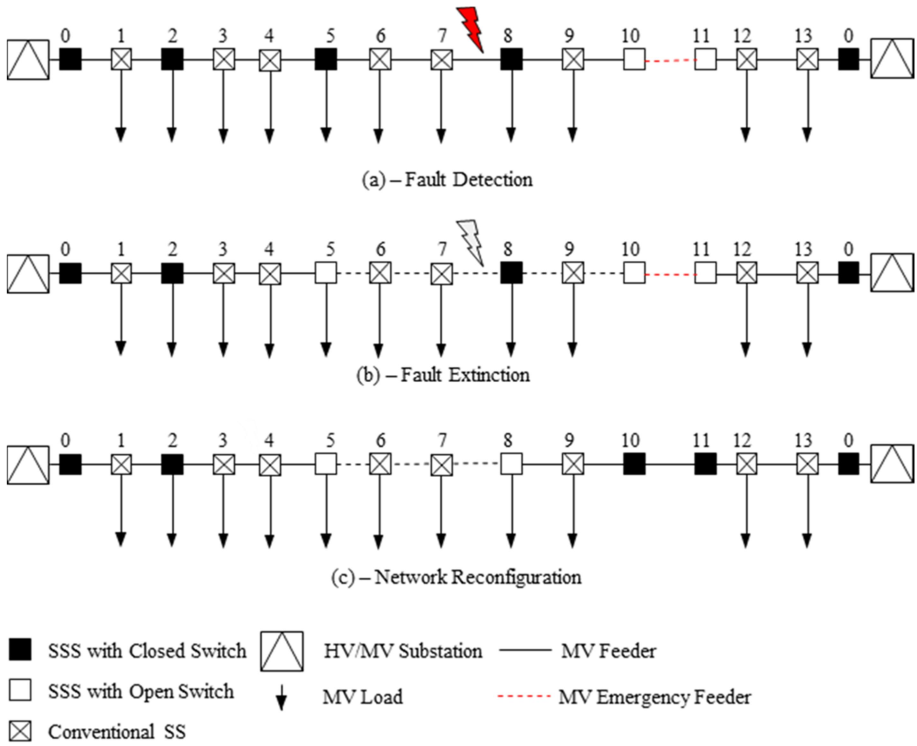


Figure 24. Distribution network managed in radial configuration with emergency tie

In order to achieve an optimal management of the distribution network, it is necessary to:

- Locate the fault, and open the switch that provides the optimal selectivity (Figure 24b);
- Operate on the normally open switches at nodes 10 and 11, in order to minimize the area of disruption. The opening of the switch on node 8

guarantees that the fault is not fed by the second HV/MV substation, and the fault is extinguished (Figure 24c).

In Figure 25 the flow chart of breakers control logic is reported.

Each SSS acquires the topology of the network, and is acknowledged of the nodes directly facing and the network management scheme (radial or meshed) (Figure 25, level a). For each time step *Δt*, each SSS acquires the current and phase measurements for the infeed and outfeed substation connections, and stores the values in a database (Figure 25, level b). Then, the current measured (I_M) is compared with a current threshold (I_{th}), which is considered equal to twice the current capacity of the line branch. If the current measured is bigger than the current threshold, then a packet is wrapped and sent to the node directly facing in the direction where the current in measured (infeed or outfeed direction), and the Short Circuit condition at time *t* is stored in a database ($SC_M(t)=1$). Each SSS also detects if there are any packets that have been sent by the neighbor SSSs (Figure 25c).

If no packets are received at time *t*, and no short circuit condition is stored in the database, then the SSS is allowed to wait to the next *Δt* cycle with no intervention. If a packet is received by any neighbor SSS, the packet is unwrapped and the information read (Figure 25, level d, right side). If the receiver SSS is in short circuit condition ($SC_M(t)=1$, Figure 25, level e, right side), the information received is compared with the local measurement of current and phases (Figure 25, level e, right side). According to the phase comparison, the fault is localized in the branch that links the receiver and the transmitter SSSs, and the receiver SSS is in charge of opening the circuit breaker.

In Figure 25, at level d in the left side of the flow diagram, if the SSS has detected a short circuit condition ($SC_M(t)=1$) but no packets are received by the facing SSS, the topology of the network is checked (Figure 25, level e, left side). If the network is operated as radial reconfigurable network, the SSS triggers the opening of the breaker and the network reconfiguration process (Figure 25, level f, left side). Otherwise, the SSS waits for a buffer time (120 ms are considered in the simulations), after that the SSS autonomously triggers the opening of the breaker for guaranteeing the protection of the network.

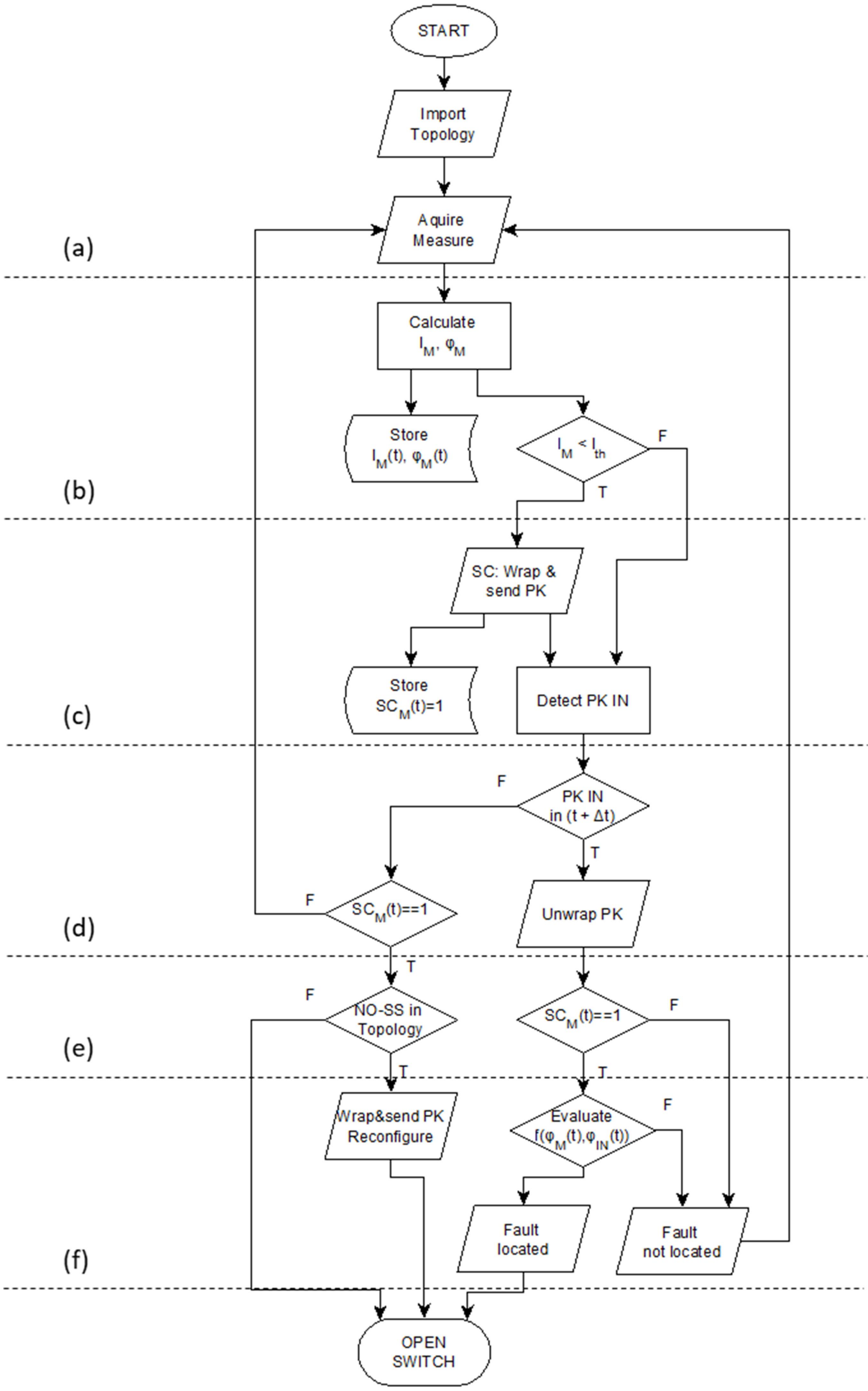


Figure 25. Flow chart of the control scheme logic

3.5 Input Data for simulations

The input data that is given to the co-simulator to perform the simulations is represented by the topological dimension and technical characteristics of the distribution network analyzed. The information of the network is organized in excel files according to the ATLANTIDE format rules. ATLANTIDE is a three years research project funded by the Italian Ministry of Economic Development under the framework of the Italian Research Fund for the development of the Italian Power System project [91].

The ATLANTIDE format is organized in three layers, that are defined by three excel files:

- Layer representing the topological representation of the network and components contained;
- Layer representing the characteristics of the components contained in the network;
- Layer representing the load and generation profiles of the network components.

In Figure 26 it is reported the organization of the ATLANTIDE format:

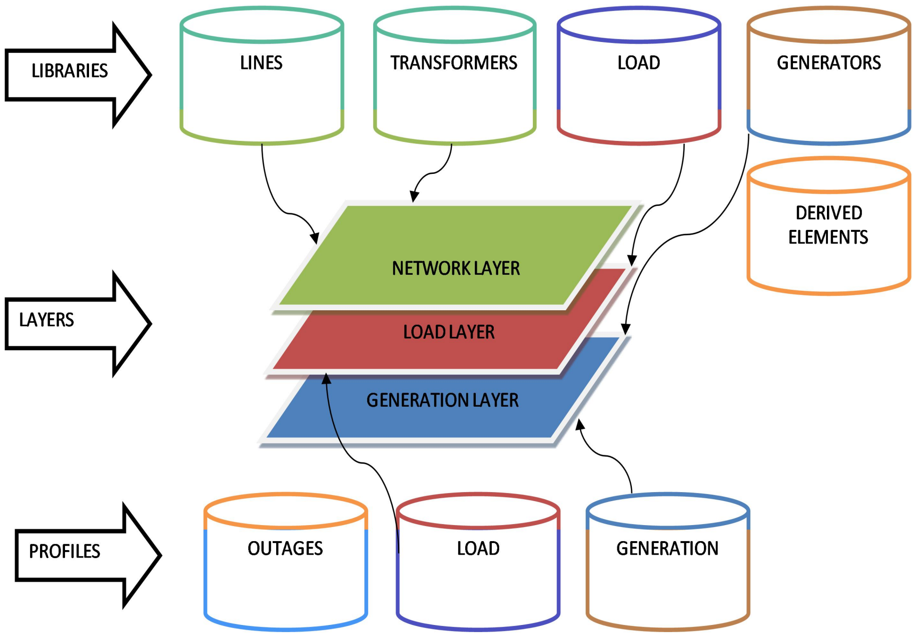


Figure 26. Schematic representation of the co-simulator input network data organization

According to the information contained in the input data, it is possible to provide to the electrical system simulator all the information necessary to perform the simulation of the distribution network.

Additional information that is provided to the co-simulator is the communication technology that is chosen for the data transmission in the SDN, along with the meteorological and geomorphic characteristics of the network site. This information, added to the topology of the active nodes extracted by the ATLANTIDE-formatted input data, allows to completely define the communication network and to allow the ICT domain simulator to simulate the data exchange inside the smart grid.

A data library with meteorological information is given as input along with the network data. Within the weather profile library, defined in an excel file, reference data are stored in terms of rainfall intensity, temperature, relative humidity, and geomorphological characteristics of the site. These parameters are used within the co-simulation software to calculate the signal attenuation during transmission. A rain intensity quantity is also randomly generated in the simulation according to a normal probability distribution, defined by average μ and variance σ, according to the reference data obtained by the Climate Atlas of the Italian Military Air Force Meteorological Service [92].

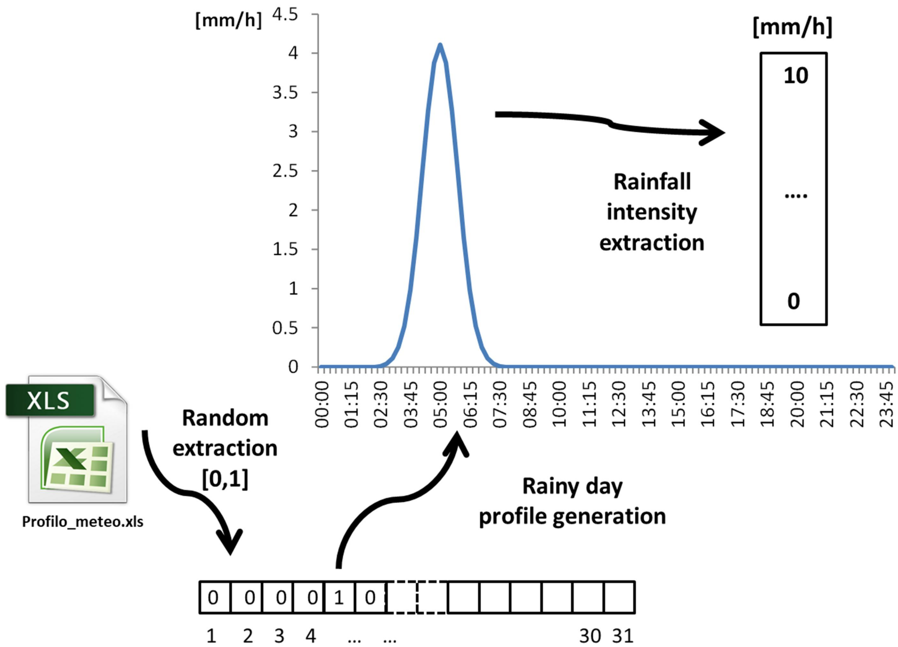


Figure 27. Process of rain intensity extraction with normal probability distribution function

For long distance wireless communication, such as in WiMAX communication system, the Longley Rice Method is used to assess attenuation in the signal propagation between the transmitting and receiving antennas, purposely revised in order to take into account the specific attenuation in rainy conditions. For short distance wireless communication, within 1 km radius, the average attenuation assessment of the signal is obtained with the Two Ray Ground Model. In both cases rain attenuation was evaluated separately according to the criteria proposed by ITU-R P.838-3 (For details, see Section §2.6).

CHAPTER IV

4. SMART DISTRIBUTION CO-SIMULATION TOOLS

4.1 Introduction

As presented in Chapter §1, different aspects of smart grids can be analyzed with co-simulation, that can be classified in phenomena with slow and fast dynamics. Each one of these categories is described by different characteristics that influence the design of co-simulators, in terms of software choices and architecture. For this reason, during the work of the PhD several versions of the smart grid co-simulation tool have been developed, and different aspects on the smart grid operation have been analyzed, building new architectures of co-simulators, as well as changing the software for studying the single domains – electric system and communication system – that form the smart grid CPS.

The evolution of the co-simulation software comprises three main versions:

- COSIM1.0, which is focused on co-simulation for slow dynamics studies;
- COSIM1.1, which improves COSIM1.0 by adding capabilities of reliability analysis with Monte Carlo method;
- COSIM2.0, which allows performing co-simulation for fast dynamics studies.

In the following sections the different versions of the co-simulation tool will be presented. Section §4.2 will introduce the characteristics of COSIM1.0, then the Monte Carlo algorithm that has been nested with the software that, in conjunction with other improvements, led to COSIM1.1. In Section §4.3 will be presented the final version of the software, COSIM2.0, along with the main reasons that conducted to innovate and substantially transform the software.

4.2 The co-simulation software for slow dynamics studies

The first version of the co-simulator developed, COSIM1.0 has been designed with the focus on studying the joint behavior of electrical system and communication system in smart grid operation for slow dynamics studies. The co-simulation architecture comprises Open Distribution System Simulator (OpenDSS) as power system simulator, whereas Network Simulator 2 (ns-2) is employed as discrete event simulator for the communication system. Both software products are free and open source. [93]

OpenDSS is a comprehensive electrical system simulation tool developed by EPRI for electric utility distribution systems [94]. Many of the features that can be found in the program are intended to support distributed generation analysis needs. It is implemented as both a stand-alone executable program and an in-process COM server DLL, in order to be driven from a variety of existing software platforms. The program supports nearly all rms steady-state analyses commonly performed for utility distribution systems planning and analysis.

The software ns-2 is an event-driven simulation tool for communication networks that has gained wide popularity since 1989, when it was first released [95]. ns-2 allows simulating wired as well as wireless networks and protocols (e.g. routing algorithms, TCP, UDP).

The whole process of co-simulation is managed by MATLAB, which works as run time infrastructure (RTI) between OpenDSS and ns-2. Figure 28 shows schematically the architecture of the co-simulation tool. The communication between MATLAB and OpenDSS is made possible by the COM interface of OpenDSS, on the other hand the integration of ns-2 in the co-simulator is obtained through a SSH/SCP interface that allows MATLAB to communicate with a Linux virtual machine, where ns-2 is installed. In MATLAB a DMS is also implemented, in order to simulate the active management of the network performed according to a centralized architecture.

The MATLAB DMS represents the core of the network management and allows performing voltage regulation and other slow dynamics intervention in the optimization of the network. The DMS supervises the network operation by gathering measures of the main electric parameters and, when necessary, modifies the set points of DERs (e.g., generators, storage devices, and responsive loads) in order to optimize the network management and minimize costs according to the optimization algorithm, which is subject to technical (e.g. node voltages and branch power flows during normal and emergency conditions) and economic constraints (e.g. costs for dispatching active resources and joule losses).

The Objective Function (OF) which is minimized by the DMS is the sum of the costs as expressed in (3.1):

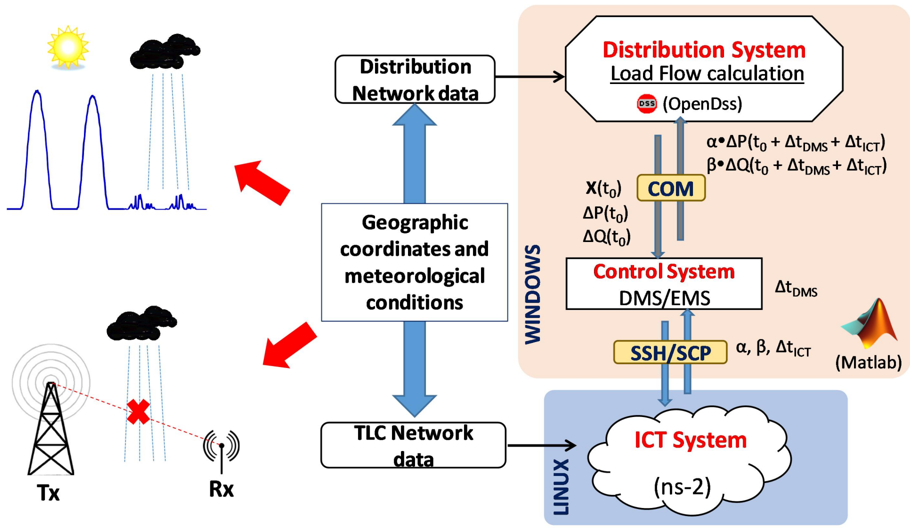


Figure 28. Schematic representation of COSIM1.0

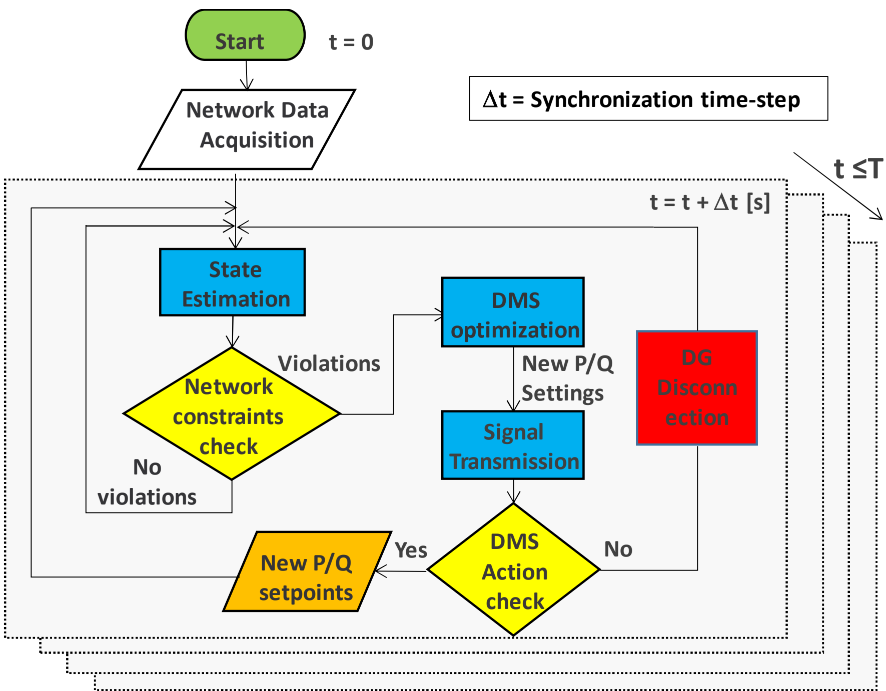


Figure 29. Flow diagram of COSIM1.0

4.2.1 Voltage Regulation

In Figure 29 the flow chart of COSIM1.0 is shown. When co-simulation starts, the RTI runs OpenDSS through the COM interface, which performs recursive power flows every Δt (according to the time granularity imposed by the simulation), and the results are assumed as pseudo measurements to use in the state estimation stage of the co-simulation procedure [96]. When a contingency is detected, the RTI pauses OpenDSS processes and calls ns-2 to simulate the data packets transmission between the measurements points and the DMS through the telecommunication network. The DMS elaborates corrective actions and new set-points are sent to the relevant units wrapped to data packets. The software ns-2 elaborates the input from the DMS before the new set points (ΔP, ΔQ) are sent to DERs for changing the network power flows, with their control and communication delays, respectively Δt_{DMS} and Δt_{ICT}, and the binary parameters (α, β) that take into account signal lost effects due to communication impairments. In the estimation of the latencies or possible communication signal losses, ns-2 takes into account the communication technology, as well as the terrain orography, the geographical position of DERs and measurement units, and finally the weather conditions, which therefore indirectly influence the network management and the production of the DERs.

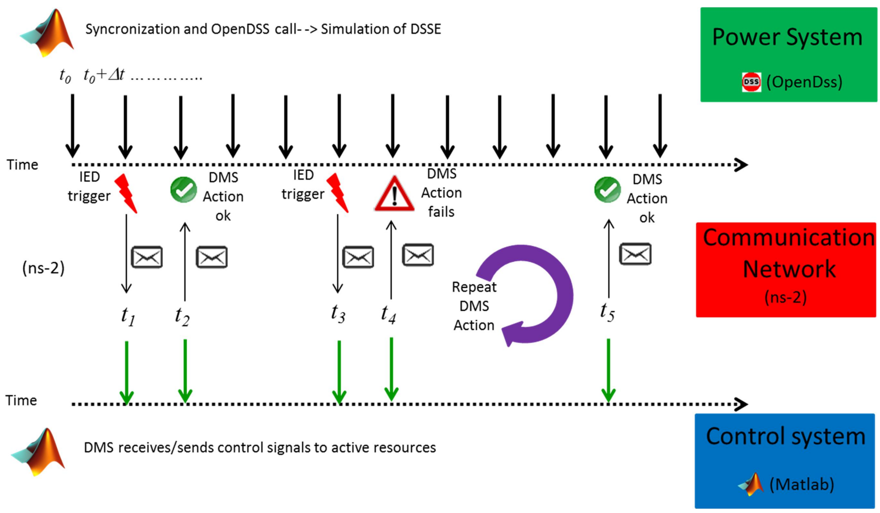


Figure 30. Event-driven synchronization method in COSIM1.0

The representation of the synchronization between OpenDSS, ns-2 and MATLAB is represented in Figure 30. The simulation time duration is discretized in short time intervals Δt, every which an OpenDSS load flow is performed. The ns-2 simulation is invoked when the IED triggers a contingency condition, then an information packet is wrapped and sent between the IED and the DMS. Therefore the contingency condition represents the main event that leads to the synchronization of the two simulations. In this sense, the co-simulation architecture proposed can be included in the event-driven category. When the message transmitted by the IED is received by the DMS, the new set points are elaborated, then delivered to each DER that is participating to the network management. If there is any failure in the packet deliveries, the DMS must be able to dynamically correct the intervention on the DERs by operating only with the DERs reachable at the moment.

4.2.1.1 Improved version of slow dynamics co-simulation tool: COSIM1.1

An improved co-simulation tool architecture has been successively realized for slow dynamics contingencies studies, COSIM1.1, which adopts ns-3 in substitution of ns-2. The main purpose of upgrading the ns-2-based co-simulation software was in fact to perform a comparison between different ICT solutions, also considering a complex architecture joints different communication technology at different voltage levels. COSIM1.1 keeps OpenDSS as power system simulator, and MATLAB as RTI and main programming platform for the active distribution management and graphical user interface.

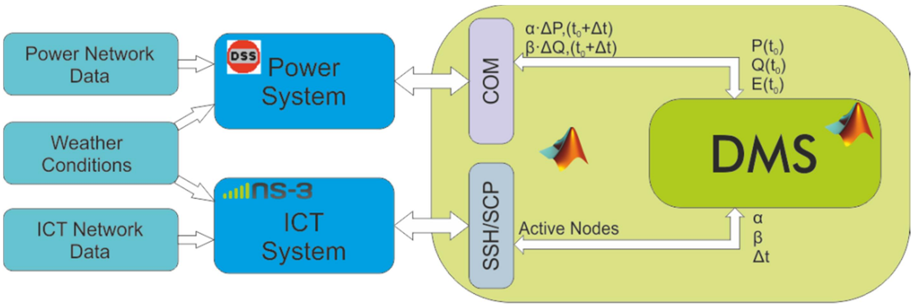


Figure 31. Architecture of COSIM1.1

Figure 31 shows schematically the final architecture of the co-simulation tool.

The open-source software ns-3 is free and publicly available for research, development, and use, which was intended as a replacement for the popular ns-2 simulator [97]. The software ns-3 is a new simulator (not backwards-compatible with ns-2) working as a discrete-event network simulator in which the simulation core and models are implemented in C++. ns-3 is built as a library which may be statically or dynamically linked to a C++ main program that defines the simulation topology and starts the simulator. Among its main advantages in comparison with ns-2, ns-3 permits a more realistic modelling of the functioning of telecommunication networks, through a better alignment with internet protocols, and support for use on physical test-beds [98]. Moreover, third party modules for ns-3 are continuously being developed and upgraded on the last generation communication technologies.

In this specific case, the need of substituting ns-2 with ns-3 was due to the wider range of communication technologies library provided by ns-3, in addition to the improved modularity of the software that allow modeling complex networks. Several last generation communication technologies can be simulated with ns-3, e.g., Wi-Fi, LTE, WiMAX, and PLC.

4.2.2 Reliability analysis

COSIM1.1 is able to perform reliability analysis of the active distribution network, according to a characterization of the communication devices that comprise the ICT layer of the smart grid in terms of Mean Time To Failure (MTTF) and Mean Time To Repair (MTTR).

For this purpose the Monte Carlo method has been adopted, with the focus of studying how the reliability of the ICT network impacts on the Smart Grid in terms of number of DMS actions and metrics related to energy produced/curtailed in the network. [52]

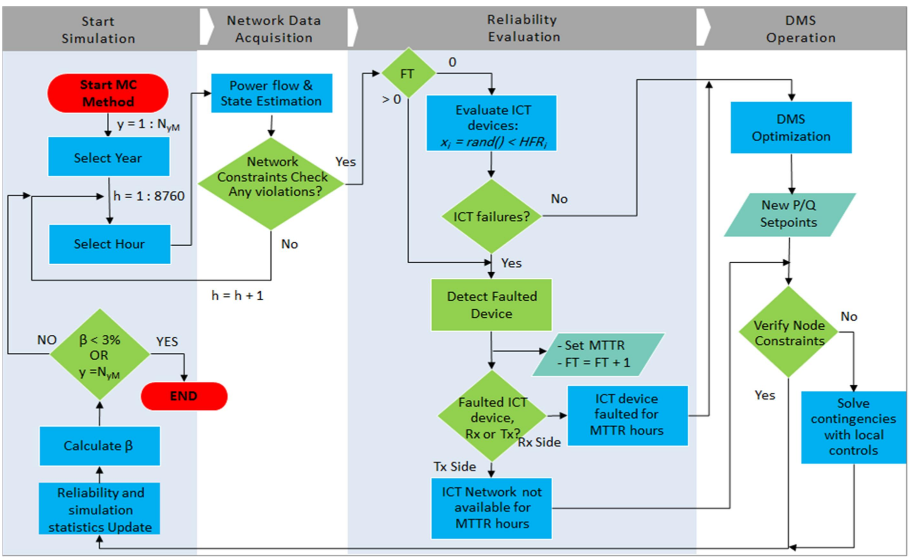


Figure 32. Flow Diagram of the Monte Carlo procedure nested in COSIM1.1

Figure 32 schematically describes the Monte Carlo procedure nested within COSIM1.1. The co-simulation runs with a synchronization of 1 hour where the power flow/state estimation permits detecting critical situations within the network (e.g. over/undervoltage, overloads). If a network constraint is detected, the availability of ICT devices is checked. For each active DER and for each ICT element, a failure rate is randomly extracted from a population of failure rates having a uniform distribution [0,1]. The failures in the ICT chain are considered uncorrelated. The number extracted is compared with an hourly failure rate (HFR) defined with (4.1):

$$HFR = 1 - e^{-\frac{1}{MTBF}} \qquad \textbf{(4.1)}$$

then, if the sampled number is lower than HFR, the ICT device is considered out of service for the corresponding MTTR hours. A counter, failure time counter (FT), keeps track of the time since the failure has happened and takes the component in a faulty state for all the MTTR time.

The DMS is the core of the co-simulation tool. It modifies the set points of DERs in order to optimize the network management and minimize costs according to the optimization algorithm, which is subject to technical (e.g. node voltages and branch power flows during normal and emergency conditions) and economic constraints (e.g. costs for dispatching active resources and joule losses).

If an ICT device is out of service, the new *P* and *Q* set-points for the corresponding active DER cannot be addressed.

A new constraints check is performed after the DMS optimization, in order to verify if all the contingencies are solved, on the contrary the intervention of the switches will be operated according to a local protection scheme.

The intervention of local protection system can cause the total disconnection of the feeder in case of overcurrent in head of the feeder, or the intervention of Loss of Mains (LOM) protections in case of overvoltage detected at the connection points of DG power plants.

4.3 The co-simulation software for fast dynamics studies

COSIM2.0 is the newest version of the co-simulation software, which has been developed in order to study how a smart grid supported by an ICT infrastructure behaves when power system time-critical events occur, such as in case of fault protection and management or reconfiguration of power distribution networks.

COSIM2.0 permits simulating electrical and ICT systems with two different specific software coordinated by a central controller: OMNeT++ simulates the ICT system, whilst DIgSILENT PowerFactory is used to simulate the power system. The two pieces of software communicate by means of a framework implemented in Python. In MATLAB a Graphical User Interface (GUI) has been realized, which allows the user to personalize the input data and to interact with the simulation.

COSIM2.0 takes advantage of the characteristics of the main software components, exploiting on one side the electromagnetic transient analysis capabilities of PowerFactory, and, on the other side, the wide choice of libraries for communication systems analysis that are offered in the OMNeT++ open source platform.

In fact, OpenDSS among its features does not offer electromagnetic transients calculations, therefore it is not a suitable solution for performing studies on fast dynamics smart grid operation. On the other hand, OMNeT++ was chosen in place of ns-3 due to the powerful LTE library written specifically for this simulator, and the possibility to install the software on a Windows machine, compared with ns-2 and ns-3 which are only UNIX-based. It represents an important feature, since also PowerFactory is released for

Windows operating systems. Having both software that share the same operating system makes realizing the Run Time Infrastructure an easier and cleaner procedure, since it avoids recurring to Linux Virtual machines, that render co-simulation architecturally complex and computationally demanding.

The schematic representation of the co-simulation software developed is illustrated in Figure 33.The simulation starts with a load flow run, which is designed to calculate the initial conditions from which the transient of the network electrical quantities evolves.

The short circuit instant and location is provided externally by the MATLAB based Graphical User Interface of the co-simulator. From the GUI are also indicated the nodes that are provided with Smart Substation capabilities. These will be the nodes monitored by the Python script about the failure conditions; the current and voltages values measured on these lines are recorded on an output variable and then returned at the end of the simulation on csv files, and rendered on graph plot. PowerFactory simulation control is managed within a for loop that sets the simulation stop instant, and the time step variable Δt set by default equal to 1ms. On each timestep, PowerFactory returns the voltage and current quantities calculated on each selected Smart Substation node to the Python RTI, then the Python scripts verify if any short circuit condition occurs (conventionally, a 2 times cable capacity is adopted as fault overcurrent threshold). This event determines the OMNeT++ call that simulates the communication of information between the IED and the control system. Since also in this case the coordination between OMNeT++ and PowerFactory simulations is led by the events that occur in the system, COSIM2.0 can be categorized as an event-driven simulator.

On the following subsections, some more details about the main components of the fast dynamics co-simulator are given.

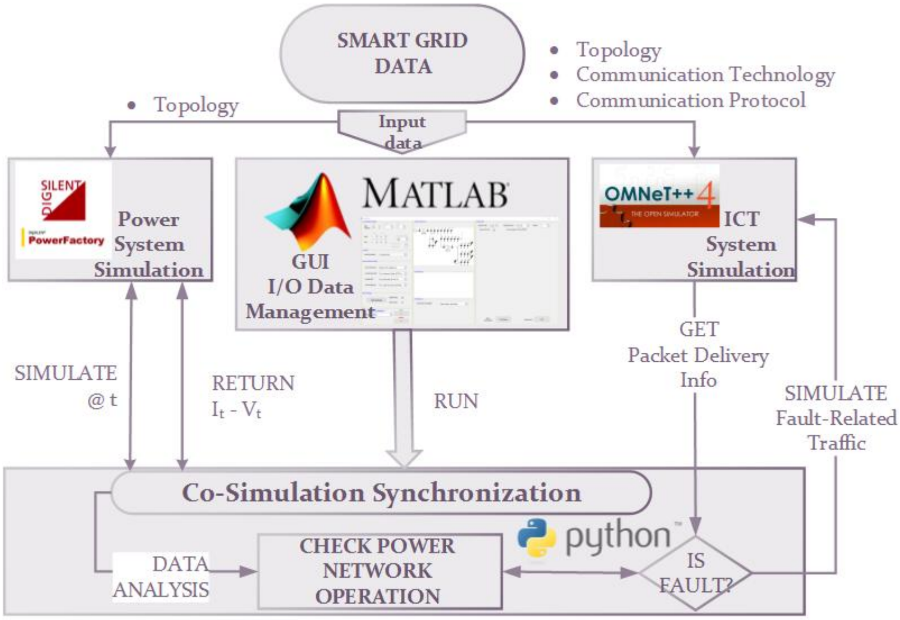


Figure 33. Schematic representation of COSIM2.0

4.3.1 Power System – DIgSILENT PowerFactory

PowerFactory is a software for the analysis of the power transmission and distribution systems developed by DIgSILENT GmbH. PowerFactory can be used to perform steady state domain analysis, such as load flow or short circuit current calculations, as well as electromagnetic transient and electrical system stability studies. [99]

The software provides component models with different degrees of detail depending on the different studies that are intended to conduct. Custom templates can also be developed, which can be interfaced with predefined network templates to design and evaluate innovative control systems.

Regarding the research activity presented, two peculiar functions of PowerFactory have been particularly exploited, and have determined the substitution of OpenDSS used in the previous version of the co-simulator: the ability to conduct studies on the dynamic evolution of electromagnetic transient when short circuits occur, and finally, the presence of a Python API with which it is possible to handle simulation externally, using PowerFactory essentially as a computing engine.

The Python script coordinates both simulations in the time axis and allows exchanging data between them through dedicated interfaces.

PowerFactory features are provided in a Python environment through a Python module ("powerfactory.pyd") that allows interfacing external software tools with the PowerFactory APIs. This solution enables Python scripts to access a wide range of features in PowerFactory:

- All objects (network elements)
- All attributes (properties of network elements, calculation results, etc.)
- All commands (LoadFlow calculations, transient analysis, etc.)
- Built-in Functions (DPL script)

Any Python script that imports this module can be run internally in PowerFactory via the new ComPython command, or externally (PowerFactory is started externally from the Python module in engine mode). In the co-simulator, this second mode is adopted. Therefore, the Python script handles the simulation entirely, while PowerFactory performs simple computing engine functions.

4.3.1.1 Dynamic network studies

For performing studies on transient domain, PowerFactory provides two simulation options that can be exploited: Root Mean Square (RMS), based on a simplified representation of transient models, and EMT (ElectroMagnetic Transient), based on a detailed model of electromagnetic transients.

In RMS simulations, the electromagnetic dynamics of the power grid are ignored, and voltages and currents are defined as phasors, represented by amplitude and phase of the sine waveforms. In this way, network voltages and voltages are determined by algebraic equations rather than differential equations (4.2):

$$\begin{aligned} \overline{u} &= j\omega L\overline{i} \\ \overline{i} &= j\omega C\overline{u} \end{aligned} \tag{4.2}$$

The only differential equation that is considered is to represent the dynamic behavior of rotating mechanical systems (4.3).

$$\omega J \frac{d\omega}{dt} = P_{mech} - P_{el} \tag{4.3}$$

In PowerFactory, RMS simulations can be performed in two different modes, using a symmetric model where the network is simplified with the single-phase equivalent of the three-phase system, or through a three-wire model, indicated for unbalanced networks, and to study asymmetric failures.
In EMT simulations, voltages and currents are represented in their instantaneous values and the dynamic behavior of the network electrical parameters is taken into consideration. Unlike RMS simulations, voltages and currents are represented by differential equations (4.4):

$$\begin{aligned} u &= L\frac{di}{dt} \\ i &= C\frac{du}{dt} \end{aligned} \tag{4.4}$$

The models used in EMT simulations are more detailed and are indicated for quick transition simulations in both balanced and unbalanced conditions of the network. In co-simulation simulations, since the rapid evolution of short circuit currents will be considered, the simulations are conducted in EMT mode.

4.3.2 ICT System – OMNeT++

OMNeT++ is one of the most widely used environments for the study of ICT systems. Released as open-source code, OMNeT++ allows the description and simulation of discrete event systems [100]. Simulations made with OMNeT++ typically cover:

- Wired, wireless or hybrid communication networks.
- Validation of hardware architectures.
- Modeling of protocols.
- Modeling of node networks.
- Modeling of multiprocessors and other distributed hardware systems.
- Evaluation of the performance of complex software systems.
- Modeling and simulating of any systems that can be represented by a discrete event approach.

The programming environment is object-oriented, based on C ++ language. Specifically, the OMNeT++ environment provides the necessary C ++ classes to model the following elements:

- Modules, gate, channel, parameters.
- Messages and packets.
- Containers (data structures such as arrays, queues).
- Data collection class.
- Statistics.

The platform on which OMNeT Integrated Development Environment (IDE) is based is Eclipse C / C ++ Development Tools.

4.3.2.1 OMNeT++ libraries

OMNeT++ implements elementary modules that allow the description of systems according to the discrete events modeling philosophy. For describing a complete communication network, it is necessary to integrate OMNeT++ with a series of libraries that model the various components whose interaction are fundamental for the correct operation of the communication systems. Among the various resources based on the OMNeT++ platform, INET is one of the most complete libraries in the description of telecommunication networks based on IP protocol and ISO/OSI stack [101]. In addition to the various components of the ISO/OSI stack, INET also implements various application models (TCP / UDP), node mobility description tools, routing protocols, IP address configuration, etc.

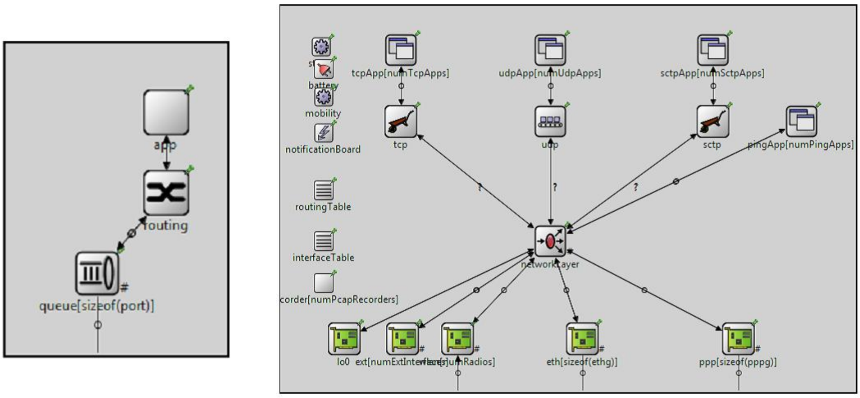


Figure 34. Comparison between hosts in OMNeT++ default environment (left) and INET environment (right) [102]

In the OMNeT++ installed in the co-simulation platform, in addition to INET, an LTE standard library is also integrated. In fact, INET does not cover the LTE standard, so the SimuLTE framework is used to assess the performance of networks built exploiting this technology. SimuLTE is based on INET, ensuring complete compatibility with modules implemented within this platform [103].

SimuLTE allows network simulation according to LTE and LTE-A standards in Frequency Division Duplexing (FDD). The eNBs and the UEs are modeled as compound modules, and can be connected to each other and with other INET framework nodes to make complex networks. The binder module allows locating the other eNBs in order to calculate intercell interferences perceived by each UE within the cell. An xml file allows describing in detail the characteristics of the communication channel, to evaluate the effects of shadowing, fading, and to set parameters such as noise, bit error rate, signal to noise ratio, etc.

4.3.2.2 OMNeT ++ simulation scheduler

The scheduler is the heart of the simulation in the OMNeT ++ environment, as its purpose is to handle the event list (FEL, Future Event List) and run the scheduled event in chronological order.

OMNeT ++ provides three different schedulers, and allows the user to define new properly defined schedulers. The scheduler used as the default in the most typical OMNeT ++ simulations is the *cSequentialScheduler*, whose behavior is simple: cyclically selects the first element of the scheduled event list, executes the routine associated with this event, and then deletes the event from the list. The second scheduler is *cRealTimeScheduler*. *CRealTimeScheduler* extends the *cSequentialScheduler* by calling a *wait()* function (for example, the *usleep()* function of the C++ language) to synchronize the simulation time with the system clock. This scheduler is particularly suitable for simulations in a Hardware In the Loop approach. The third scheduler is called *cSocketRTScheduler*, whose behavior is similar to *cRealTimeScheduler*, except that during calls to *wait()* function, the scheduler waits for incoming messages from an external device through appropriate socket.

To realize the synchronization between the simulation of the ICT system and the simulation of the electrical system, a special scheduler, called *cosimScheduler*, was developed.

The following box shows the definition of the *cosimScheduler* class

```
class cosimScheduler : public cScheduler
{
public:
    cosimScheduler();
    virtual ~cosimScheduler();

    timeval baseTime;
    virtual void startRun();
    virtual void endRun();
    virtual void executionResumed();
    virtual cMessage *getNextEvent();

    void sendACKGrant(bool withSleep);

protected:
    std::string pendingReceivedMsg;
    time_t simulationBeginTime;
};
```

The *cosimScheduler* class is derived from the *cScheduler* class, which is specifically provided by OMNeT ++ for the definition of custom schedulers. In addition to the constructor and destructor functions, a number of functions are described which draws on the work published in [104], where OMNeT ++ is used within a heterogeneous platform of HLA simulators:

- *startRun*: starts the simulation and activates the listening function of the Socket through which OMNeT ++ communicates with Python for information exchange from and for simulation in PowerFactory.
- *endRun*: Determines Socket Closing and Simulation Termination
- *executionResumed*: allows you to resume the simulation after a pause
- *getNextEvent*: selects the next event from the Future Event Set and, in the case of an empty event list, requires Python to advance the simulation time and wait for new events from the Socket;
- *sendACKGrant*: handles the wait for information from Python

4.3.2.3 MyUDPApp application

To ensure a flow of information, to the Python platform that manages the synchronization of the simulation and between the nodes belonging to the network, in addition to the scheduler definition it is necessary to design a specific application for traffic generation and management. In fact, information such as packet reception times and eventual failures in reception can only be handled on the highest level of the ISO/OSI stack. Writing an application also gives the advantage of making the modeled system modular, and therefore can reuse the same code with other network technologies or configurations.

Within the OMNeT ++ environment, the scheduler reads the call to transmit the packets between different nodes and communicates it to the respective UDP application, as described by the code lines in the box below and extracted from the cosimScheduler.cc file

```
cModule* App = modSource->getSubmodule("udpApp",indexSource);
MyUDPApp* udpApp = check_and_cast<MyUDPApp *>(App);
udpApp->scheduleSend(fTime, destAddr);
udpApp->connectSocket = connectSocket;
```

The *scheduleSend* function is charged of scheduling a selfMessage instantly defined by the fTime variable and the destAddr given as arguments, defined by the input information obtained from Python.

4.3.3 OMNeT ++ Synchronization – PowerFactory

The synchronization between OMNeT ++ and PowerFactory is managed in COSIM2.0 through a Python code, which allows managing synchronous co-simulation through the exploitation of appropriate interfaces.

Python manages simulations in PowerFactory and OMNeT ++ environments with two different modes:

- PowerFactory provides a Python library that allows easy access to software features, access to data and their parameters, and to simulation results. Simply managing the PowerFactory simulation from the python environment is simply by loading this library and calling the functions defined in the same, appropriately documented in the manual supplied with the software
- OMNeT ++ does not have actual APIs. However, it is possible to integrate OMNeT ++ into a platform that includes other computing tools through different methodologies. In [105], three integration solutions are suggested: socket connection, source code integration, shared libraries utilization.
    - The socket connection method is the simplest technique to be implemented, and infers realizing a connection through TCP/UDP sockets between OMNeT ++ and the software/hardware that to be integrated within the simulation. It does not require many rows of code to be implemented, and permits to manage stable streams of information through simple ports (sockets), that can then be processed through proper programming languages.
    - The source code integration method implies a complete integration of C++ source code within the OMNeT++ environment, with which it is possible to manage the external application that is intended to interact with the ICT simulation. It is a more precise method than the socket connection method, albeit it implies writing new C++ code that will be embedded in the build of OMNeT++, making the compilation of the whole software potentially unstable, due to external dependencies that may create conflicts with the OMNeT++ environment.

- The last methodology listed, shared library integration, implies the integration of binary code within OMNeT++. In this way, the compatibility issues enunciated for source code integration are avoided as there is a real separation of the two environments at the source code level.

In the software project, it was decided to adopt the first solution, i.e. the use of sockets, to ensure the flow of information from and to OMNeT++ within the co-simulation framework.

A socket is a system routine through which it is possible to exchange information with another program that can be connected through a shared LAN network or in the same machine. In order to communicate, the two software must exchange their IP address and their TCP port. A TCP socket (the socket that is used in the co-simulation software) is not an actual connection, but rather the endpoint of the specific connection. The purpose of ports is therefore to differentiate multiple endpoints of a specific network address. A socket can therefore be viewed as a file-like object that allows a program to accept incoming connections, make outbound connections, and send and receive data via the send () and recv () system functions.

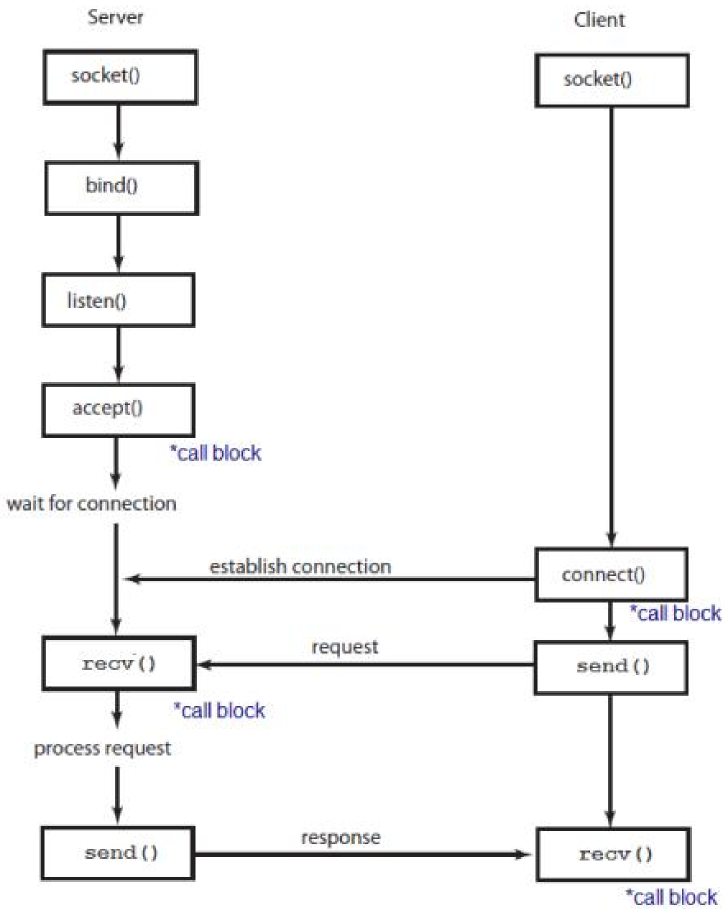


Figure 35. Schematic representation of a client-server system made with sockets

Socket connections respect the client-server logic. The server is the software that creates the socket and waits for external connections to a specified port. The client is the software that connects to the address / port pair by making the process of sending and receiving data active. In the co-simulation software implemented, OMNeT ++ generates the port, and Python connects to it by sending data packets. Within these packets there is information about the source and recipient of the data traffic, in addition to the information about the instant in which the transmission is scheduled and the measurements of the node (electric currents and phases)

The Python code represents the Run Time Interface (RTI) of COSIM2.0. For each time-step Δt, the Python code calls PowerFactory for solving the differential algebraic equations that describe the electric network analyzed during the time interval, and contemporarily calls OMNeT++ that executes the simulation during the subsequent time sample. When a short circuit condition is detected in the electric network, a new event is scheduled in OMNeT++ that describes the communication between the SSS involved in the fault detection. The scheduler is the heart of the simulation in the OMNeT ++ environment, as its purpose is to handle the event list (FEL) and run the scheduled event for the instant immediately after the current time. In order to coordinate the OMNeT++ simulation with the Python RTI, a customized scheduler is purposely developed.

In Python it is also programmed the fault protection and management logic assigned to each smart secondary substation that is triggered when critical events occur and that implement the decentralized control discussed in previous section.

COSIM2.0 is implemented according to an object oriented programming, in order to better describe a decentralized architecture of the operation of the network. Each SSS is represented by a Python object, and the operation is distributedly realized by means of the point-to-point communication between each SSS.

CHAPTER V

5. CO-SIMULATION CASE STUDIES

5.1 Introduction

In this chapter examples of the analysis of the smart grid with a co-simulation approach will be given.

In the first section some case studies of co-simulation for slow dynamics operation will be described: the first illustration will present the use of co-simulation in a study of voltage regulation, where the ADM will be evaluated jointly with the WiMAX technology performances. The second one presents an analysis with a co-simulation approach that is focused on the analysis of the reliability of the smart grid. Also in this case the communication network is realized with a WiMAX infrastructure. The first section closes with a comparative analysis between different communication system solutions, where more technologies are combined in hybrid architectures for the distribution network management.

In the second section the co-simulation approach will be applied on a case study where fast dynamics regulation scenario will be analyzed. The communication network is implemented with an LTE architecture. In this case the focus is on determining if the LTE performances are suitable for maneuvering the breakers in a decentralized control framework.

5.2 Slow Dynamics studies

5.2.1 Voltage regulation

The network analysed in the case study has been chosen in the database made available by the Italian ATLANTIDE research project for studying the active distribution networks under different planning scenarios.

The network selected is the representative network for the rural context, consisting in 103 MV nodes supplied by one HV/MV substation and disposed on 7 relatively long feeders (mostly small section overhead conductors for a total extension of about 160 km), the longest being around 25.5 km. A 25 MVA 132/20 kV transformer is located in the primary substation (Figure 36).

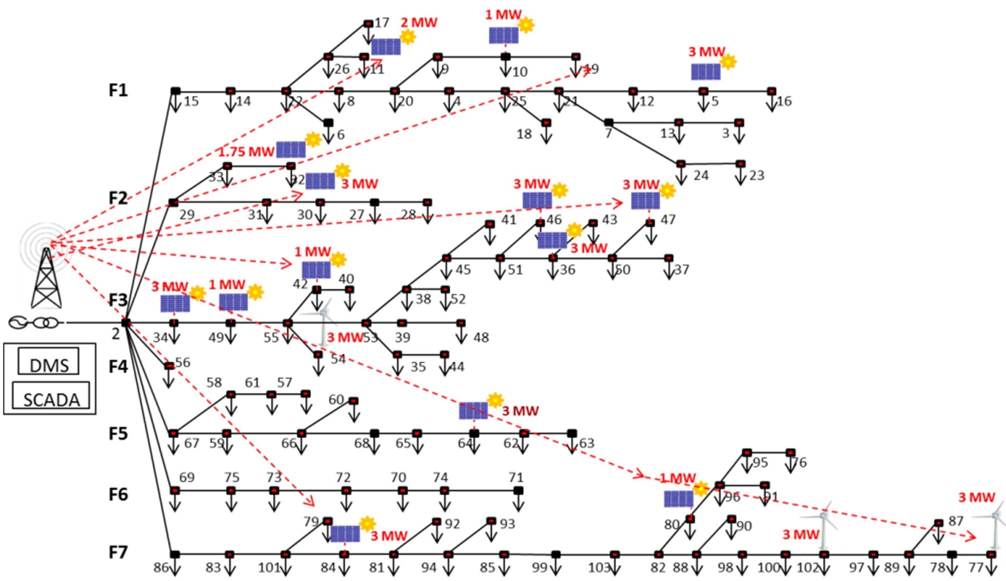


Figure 36. Rural test network – Voltage Regulation case study

The used planning scenario, named in the ATLANTIDE project as RoadMap, considers an intensive growth in the number of photovoltaic and wind distributed generators from a reference scenario set in 2010.

The simulations discussed in the following refer to a PV installed power equal to 31.75 MW and 9MW of Wind (Table 7). The nominal load - a mix of agricultural, residential and small industrial customers - is about 19.8 MW (with a 0.9 power factor).

Table 7. Total Load and Generation in the network

Feeder	**WIND [MW]**	**PV [MW]**	**LOAD [MW]**
F1	0	6	4
F2	0	4.75	2.5
F3	3	14	4
F4	0	0	0.3
F5	0	3	2.8
F6	0	0	3.7
F7	6	4	2.5
Total capacity	*9*	*31.75*	*19.8*

Load and generation are considered with a variable profile that is dependent on the hour of the day and the seasonal period of the year. All the profiles are given with a 30 minutes discretization interval. When shorter timesteps are adopted in the simulations, a linear interpolation of the profiles is considered.

In Figure 37 the daily profiles of loads are reported, according to the load type considered.

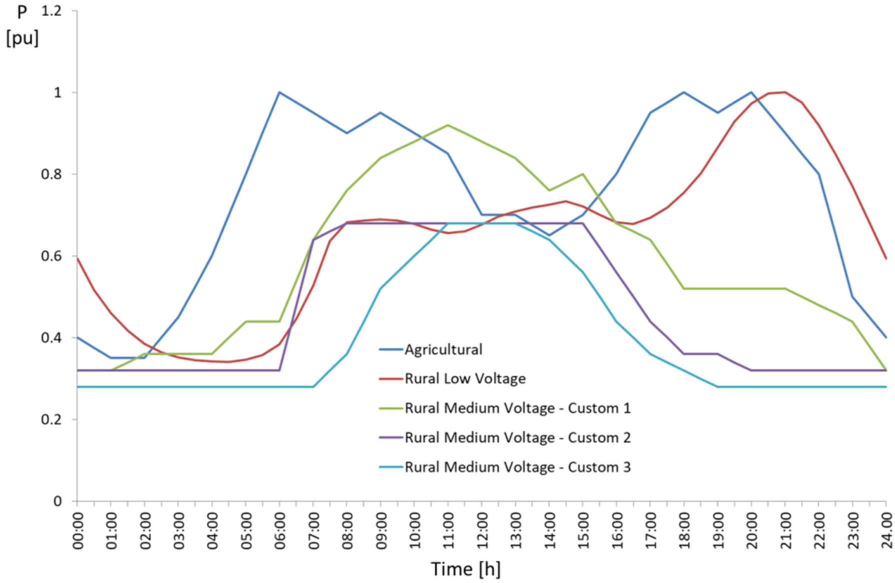


Figure 37. Load profile for different load types in rural networks

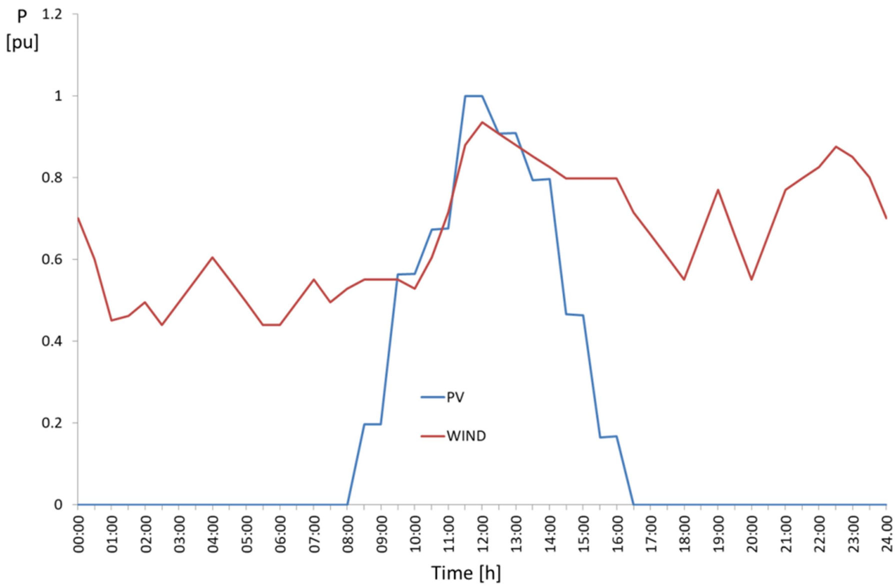
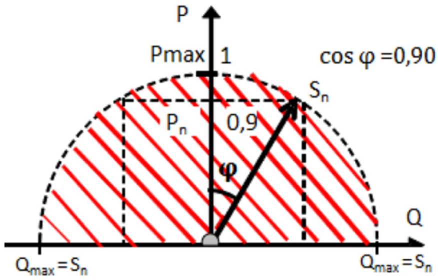
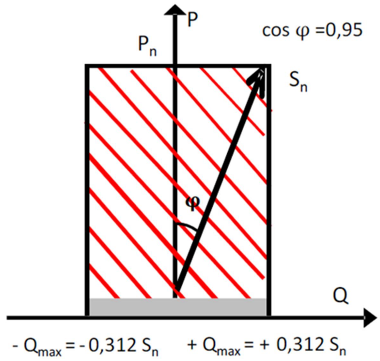


Figure 38. Wind and PV power plant generation profiles

In Figure 38 the daily profiles of photovoltaic and wind power plants are represented. Generation systems are controlled by the DMS considering the capability curves of wind and PV systems (Figure 39) according to the Italian Standard CEI 0-16 [106].



(a)



(b)

Figure 39. Capability curves for a) PV and b) Wind generators [106]

In order to show the capabilities of the co-simulation platform in simulating the operation of smart distribution networks, different operating conditions are illustrated in the following examples.

5.2.1.1 The reference scenario: passive management of the distribution network

Traditionally, distribution systems are not equipped to control distributed generation spread along the feeders, therefore in case of contingencies the intervention of protection systems may disconnect part of the feeder. In case of overvoltage caused by distributed generation, the Italian standard requires the intervention of the LOM protection after the voltage overcomes the threshold of 1.1 p.u. for more than ten minutes.

In Figure 40 a typical situation of overvoltage caused by the production of a PV system is showed. This profile is obtained with a co-simulation conducted on the rural test network with COSIM1.0 with a 5 minutes time step. The electric power produced from PV plants connected to the rural network causes a problem in terms of overvoltage when there is high sun radiance, approximately from 11 am to 3 pm.

The picture is related to the voltage and active and reactive power of the node 47 of the test network simulated. At 10:50 an overvoltage is detected. The interface protection waits for 10 minutes before the intervention; this waiting period allows a solution of the contingency by the centralized control system, or autonomously by a variation of the load and generation profiles of the contiguous nodes. If the overvoltage remains for 10 minutes, then the disconnection of the generator from the network is applied. A period of 15 minutes has been chosen as a proper time interval of disconnection, in order to reduce the number of disconnections and reconnections to the network and allow a variation of the causes of the contingency in terms of load and generation profiles of the neighbouring nodes. In Figure 41 the power profile of the PV generator at node 47 is show, where it can be observed the sequence of production and subsequent disconnection due to the intervention of the LOM protection described.

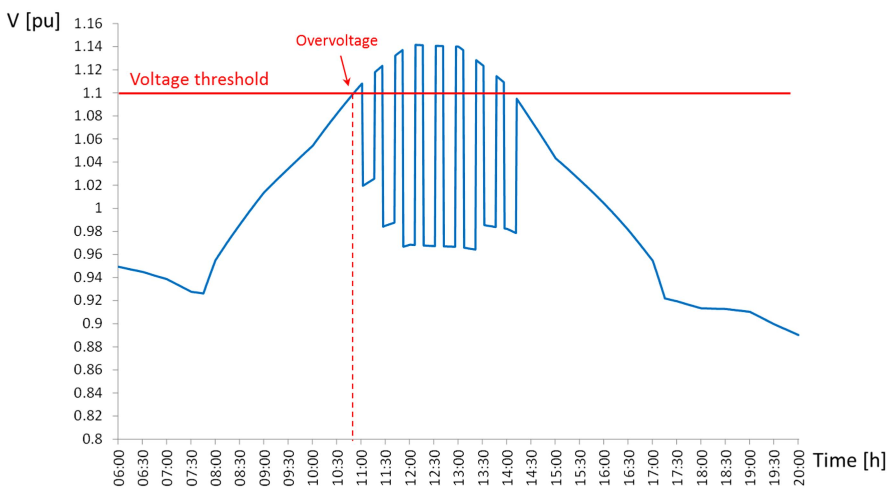


Figure 40. Voltage profile at node 47 - passive operation mode

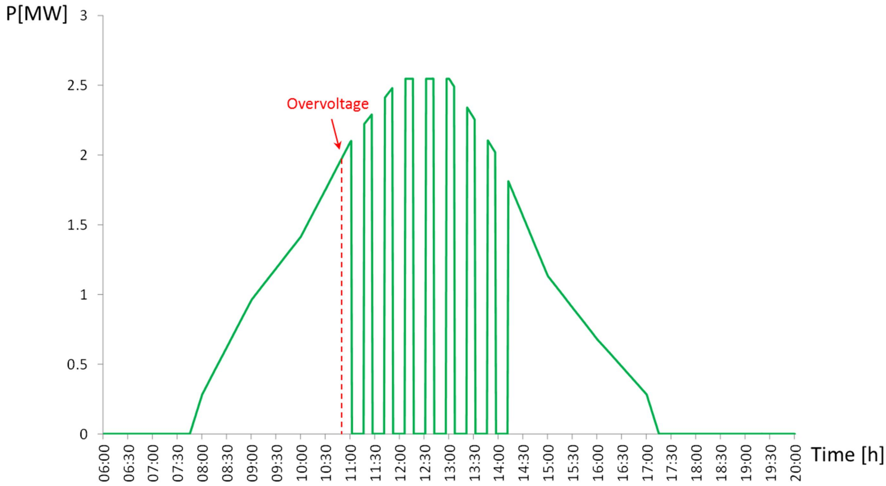


Figure 41. Active power production of PV generator at node 47 – Passive operation mode

5.2.1.2 Simulation of smart distribution system operation

A series of co-simulation studies have been executed with COSIM1.0 on the test network, where the centralized DMS controls the active sources remotely for voltage regulation. Three control strategies are considered:

- Optimal P and Q control, where the DMS actions consist of generation dispatching and generation curtailment of active and reactive power,
- Optimal P control only, where the DMS operates only with active power generation curtailment and generation dispatching, and
- Optimal Q control only, where the DMS utilizes only the reactive power dispatching in order to solve contingencies in the power network.

On this specific network, since the active sources consist of PV and Wind generators, active power dispatching is not allowed, because the RESs always produce the maximum power disposable, therefore only generation curtailment is performed by the DMS on active power generation.

The communication infrastructure is realized with WiMAX technology. A WiMAX Base Station is installed in the HV/MV substation, as interface between the DMS and the active nodes. Each active node is equipped with a WiMAX Subscriber Station, connected to the IED, which reads voltages and currents, and communicates to the DMS if any overvoltage or undervoltage is detected. When alerted, the DMS runs its optimization algorithm and defines new set points for the active nodes.

Optimal weather conditions are considered, and the WiMAX communication infrastructure is considered as exclusively dedicated to distribution network management data traffic.

A time step of 1 minute is considered in this case. In fact, a finer detail would not give more significance to the result, and would render the simulation consistently slower.

P and Q control

In Figure 42 the voltage profile at node 47 is shown. The red line describes the voltage profile before the DMS intervention, meanwhile the blue line describes the voltage profile after the P/Q regulation.

In Figure 43 the details about the DMS intervention are reported. It can be noticed that at 10:40 am, when the voltage exceeds the voltage upper threshold, the DMS optimization requests a generation curtailment at the generator 47; a variation of reactive power generation is also requested, as shown in Figure 43, for power flow management according to the line capacity constraints.

Reactive power dispatching is an important mean of regulation at 7:30 pm, when an undervoltage is detected at node 47. The injection of reactive power in the network allows increasing the node voltage above the lower threshold and restoring the network inside the allowable voltage range. In fact, in this network, characterized by long overhead lines with R/X ratio close to unity, the participation of the generators to the Volt/VAR regulation (reactive support) is a valid opportunity that reduces the curtailment of the renewable power production in case of overvoltage and allows sustaining the voltage in case of undervoltage, a typical issue for long rural networks.

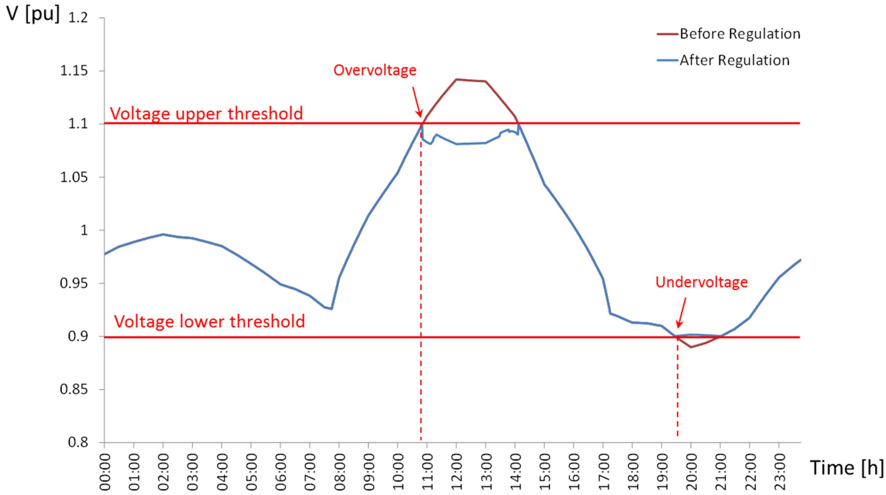


Figure 42. Voltage profile at node 47 (Optimal P/Q control)

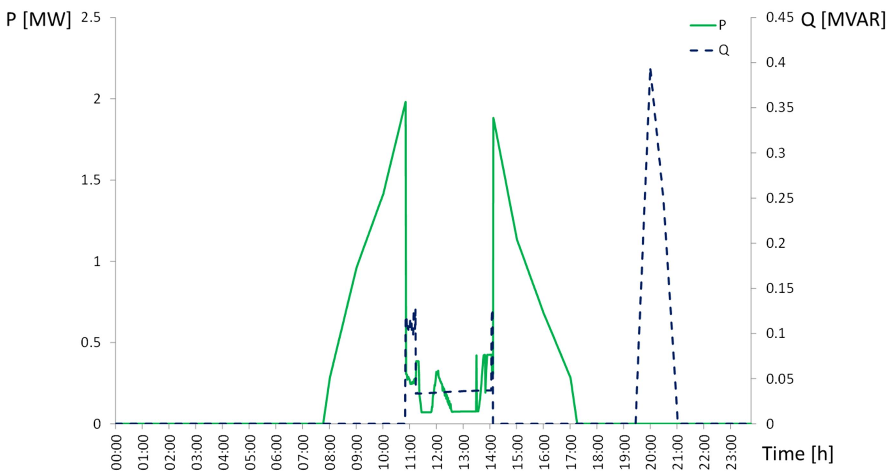


Figure 43. Active and Reactive power profile at node 47 (Optimal P/Q control)

P control

In Figure 44 the voltage profiles of a simulation with active power control managed by the DMS are shown. With the red line is represented the voltage at node 47 before the DMS intervention, with the blue line is depicted the voltage at node 47 after the DMS intervention. In Figure 45 the active power generated by the PV plant at node 47 is shown. The DMS can manage the PV generator only with a generation curtailment intervention, therefore only the overvoltages are solved by the DMS, meanwhile the undervoltage at 19:30 remains unsolved.

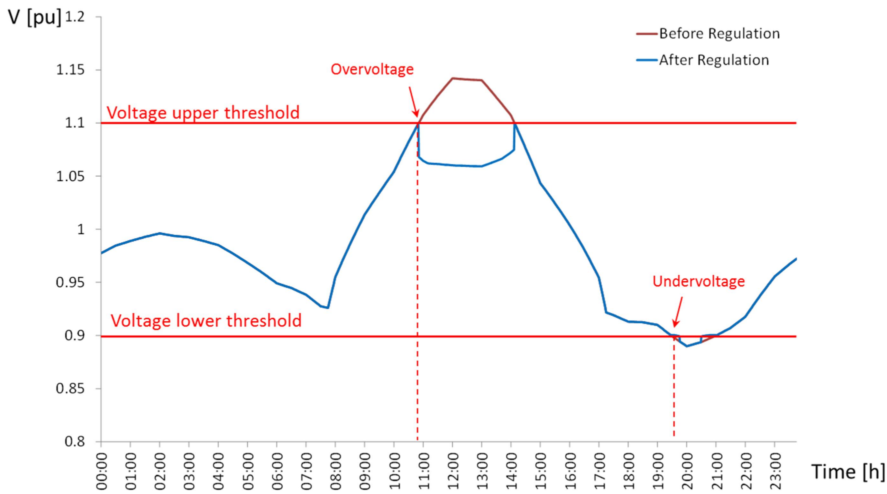


Figure 44. Voltage profile at node 47 (Optimal P control)

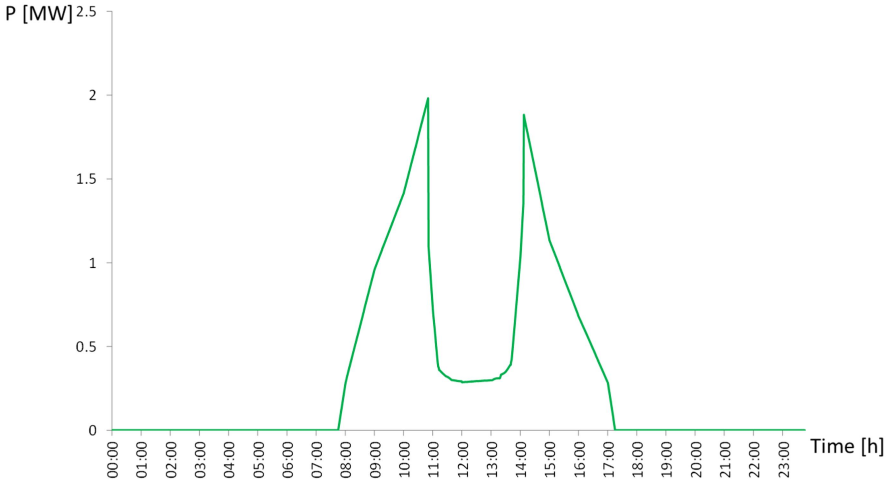


Figure 45. Active power profile at node 47 (Optimal P control)

Q control

In Figure 46 the voltage profiles of a simulation with optimal reactive power control are represented, meanwhile in Figure 47 the active power generated by the PV plant at node 47 and the reactive power exchanged are shown. It is observed that the reactive power dispatching is insufficient to perform an optimization of the power flow according to the constraints of the network, therefore the contingency issue is solved by the intervention of the breaker installed at the top of the feeder, where an overload is detected. On Table 8 current measurements and the loading ratio of the overloaded branches at 11:00 am are reported.

Table 8. Branch currents over technical limits

ID Line	Branch Current [A]	Branch Current Capacity [A]	Branch Loading [%]
N_002-N_034	241.48	190	127.1
N_049-N_055	170.37	140	121.7

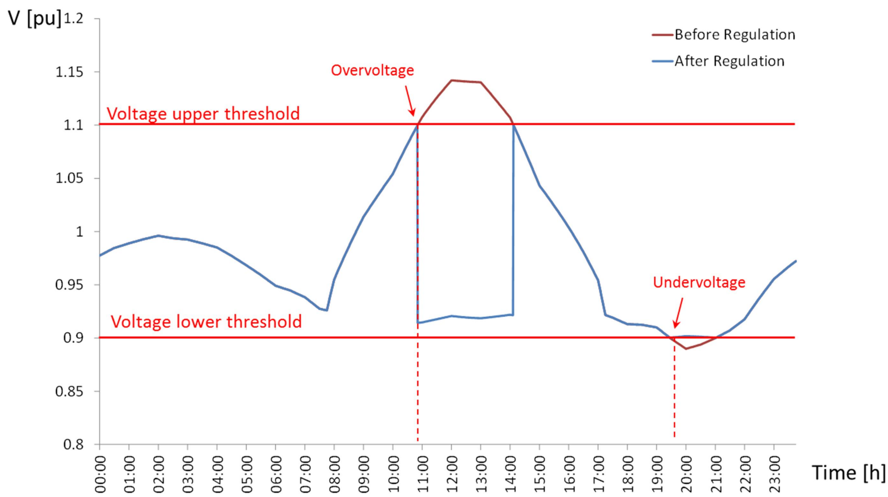


Figure 46. Voltage profile at node 47 (Optimal Q control)

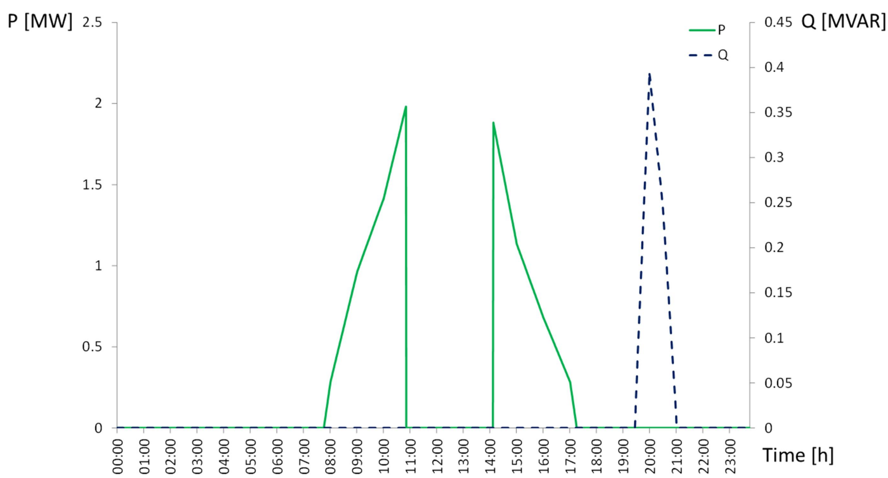


Figure 47. Active and Reactive power profile at node 47 (Optimal P/Q control)

Summary of results and reinforcement of the network

In Table 9 a summary of the simulations is reported, where the different DMS strategies are compared in terms of energy curtailed for each feeder. In general, energy calculations are obtained integrating the power profile figures, considering a constant power value over the one-minute discretization interval adopted. The energy curtailed is calculated by subtracting the energy produced on a daily bases under the DMS operation from the energy that would be generated with the scheduled generation profile. It is observed that contingencies occur only on feeders 3 and 7, where there is a strong unbalance between generation and load (Table 7), whereas energy curtailment in the other feeders is equal to zero. The P/Q control allows to decrease the generation curtailment of active power (1188 MWh, with a reduction of 72% from 4216 MWh curtailed in the traditional distribution network with passive protection systems), by using both active and reactive power for management of power flows and voltage regulation.

Table 9. Energy curtailed in MWh for different control strategies

Feeder	**Passive Network** *[MWh]*	**P/Q Control** *[MWh]*	**P Control** *[MWh]*	**Q Control** *[MWh]*
F1	0	0	0	0
F2	0	0	0	0
F3	4117.65	989.86	1122.61	3743.40
F4	0	0	0	0
F5	0	0	0	0
F6	0	0	0	0
F7	98.48	197.89	435.77	184.16
Total	*4216.13*	*1187.75 (-72%)*	*1558.38 (-63%)*	*3927.56 (-7%)*

In the P control case, the generation curtailment measured on the active sources increases when compared with the P/Q control, but a reduction of 63% in terms of energy not produced is obtained when compared with the passive network operation mode. If a Q control strategy is adopted, the reduction of energy curtailment from the passive case is only 7%. This result is determined by the technical constraints (overcurrent) in the network that cannot be solved with only reactive power dispatching; in fact, in case of overcurrent in the feeder, the use of voltage regulation without control in the active power not permit the resolution of those contingencies. For this reason, in the Q control, the overvoltage issues are mainly solved by the intervention of the switch at the top of the feeder, since no feasible solutions can be found by the DMS.

In order to compare different distribution planning alternatives (both network and no-network solutions), another solution has been analyzed, where a refurbishment of the network is considered (Table 10). In particular, the reinforcement involves the branches that connect nodes 2-34, 34-49 and 49-55, where overloads are detected for about 370 hours/year. Table 11 summarizes the results in terms of energy not produced for the different control strategies (with/without network reinforcement). With the reinforcement of the network, only 68 interventions by the DMS were necessary for solving contingencies, resulting in a reduction of the energy not produced and of the technical issues. In fact the sizing of the new conductors was chosen in order to solve the main overload issue, and the bigger cross sections reduce the voltage drop along the feeders and the number of the overvoltages along a year also. For the network solution, an economic analysis was performed in order to compare the two solutions in terms of yearly costs, by adding the investment costs with the costs connected to the energy management of the active resources [57]. The period taken into account for the planning study is 5 years, whereas the technical life of every new branch is equal to 40 years. The costs associated with the dispatching of active power are equal to 50 €/MWh, meanwhile the reactive power has been considered as not remunerated. For this calculation, a P/Q control strategy has been adopted. The results are reported in Table 12.

The analysis demonstrates that the second option represents a fair compromise between active management and refurbishment of the network.

The reduction of energy curtailment on the generating plants allows a strong saving in the management costs associated with the optimal control of the active resources, resulting in a more economical solution. Also, a local redesign of the most overloaded branches allows a more efficient impact of the active management of the generation plants, since the reduction of the energy not produced by the active resources when compared with the passive network simulation is higher.

Table 10. Network reinforcement

			Original network			**Reinforced network**		
Nodes	*Branch length [km]*	*I_{MAX} measured [A]*	*Size [mm^2]*	*Material*	*Capacity [A]*	*Size [mm^2]*	*Material*	*Capacity [A]*
2-34	12	310	35	CU	190	185	AL	330
34-49	9.2	240	35	CU	190	150	AL	280
49-55	1.3	220	25	CU	140	120	AL	260

Table 11. Energy curtailed in MWh

Feeder	**P/Q Control**		**P Control**		**Q Control**		**Passive Network**
	[MWh]		*[MWh]*		*[MWh]*		*[MWh]*
Original network	1187.75	(-72%)	1558.38	(-63%)	3927.56	(-7%)	4216.13
Reinforced network	88.65	(-76%)	107.83	(-71%)	301.06	(-19%)	372.67

Table 12. Comparative economic analysis between ADM and ADM + network reinforcement

	Original network [k€]	**Reinforced network [k€]**
Investment on reinforcement	-	68
Energy not produced	1300	98
Total Yearly Costs	1300	166

It is important to remark that the network solution investigated is not the optimal solution from a planning point of view. In fact, in order to find the optimal coordination between action on the reinforcement of the network and active management of the active sources it is necessary to apply heuristic optimization techniques [57].

Simulation of ICT failures

In this section it is presented a case study where the DMS signal is not delivered correctly to all network DERs. In this case it is considered a temporary failure, caused by an increasing of path loss due to unfavorable weather conditions.

More specifically, the communication failure concerns the nodes 47, 10 and 80, during a contingency instant. The contingency consists of an overvoltage at node 47 during the PV generation peak of a summer day.

The simulations are conducted with COSIM1.0, with a 1 minute timestep.

In Figure 48 the results are reported, referring to the voltage profiles at node 47. It can be noticed that when voltage at node 47 exceeds the upper threshold of 1.1 p.u. (t_0=11:55am), the DMS intervention is not efficient in solving the contingency. This result is due to the ineffectiveness of the control signal on node 47, which is not accessible by the DMS because of the ICT connection failure between the DMS transmitter antenna and the receiver antenna of node 47.

The centralized DMS control protocol is based on TCP, therefore DMS is able to detect the communication failure with node 47, 10 and 80 due to the reliable features of the TCP protocol (e.g. . the three-step handshaking) that allow diagnosing the TCP connection and sense the delivery of the data control. These nodes are therefore removed from the list of active DERs for a short period (in this case 30 minutes are considered), and the network active management is temporarily deployed with the remaining DERs which are reachable by the DMS. Since in this case a temporary failure is considered, the nodes 47, 10 and 80 are considered again accessible by the DMS after the 30 minutes period, and the active management proceeds with all the active resources available.

In Figure 49 and Figure 50 the active and reactive power profiles of generators at nodes 36, 46, 47 and 34 are reported. These are the most important active resources connected to the feeder F3. The profiles of generators at nodes 49, 42 and 54 are not shown because they are irrelevant for the voltage regulation in this particular scenario.

The Figure 49 shows that at t_0 (11:55 am), when overvoltage is detected, the DMS intervention is effective only on generators at nodes 36, 46 and 34. As the control signal cannot reach the generator at node 47, it maintains the default generation profiles. Therefore, since the planned operation of DMS on generator at node 47 is not applied, the DMS intervention results into an increase of voltage at node 47.

As generator at nodes 47, 10 and 80 are detected as unavailable, the active management is planned with the remaining active nodes for the following 30 minutes starting from t_0 (t_1:t_2 interval, from 12:00 am to 12:25 am). Figure 49 and Figure 50 show the generation curtailment intervention and the variation on reactive power dispatching at generators 46 and 36 during the period between t_1 and t_2.

At t_2 the DMS sets a new optimization of the network with all the DERs. Since generator at node 47 is sensed as again available, the voltage regulation is assigned mainly to this resource, with a generation curtailment of 1.3MW.

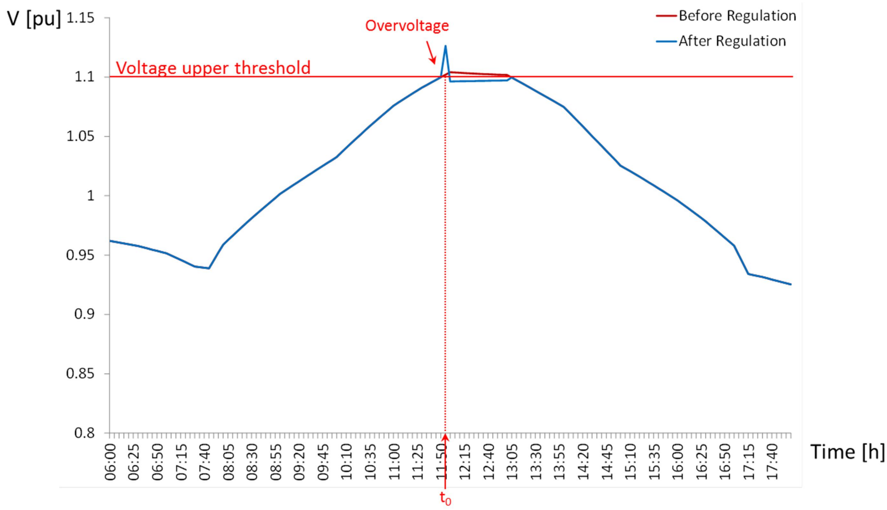


Figure 48. Voltage profile at nodes 36, 46, 47 and 34 – Node 46 unreachable

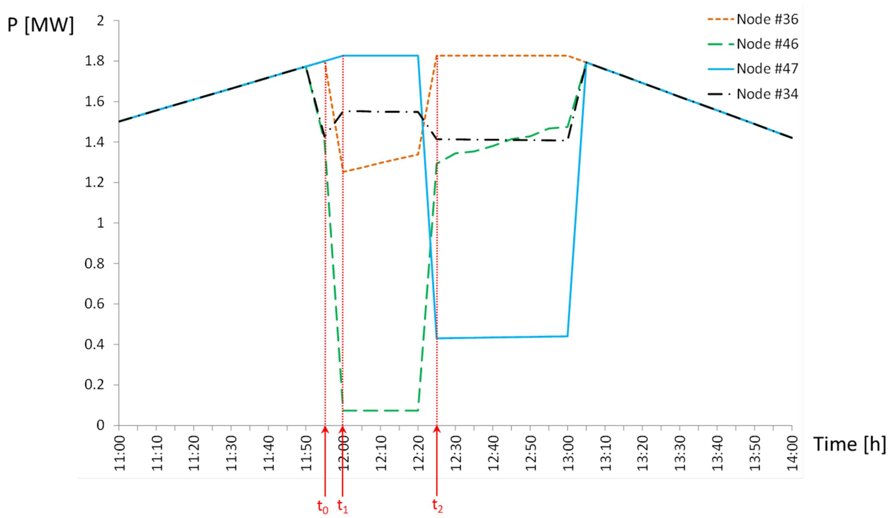


Figure 49. Active power profile at nodes 36, 46, 47 and 34 – Node 46 unreachable

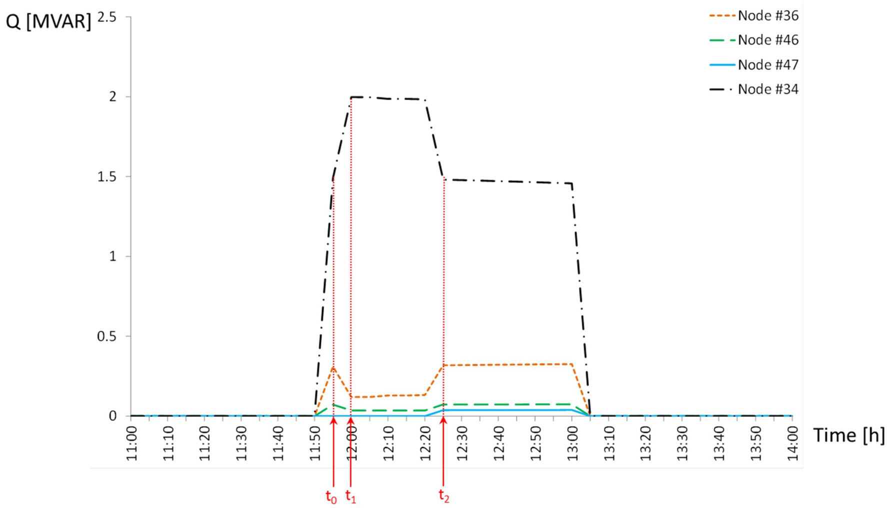


Figure 50. Reactive power profile at nodes 36, 46, 47 and 34 – Node 46 unreachable

Overall, the management system of the active network demonstrates to be flexible against any temporary failure of links to resources active. Obviously, the lower the number of active resources, the higher the dispatching costs. Also, with a limited number of resources, the algorithm of optimization faces growing difficulties to comply with the technical constraints of the network.

It is demonstrated in the following co-simulation case where the control signal on both nodes 47 and 46 are undeliverable. The voltage and power dispatching profiles are represented on Figure 51, Figure 52 and Figure 53. In this case, the network management between t_1 and t_2 is realized by the total curtailment of active power generation at node 36.

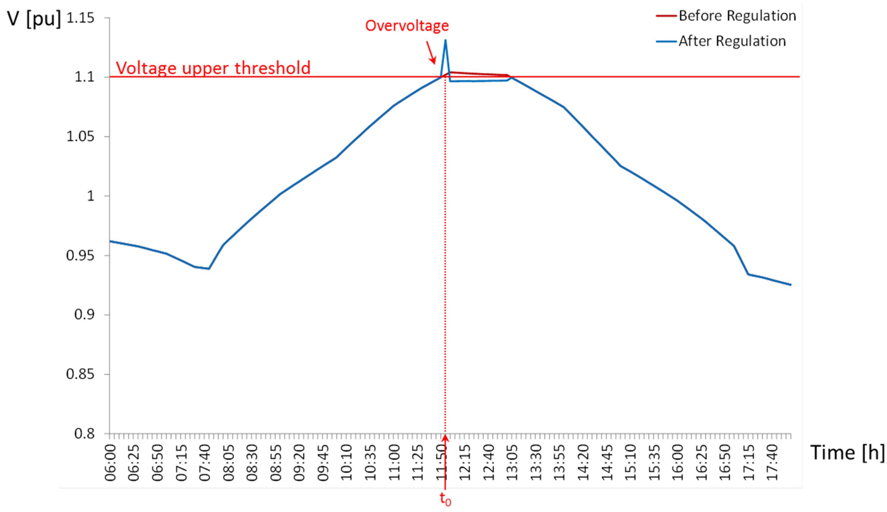


Figure 51. Voltage profile at nodes 36, 46, 47 and 34 – Nodes 46 and 47 unreachable

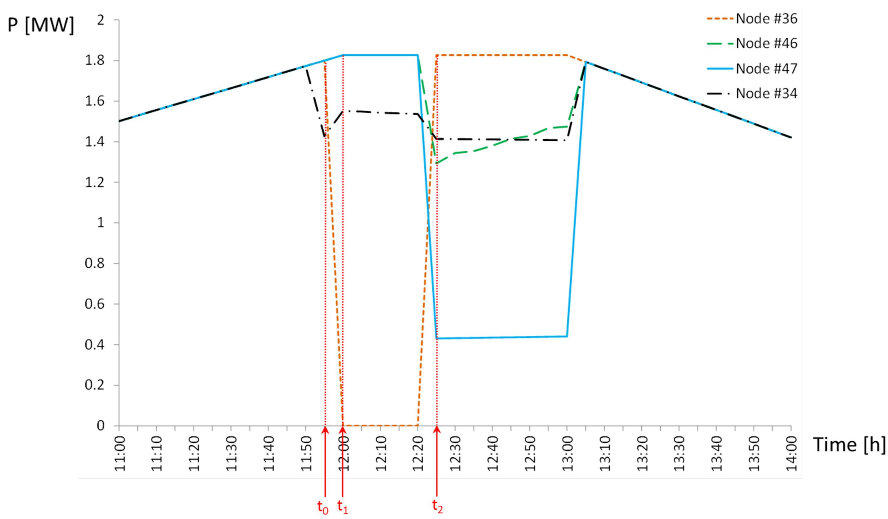


Figure 52. Active power profile at nodes 36, 46, 47 and 34 – Nodes 46 and 47 unreachable

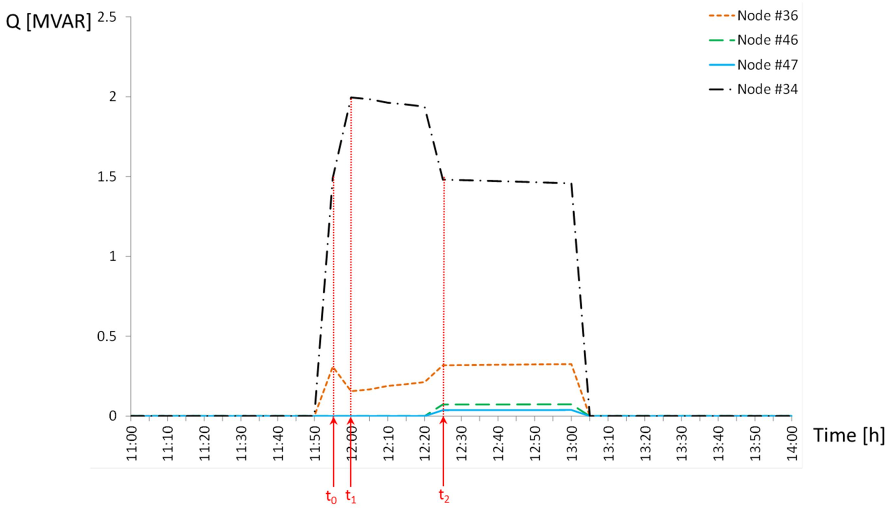


Figure 53. Reactive power profile at nodes 36, 46, 47 and 34 – Nodes 46 and 47 unreachable

Table 13. Signal transmission latency

Packet size [bytes]	Transmission delay [ms]
100	10,6
500	26,8
1000	42,3
1500	58,8
2000	74,3

As the final results in Table 13 it is presented how communication latencies during DMS communication to DER IED vary according to different packet sizes. The transmission delay reported represents the average delay value for the packet delivery from the DMS to the dispatched resource. 5 different packet sizes are considered, from 100 B to 2000 B. It can be noticed that even with the most severe condition, with 2 kB of packet data to be delivered, the transmission delay with a dedicated WiMAX infrastructure are suitable for voltage regulation.

In conclusion, WiMAX technology proves to provide good performances in terms of latencies for slow dynamics network operation, although the transmission delay can be critical for fast dynamics intervention on the network, such as in case of fault management. On the other hand, a further investigation on slow dynamics operation is needed for analyzing the impact of the ICT infrastructure reliability on network operation. For this purpose, a Monte Carlo analysis procedure is nested in the co-simulation tool for a comprehensive reliability investigation on the smart distribution network active management.

5.2.2 Reliability analysis

The reliability of the communication network represents an important issue that needs detailed investigation, since it has a strong impact on the distribution network both technically and economically.

The Monte Carlo approach is a very computational demanding method for performing statistical studies. For this reason, a simplified version of the network analyzed in the previous subsection has been analyzed with COSIM1.1, in order to obtain significant results with faster simulation time.

The Monte Carlo algorithm adopts a stopping criterion, which is based on the convergence of a β parameter defined as in (5.1):

$$\beta = \left| \frac{AFR_T - \overline{AFR_{SIM}}}{AFR_T} \right| \quad \textbf{(5.1)}$$

where AFR_T is the AFR calculated, based on the assumed reliability parameters (Table I), whereas AFR_{SIM} is the AFR calculated during the simulation by counting the mean number of failures occurring in a year.

Table 14. Reliability Data for ICT Devices

Equipment	MTTF [Hours]	MTTR [Hours]
DMS/EMS	800x8760	8
WiMAX Tx Antenna	15x8760	12
WiMAX Rx Antenna	15x8760	12
Router TX	45x8760	4
Router RX	7x8760	4
IED	800x8760	8

When β converges below 3%, the Monte Carlo simulation stops. Additionally, a minimum number of years simulated is considered, in order to avoid any local minimum that can be obtained at the first years when the algorithm is still far from convergence.

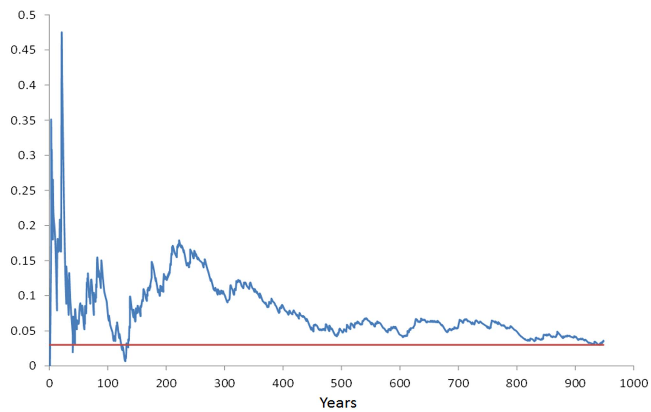


Figure 54. Convergence of beta parameter over years

In Figure 54 the convergence of β is graphically represented. It demonstrates how, in order to obtain a good quality of the results, more than 900 years simulated are needed, after which β describes an asymptote.

The graphical representation of the network analyzed is shown in Figure 55.

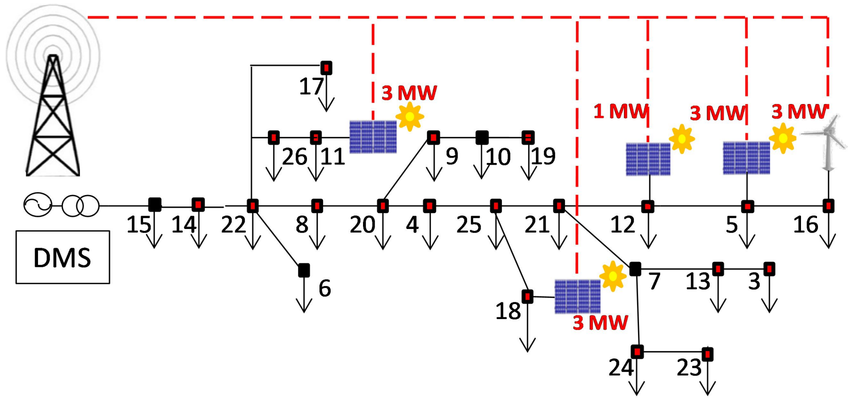


Figure 55. Rural test network – Reliability analysis case study

The single feeder network is long about 15 km with several lateral branches, with 26 MV nodes supplied by one HV/MV substation. Five DERs are installed in the network: 3 PV power plants 3 MW size are connected to nodes 11, 18 and 5; 1 PV power plant 1 MW size to node 12, and one 3MW wind generator to node 16. The total peak load demand is about 3 MW.

The DERs provide ancillary services such as Volt/VAR regulation and active power generation curtailment in order to solve overvoltage, undervoltages and power flow congestions under DMS request.

The network is characterized by a substantial unbalancing between generation and load, therefore DMS active management is important for keeping the electrical quantities between the technical constraints. Therefore, a high reliability of communication network is essential for ensuring the correct and timely delivery of the DMS control signals to the dispatched DG units.

In order to quantify the effects of communication network failures on the smart grid management, the energy not produced is assumed as evaluation metrics, where the reference scenario is represented by the smart grid managed with an ideal ICT network.

In Figure 56 the voltage profile of the active nodes in the reference scenario (ideal ICT network) is shown, referred to a typical summer day. It can be noticed the generation dispatching effect on nodes 16, 5 and 12, where the voltage rise is shaved due to the DMS intervention.

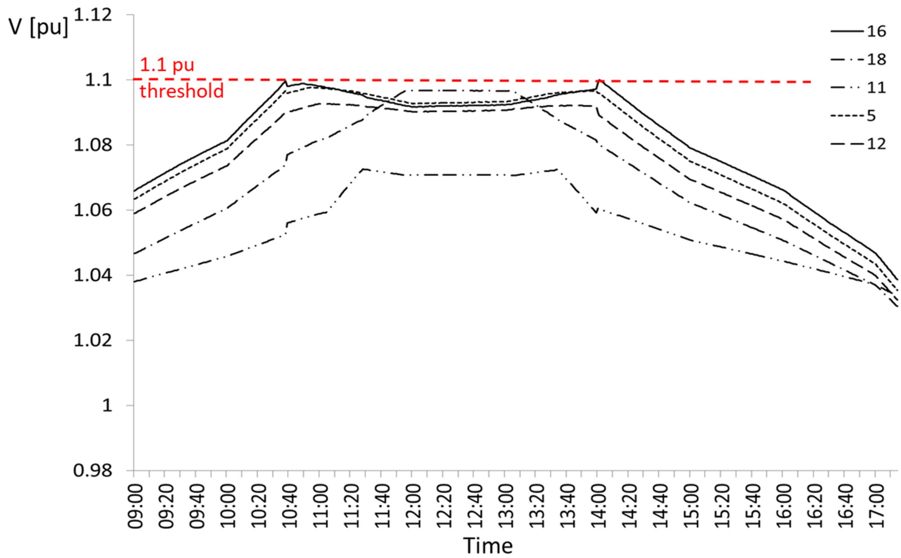


Figure 56. Voltage profile on nodes 16, 18, 11, 5 and 12 - Reliability case study

Table 15. Energy not produced for each Active Resource

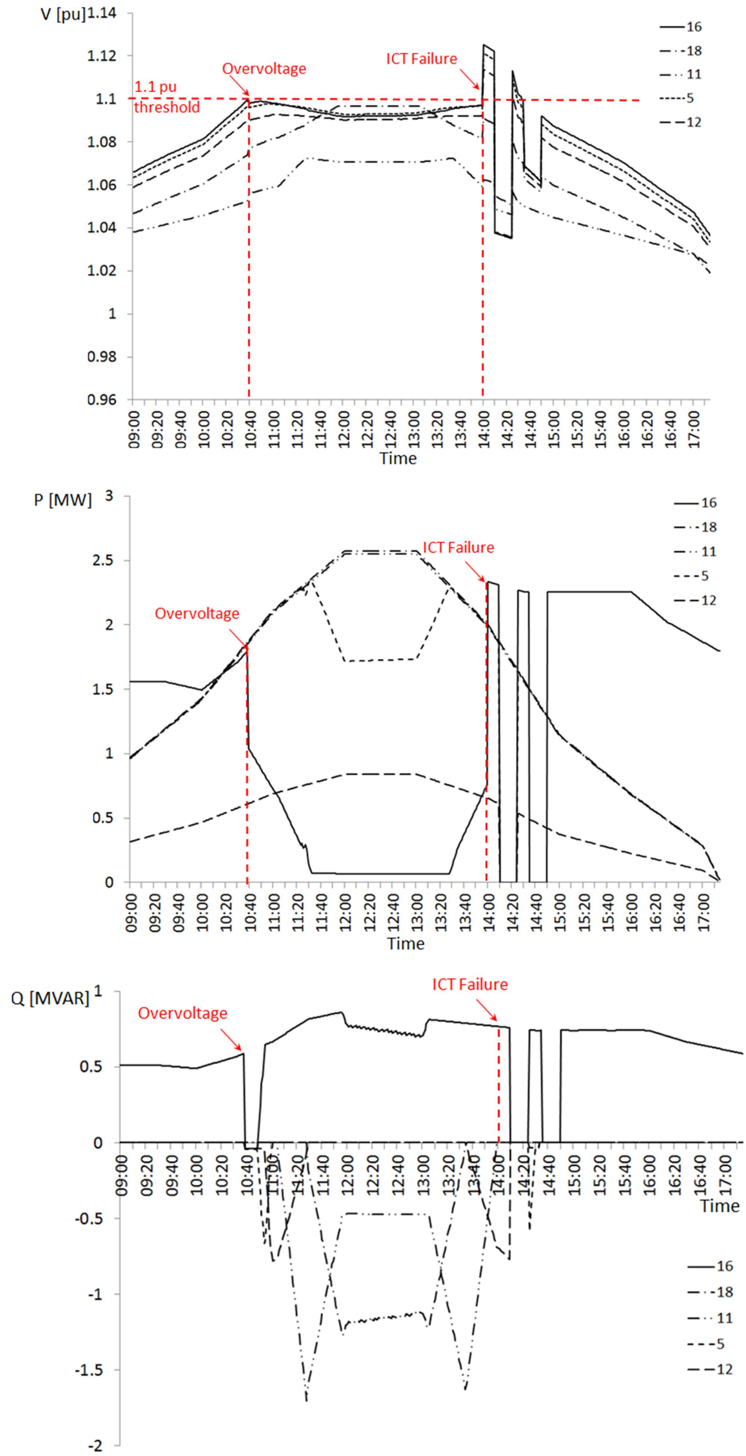
Ideal ICT		**ICT modeled with reliability parameters**		**No ICT Passive network**	
Bus	*Energy not produced [MWh]*	*Bus*	*Energy not produced [MWh]*	*Bus*	*Energy not produced [MWh]*
16	620.68	16	619.30	16	876.91
5	51.25	5	52.09	5	517.24
12	0	12	1.09	12	97.45
18	0	18	3.82	18	0
11	0	11	0	11	0
Total	671.93	Total	676.30	Total	1491.60
		ΔP%	+0.7%	ΔP%	+122%

The results of the Monte Carlo simulation are summarized on Table 15 in terms of energy not produced.

Three cases are considered: Ideal ICT network, ICT network modeled taking into account the reliability parameters listed in Table 14, and passive network. In this last case, no active management is implemented, hence contingencies are solved by applying a local protection scheme.

In case of ideal ICT modelling, DERs 16 and 5 are requested to curtail their energy production, while DER 12, 18 and 11 participate to the voltage regulation only with reactive power dispatching. About 450 DMS calls are necessary to solve the contingencies during a year (considering 1 hour check intervals).

In case of detailed ICT modelling slight variations of the energy curtailed are observed on the DERs connected to nodes 16 and 5. In fact, the DMS curtails first the wind generator at node 16 for solving contingencies in normal operation, because its cost is lower than the cost for photovoltaic energy curtailment (it is considered the actual Italian incentive scheme the subsidies for PV system energy production are higher than the ones for wind energy). It can be also observed from Table 15 that node 11 has no energy curtailed. This is due to its position in the network that does not determine any critical situation, even when the node is not served by the ICT network. The energy not produced by node 5 increases when ICT faults occur, and there is also some energy not produced at node 12 and node 18 because of the disconnections. Globally there is an increase of the energy curtailed caused by the failures on the ICT control and communication.



(a)

(b)

(c)

Figure 57. Voltage (a), active power (b) and reactive power (c) during ICT failure - ICT modeled with reliability parameters scenario.

The situation described can be further explained considering the Figure 57, where the evolution of voltage, active power and reactive power measured on the generators of the network are illustrated. At 10.25 am an overvoltage at nodes 16 is detected, then the DMS optimizes the dispatching of the DERs in the network, curtailing the power at node 16, 5, 12, 11 and 18.

This simple example demonstrates the short difference between the results obtained in the case with ideal ICT, and in the case when detailed ICT modelling is considered. At 2 pm, when the receiving antenna at node 16 is out of service, nodes 16, 11 and 12 are disconnected from the network. It again demonstrates that this network is deeply reliant on the operation of node 16: the generation curtailment on this node is strictly necessary since generation dispatching of reactive power and active power curtailment on the remaining nodes is insufficient to obtain an acceptable voltage profile in the network.

Finally, in the last column the results of a simulation with the network with passive management are reported. In this case each time voltages at DER connection node increase above 1.10 p.u. the generators are automatically disconnected by the tripping of the LOM protection. In this case the energy curtailed is 122% higher than the case with smart grid ideal operation.

5.2.3 Co-simulation of multiple communication systems

COSIM1.1 has been then exploited for analyzing the network shown in Figure 58, where a LV network is derived from a MV network through a 20/04kV 1MVA transformer. The network considered is fed by one HV/MV primary substation, and extends globally for about 8 km. The network supplies 17 MV nodes, which aggregate mixed loads and two generation plants, and a LV network with feeder length less than 1 km.

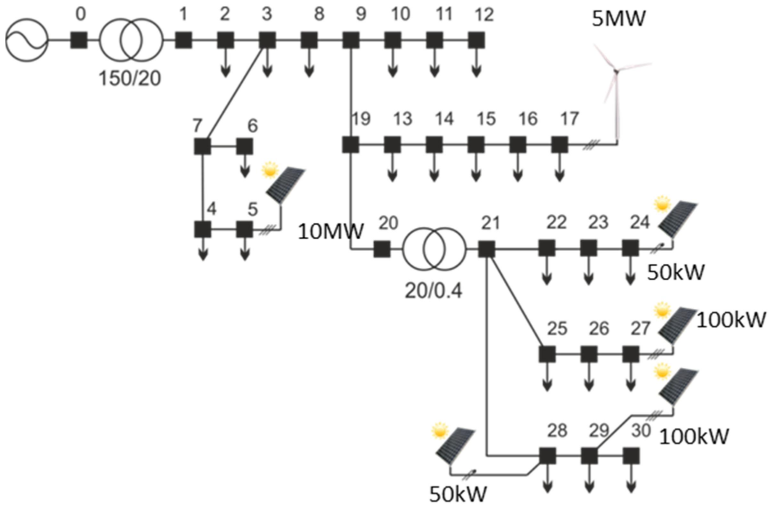
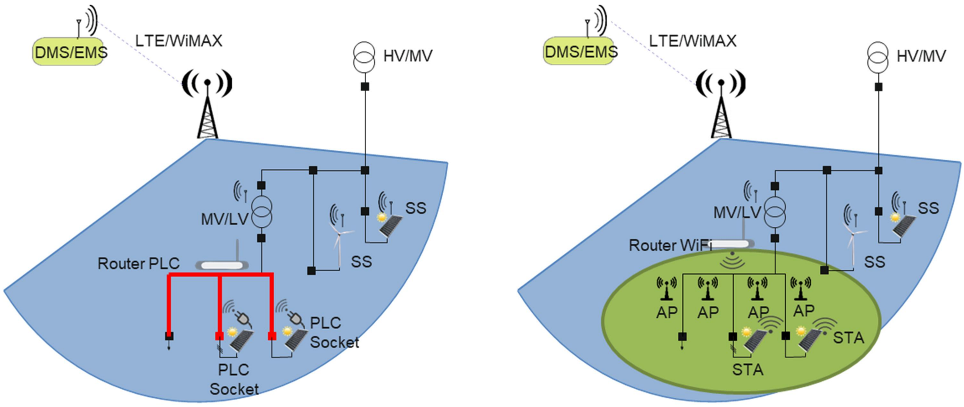


Figure 58. MV/LV network

The total demand is 3 MW on the medium voltage network, while it is 280 kW on the low voltage network. The loads are related to three types of consumers (residential, industrial and commercial), while two types of production plants are considered (photovoltaic and wind). All these customers are modeled with their hourly profiles. The sizes of the generators connected to the network are specified in Figure 58.

The communication infrastructure is deployed with OFDMA-based technology (WiMAX or LTE) as the backbone of the ICT network, with the possibility of having a second technology, Wi-Fi or PLC in cascade, for serving the LV smart user nodes equipped with IEDs.



(a) (b)

Figure 59. Distribution network communication scheme:
(a) LTE/WiMAX+PLC; (b) LTE/WiMAX+Wi-Fi

In Figure 59(a) the ICT architecture with Wi-Fi for the connection to LV DERs is depicted. The backbone is supposed to be built with LTE/WiMAX technology, which allows the bidirectional connection of DER with the DMS. The DERs connected at MV level directly communicates through LTE/WiMAX, while the DER resources at LV level communicate by means of the Wi-Fi network with a data concentrator (router) that is placed in the MV/LV substation. The router has the task of redistributing the data packet to the resources that are connected to the low voltage network. The Wi-Fi network is implemented with the AP-STA topology, where the access points (APs) are placed on a grid 100 m spaced, in order to guarantee a good coverage of the area and an efficient Wi-Fi communication service between the data concentrator substation, the Wi-Fi APs, and the IEDs located at DERs.

The architecture with PLC is depicted in Figure 59(b). In this case each LV active node is equipped with a PLC socket, which permits receiving and sending data packets, from/to the data concentrator located at MV/LV substation through the LV power cable. The PLC system adopts the carrier sense multiple access with collision avoidance protocol (CSMA/CA) in which each PLC socket, before sending a data packet, verifies that the transmitting media is idle and not busy with another data transmission. If the transmission channel is idle, the packet is sent, otherwise a backoff time is randomly calculated, and a new attempt of data sending is scheduled. When the packet is sent, the transmitting device waits for an acknowledgement packet that confirms that the packet is correctly received. The reception of the packet is determined by the correspondence of the IP address registered on the header of the packet with the IP address that is assigned to the receiving device. If there is correspondence, the active node reads the data frame and applies the correspondent control action, otherwise the packet is ignored.

The co-simulation tool is used to simulate voltage regulation applications in a Smart Grid context. As in the previous cases, a one-minute time step is considered in the co-simulation.

In Figure 60a the voltage profiles for critical LV nodes equipped with DG N24, N27, N28 and N29 are reported. When overvoltage or voltage drop exceeding statutory limits are detected, the OPF is run in the DMS module in order to find the optimal way to make the network complying with technical constraints. This means that new set-points for active and reactive power have to be sent to controllable loads and eventually a new tap is selected in the transformer.

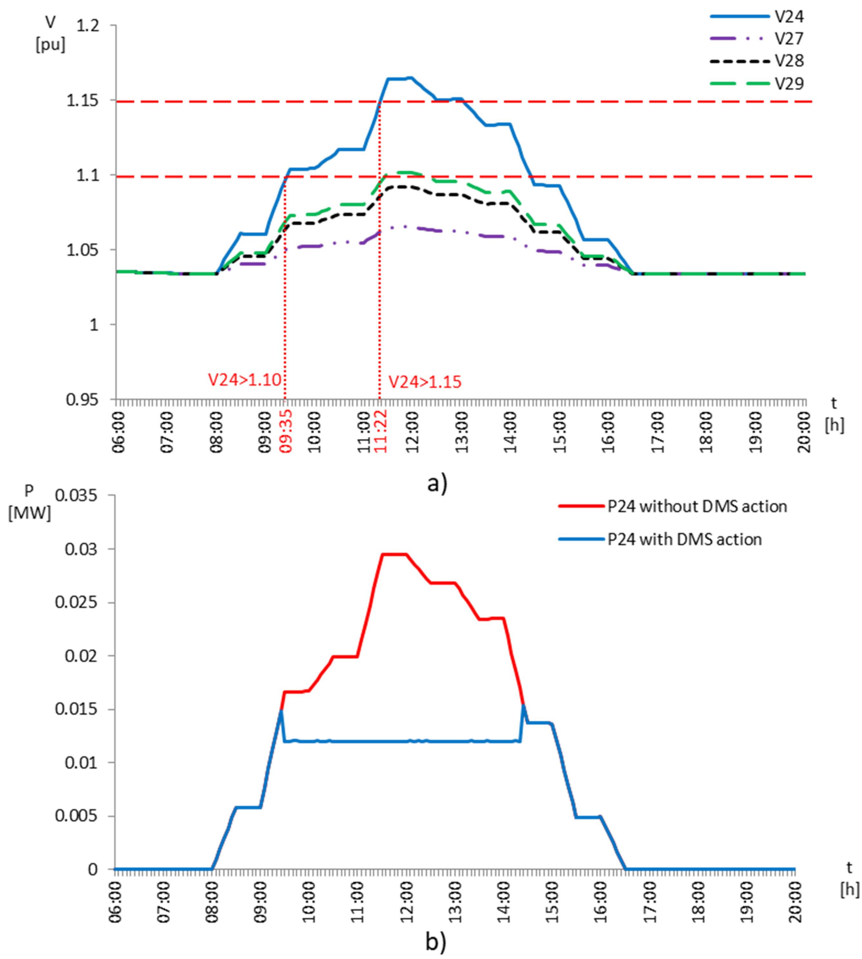


Figure 60. a) Voltage profiles in low voltage generation nodes; b) Power profile at N24

In order to show how the co-simulation works, suppose the voltage exceeding the threshold of 1.1 p.u. at 9:35 a.m. (Figure 60a). The IED located at node N24 reveals this overvoltage and sends a warning message to the DMS, which defines the new set points for the DERs in the network in order to fix the voltage issue. The new state is depicted in Figure 60b where the power profile shows that the DMS required the curtailment of the power generated by the PV connected at N24.

A comparison for the same control with different ICT system configurations has been performed, by adopting the UDP protocol which minimizes the data traffic on the network. Table 16 shows the results related to the delays that has been measured in the simulation with four different ICT configurations: only WiMAX network or LTE network that cover both MV and LV nodes (direct communication between DMS and each DER), LTE + Wi-Fi network (according to Figure 59(b) scheme) and LTE + PLC network (according to Figure 59(a) scheme). For these simulations a packet size of 800 bytes has been considered, since it guarantees to contain the message frame with many standard protocols regarded as good candidates for smart grid regulation and control, such as IEC 61850 and IEC 62056 [107], [108].

Table 16. Average latencies in the active management of the SG

From/to	WiMAX (ms)	LTE (ms)	LTE+Wi-Fi (ms)	LTE+PLC (ms)
IED-DMS	40.40	28.92	34.46	368.82
DMS-N05	39.82	13.90	34.07	36.02
DMS-N17	40.06	14.00	32.12	32.12
DMS-N24	40.23	16.90	39.38	370.82
DMS-N27	39.90	13.82	46.42	1305.92
DMS-N28	39.98	16.00	72.87	2028.92
DMS-N29	40.16	14.99	97.95	2435.62

Table 16 results emphasize the better performances of the use of full wireless technologies. Since interferences are not considered in these simulations, latencies may be higher, but the high margin with the values indicated by the Standard IEC 61850 (500 ms) for the delivery of complex messages, such as low speed auto-control functions, transmission of event records, and reading or changing set-point, shows the good adequacy of these technologies for supporting the voltage regulation of the power network.

When the PLC architecture is adopted for the connection of LV users (LTE+PLC), a significant increase of delays when transmitting signals to the low voltage DERs is registered. This is due to the low bitrate of this technology that determines the sequential allocation of the communication channel for every packet transmission, combined with the high noise that cause frequent packet resending. More specifically, about 3 seconds represents the maximum latency that is measured in the LTE+PLC infrastructure, that, although not aligned with the requirements of IEC 61850, is in general suitable for voltage regulation (slow variations).

5.2.4 Concluding remarks on slow dynamic simulation study

This first set of case studies, conducted with COSIM1.0, highlights the usefulness of co-simulation for analyzing and comparing different active resources control strategies: Optimal P/Q control, Optimal P and Optimal Q control, and evaluating the impact of ICT reliability in the Smart Grid management. The study demonstrated that the active management system proposed is flexible against any temporary ICT failure in operation that involves slow dynamics issues, such as voltage regulation and the management of power flows in the networks for solving congestions. The simulations showed that an improvement in the efficiency of the optimal control of the active resources is obtained by using the P/Q control supplemented with a local reinforcement of the power network. Then the Monte Carlo method nested within COSIM1.1 has allowed analyzing the impact of the communication network reliability in the smart distribution network operation. The WiMAX technology is adopted as smart grid communication layer in this first case, and both analysis (distribution network management and reliability analysis) demonstrate that WiMAX well suits smart grid applications.

The last study conducted with COSIM1.1 allows performing a comparative analysis between different ICT solutions for distribution network management. Although all the solution proposed are suitable for voltage regulation applications, LTE outperforms in terms of latencies, that make this technology also suitable for supporting fast dynamics operation, e.g. fault management applications.

5.3 Fast Dynamics study

The electric network considered in this case study is an urban medium voltage (MV) network, which presents 7 feeders that depart from a single HV/MV primary substation. All feeders present an emergency tie comprised between two normally open switches that can be operated for network reconfiguration. The network extends for about 10 km, and supplies 103 MV nodes that supply power to mixed residential and commercial loads. Each MV node represents a secondary substation, with a set of disconnecting devices and ICT capabilities depending on it being a smart secondary substation paradigm or a conventional one.

A short circuit between nodes 66 and 67 is considered (Figure 61). It represents a fast dynamics phenomenon, which is therefore analyzed with the final version of the co-simulation tool, COSIM2.0.

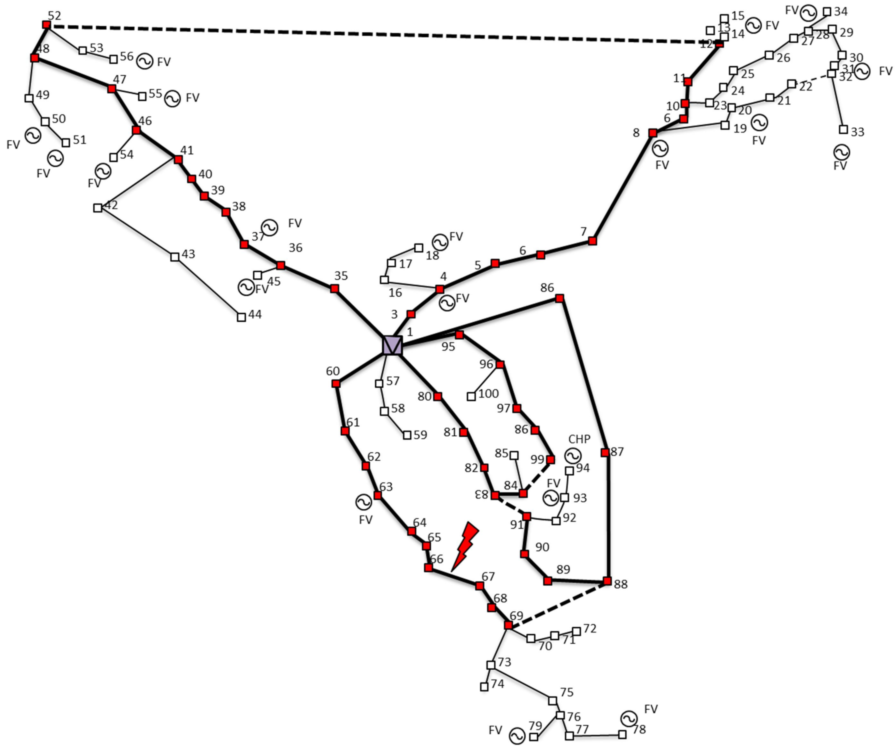
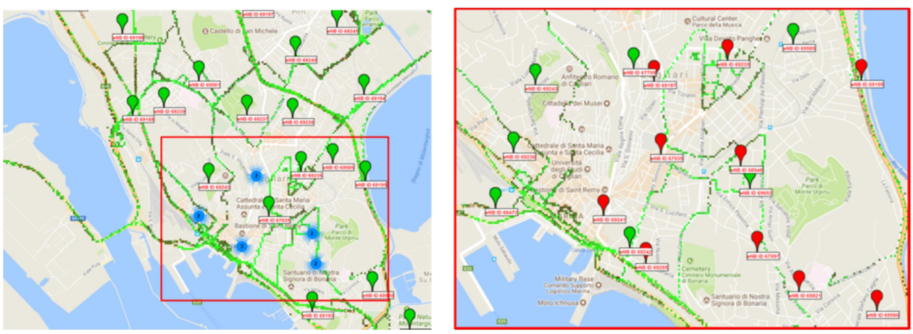


Figure 61. MV network considered in the case study



(a) (b)

Figure 62. eNB distribution in urban scenario (City of Cagliari)

The communication network is implemented with LTE technology.

A real LTE urban network scenario has been analyzed for choosing the proper parameters adopted in the simulation. In more details, geo-referenced data of the towers distributed in the city of Cagliari of a commercial telephone mobile operator have been considered (Figure 62a)

Afterwards, it has been chosen to restrict the simulation to a specific area of the communication network (Figure 62b). In more details, the simulation is restricted to the area around the short circuit location, where the actual communication between the secondary substations is performed. The portion of network chosen is constituted by 10 Base Stations, which operate on the Band 3 (1800 MHz). In Table 17 the values that have been adopted for the parameters of the LTE network are reported.

Table 17. ICT network parameters values

Parameter	Value
Scenario ITU	URBAN_MACROCELL
Carrier Frequency	1800 MHz
Bandwidth	20 MHz
Antenna Gain eNB	18 dBm
Thermal Noise	-101 dBm
UE Noise Figure	2 dBm
eNB Noise Figure	5 dBm

The area selected is overlaid with the portion of the power network interested by the short circuit (Figure 63).

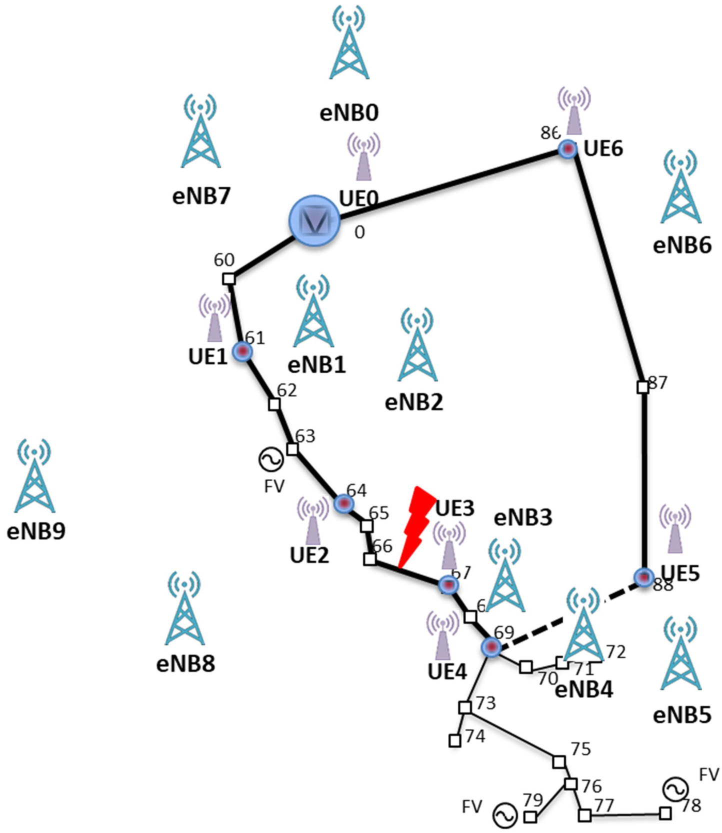


Figure 63. Distribution of LTE eNB and UE over the MV distribution network

Each Smart Substation is provided with a receiver LTE antenna (UE). A directional LTE antenna is considered, characterized by 28dBi Gain.

The communication between SSS is performed with UDP protocol. A data packet of 200 Byte is considered for transmitting current and phase measurements between the substations. An additional frame of 16 Byte is considered for data packet cryptography.

Different scenarios are considered in the co-simulation performed, that consider a variable data traffic performed by the generic Mobile Broadband (MBB) users that share the LTE infrastructure with the Smart Grid traffic.

Two traffic types are considered: a constant traffic, which simulates a video streaming, with a datarate of 100 Kbps, and a VoIP traffic, which consists of a burst traffic of 172B data packets with random burst and sleep duration. The position where the generic LTE users are located around the LTE base station is selected randomly by OMNeT++, as well as the instant when traffic starts.

Because of the randomness of the scenarios, each simulation is repeated 10 times with different constant seeds of the pseudo random number generator (PRNG) to get more accurate results.

The scenarios will be explained as follows.

First, an ideal scenario with no background traffic is analyzed. The network is considered as operated both in meshed and radial network configuration, in order to demonstrate the efficiency of the control logic in the management of the network in short circuit conditions, according to the dataflow of the control system proposed by the authors. Secondly, the background data traffic is increased by increasing the number of LTE users connected to the Network, and considering from 10 to 30 users per cell contemporarily active in downlink traffic during the short circuit event. Performances in terms of coverage and latencies are analyzed.

In all scenarios, the synchronization time step between OMNeT++ and PowerFactory is set to 1 ms, meanwhile 0.1 ms is assumed as integration step size within the PowerFactory electromagnetic transient solver. It means that the simulations performed with these settings can generate a synchronization error up to 0.9 ms, which can nonetheless be considered as an acceptable error if compared to communication and breaker intervention latencies, as it will be shown in the next subsections.

5.3.1 First Scenario: ideal radio channel – meshed network.

The first scenario analyzed considers a closed loop network operation. It means that the network is operated with the switches at the substations 69 and

88 normally closed. Therefore, the short circuit between 66 and 67 is fed by both HV/MV substations.

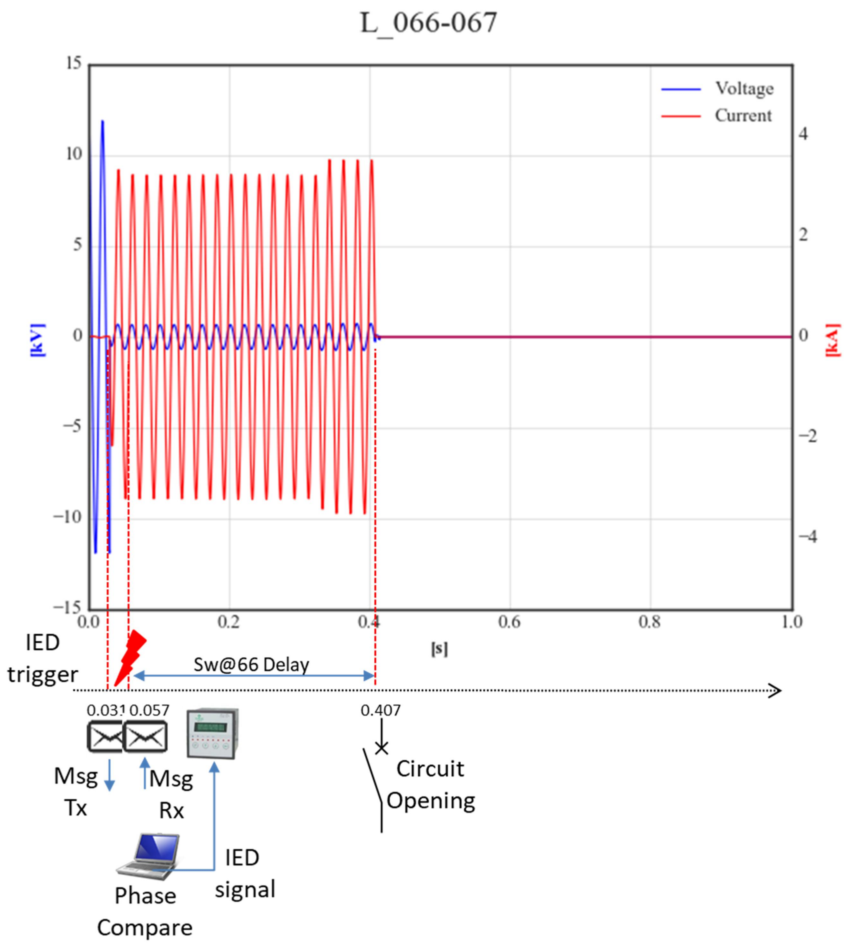


Figure 64. Voltage profile at node 66, and current profile in branch 66-67

In Figure 64 it is showed the voltage at node 66, and the current that flows in the branch between nodes 66 and 67. At 31 ms the short circuit between nodes 66 and 67 causes an overcurrent in the line. The overcurrent is detected at 31 ms by the measurement system in the smart secondary substation at node 64 that sends a message to the neighbors with current and phase measurement:

Table 18. Node 64 measurements

	Current [kA]	Phase [rad]
Infeed	1.772	2.92 (cos(φ) = -0.976)
Outfeed	-1.786	0.220 (cos(φ) = 0.976)

At 56 ms, the substation at node 64 receives the message from the preceding SSS, at 57 ms it receives the message from the following SSS.

Table 19. Node 64 received measurements

	Time Rx [ms]	Current [kA]	Phase [rad]
Preceding SSS (node 61)	56	-1.057	0.077 (cos(φ) = 0.997)
Following SSS (node 67)	57	-1.433	0.259 (cos(φ) = 0.967)

A phase comparison between the local measurements allows detecting the location of the fault. In this case the fault is localized in the branch between the nodes 64 and 67, since the cosine of the phase of nodes 66 and 67 present the same sign. Therefore, the IED activates the opening of the breaker in the outfeed of the substation. The mechanical opening of the breaker is characterized by a mechanical delay, that is randomly extracted with a Gaussian distribution (with average μ = 0.2 s and standard deviation δ = 0.05 s). In this case, the opening is completed in 377 ms, which comprises 27ms of telecommunication delay and 350 ms of mechanical delay.

In Figure 65 the sequence of messages in Node 67, along with the voltage profile at the substation and the current profile in the branch 67-68 are shown.

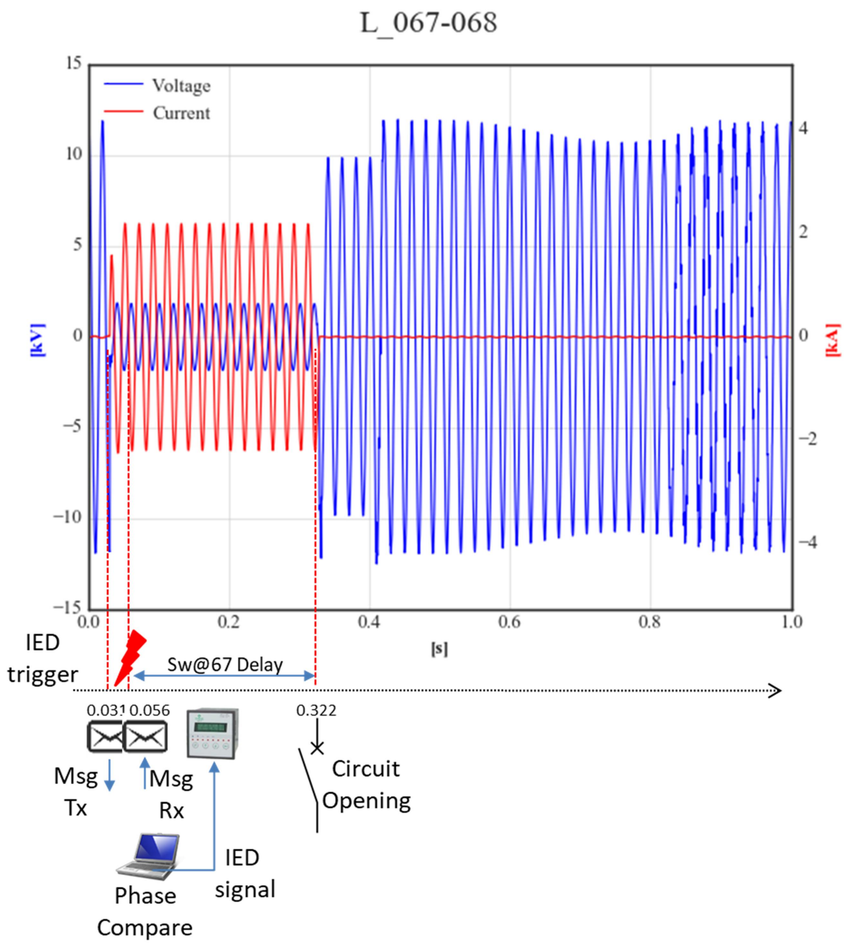


Figure 65. Voltage profile at node 67, and current profile in branch 67-68

In Figure 66 it is reported the boxplot representing the results that have been obtained in terms of delays in the communication with the neighbors during the 10 repetitions of the scenario. It can be observed that most of the communication between two neighbor SSS is completed with a median time of 30 ms delay

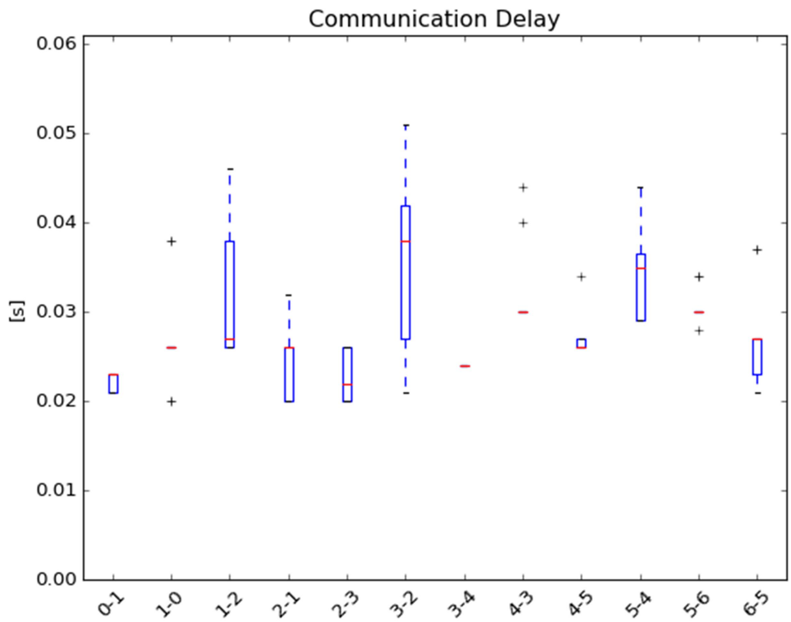


Figure 66. Statistical distribution of delays in LTE communication between SSS

5.3.2 Second Scenario: ideal radio channel – radial network

In this scenario, the emergency tie between nodes 69 and 88 is considered normally not operative. The switches at nodes 69 and 88 are in this case normally open, and the network is operated as a radial network.

Therefore, when a fault condition is detected, the emergency tie is exploited for reconfiguring the network and minimizing the network area affected by the fault.

In Figure 67 and Figure 68 the voltage and current profiles at nodes 66 and 67 are represented. In this case, since the network is operated as radial, the short circuit between nodes 66 and 67 is only fed by the substation at node 66, therefore no overcurrent is detected in the branch 67-68.

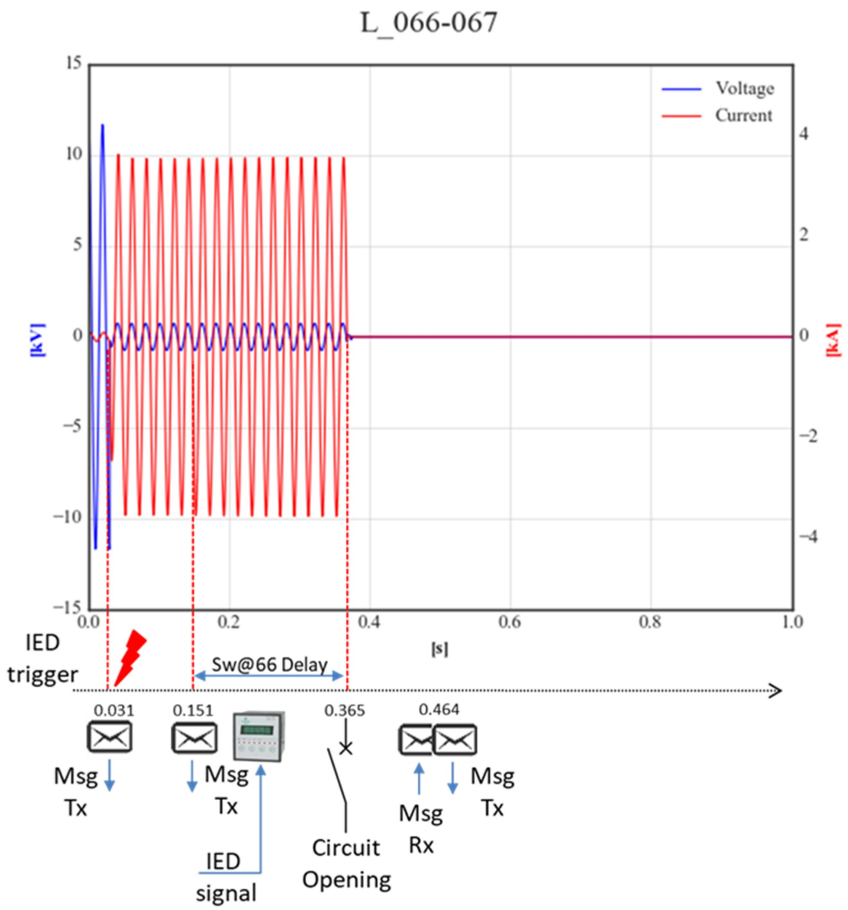


Figure 67. Voltage profile at node 66, and current profile in branch 66-67

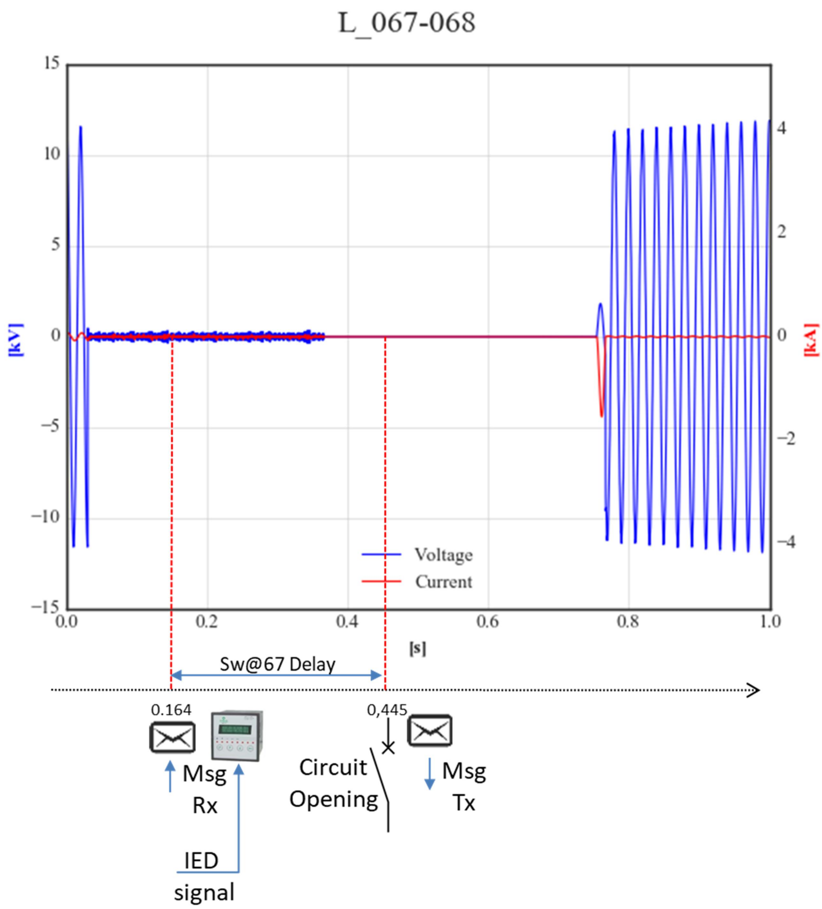


Figure 68. Voltage profile at node 67, and current profile in branch 67-68

At node 64, when 120 ms have elapsed after having detected the short circuit without any message reception from the follower node, the IED is triggered for opening the breaker and extinguishing the fault current. Since the topology is known, the reconfiguration procedure is also triggered. A message to the following SSS (node 67) is sent for opening the switch and insulating the faulted branch. The node 64 will wait for the confirmation of the switch opening, that, due to the mechanical delay in the switch, arrives with a feedback packet at 0.464 seconds. Afterwards, the node 64 sends a message to nodes 69 and 88 for triggering the closure of the terminals of the emergency tie. It allows feeding the branches that are out of service after the breakers at 66 and 67 are open.

The voltage profile at node 69 and the current profile in the branch 69-88 are represented in Figure 69.

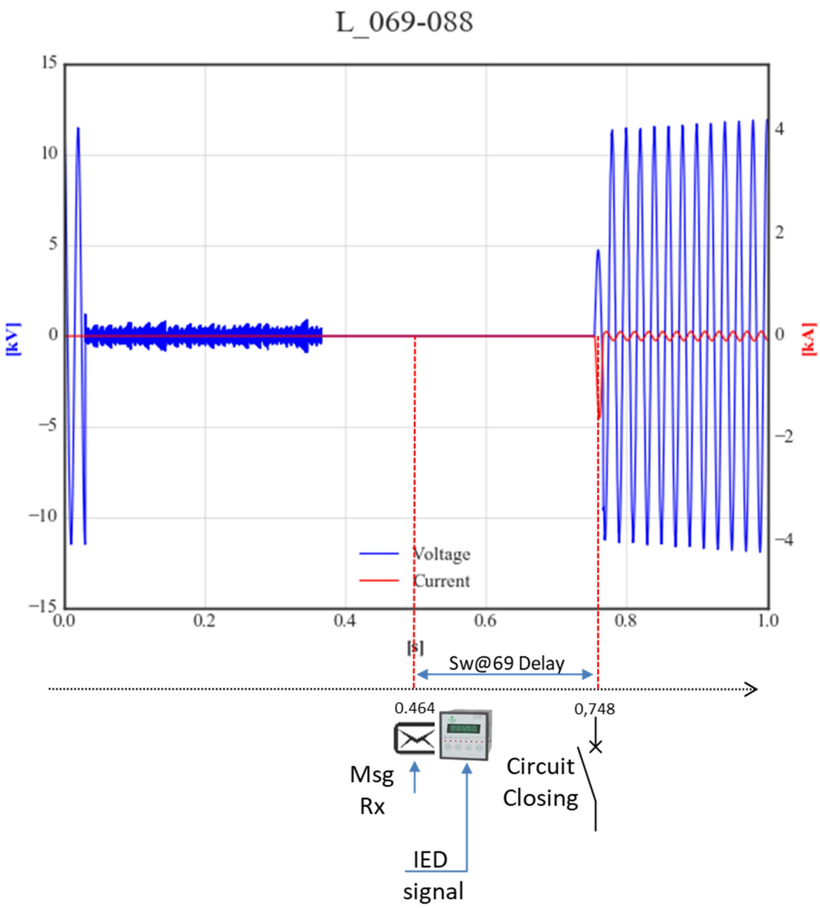


Figure 69. Voltage profile at node 69, and current profile in branch 69-88

The whole reconfiguration is performed in 717 ms. This delay is in compliance with the performances required for transient interruptions on electric networks according to the Italian Authority [109] which requires to limit under 1 second the short service interruptions.

5.3.3 Third Scenario: meshed network with background traffic

A new set of simulations were performed in the same network by considering different background conditions, in order to verify the LTE performances in realistic scenario where other users are contemporarily connected to the same communication network.

The first scenario considers a variable number of generic Mobile Broadband (MBB) users that are contemporarily active in the LTE network. 4 cases were considered: 0, 10, 20 and 30 MBB active users per cell.

From Figure 70, it can be noticed that the system shows good performances in terms of delays and coverage with 10 active users per cell. 10 users per cell are currently considered a figure that well describes the current LTE usage in a dense urban scenario with optimal exploitation of LTE network [110]. A situation of overcharging of the LTE network is analyzed with 20 active users per cell: the simulation shows a reduction in the total coverage, which decreases to a figure of 90%, and a slight increase of the transmission delay of the packets between the substations. The coverage further decreases in the scenario with 30 users per cell, that clearly shows the congestion of the network and the poor performances of the UDP protocol in terms of packet loss. In the simulation a slight improvement in the average communication delay is also observed in this scenario, due to the reduction of the users served by the LTE network.

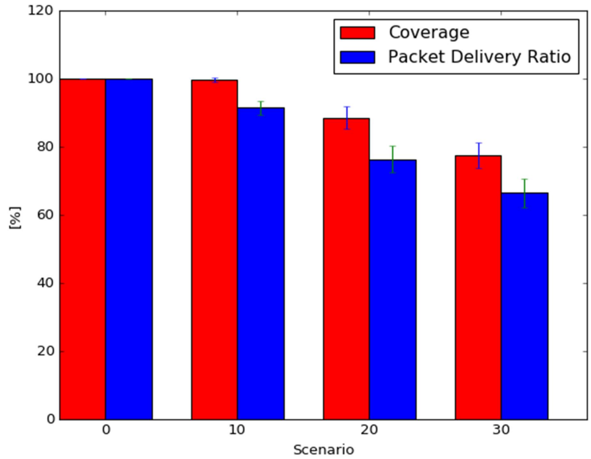


Figure 70. Coverage and Packet Delivery Ratio in background traffic scenario

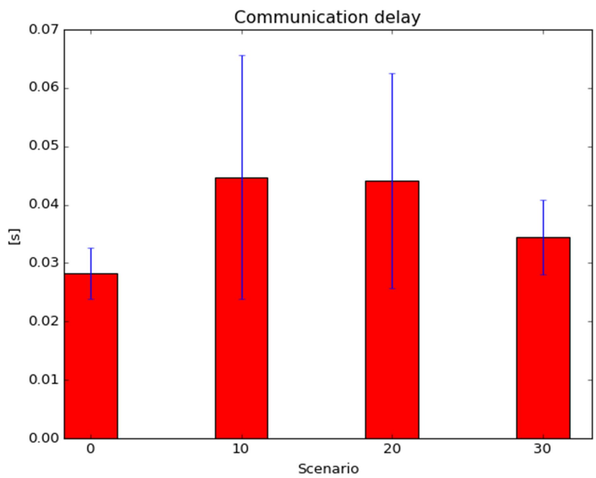


Figure 71. Communication delay in background traffic scenario

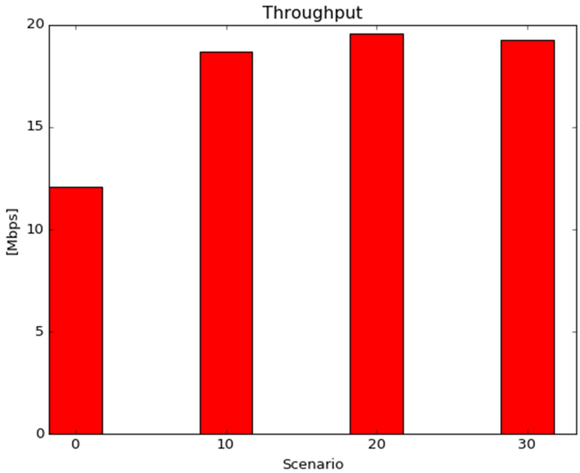


Figure 72. Network throughput in background traffic scenario

In the scenario with 30 users, the low coverage causes some difficulties in the optimal management of the short circuit condition. More in details, some of the 10 repetitions in the simulations of the scenario were characterized by the node 64, assigned to the extinguishment of the short circuit in the ideal scenario, being out of coverage.

In this case node 61, since it doesn't receive any message from node 64, triggers the IED in order to open the breaker. This scenario causes a larger area of the network that is out of service due to the reduction in the performances of communication between the SSS. LTE reveal to underperform when a large number of users are contemporarily connected to the network, nevertheless the algorithm demonstrates to be robust in this case, since it finds a non-optimal solution that manages short circuit conditions also in a congested communication network. In Figure 73 and Figure 74 the voltage and current profiles in nodes 61, 67, and branches 61-62 and 67-68 are presented.

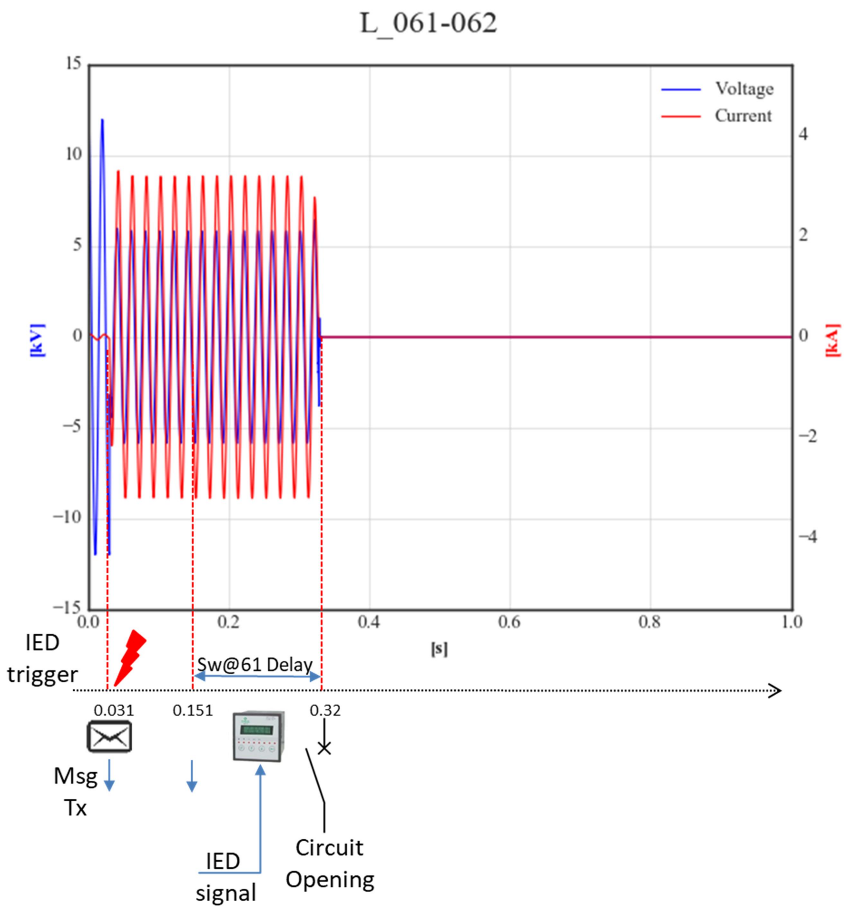


Figure 73. Voltage profile at node 61, and current profile in branch 61-62, scenario 30 nodes per cell

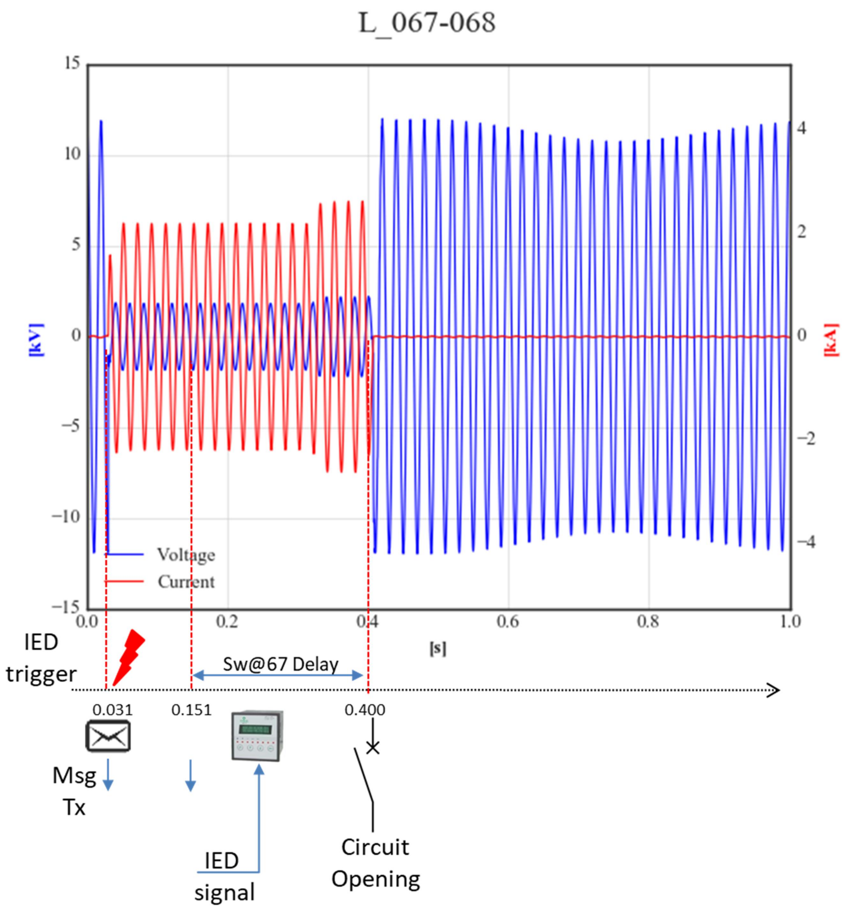


Figure 74. Voltage profile at node 67, and current profile in branch 67-68, scenario 30 nodes per cell

In synthesis, the simulations highlight the potential of LTE as a technology for implementing the communication layer in a smart grid, where the protection function is committed to a decentralized management scheme. The results demonstrate that LTE provides good performances in terms of latencies in the ideal scenario, where no background traffic is considered. The delays obtained in the simulations show that the fault extinction is accomplished in a short time window, taking also into account the mechanical delay of the breakers, both in radial and meshed operation of the distribution network.

The other scenarios analyzed reveal that the performances of LTE decrease when the LTE network is shared with other data traffic, such as in case of mobile broadband applications. In this case, the results show that the performance of LTE network is consistent with the limits for highly time-critical MBB applications, such as VoIP traffic [111] when the network is charged with 10 active users per cell, while they decrease substantially when the LTE network is overcharged. In the most unfavorable scenario analyzed, the simulation indicates that the decentralized protection scheme implemented is able to perform the operation of the electrical network for the fault management, although the area disconnected by the service may be larger than the optimum selectivity.

5.3.4 Concluding remarks on fast dynamic simulation study

In conclusion, the simulation demonstrates that the LTE technology is a strong candidate for operating as communication layer for the smart grid. A proper design of the communication network is necessary in order to avoid possible congestions that can cause a lowering in the performances, especially when time critical intervention of network operation are required, such as in case of fault management. A possible solution for preventing performances reduction may be the arrangement of special LTE bands purposely dedicated for smart grid operation, in order to limit the inter-cell and intra-cell disturbances and achieve an optimal utilization of LTE bandwidth for smart grids applications.

6. CONCLUSIONS

The design of next generation smart electricity grids requires a tight coordination between computation, communication and control elements on the one hand, and the electrical system on the other hand. Co-simulation tools are essential in smart grid planning for evaluating the most suitable technology to deploy, and providing metrics about the communication performances and reliability. Having this in mind, during the three years doctorate period, an extensive research work has been done on developing co-simulation platforms for studying the smart grid as a cyber-physical system, where ICT system and distribution network interact with each other to reproduce the true behavior of the smart grid. Different active management techniques for smart distribution networks have been investigated considering the different options of communication technologies (e.g. WiMAX, Wi-Fi, LTE, and PLC). A set of case studies are investigated, where smart grid operation scenarios are analyzed, showing the functionalities of the software tool developed. The case studies refer to DER dispatching for solving network contingencies (slow dynamics phenomena), and fault management and subsequent network reconfigurations (fast dynamics phenomena).

Several co-simulation platforms have been developed.

The first one, COSIM1.0, is purposely developed for analyzing the slow dynamic operation of Smart Distribution Networks and comprises OpenDSS as power system simulator, whereas ns-2 is employed as discrete event simulator for the communication system. An improved variant of this version of co-simulation software, COSIM1.1, adopts ns-3 in place of ns-2, for exploiting a wider and newer range of communication technologies and describe complex modular networks.

The newest version of the software, COSIM2.0, oriented on fast dynamic operation, permits simulating electrical and ICT systems with DIgSILENT PowerFactory and OMNeT++, respectively. This co-simulator takes advantage of the characteristics of the main software components, exploiting on one side the electromagnetic transient analysis capabilities of PowerFactory, and, on the other side, the wide choice of libraries for communication systems analysis that are offered in the OMNeT++ open source environment.

The co-simulation tools developed during this Ph.D. study allow analyzing smart grid management applications with different combinations of wireless and wired communication systems, emphasizing the potential impact of latencies, background traffic, interferences and reliability of communication systems on the active management of smart distribution networks, as testified by the results presented also in several papers presented at top rank international conferences and/or published on peer review journals with high impact factor.

Future research work on this field should focus on the integration of the co-simulation tool in an actual physical test-bed. Interfacing the co-simulation software tool with digital real-time simulators and physical components (such as PMUs, 61850 compliant devices, etc.) will allow validating the results obtained with the co-simulators as well as reproduce active management strategies implemented on a real-time environment, and testing the feasibility of the smart grid optimization methodologies proposed.

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8. LIST OF PUBLICATIONS OF MICHELE GARAU

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