POLITECNICO DI TORINO
Dipartimento Energia

Warsaw University of Technology
FACULTY OF ELECTRICAL ENGINEERING

M.Sc. Thesis

Academic year 2017/2018

The use of smart transformer in the presence of dispersed generation

Andrea Trentini

Polish supervisor:

Dr Inż. Łukasz Rosłaniec

Italian supervisors:

Professor Iustin Radu Bojoi

Professoressa Angela Russo

Acknowledgements

Firstly, I would like to express my deepest gratitude to my family, relatives and closest friends which always have supported me during my whole university and school career. If I reach this point, writing down this thesis, it is thank to them, which have never let me to give up, even in the hardest moments.

Secondly, I am grateful to the teachers I have met during my pre-university studies, starting from where I was a child until old enough to choose my own destiny. Especially, I would like to thank my high school "IIS Giacomo Floriani" in general and in particular its address of IT technology. This school and its teachers made me develop a passion for the electrical subject, convincing me that the choice I made was the right one. Besides, by means of some school trips and exchange programs I opened my mind and found out many aspects about the world outside my little village.

In addition, it is necessary to mention my bachelor degree in Industrial Engineering in Università degli studi di Trento. I attended lots of mechanical courses and subjects about materials. After three years of studies and the graduation I realised that this was not my path, so I changed my career choosing the Master of Science in Electrical Engineering held by Politecnico di Torino. At this regard, I am going to acknowledge Politecnico di Torino to welcome me in this university and giving me the opportunity to study Electrical Engineering and to participate in the Erasmus program, going to the amazing city of Warsaw. Concerning this, I would like to thank professors Enrico Carpaneto who managed my admission in the course, Gian Mario Pellegrino who helped me during my mobility, Iustin Radu Bojoi and Angela Russo as my supervisors of Politecnico di Torino for this thesis.

Therefore, I am grateful to Warsaw University of Technology and the city of Warsaw to have host me for almost one year in a wonderful environment full of multi-cultural aspects and diversity from what I was used to. I faced on other ways of organisation, teaching and studying, adapting myself in another system completely different from the Italian one in order to accomplish my goals. In particular, I would like to thank dr inż. Łukasz Rosłaniec being my thesis coordinator and proposing me this really interesting topic.

Finally, last but absolutely not the least, I want to express my sincere gratitude to all my friends and amazing people I have met in my path, from my childhood, schools and university to the ones met during the Erasmus.

Contents

Abstracts

High penetration of distributed energy sources in distribution network, in particular wind generation, photovoltaic systems, small cogeneration power plants (units based on the combination of the production of heat and power) causes radical change in the classic interpretation of the electricity grid. Despite the various advantages due to this development of dispersed generation, one of the main driving force which constrain the distribution system to evolve is the possibility to obtain bidirectional power flow caused by changing profiles of loads and generations. Therefore, this increasing role of decentralised generation may influence electrical system performances and cause severe problems such as over and under voltages, overloads and high energy losses. For this reason advanced microgrids and especially smart grids are used in modern energy systems to integrate these technologies with energy storage systems, communication network and in particular with smart transformer devices. Smart grids increase total efficiency of the network, reducing losses and costs, being able to monitoring, communicating and analysing every possible aspect of the grid.

One of the main components of a smart grid is the smart transformer: it consists of a transformer based on power electronic devices provided with efficient control and communication systems. In particular it allows the electrical separation of low voltage and medium voltage grids as they act independently. In this way it is possible to allow bidirectional power flows and improving the electric power quality of the system filtering and mitigating disturbances such as flicker, sags and harmonics flowing from one side to another of the smart transformer.

1. Introduction

This thesis deals with the influence of distributed energy sources on the distribution network and the employment of various smart transformer topologies in order to manage the problems introduced by this kind of generation. After a brief introduction of electric power quality (EPQ) and transmission and distribution networks it will be discussed the concept of dispersed generation in general, its advantages and disadvantages and its impact on electric power quality and on distribution network. Then, the concepts of microgrid and smart grid will be introduced, following with the aspect of smart transformer, its characteristics and advantages on the distribution network.

Different topologies of smart transformer, or devices which can be classified as smart transformer, will be analysed, describing their features and influence on electrical networks.

Technically, the aim of this thesis is to show the possibility to change a conventional transformer interfacing medium and low voltage network into a smart device which gives the possibility to control and respond to the modifications introduced in the system (especially on the voltage level) by dispersed generation.

2. Electric Power Quality (EPQ)

First of all, to properly understand the concept of electric power quality and dispersed generation it is necessary to introduce the concept of transmission and distribution system.

2.1. Transmission and distribution system

The electricity is produced in generating stations (principally still based on fossil fuels) at a value of tens kilovolts and then, by means of some step-up transformers, the voltage is increased from 44kV up to 765kV. Once the power is flowing in the system the electricity coming from different power plants is combined into the transmission network and immediately used by the customer which can be high voltage users (industrial power plants and factories) or flowing to the distribution network, passing firstly through an electrical substation and serving medium/low voltage users (industrial and city customers). [1] [2] [3]

The majority of transmission lines operate in three phase alternate current, sometimes single phase is used to feed railway system. High voltages are used to minimise the losses due to the flowing of the current, in fact, increasing the voltage, keeping the same power flow $V \cdot I$, it means a reduction of current which leads to a square decrease of power losses for the Joule's law ($P = I^2 \cdot R$). Besides, the most common ways to carry the electric power are through the overhead lines or underground power cables.

Overhead lines allow the current transmission by means of non insulated conductors based on copper or aluminium. Although copper is more refined than aluminium alloy, this last material is more common because it is lighter (so easier to sustain by the steel poles) and especially less expensive; the conductor consists of many strands and it is possible to reinforce it with steel strands as well. For these reasons aluminium alloy is the most used conductor material for overhead lines. It is also possible to encounter bundle conductors when the need of current is higher than the current capacitance of the single conductor, in this way it is possible to increase the current capacitance of the line and reduce the power losses caused by corona discharge.

On the other hand, underground transmission is characterised by higher costs of installation due to the excavation and the cable which has to be well insulated and shielded. There are also some operational limitations but the maintenance costs are lower than overhead lines, the cables are not visible and much less affected by the weather conditions, as they are buried underground. One of the main use of underground transmission is in urban areas where there

is no space for an overhead transmission or locations sensitive from an environmental point of view where overhead lines would badly affect the landscape and natural habitat.
Nowadays, the level of high voltage considered in the transmission network is 110kV or more (above 765 kV become extra high voltage), while lower voltage levels (like 66kV or 33kV) are considered sub transmission voltages.
Moreover, it is possible to find transmission lines which operate with HVDC (High Voltage Direct Current) technology: this method is used to reach high efficiency on long distances (in submarine cables as well) and in particular between areas which are not synchronised. [3] [4]
After all these consideration it has to be known that the main feature of transmission system is the closed loops operation, in this way it is possible to reduce the number of stand-alone plants required, because each station works at the same time, even in case of faults or emergency in others connected to the network. Another advantage of the closed-loop operation consists of the fact that when light loads are present one or some stations or generators may be turned off, improving the operational economy of the whole power plant and network in general. [2] [5]

Nevertheless, the concept of dispersed generation is strictly connected with the distribution network. This network consists of the last point of the electricity distribution, which connects the transmission network to each customer (on medium and low voltage side). One of the main characteristics of the distribution network is that, in opposite to the transmission network, it cannot operate in closed loop configuration, in order to guarantee the safety of the customers being sure of the network opening in case of malfunction or problems of any type. In some cases, as it will be soon explained, it is possible to obtain a closed loop operation for a short time, especially in services which need a continuity of the electrical supply, such as hospitals and servers.

It is possible to identify two types of distribution network: radial or radial with parallel circuits network. A distribution system is defined as radial when each customer is supplied by just one source, like tree where the trunk represent the source and the branches the users connected to it. It is possible to implement this kind of network adding some emergency connections to change the configuration of the system in case of complications (i.e. works on the lines, faults, etc). This operation is possible by means of some switches, and just in this case it may be acceptable to have a configuration in closed loop in a distribution network lasting for a short time. On the other hand, a radial with parallel circuits network system works by means of several sources operating in parallel. This last type of distribution system is used in the presence of concentrated loads, while the radial one is common in suburban and rural areas.

Moreover, distribution network can be classified in two different type of system, basing on the voltage level in each: primary and secondary distribution.
Primary distribution consists of the connection between the transmission system (ending with a step down transformer) with the beginning of the secondary distribution, where is located a secondary substation in which the medium voltage is decreased again in low voltage to be suitable for the final users of the electric system. The voltage range of this primary distribution is 4 kV – 35 kV phase to phase and only large user (such as factories and industrial customers) are supplied directly from this type of network.
Secondary distribution is obtained lowering the voltage at a level suitable for the end users of the electric network (household appliances, industrial customers, etc). The electricity is delivered in most of the world at a frequency of 50 Hz, a root means square voltage value of 220/230V in single phase and of 400V in three phase configuration, while just in some areas and countries (such as USA) the frequency used is 60 Hz and voltage rms value 120/240V. The distribution occurs by means of four wires: adding to the three phase a neutral wire it is possible to obtain both configuration of single and three phases suitable for each customer. Furthermore, the connections on the utility service and on the customers have to be grounded in a specific way (TT, TN, IT) in order to protect the users in case of high short circuit currents caused by possible faults and to prevent damages to the distribution network due to extreme voltage drops in the end line. [2] [5] [6] [7]

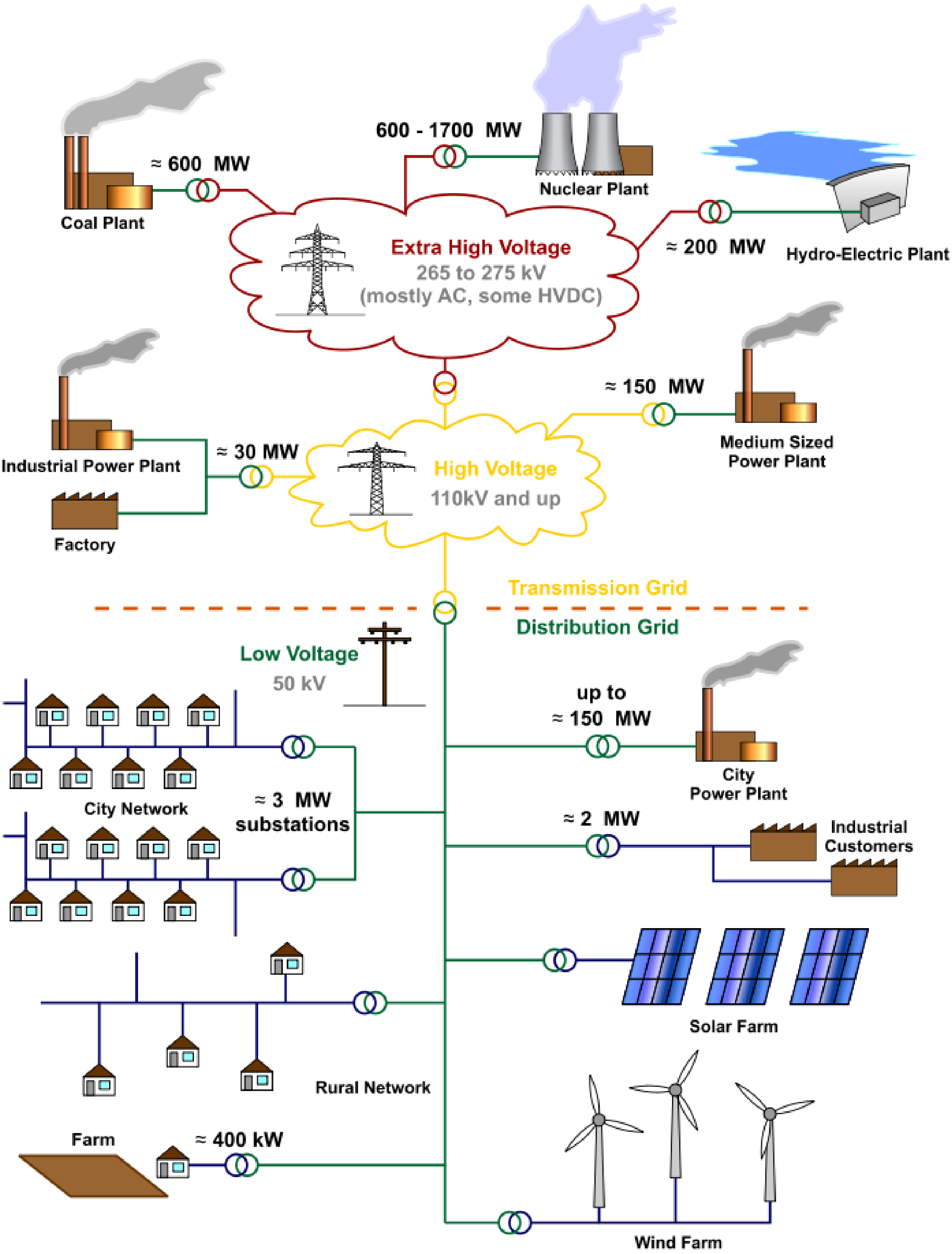

Figure 1. Example of an entire energy system, starting from the production, going through the transmission grid and focusing on the distribution network where the dispersed generation (wind and solar farm in this case) is connected. [6] [6] [6]

2.2. Electric Power Quality parameters

Electric power quality (EPQ) is defined as a set of electrical boundaries that allows all the equipment present in the power system to function in its intended manner without significant loss of performance or life expectancy, in other words the power quality is equal to the degree of how the power features and characteristics of the network line up with the ideal cases of voltage and current waveforms. [1]

The power quality is characterised by a number of parameters which define the quality of the electrical energy of the entire network and, at a normal operation of the power system, they have to satisfy existing requests. The first parameters group of EPQ is represented by the voltage frequency in network supplying, in particular the main index is frequency deviation.

The second group of EPQ parameters is defined by the network voltage, which its main indexes are voltage deviations and their oscillations, harmonics, unbalances, dips and many more. [8]

Power quality issues, such as overvoltages, undervoltages, sags, swells, notches, spikes, interruptions (shown in Table 1), voltage unbalances, flickers, harmonics, dc components in ac networks and frequency fluctuations can directly damage components of the electric power system. [1]

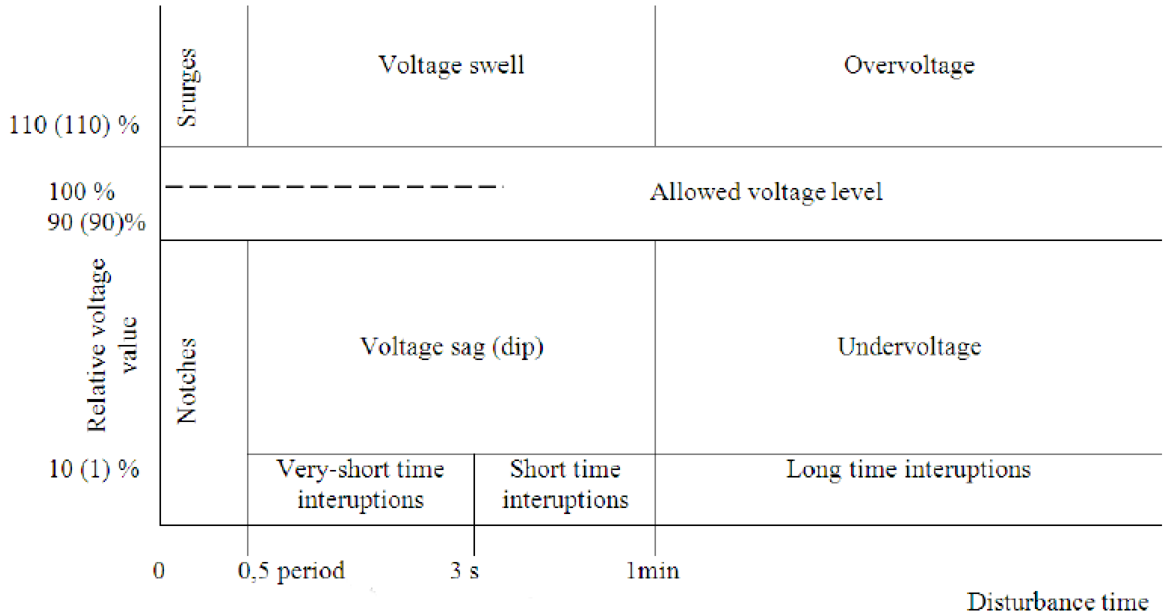

Table 1. An overview of the classification of different voltage disturbances on electric network based on level of voltage deviation and disturbance time duration. [1]

Electric power quality levels considered acceptable in Europe are determined by standards, other neighbouring countries and European power supply companies. In case of emergency and post-fault conditions, associated with unforeseen conditions (fires, explosions, etc) and natural disasters (earthquakes, hurricanes, avalanches, etc) these standards and norms are not applied.

As already discussed EPQ defines a set of parameters which describe a consumer power supply and its ability to accurately operate under certain supplying conditions. For this reason a proper monitoring system has to be employed and implemented in order to control potential equipment malfunction due to a not correct supplying.

One of the most common causes of the highest harmonics are converters, which usually transform voltage and frequency (50 Hz) to other values in function of the load connected. It is possible to find high and low voltage converters used in a few applications such as electric arc furnaces, all kinds of welding aggregates, adjustable and not adjustable valve electric drives, aggregates for electrolyses, discharge lamps employed for illumination purposes and many more. Consequently, in these cases the spectrum of the harmonics current generated in the network is wide and the operation of fast varying and unstable loads cause voltage oscillation in the whole system.

Voltage asymmetry, on the other hand, is mainly caused by unbalanced operation conditions of the three phase power network. These unbalanced conditions include irregular loading of the system, in fact it is possible to notice voltage asymmetry in proper devices which work in specific modes, such as, also in this case, electric arc furnaces. Besides, this kind of issue concerning the electric power quality may be also caused by a difference in the phase impedances of the power system. [1] [8]

3. Dispersed generation

Firstly, it has to be marked that dispersed generation is also known as distributed generation, distributed energy resources, distributed energy sources, on-site generation, embedded generation, decentralised generation and decentralised energy sources. [2]

Dispersed generation is defined as a set of small scale (up to 10 – 150 MW) generation units, or technologies in general, connected to medium voltage (MV) and low voltage (LV) distribution network in order to produce electricity close to the end users of power. These technologies are often modular, also renewable and spread among the territory, therefore it is possible to obtain several benefits to the network and power system. [2] [9].

Few years ago this concept of distributed generation was considered as an innovation idea, nowadays is much more common and renewable energies are one of the fixed point to improve as to reduce the greenhouse effect and basing the electric network on a clean source. Actually, the idea behind the concept of dispersed generation is not new at all, in fact, in the early days of the electricity, on-site generation was an embedded feature of the network. Power plants were spread throughout the territory and the electric customers were supplied by each power plant nearby. At first, the voltage supplied was limited because it was DC based and it was difficult to cover long distances between the plants and the consumers. To sort this out, local storages were used but later, with the arrival of alternate current and transformers, it has been possible to reach longer distances and higher powers, also because of the economies of the scale in electricity. As a result, the electric system increased, basing on large-scale power pants interconnected by means of transmission and radial distribution grid. The balance of demand and supply was achieved performing an average of the continuous and instantaneous change of the large amounts of loads. Despite the convenience of settling a large-scale power system, in these last years (since the 21st century) the changes in the economy, environmental regulations and technological innovations as well lead to a renewed interest in distributed generation. [9]

In dispersed generation highly efficient energy sources are used, providing lower cost electricity and capital investment, higher power reliability and security; for example decreasing the vulnerability of the electric system it is possible to prevent damages caused by extreme weather conditions and terrorist attacks. Besides, dispersed generation is characterised by few environmental consequences than traditional power generators, in fact the pollution produced (greenhouse gas) is lower. [2] [9]

3.1. Decentralisation: advantages and disadvantages

An example of electricity network still based on centralised and large-scale power plants, using mostly fossil fuel like coal, oil and nuclear generation is the American one. This system has many disadvantages, such as problems about the transmission system: being a centralised power plant it requires an enormous transmission and distribution network characterised by long distances to cover with cables and lines. In this way the power losses are high and it is expensive to create such a network, creating also concerns on environmentally sensitive locations. Moreover, as already said, a centralised generation involves environmental problems such as a massive pollution, releasing greenhouse gasses in the atmosphere and nuclear waste in case of nuclear power plants. [10]

Therefore, concerning IEA (International Energy Agency) this renewed interest in distributed generation can be explained by five factors: peak shaving, electric power quality, use of the local network, grid support and environmental aspects which can be grouped under two main reasons: electricity market liberalisation and environmental concerns.

A) Electricity market liberalisation:

Distributed generation can be seen as a tool which can let suppliers and customers, basing on their need, to look for and often find the most suitable electricity service. This kind of generation also allows the users and suppliers involved in the electricity sector to adapt their system on changes in the market conditions; this adaption and flexibility are extremely important in liberalised markets as to achieve the best suited configuration of the network. [9]

This flexibility is achieved by the modular system of the embedded generation: in this way it is possible to provide power in the established location when it is needed. [11] The modular generation is characterised by small size power plants which means an easier and faster possibility to build distributed energy sources than a large scale generation unit. [9]

Moreover, this feature of flexibility leads to a fast responding of the plants to demand variations. For example, a small scale modular generation units consists of photovoltaic panels: various units can work as stand-alone or integrated to the grid. Anyway, users which have installed a photovoltaic power plant result to contribute more in the power grid than take out, this leads to an advantage for both users and suppliers. [10] [12]

1) Peak shaving or peak use capacity or standby capacity:

As partially already said, flexibility can be reached in several aspects: size, operation and expandability which leads to a flexible reaction to the evolutions of the electricity price. Thus, this use of embedded generation soften the price fluctuations, for this reason distributed energy sources are used in particular in continuous or peaking mode (peak shaving), especially in the US. On the other hand, in Europe the marked request concerning dispersed generation is driven by heating demand (by means of cogeneration) and still improving, introducing more efficient renewable energy technologies. [9]

2) Electric power quality and reliability:

Dispersed generator contributes to reduce power imbalance and power transfers between each region, through its flexibility it is possible to respond in a fast way to demand variations and provide reliability and stability to the network. [12]

Reliability problems are referred to interruptions of the network, leading to a disconnection (or a heavy drop of the voltage close to zero) of the customers and suppliers.

European electricity reliability has improved reaching a high level, although some black-outs occurred during last years. Electricity market liberalisation makes the users aware of the importance of the reliability of the electrical service. A high level of reliability involves high capital and operational expenditures (which can be considered as initial investments and maintenance costs), in order to obtain a proper generation infrastructure and network. It can be thought that a competition on prices can lead to a decrease in the reliability but it is too important to be undervalued; many industry sectors (such as metal, telecommunications, paper, petroleum, refining, etc) need a proper working of the electricity service and it can happen that in case of a too low reliability level they can decide to invest capitals in this on-site generations, improving the efficiency of electricity supply and services.

Apart from reliability problems it is possible to have voltage deviations which can affect electric power quality. This aspect will be analyse in the following chapter but it is known that power quality is referred to how each characteristic of sinusoidal shape of voltage and current waveforms differ from the ideal ones. These voltage deviations can be caused by faults, switching operations, disturbances from loads and can result in phase imbalances, harmonics, voltage flicker and dips, interruptions and transient states. The presence of dispersed generation in the grid can improve this aspect and the electric power quality in general.

3) Use of the local network (alternative to expansion):

Changing large scale power plants with many small scale generation units means substituting (or bypassing) the costs of a large transmission and distribution network with dispersed generation. This can be achieved only if fuels are available in the desired location in sufficient quantities, in this way it is also possible to avoid the problem of long transportations of fuels to the large power unit.

4) Grid support

Moreover, distributed energy sources support ancillary services, in particular the ones to maintain a suitable operation and stability of the grid. This support may consist of the ability to instantly generate active power as to stabilise the frequency drop due to a lack in generation or and exceed in customers demand. Reactive power can be generated on demand as well to adjust problems related to the voltage.

B) Environmental concerns:

The research of clean energy solutions makes the environmental policies the major factor for the demand of on-site generation, at least in Europe. In this way, looking for clean energy solutions (renewable energy sources) means basically searching for dispersed generation, as renewable generations are characterised by a decentralised nature, except off-shore wind farms and hydro power plants.

A particular feature, and one of the most common solutions concerning dispersed generation, consists of the optimization of energy and heat transmission: the cogeneration units. By means of this technology it is possible to combine electricity and heat generations, which also makes more sense than having them separately. Cogeneration, also known as CHP (Combined Heat and Power), is one of the most efficiency distributed energy sources and the emission avoided by the combination of these two generations it can be already considered energy saved. [9]

Moreover, with dispersed generation it is possible to exploit cheap fuels like landfills gasses and biomass and because of this (and the use of renewable resources) pollution is reduced as the noise compared to big power plants. These facts make distributed energy sources more suitable for on-site installation. [11][13] However, public resistance to the construction of wind farms and the use of biomass may be strong.

To sum up this section it is possible to observe that in contrast of using few large-scale power plants located far from load centres distributed generation exploit small and many small-scale power plants which provide electricity on site and close to load centres. [10]

Liberalising the electricity market the cost of electricity decreases, while reliability and power quality increase as many consumers switch to distributed generation to be protected against power outages (voltage drops said before). [12]

Nevertheless, each plant of distributed generation is characterised by a level of power equal to 10 – 150 MW, while a large scale power plant often reach beyond 1 GW, thus it has to be designed a proper power network in order to satisfying the needing of the customers considering the difference level of output powers. [10]

3.2. Types of dispersed generation:

Many types of sources can be used for dispersed generation, renewable and fossil fuel based, such as gas turbines, combustion engine, wind turbines, fuel cell, photovoltaic system and many others less common but which can be considered as well.

In this thesis it will be talked always about distributed energy sources in general but it has to be known that when renewable energy sources are used it is possible to talk about "Renewable Distributed Generation" (RDG). [14]

4. Influence of Dispersed Generation on Electric Power Quality

Distributed energy sources interconnected with distribution network are continuously increasing thanks to the electricity market liberalisation and advanced developments in technologies of energy generation and distribution. Benefits that dispersed generation offers, public regulations and economic opportunities promote the spread of these units throughout the distribution network and the world.

However, this expansion of distributed generation is rising problems such as voltage regulation, coordination of network protection, detection of losses and disturbances on distribution network. Obviously, in order to have a normal working of the network, exploiting opportunities of distributed generation technologies, it is necessary to solve these problems quickly and the utility network has to guarantee, maintain and improving continuity supply of the electricity and a suitable electric power quality delivered to the end users of the network. [15]

In particular, the diffusion of renewable energy sources like photovoltaic (PV), wind generators and other distributed resources like cogeneration power plants can modify the normal interpretation of the electricity grid. Variable load and generation cause power flow varying in amount and in direction as well; operation in medium or low voltage can affect distribution networks with different types of disturbances. Inverse impact of connection of power units to medium and low voltage grids can be minimised and power quality improved choosing optimal connection points of dispersed generation with the distribution network. [9][16][17]

Connection point of dispersed generation to the distribution network is the main force which drives the overall costs. In general terms, connection cost is higher for higher voltage level of energy introduced in the grid but the impact of generation on local network performances is lower (especially in terms of power quality and steady state waveforms). On the other hand, connection at lower voltage levels makes the realisation of generation project, and people working on distributed resources more secure. Therefore, an appropriate compromise has to be found and it requires an opportune economical and technical analysis among these two aspects. [18]

In this chapter some aspects of dispersed generation impact on the electric power quality and on other characteristics of the electric system are taken into account.

4.1. Impact on distribution network

Distribution network can be affected by stability and security issue. Taking into account the interconnection of dispersed generation when a fault occurs there is the possibility of continuously supplying it from different sources and from the generator connected to the faulted feeder. Faults on distribution networks are quite common and to avoid this security issue it is necessary to disconnect the generator which supply the feeder and isolate the fault in the distribution network.

Isolating the faults and clearing it can make one or some areas of the distribution network in islanded mode. Therefore, to keep the area stable, the dispersed generator has to be equipped with a proper control and regulators to adjust voltage and frequency of the system. [19]

4.2. Impact on losses

A significant penetration of dispersed generation in distribution network affects the energy losses in the grid and involves several technical issues. Due to the energy injections from the generators energy losses increase, especially when a strong presence of dispersed generation exists. Nevertheless, location of distributed generation, load consumption profiles and generator injection profiles modify the energy flows in the grid; this makes the relationship between energy injections and losses difficult to evaluate.

In order to assess dispersed generation effects on energy losses in the distribution network several statistical approaches are used, aiming in particular to define the optimal location and size of the various generating units.

Knowledge of dispersed generation impact on losses is important for planning purposes: it is necessary to design the most suitable configuration of the grid and select the optimal structural improvements. Moreover, evaluations of losses on wide distribution networks are very important in order to estimate the behaviour of energy losses of the national network.

Energy losses analysis requires to consider the topology of the grid and time dependency of energy flows, the complexity is remarkable when a small number of distributed energy sources and networks are taken into account, therefore when a large number of units are used the losses estimation could be really difficult. Consequently, basing on losses indicators observation, simplified methods are used. The most common losses indicators are the total rated power of the dispersed generation power plants and the total energy produced by the distributed generation units for an entire year. Both method take into account the dispersed generation units connected to the network considered and the last indicator is easier and more satisfying than the previous one but it takes one year and a proper characterisation of the network and its devices to obtain the information required.

Nevertheless, various methods implementing different indicators and algorithm which do not require complex and expensive approach may be obtained. These methods can be used in order to achieve the optimal configuration of dispersed generation and the assessment of energy losses in the whole network. [20]

4.3. Impact on frequency

System frequency can be considered at the same level as a public good, in economic terms, and the grid operator has to take care of it, as any other service which it provides. Frequency deviations from the rated value (which can be 50Hz or 60 Hz as explained in paragraph 2.1) may be caused by imbalances among electricity demand and supply and have to be kept under control within very narrow margins in order to guarantee a normal functioning of the industrial and household users connected to the network. Introduction of distributed energy sources has to be planned upfront, especially when a significant amount of dispersed generators is taken into account. This is because the installation and connection of distributed generation affects the system frequency: different power sources and relatives converters or transformation principle work differently and this leads to a higher necessity of control from the grid operators in order to obtain a suitable efficiency of the electric network. [9]

4.4. Impact on voltage level

Dispersed generation and electric power quality are bounded by an ambiguous relation. On one hand distributed generation is characterised by healing effects on electric power quality such as on voltage support and power factor corrections. On the other hand, instability of the voltage profile and problems concerning voltage control may occur when a heavy use of dispersed generation is introduced in the power grid. This voltage instability may be a consequence of bidirectional power flows and complicated equilibrium of reactive power in case of weak control. Dispersed generation connected to distribution network can significantly affect the voltage level, in particular rising it in systems characterised by a radial distribution. [9]

Operations of distributed generation can cause a voltage increase up to 5% of nominal voltage in low voltage grid in case of energy sources connected to medium voltage grid or in the same area of the distribution network. So, when the network is unloaded or low loaded, voltage overvoltages can occur in medium and low voltage grids caused by the operation of dispersed generation.

Therefore, operations with distributed energy sources, especially using renewable technologies, badly affect the voltage quality and problems concerning overvoltages have to be solved. For example, significant renewable power sources, such as wind power plants, connected to the distribution network in medium voltage grid can be controlled by DNO (Distribution Network Operator) when power dispatching SCADA (Supervisory Control And Data Acquisition) can set power factor. [21]

In addition, some distributed generation units like photovoltaic panels and fuel cells produce energy in direct current form. Thus, these technologies need a DC-AC interface to be connected to the AC grid and many other units like wind turbine and microturbine have to exploit grid converters to contribute in the electricity network. These interfaces made up of power electronic devices determine an increase of voltage perturbations, contributing to higher harmonics (on voltage and current) which have to be kept under control, without exceeding standardised limits set to guarantee a proper power quality to the electricity customers. Distortions in current and voltage waveforms deteriorate the electric power quality of the electricity delivered to the end users of the network, in this way the correct operation of their system can be jeopardised. [9][15]

Finally, another dangerous condition may be encountered in a “islanding” situation. In this circumstance a part of the distribution network disconnected to the grid is kept energised by a local generator which can lead to unsafe conditions for the maintenance personnel and general users. [9]

4.5. Impact on reactive power

In distributed energy sources are often used generators which are not capable of providing reactive power. However, through a power electronic interface it is possible to deliver a component of reactive power as well. [9]

4.6. Impact on protection

Dispersed generators connected to distribution network (such as synchronous or induction generator) affect fault current changing its magnitude, direction and duration: characteristics of distribution network, in particular impedance, result modified, thus the fault current characteristics change either. For example, fault current increases when dispersed generators are connected. Consequently to this, protection selectivity devices is affected and it has to be taken into account for a proper design of the switchgear. Therefore, protection selectivity has to be checked and in need changed for each dispersed generator connected to the distribution network, in order to not disturb the correct working of protection switchgear. [19]

5. Microgrids

Microgrids are defined as electricity distribution systems made up of integrated distributed energy sources, interconnected loads and storage energy systems which operate as an unique controllable entity, feeding different low voltage loads and capable to operate grid-connected or in a stand-alone (island) mode as well. [2] [22]

This group of electric sources and loads is normally connected to the centralised macrogrid and it acts as a single unit which can be controlled by a dispersed generation governor linked with each storage system and distribution unit, by a central controller or by a load regulator. [23]

This connection between the microgrid and the main gird is possible by means of a single point of common coupling (PCC) which can be disconnected, passing from a grid-connected mode to a island-mode. [2]

Microgrids are characterised by highly reliable electric power thanks to the presence of multiple distributed resources and the ability to isolate themselves in the island-mode.

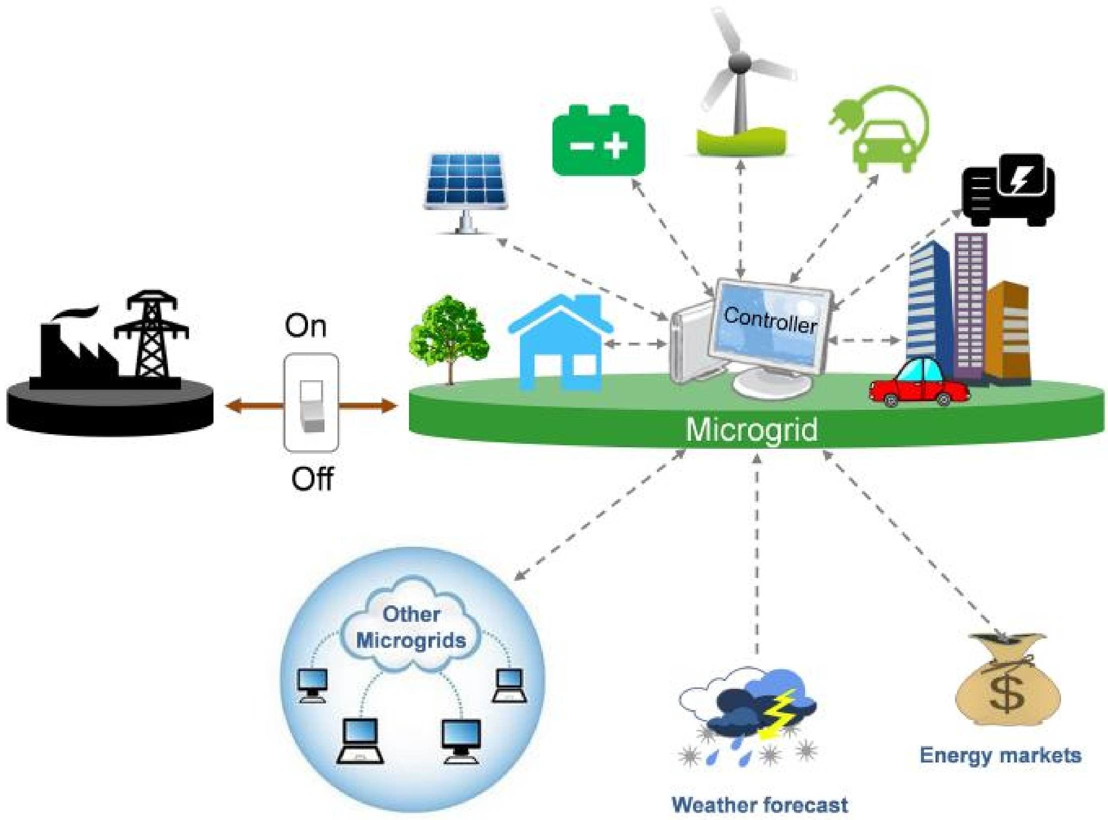

Fig. 2 An example of microgrid showing the centralised grid (represented with a power plant), point of common coupling as a switch and the actual microgrid connected to dispersed generation, low voltage users and other microgrids. [24]

As shown in Fig. 2, energy resources of microgrid generation may include solar, wind, fuel cells and other renewable or fossil energy sources, stationary storage devices, and electric or hybrid system related to transportation systems. Moreover, weather forecast and especially energy market play an important role in the control of the microgrid.

Basic microgrid architecture is shown in the following Fig. 3 and, except dispersed generation, energy storage systems and components already said, it is composed of power electronic converters, distribution lines, instruments and monitoring devices, a suitable controller for the operation control and for the whole microgrid itself (MGCC – Microgrid Central Controller). [22][23]

In addition, microgrids are composed of two buses:

- AC bus: where utility gird, ac loads and, in some cases, distributed sources as well are connected;
- DC bus: where distributed resources, dc loads, plug in devices and storage devices are connected. [22]

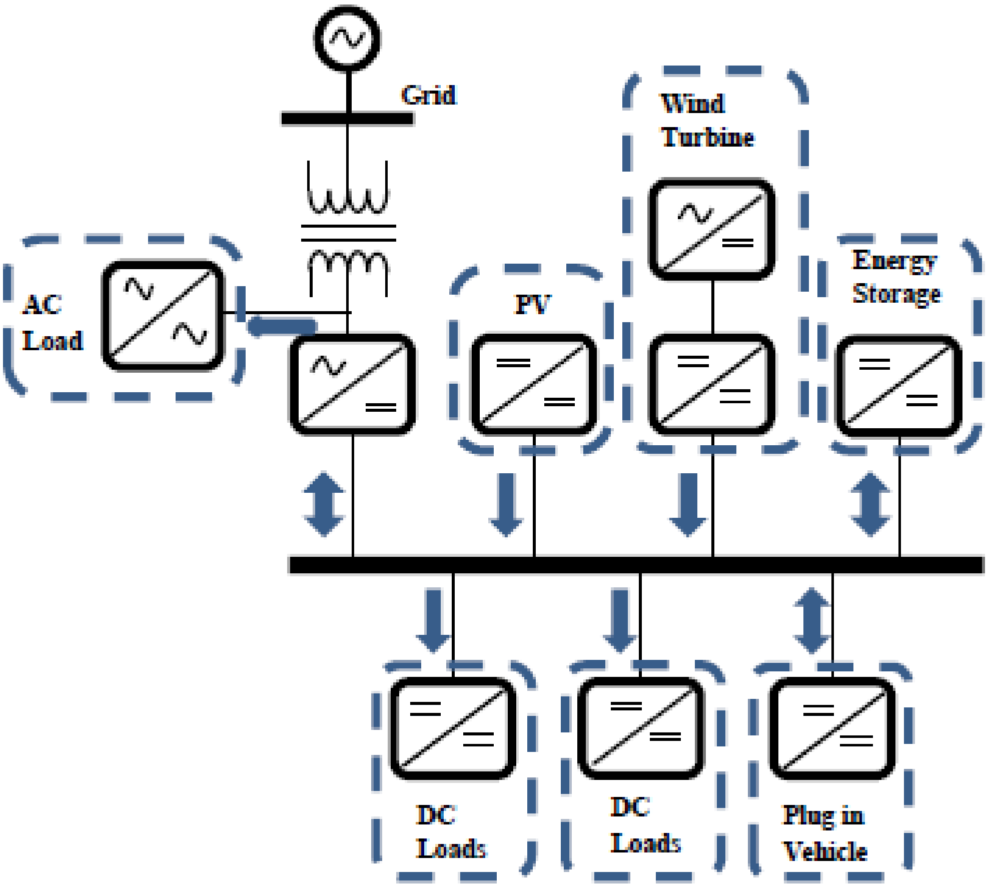

Fig 3: Basic microgrid architecture showing AC bus, DC bus and the other aspect explained in this chapter. [22]

Microgrids introduce several benefits in the distribution network such as improved transient and steady state, better energy and market strategies, superior control and environmental impact, higher reliability, efficiency and power quality also thanks to the presence of storage systems. In spite of these advantages, to reach these benefits it is necessary to design a proper plan to esteem the demand, a reliable protection tactic in order to ensure bidirectional power flow and a suitable voltage and frequency manipulation technique of power electronic devices. Therefore, to keep microgrid stable in any case (also when faults and disturbances occur) several control techniques are used. [23]

It is possible to identify three important factors which have to be taken into account for a proper working of a microgrid:

1) *Integration of dispersed generation*: operation of microgrid is improved if a successful integration of distributed resources is reached. Electric power quality improves, environmental impact decreases while reliability and efficiency of the system increase.

2) *Operation and control*: taking into consideration the double working principle of a microgrid (stand-alone or islanded mode) suitable control strategies have to be implemented in order to disconnect the microgrid from the macrogrid during abnormal and faulty conditions. In addition, power electronic converters are used to interface distributed energy sources and microgrid because the majority of power units cannot be directly connected to the microgrid due to their features. Besides, steady state, dynamic and transient stability have to be kept under control as load fluctuations in steady states lead to dynamic instability.

3) *Protection and coordination*: Protective relay devices and circuit breakers are used in microgrids in order to detect abnormal conditions and isolate the faulty location with the other part of the system. In this way it is possible to guarantee safety of users avoiding damages of the microgrid. [22]

Finally, connecting this technology to the following chapter, it is possible to say that microgrids are the basic aspect to develop smart grid networks.

6. Smart grids

Requirements on distribution power network are constantly increasing, especially the fact to counterbalance bidirectional power flow, load and voltage fluctuations caused by the heavy penetration of distributed energy sources in the electric system. [25]

Nowadays many grids and transformer substations are no longer able to manage the requirements of the progress of the power system. Consequently, always more supply breakdowns occur in the distribution network, increasing periods of inactivity. [25]

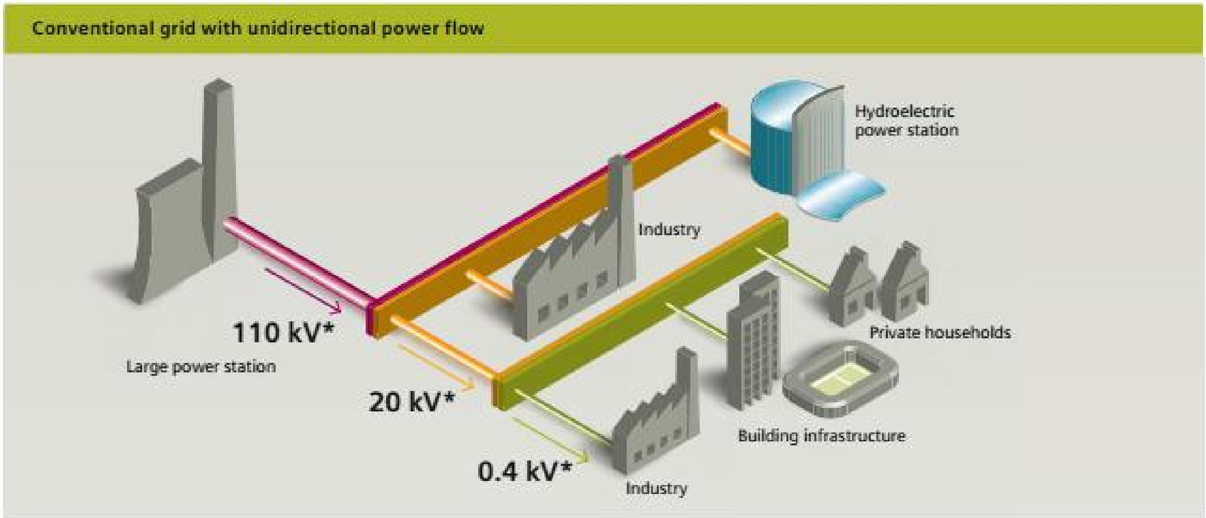

Fig.4. An example of conventional grid, passing from high voltage, through medium voltage and ending with low voltage network, characterised by their supply and customers. [25]

Therefore, a radical change in the power network is needed and it takes place with the new concept of smart gird. Technically, smart grid consists of a microgrid implemented by digital technology in order to accomplish the technical features requested by the development of distribution network. [2]

More precisely, European Union defines a smart grid as “an electricity network that can cost efficiently integrate the behaviour and actions of all users connected to it - generators, consumers and those that do both - in order to ensure economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety”.

On the other hand, DOE (US Department of Energy) performed analysis on the electric grid and concluded that smart grid would be consider such that if takes upgrades in:

- Reliability: reducing fluctuations in frequency and voltage improving electric power quality.

- Security: reducing vulnerability to attacks of any type and natural event which can jeopardise the correct working of one or more units or causing damages on the lines.
- Economy: decreasing electricity prices and giving more option and opportunities to the customers.
- Efficiency: reducing losses, maintenance and capital expenditures.
- Environmentally: having a positive impact exploiting renewable energy sources.
- Safety: protecting customer and workers.

Once all these characteristics are achieved, electric grid, services connected to it and internet will act like a single global network, allowing bidirectional power flow, increasing efficiency and electric power quality.

In particular, important technologies which permit to solve problems introduced, such as load fluctuations due to electric vehicles and ones concerning dispersed generation, consist of energy storage systems, communication and information systems and integrated platform of telecommunication. [26]

Firstly, energy storage system is a fundamental element to solve many problems connected to the variable configuration of distributed resources and electric vehicle: it is possible to implement various logics of power management and provide energy to the electric system when the request is high. Besides, in case of a frequency drop a proper energy storage can avoid the system collapse, reducing the unbalance between generation and load: releasing the energy at an established moment it is possible to maintain the load supplied and the frequency grid to the nominal value (within a tolerance range), guaranteeing stabilisation of the grid. Moreover, energy storage systems can be exploited also for voltage control purposes, especially to maintain bus-bars voltage within legal limits because of reliability, security and efficiency reasons.

Secondly, it has to be marked that the key point of a smart grid is to monitor and control as many components as possible, and this is achievable especially by means of a reliable telecommunication infrastructure system.

By means of a proper telecommunication system it is possible to allow communications between customers to the DSO (Distribution System Operator) and between this last one with the TSO (Transmission System Operator) and vice versa, enabling two-way flow communications.

Technologies adopted for this system are determined by the application, regulation and conditions (such as power transmitted, allowed frequency bands and licences) and by the local

structure of the network (taking into account distances and if it is associated to a city or a rural region).
Telecommunication systems are usually heterogeneous, achieved by optical fiber or copper cables, power line system in high speed or broadband, public or private wireless networks.
These system should adapt to every condition and customer, which has to be provided by a suitable telecommunication system either. Integrate digital communications and advanced metering devices available for every entity of the power system provide information which have to be transported and routed, in order to monitor the operations in real-time and controlling dispersed generation integration in a smart way. All the data collected must be part of a proper ICT infrastructure, a SCADA system (Supervisory Control and Data Acquisition), which has to adapt the electricity demand and market conditions, offer grid automatic reconfiguration and safe integration of dispersed generations; in this way it can keep the knowledge of the status of the system and evolve. [25] [26]

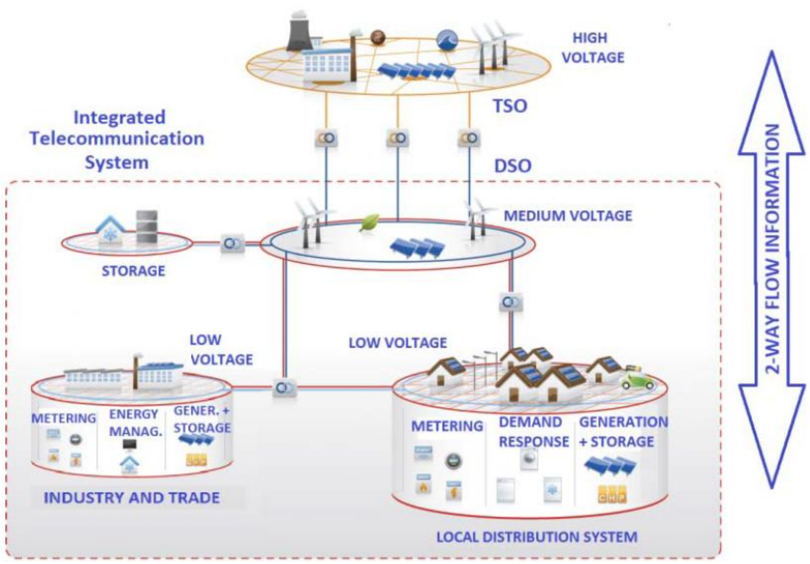

Fig.5. An example of smart grid and how the telecommunication system works.

To conclude this telecommunication topic it is possible to affirm that to keep a successful smart grid operation it is necessary to guarantee a suitable and stable communication with user and suppliers on low voltage and medium voltage network in any case, also when blackouts or faults occur. [25] [26]

Grid development can solve problems like load growth caused by additional or expansion of renewable energy sources. On the other hand, the effects on the network due to bidirectional power flow, voltage and load fluctuations can be mitigate only by intelligent solutions, which becomes the main task for the distribution network.

The answer consists of an active smart distribution grid characterised by smart transformer substation as fundamental component. In this way it is possible to rapidly and automatically react to blackouts clearing the fault and actively manage the load in distribution network. [25]

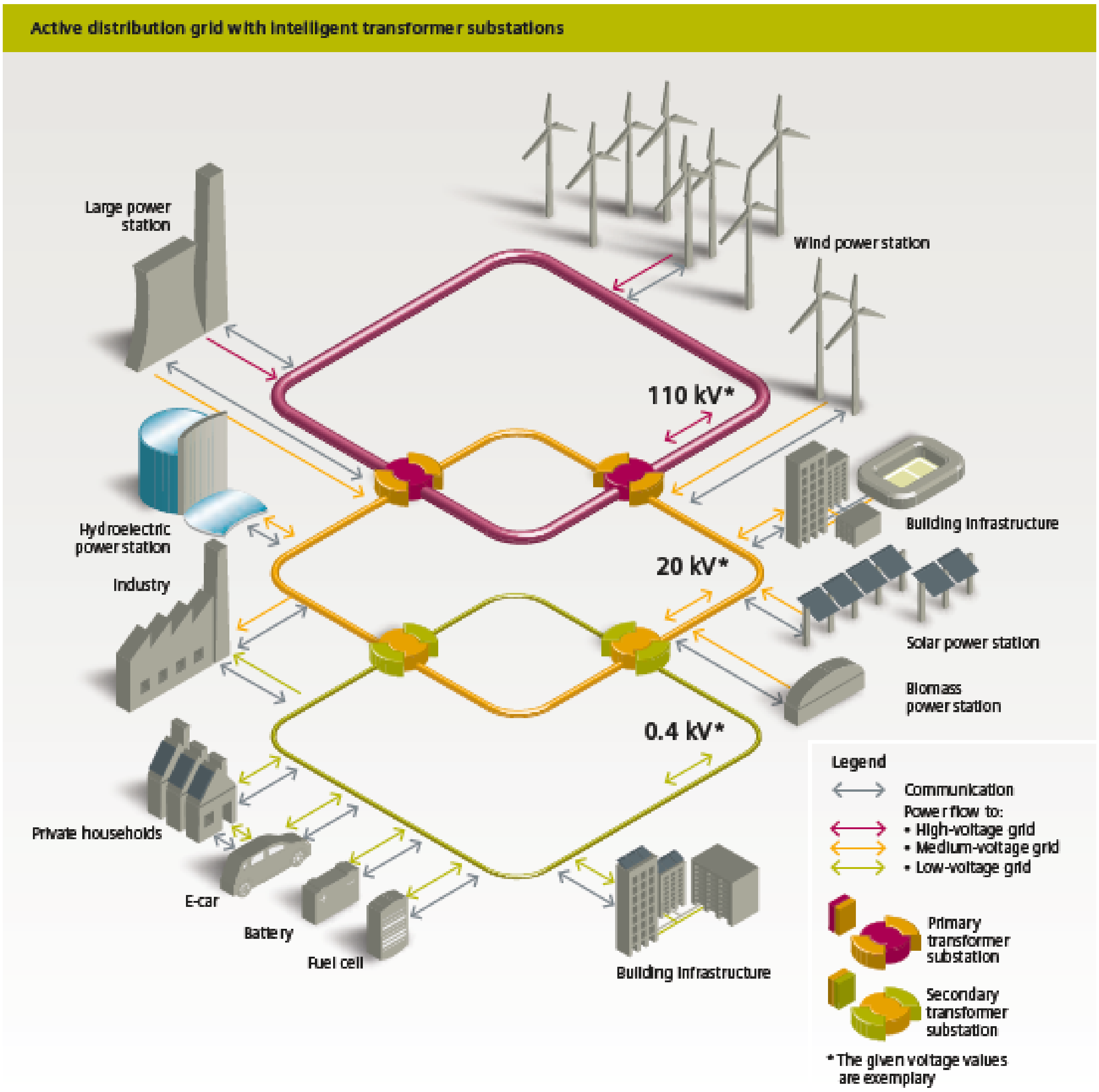

Fig.6. An example of active distribution smart grid implemented with intelligent transformer substations, situated in HV/MV and MV/LV grid. [25]

7. Smart transformer substation

A smart transformer substation can be schematised in four elements:

1) Medium voltage switchgear: it is composed of mechanisms capable of actuate circuit breakers or disconnectors controlled from external switching points. It presents intelligent indicators to detect short circuit and ground fault currents and their direction. Besides, it also contains sensors to measure voltages and currents of the network.
2) Transformer: which consists of a standard or a regulated distribution transformer.
3) Low voltage side: characterised by position indicators, measurements of electric power quality and acquisition of load conditions.
4) Telecommunication and control unit: in order to communicate with the whole smart grid and adjust the operation depending on the various situations.

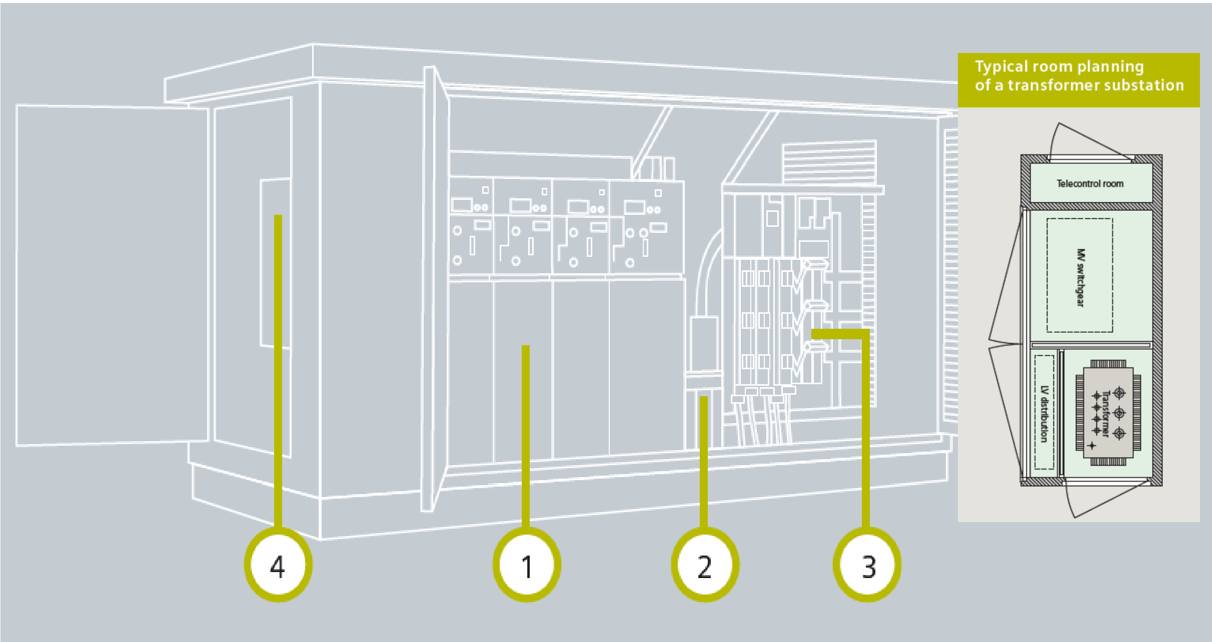

Fig.7. Conceptual design of an intelligent transformer substation. [25]

A substation implementing such a technology leads to higher reliability of the electricity supply and a better control of the electric power quality in the distribution network. Nevertheless, maintenance and design of a smart grid and substation are quite complicated tasks to face on for municipalities and operators; integration of IT systems, transducers and communication systems simplifies these challenges.

Smart transformer substations allow to manage distribution grid in low voltage level handling data (also through smart meter), to compensate reactive power, current and voltage harmonics, regulating the transformer inside and coordinating variable load and supply. Moreover, by means of this technology it is possible to check and control medium voltage side of the grid, regarding especially unfortunate fault location and an automatic supply recover. Besides, it is possible to provide and transmit indications and measured values from both side of the network. [25]

8. Smart transformers

Electric power of dispersed generation obtained by wind energy, photovoltaic elements, etc. reduces the distances over it has to be transmitted. In other words, this turns on a reduction in upstream grid losses and in transmission. It is necessary to face problems with this kind of generation in case of inadequate power consumption in particular rural areas: in these cases, voltage grid increase up to its upper limits, triggering a power shutdown of the generation process. This is not going to happen if the surplus energy is transmitted to the medium voltage grid where it would be dissipated in high-consumption areas. In order to control this energy flux from low voltage to the medium one it is fundamental to adopt a suitable technology which can be an intelligent transformer characterised by a variable voltage ratio: in this way it is possible to perform the action of switching without interrupting the energy flow. This intelligent solution employs an on load tap changer on the medium voltage side of the transformer. [27]

Moreover, the integration of a large amount of renewable energy resources requires the ability of the microgrid to control the voltage levels within certain limits. This control can be accomplished by load scheduling, but also improving lower and upper limits into the smart transformer (which can be shortened with ST). Consequently, the smart transformer can perform the function of power exchange controller, mitigating at the same time voltage fluctuations. In order to reduce the needed communication data to control the power exchange only the smart transformer needs to achieve the set point, without exchanging the new set points with all the elements of the microgrid.

Therefore, it is possible to employ a smart transformer which can be characterised by a conventional controlled tap changing technology connected to the microgrid Point of Common Coupling (PCC). In this particular condition it is possible to talk about smart transformer because the control strategy applied is able to manage the power exchange to a proper value controlling the microgrid voltage. [28]

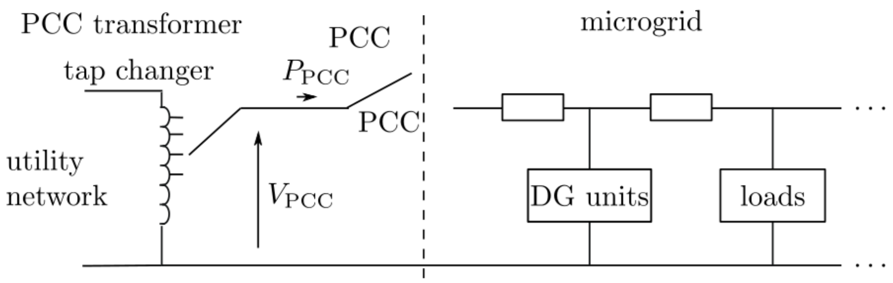

Fig. 8. An example of smart transformer scheme, in this case using a tap changer. [28]

On the other hand an important role in the improvement of the electric system is played by power electronics. In fact, the majority of the elements connected to the distribution network (either loads and sources) are interfaced by power electronics converters. Besides, many solution proposed in order to improve the stability and reliability of the power system are based on power electronic: these technologies can be Solid State Transformers (SSTs), electronic circuit breakers, Flexible AC Transmission Systems (FACTS), active filters and High Voltage in Direct Current (HVDC). A distribution transformer based on power electronics devices can turn in an optimal candidate to improve and implement new operation in form of ancillary services. [29]

Therefore, a smart transformer consists of a transformer based on power electronics characterised with an effective control and communication system. Although the smart transformer characteristics in the medium voltage distribution system still have to be fully discovered, it is possible to expect this technology to play a significant role in the future power network. [30]

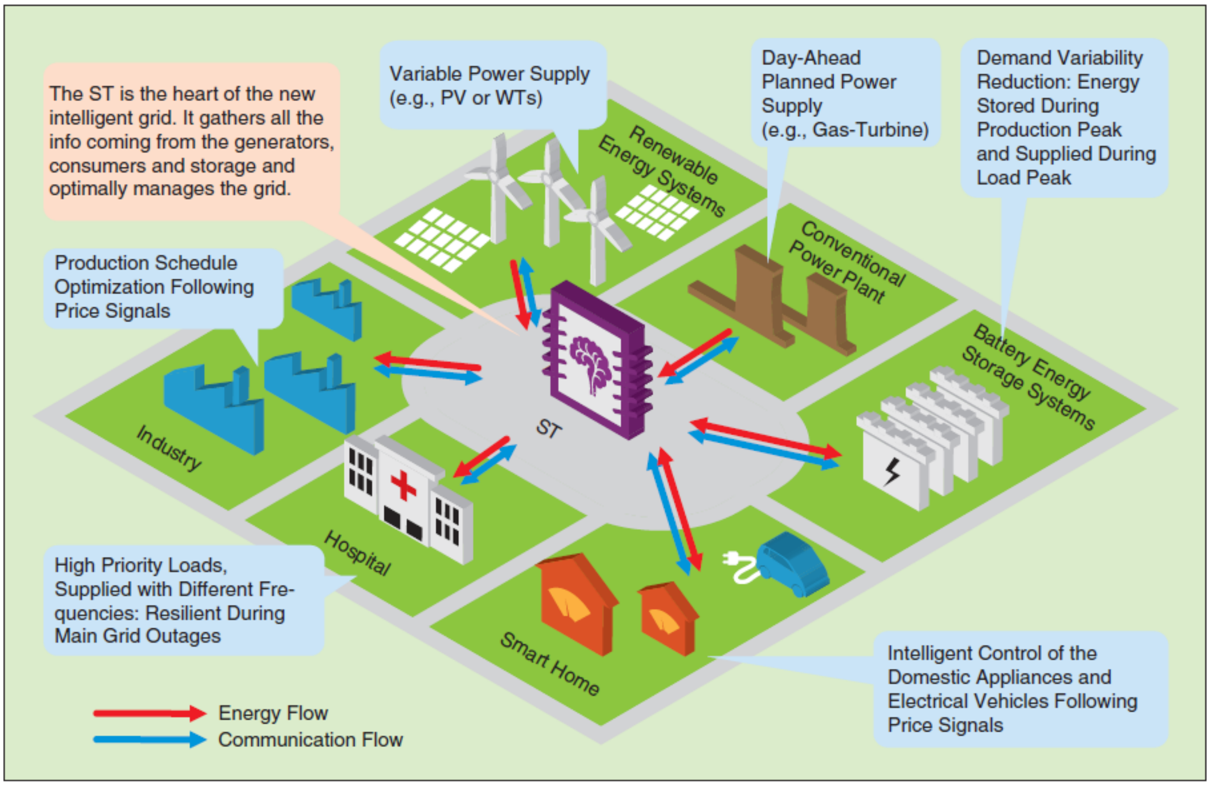

Fig. 9. Smart transformer and its role in the smart grid [29]

As it is possible to see in figure 9 the smart transformer (situated in the middle) is able to manage either power flow (red arrows) and communication flow (blue arrows). Conventional power plants and renewable energy systems are regulated in a efficient manner, besides, intelligent loads can be controlled as to turn on at certain times, in order to improve the balance between demand and response, considering energy cost as well. From the point of view of the industry the smart transformer may play an important role in the ancillary services as enabler allowing provision. Smart transformers, with their the ability to control at the same time different harmonics and owning a large amount of DC links, make possible to supply different types of loads working in DC or at different frequencies.

Smart transformers have to face some challenges beginning with the need of the smart grid for certain functionalities and ending at each component level guaranteeing a reliable operation. Smart transformer can actually help to solve many system challenges but the starting point is that it has to compete with an already proven and developed technology which is the traditional transformer, especially in terms of reliability, cost and efficiency. Besides, at the same time, smart transformers offer a very wide range of new functionalities which involve working conditions very different from the traditional transformer; this fact increases the difficulties of the new technology difficult to confront with the old one, in particular in terms of efficiency and reliability. In fact, nowadays, distribution networks work with dynamic high power profiles and numerous abnormal conditions (faults, inrush currents, etc) which affect the internal temperature of the power electronic devices (based on semiconductors) of the smart transformer. As a result, power converters are subjected to mechanical stress and possible failures may happens, making smart transformer not suitable in the distribution network. However, a modular architecture applied to the smart transformer can develop the active thermal control: it is possible to improve the internal energy flows making them route, regulating the thermal loading of the power semiconductors.

Solid state transformer (SST) concept was firstly introduced by McMurray in 1968, who proposed an equipment based on solid state switches at high frequency isolation which acted like a traditional transformer. Then, Brook in 90th century highlighted the capability of the waveform conditioning of the output voltage in high frequency AC/AC converters, then an actual application of SST emerged a decade years later in traction systems. The classical solutions were based on Low Frequency Transformers (LFTs), characterised by a heavy, bulky and an inefficient system. On the other hand, solid state transformers could offer many benefits in these aspects, especially weight and volume reduction around 20-50% (which were and are highly desirable) and efficiency improvements (up to 96%). However, solid state transformers did not turn into an industrial product, mainly because the gain margin at 50 Hz was severely reduced. The main limitation of solid state transformer in transport system and in general is that their use could only be justified in terms of hardware gain (weight and volume reduction), and the other functionalities covered a very limited role.

On the other hand, replacing low frequency transformer, connecting MV to LV grid and offering DC connectivity to either MV and LV grids, the SSTs potential to improve the microgrids into smart grids in power distribution is much higher. In this case, weight and volume involve a limited impact on the usage of SST while reliability and efficiency are the most important requirements: service interruptions and high losses cannot be tolerated. As a result, the need of control and communication functions summed with all these functionalities summed turn this device into a smart solid state transformer, or what it is simply called, a smart transformer (ST). [29]

Therefore, using smart transformer in the distribution system leads to several potential (and actual) advantages and features, such as:

- ✓ Easier integration of storage devices and energy production (dispersed generation).
- ✓ Voltage transformation achievement with galvanic isolation.
- ✓ Creation of a bidirectional channel of communication, so to allow surveillance, control and improve efficiency, interactivity, safety and reliability.
- ✓ Transformer volume and weight reduction due to high frequency operations (> 1 kHz).
- ✓ Current flows and losses reductions in the distribution lines, also with an harmonic decrease.
- ✓ Automatic voltage regulation and adjust of congestion lines, in order to improve the management of the network distribution.
- ✓ Improving a stable and optimal supply it is possible to notice an immediate energy consumption reduction.
- ✓ Electrical equipment protection against power fluctuations, increasing in this way its lifetime and safety.
- ✓ Capacity of bidirectional power flow, which enables the connection of distributed energy sources with energy storage devices and various loads.[31]

8.1. Topologies

In this chapter topologies of smart transformer based on power electronics converters are described, considering in particular the following figure, which helps to understand the division and classification of the various types.

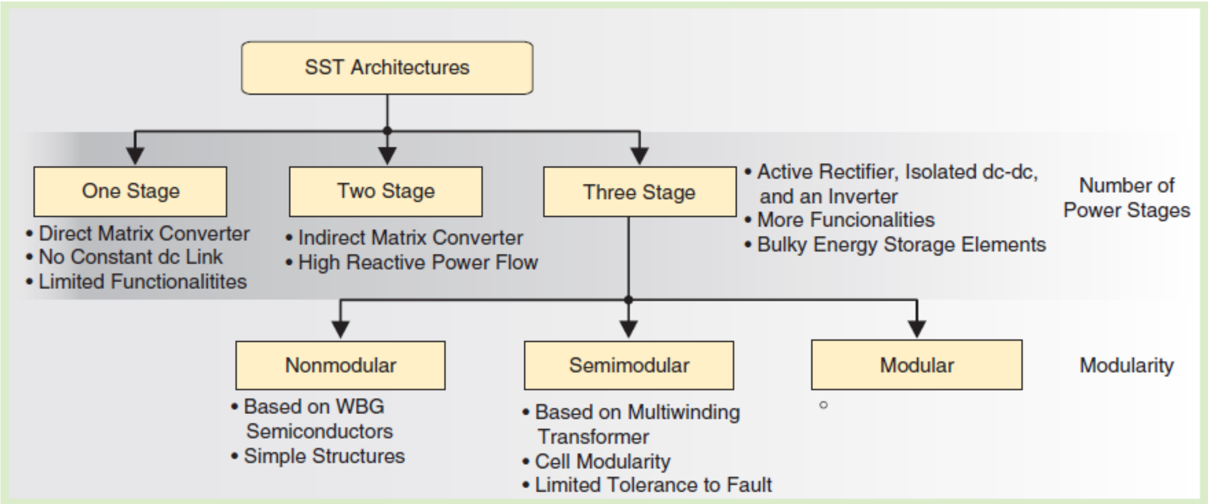

Fig. 10. A scheme of possible topologies of smart transformer. [29]

Figure 8 provides an overview of possible architectures of smart transformers. Specially, the three stage configuration is characterised also by DC/DC connectivity, this makes this topology more suitable for a smart transformer. [29]

The single stage smart transformer consists of a matrix converter, marked out of low component count but offering limited grid services. This topology, in fact, offers a solution characterised by a reduced size and low cost thanks to its structure simplicity and limited number of elements but it does not present a continuous bus (DC link) implicating difficulties in the connection with DC transmission, such as with distributed (especially renewable) energy sources, energy storage devices and with DC grid. [31] [32]

The first topology is followed by the two stage smart transformer: this technology is based on an AC/DC conversion isolated either in medium or low voltage side and it can be realised with a common DC link or a separate one supplied with multi-winding transformers. These facts lead to a major cost and a higher presence of components which can fail. [32]

Moreover, two-stage smart transformer includes two possible topologies itself depending on the position of the DC link. The first topology is characterised by a HV-DC link: it allows

galvanic insulation and integration of renewable distributed generation but, because of high losses, difficulties in the compensation of reactive power and wide ripple currents, it is not compatible with the characteristics required by the smart grid. The second topology presents a LV-DC link: the output power quality is increased and also the connection of dispersed generation and energy storage elements is improved. However, also this structure suffers of difficulties in reactive power compensation in the high voltage side, consequently voltage undulations are present in the DC link. [31]
The third smart transformer topology is defined as the three stage smart transformer and it is characterised by an AC/AC conversion either in medium and low voltage sides, whilst the DC links (low voltage DC link and medium voltage DC links, also represented as the high voltage DC link) are combined by means of a medium frequency DC/DC converter. Although sometimes the MV-DC link is not available, this topology of smart transformers provides the highest level of additional and reliable services to the grid. [32]

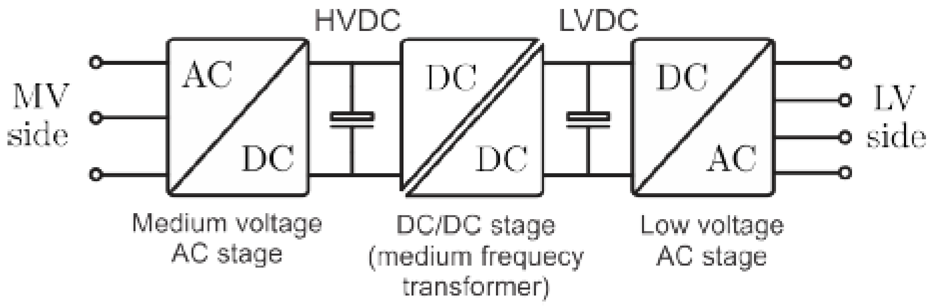

Fig.11. An example of three stage smart transformer used in distribution system.

In terms of smart transformer architecture the next choice is the degree of modularity. Power rating and voltage level affect in a significant way the choice of modularity in a smart transformer. As the name bring to mind, modular architecture consists of many modules of LV current rating used as building blocks for the whole network. This modular architecture cause a considerable amount of advantages to the electric power system, such as improving voltage and power scalability and maintenance, implementing the fault tolerance strategy. Differently, a single power structure is the base of a non modular system, usually exploiting semiconductors with a wide-band gap. This architecture has the main advantage of using a small number of elements, meaning semiconductors, sensors, drivers and also a single transformer.

In the next figure it is possible to observe a choices scheme of the modularity degree in a three stage smart transformer.

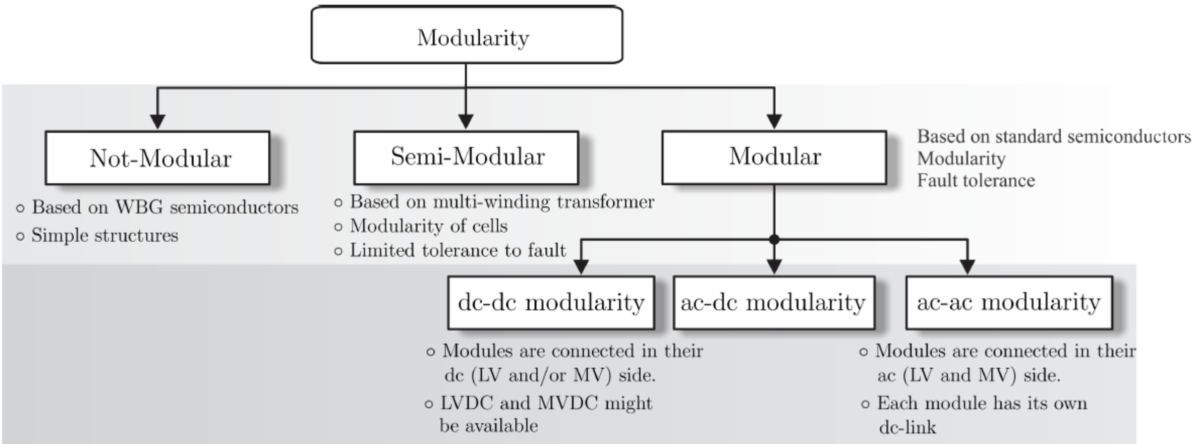

Fig. 12. Possible realisations of modularity in a three stage smart transformer. [32]

Moreover, the concept of semi-modular architecture is taken into consideration. In a modular configuration a module is a complete power converter, while in a semi-modular structure it is a part of the converter. An example of this modularity could be seen in a structure using DC/DC converter based on a multi winding transformer and multiple active bridge. This architecture topology takes the equal advantages of a complete full modular structure, but using less transformers. [29]

8.1.1. Three stages smart transformer

Three stages smart transformer topology is the one investigated the most in this thesis, as it results the most efficient one, performing several important internal and external functions. Examples of internal functions can be found in power factor correction, control of bidirectional power flow, harmonic isolation, fault limitation and isolation, AC and DC voltage transformation, status monitoring, encryption of data, voltage sag compensation, instantaneous voltage regulation and many others. Concerning external functions instead, it is possible to include vast data services, communications and distributed control. [33]

As already said before, three stages smart transformers and smart transformers in general have to compete with the traditional transformer, proving their efficiency and reliability in front of a high flexibility and control freedom in order to adapt to the various changing of the network system. One of the main characteristics of this topology of smart transformer is that, being a three stage converter based on power electronic devices, it can allow the electrical separation of medium and low voltage grids; in this way the two sides are physically connected by means of an average active power exchange, acting independently one from another. As a result, a filtering effect for possible disturbances on the two grids is created: any perturbation on the electric system such as harmonics, sag, flicker can be filtered by the smart transformer (exploiting a suitable control) without affecting the other side. This is one of the key points in favour of the smart transformer over the traditional one, which is incapable of this grid separation, limiting the possible developments and improvements of the grid and hosting capabilities. [34]

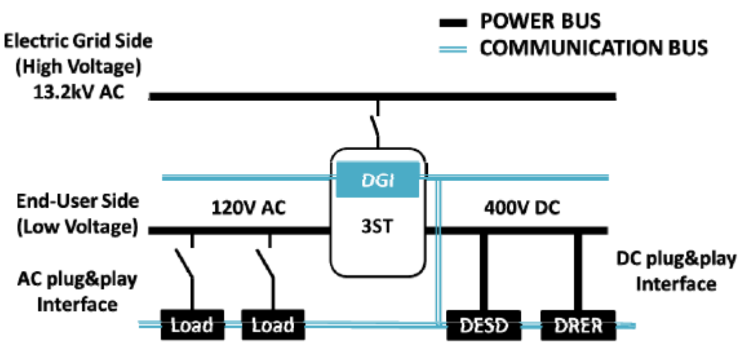

Fig. 13. A scheme of connection of a three stage smart transformer. [33]

One of the important things about three stages smart transformer is the distributed grid intelligence system (DGI) embedded in every device of the smart transformer, which it is responsible to manage the interconnection and communication amongst the elements of this topology. This intelligent system has to collect, process and transmit data, in order to adjust the power flow over a wide area. Besides, in these functions are included voltage transformation, link to Information and Communication Technologies (ICT), integration of dispersed generation (especially the renewable one) and distributed energy storage devices. [33]

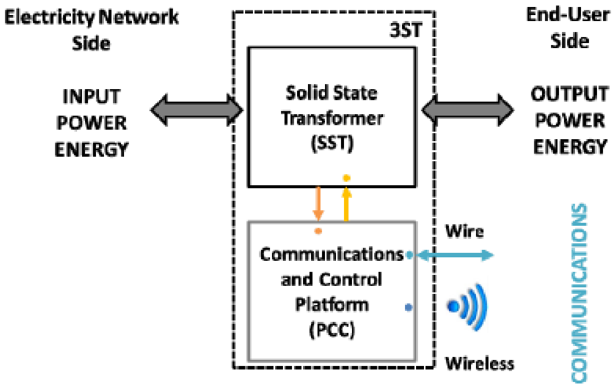

Fig.14. Modular scheme of a three stage smart transformer. [33]

Therefore, a three stages smart transformer consists basically of two separate but interfaced modules: the solid state transformer, which is responsible for the power flow process and a platform of control and communication, in charge of data flow processing. SST module, as this smart transformer topology name suggests, is composed of three stages transformations: an AC/DC rectifier, an intermediate DC/DC stage and an inverter DC/AC. The external elements of the smart transformer are inverters, while the DC/DC stage consists of a Dual Active Bridge (DAB) converter, which can transform the voltage using a High Frequency (HF) transformer. [33] [34]

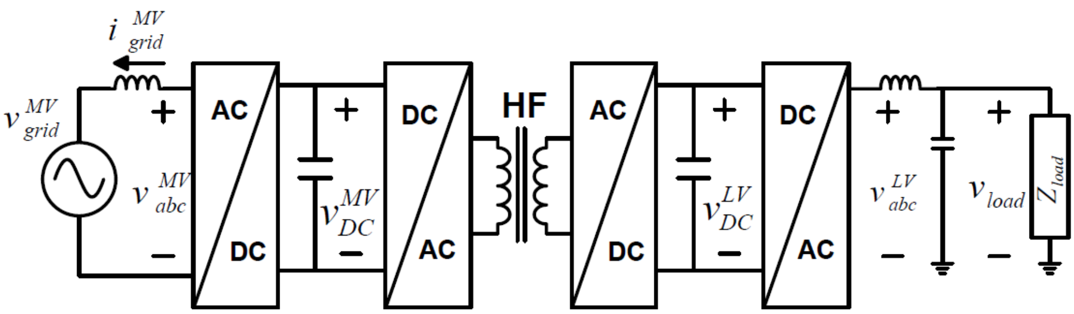

Fig.15. Schemes of a three stage smart transformer. [34]

Confirming the fact said before, this configuration, characterised by a high frequency transformer in the middle and two DC links, permits the electrical separation of MV and LV sides, leading to the two grids independence. Thanks to this, any disturbance upstream and downstream can be filtered, compensated and so mitigated by the actions of this smart transformer. The disturbance could consists of a condition of unbalanced loads in low voltage network, creating a cascade effect: the unbalance currents requested by the loads could provoke unbalanced voltages in the low voltage side and unbalanced currents at the medium voltage side of the traditional transformer. Using a smart transformer with a proper control it is possible to provide balance voltage in low voltage grid, requesting also from the medium voltage side a balanced current. Thanks to this function the electric power quality in both sides of the smart transformer improves, providing a better service to the customers. [34]

Besides, three stages transformer may include in the DC/DC stage a bidirectional multiport converter, in order to integrate dispersed generation, in particular distributed renewable energy resources (DRER) and distributed energy storage devices (DESD), enhancing in this way efficiency and reliability of the power system. [33]

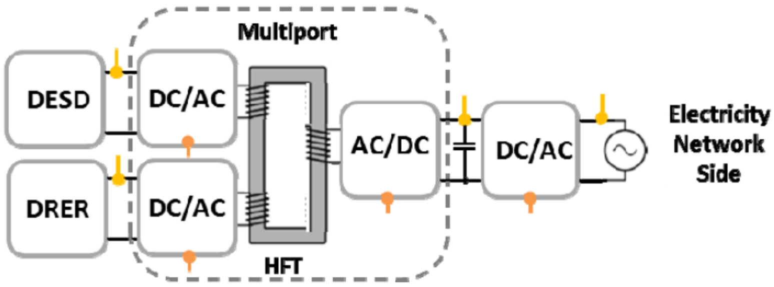

Fig.16. Multiport converter in the three stages smart transformer. [33]

The main characteristic of the smart transformer is the interface of power electronics with the grids. Creating a new control point between medium and low voltage grids it is possible to enable new feasibility on grid optimisation. [34]

The power electronics components of a three stages smart transformer are described in the following subparagraphs.

8.1.1.1. Medium voltage converter

The first part of the electronic components described is the Medium Voltage AC/DC converter, which absorbs the active power from the medium voltage grid in order to supply the next stage (so the further low voltage distribution network) and controls the reactive power for the services related to the grid.

The first immediate way to realise this converter is to choose a multilevel topology, such as the three levels one with neutral point clamped [Figure 17 (a)] and to fulfil the requirements of the blocking voltage it is compulsory to use series-connected devices (or also wide-bad gap transistors). This topology presents various advantages, such as the DC link availability, the fact that it is already used in industries, and its simplicity. On the contrary, this solution can be inefficient under an energetic point, as the reduced levels number involves the use of bulky filters with a rather high switching frequency.

The second topology of medium voltage converted consists of a cascaded H-bridge converter [Figure 17 (b)], already employed in many MV drives. This approach is more modular than the first one, this fact, together with the operation at low frequency of the basic cell and the low complexity of control are the main responsible of this technology. However, with this H-bridge converter it is not possible to obtain the DC link and each cell needs an isolated supply, therefore several DC/DC converter have to be used in order to build the whole structure. In fact, the direct connection is one of the main advantages of the smart transformer as to be considered “smart”, it is considered mandatory to realise an intelligent node in the grid.

The other topology taken into account lies in the modular multilevel converter (MMC) [Figure 17 (c)], which, aside from fulfilling modularity requirement and operating at low frequency, the DC link is available in the structure. Therefore, this converter is the preferred topology for HV girds, even though its advantages in MV levels still have to be fully discovered and bulky DC capacitors and complex control still represent a problem.

One of the advantage of modular topologies consists of the ability to perform advances control, thanks to the internal power routing; for example it is possible to unload modules that present problems such as degradation. [29]

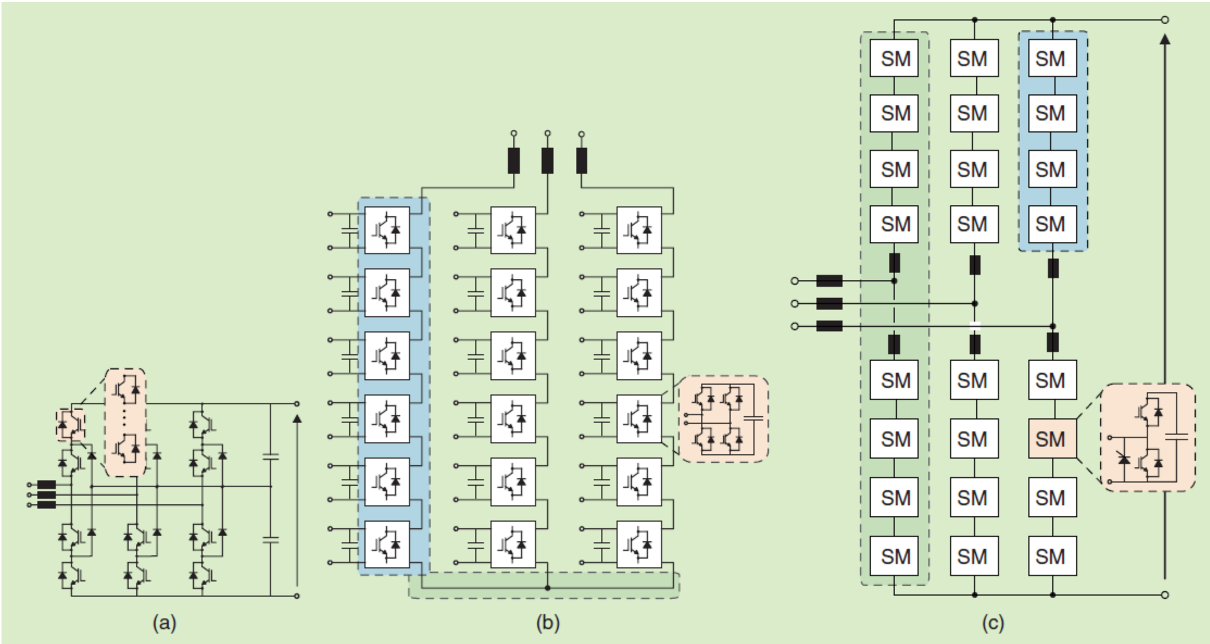

Fig. 17. Possible schemes of medium voltage converter. [29]

8.1.1.2. DC/DC converter

The next part of the three stages smart transformer taken into consideration resides in the DC/DC converter. Due to its strict requirements, like high current capability on low voltage side, high frequency isolation, HV capability on MV side, high rated power and a significant efficiency it turns to be the most challenging stage in the smart transformer design.

For this reason, is possible to adopt two different solutions. The first one employs standard converters characterised by HV rating devices, whilst in the second one various modules share the overall voltage and power, basing on the modularity concept. Despite the presence of a great number of components, the second solution possesses several advantages respect the first one, for example low electromagnetic interference emission (*dv/dt*), potential in using standard, low voltage rating devices and, obviously, modularity itself. The modular structure, in particular, permits to implement a recurring strategy to increase availability and fault tolerance.

Various converters can be used as the core of smart transformer modules: the ones taken into account are the Dual Active Bridge (DAB) in Figure 18 (a) and the series-resonant converter (SR) in Figure 18 (b) due to their benefits of high power density, soft switching and high efficiency. DAB converter is employed in particular when the output power flow or output voltage control is required, because it working principle is based on transferred power active control. On the other hand, SR DC/DC converter, also called DC transformer, is characterised by an output voltage well-regulated for a wide range of loads (in discontinuous conduction mode); in this way it is possible to avoid control loops requirements and reduce sensors number.

Moreover, an alternative solution to the DAB and SR converters can be found into the Multiple Active Bridge (MAB) converter in Figure 18 (c). MAB converter is characterised by the same basic features as DAB integrating more active bridge to a single transformer, thus the number of high frequency transformers is reduced.

The fundamental idea is that using various DC/DC converters it is possible to create a more complex structure, specially on MV side parallel connection can be used and on LV side series one. Therefore, in a detailed operation voltage ripple on low voltage side is reduced. In case of single output converters (Dual Active Bridge and Series Resonant) series or parallel connection is compulsory, while an extra degree of flexibility is given relatively to the Multiple Active Bridge converter. [29]

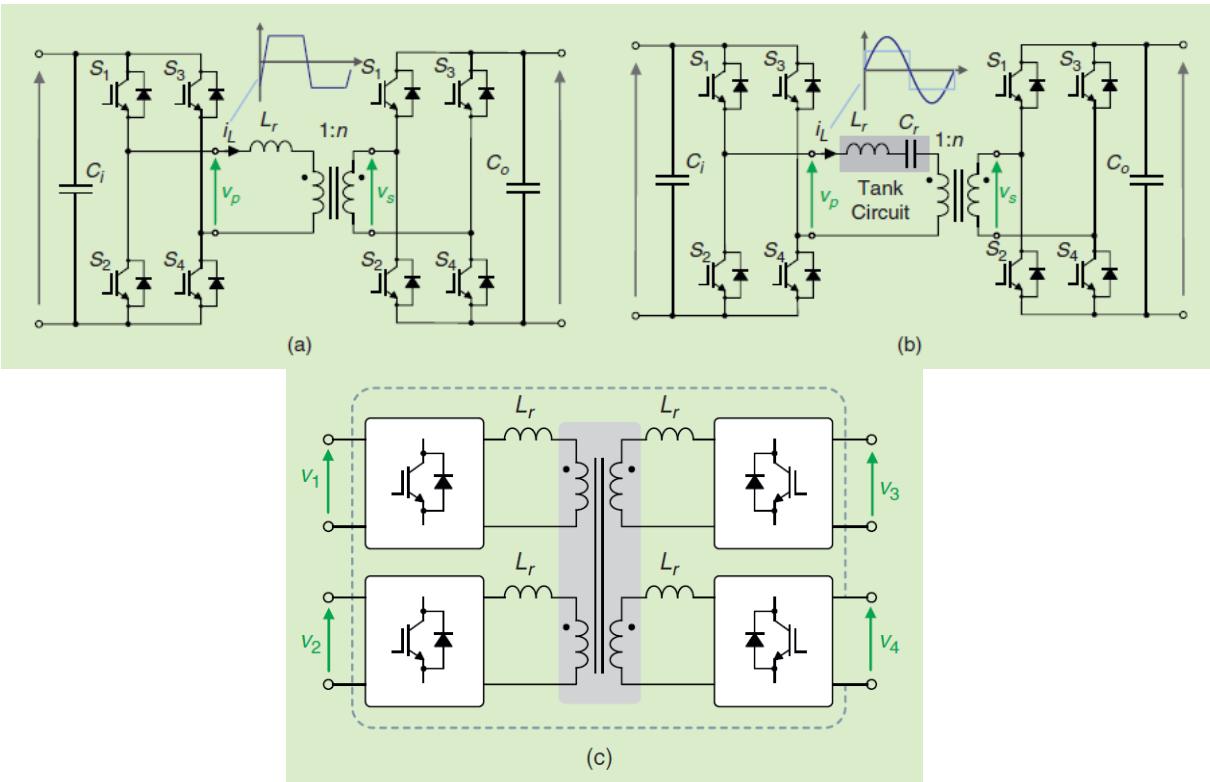

Fig.18. Possible schemes of DC/DC converters. [29]

8.1.1.3. Low voltage converter

The last part of the three stages smart transformer described is the low voltage converter: this device is the most exposed to the disturbances occurring in the LV grid and it has to feed the highest current among the overall apparatus of the smart transformer. Choice of low voltage devices is very wide, then the choice of topologies is wide as well. Replacing the transformer in distribution systems (especially in TT type) the neutral wire is necessary and it can be connected to the DC link middle point. Besides, in all cases it is possible to employ an additional DC/DC converter in order to correct the voltage division among the capacitors.

The simplest solution for this LV converter consists of the Half Bridge (HB) type, in Figure 19 (a), (b) and (c), and in particular, three level converters are the most likely approach also confirmed by industries. For this reason, clamped neutral point (T – type or standard) allows to use devices at 600V, improving system efficiency and output waveform. When multiple converters are connected in parallel, proper controls are performed, reducing filter size but taking into account the circulating current, in fact control to limit the current is a mandatory feature. Since the variability of LV network, fault current is a problem to not undervalue: despite traditional transformer are characterised by high overload capability in power and time, converters based on power electronics have time constants much smaller. [29]

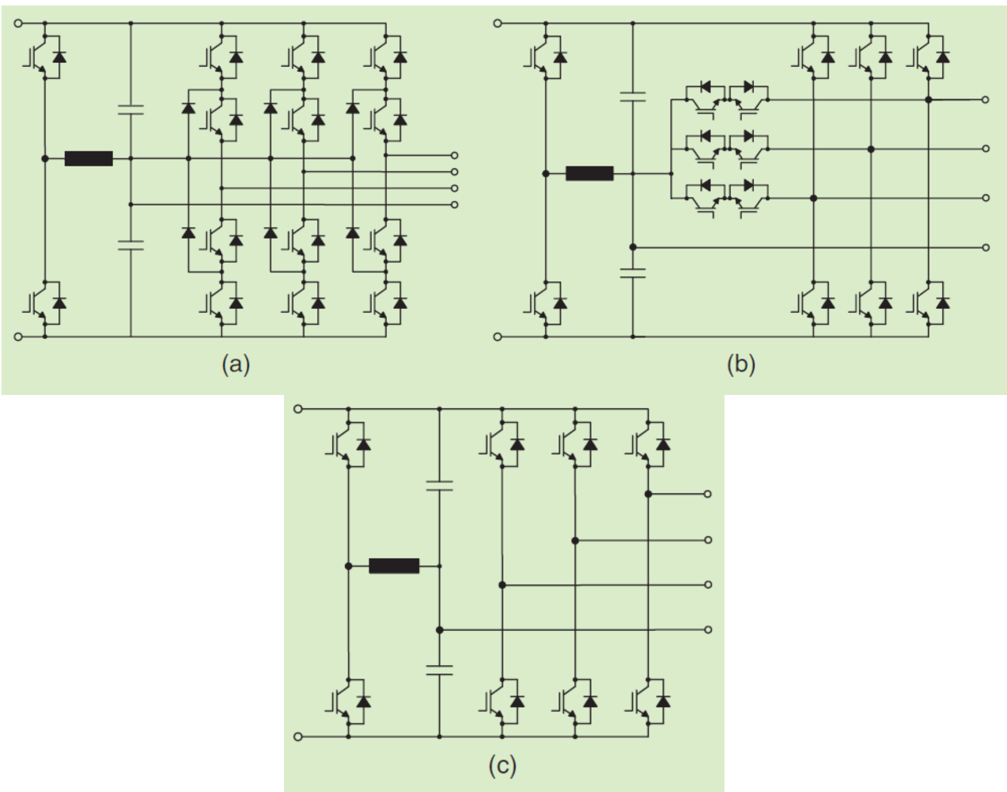

Fig.19. Possible schemes of LV converters. [29]

8.1.2. On Load Tap Changer

Although on load tap changer (OLTC) not always involve power electronics converter in its technology, it can be considered a smart transformer as well and several solutions can be adopted as the transformer tap changer.

The first solution is represented by an approach using taps on the low voltage side of the distribution transformer and a combination of LV switchgear composed of circuit breakers, contactors, solid state relays (usually thyristor based) and a suitable control unit. [27]

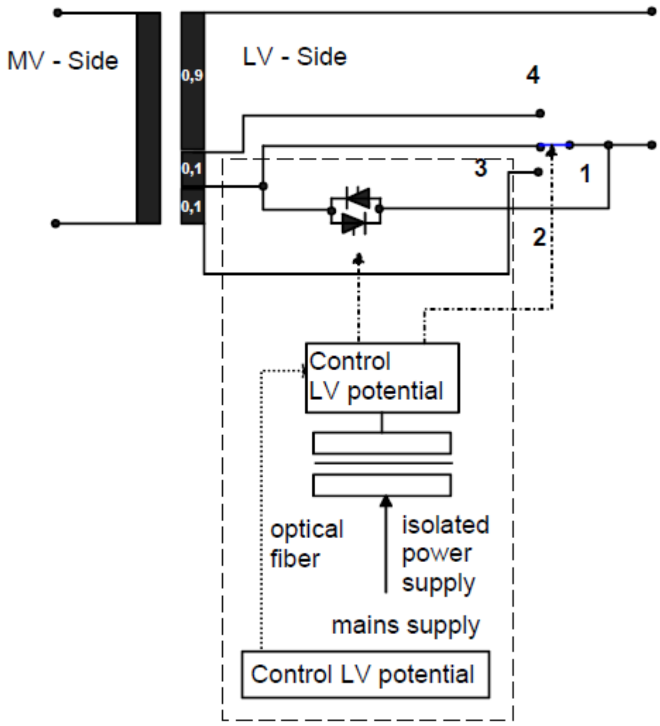

Fig. 20. On load tap changer example, with taps on LV side. [27]

Usually, number of winding turns in low voltage stays in a rage of 25 – 80, thus it could be possible a voltage step of 1.25 – 4 %. Technically, with OLTC, it is possible to create two additional taps in any low voltage winding, then to provide a wider control range over the transformer voltage ratio it is required to create taps after 2, 3 or 4 turns. In this way, the output voltage step at LV side will vary in a range from 5 to 8%.

On the control part of the OLTC, a control unit governs the switchgear in order to accomplish the optimal coordination of electronic and mechanical switching devices. Across the mechanical switchgear the voltages are measured in a way to reduce the "on" time of the solid state switch to a minimum, this takes the reduction of the switching time as well. [27]

Another possible solutions consists of a system employing diodes and IGBTs (Insulated Gate Bipolar Transistors) so as to obtain bidirectional switches. These switches are activated through optical channels, ensuring noise immunity and high electrical insulation. In this case, tappings are situated on the high voltage side of the transformer, making possible to handle lower currents and higher voltages, contrarily to the first OLTC. [35]

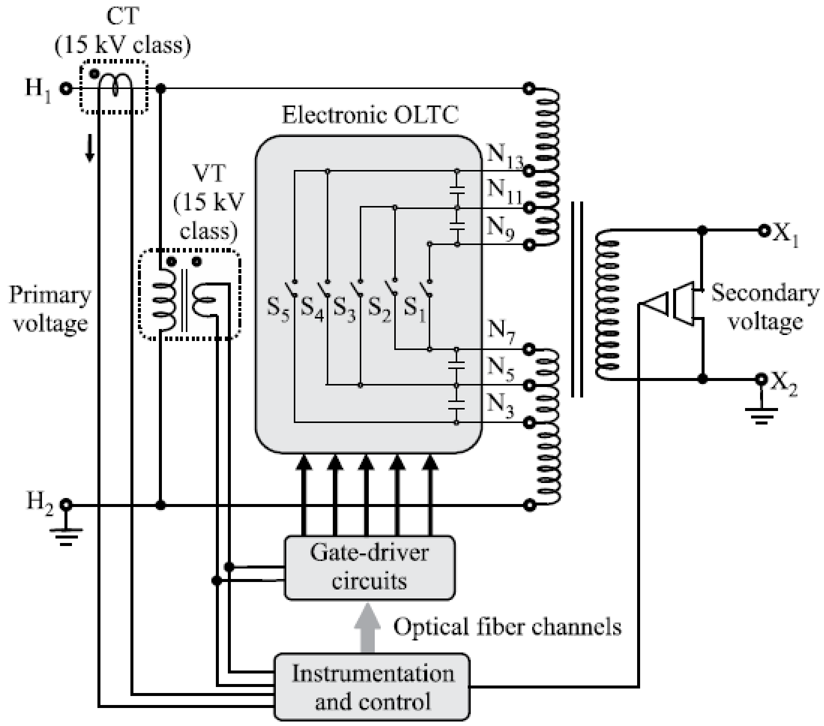

Fig. 21. On load tap changer using electronic devices. [36]

It is possible to notice the presence of a current transformer (CT) which measures the primary current: it enables the taps commutation during current zero crossing, preventing high short circuit currents in the whole commutation process (also limited by the tap winding inductance). This transformer also employs a voltage/potential transformer (VT – PT) which ensures required insulation for the control system and feeding it, together with gate-driver circuits, instrumentation and the communication systems. Besides, this voltage transformer ensures the operation system independently to the voltage availability in the LV side of the transformer.

In order to regulate the voltage delivered to the end users of the network and to allow the calculations of active, reactive and apparent power, secondary voltage and currents are measured in the LV side of the OLTC. An important feature is that all the rms values of the measured variables (primary and secondary voltages and currents) are transmitted through the communication system to the power utility. In particular, secondary voltage is compared to a voltage reference in the control unit, adjusting the voltage level within an acceptable range suitable for the end users of the grid. Rms value are not the only information transmitted but also tap position, transformer oil temperature, load parameters and operation mode of the transformer (automatic or management) are communicated to the control unit.

Moreover, the transformer may be actuated remotely adopting a bidirectional communication system with the company of the power utility. Thanks to this system it is possible to operate some direct actions such as load shedding, define remotely which transformer tap must operate, specify the operation mode of the transformer for voltage regulation and an income control in function of the voltage level supplied. [35][36]

In addition, processing the obtained data from the OLTC, it is possible to operate multiple actions on the network management, like:

- Plan maintenance and network modifications (especially expansion).
- Verify energy demanded in LV side of the OLTC, indentifying potential discrepancies between the energy provided and the billed one, cause by possible power losses or thefts.
- Reactive power correction.
- Identify overloads, load profile and configuration of user consumption.
- Study power flow and in particular practicability for the integration of dispersed generation. [35][36]

Finally, the electronic On Load Tap Changer is characterised by a protection system design to deal with voltage spikes which can occur during the commutation process, overvoltages in the HV (MV) side of the transformer and atmospheric discharges in both voltage sides. Protection switchgear employs a normally closed electromechanical switch situated in a parallel connection with the switch S_1 in Figure 21. This protective switch enables the protection of the other switches against possible overcurrent due to short circuits occurring in LV side and prevents the electronic switches to support the whole primary transformer voltage during the start-up process. [36]

8.1.3. UPFC as smart transformer

As already seen, the higher penetration of dispersed (and in particular renewable) generation through the distribution network can be accomplished by adding intelligent controls, energy storage systems and regulatory devices, for example based on the UPFC concept. UPFC (Unified Power Flow Controller) does not correspond to the typical definition of smart transformer but it presents similar feature, it is applicable in distribution network and it constitutes one of the most versatile FACTs devices (Flexible AC Transmission Systems). This technology offers important enhancements about the power system control, leading to the possibility to separately control bus voltage, line active and reactive power. Therefore, UPFC are widely used to improve the existing transmission and distribution networks. [37] [38]

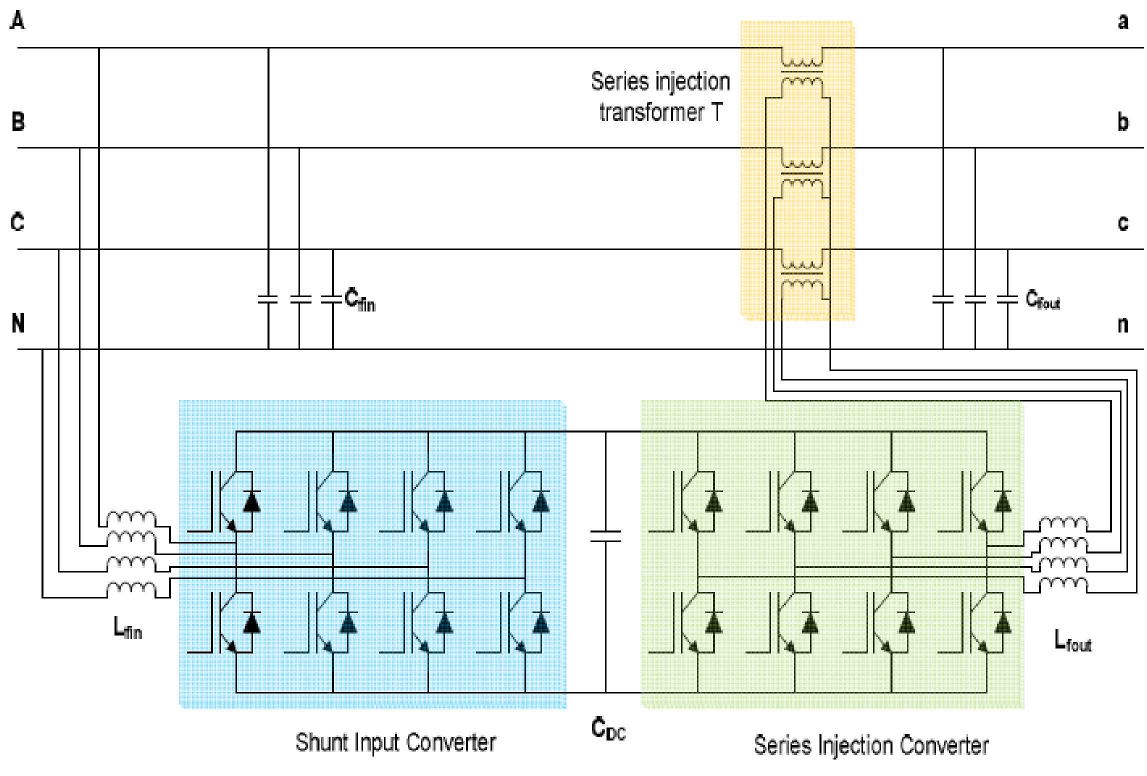

Fig.22. Four wire UPFC voltage regulator. [37]

The major limitation of this device is that it is not capable to control the zero sequence input current, due to the absence of any reserve to coerce the input shunt converter to draw a zero sequence current, causing a development of upstream zero sequence voltages. Four wire UPFC (as shown in Figure 22) is one of the most typical devices to regulate the voltage in LV distribution networks, in this case it can regulate independently system voltages and currents and eliminating a possible neutral current from its input terminal. Despite the popularity of electrolytic capacitors (due to low cost per unit capacitance and high volumetric efficiency) they suffer from short life time, limitations on temperature, high size and low ripple current capability. Consequently, non polarised capacitors are the preferred ones to be employed, also because the reduction of the DC bus capacitance. However, this reduction on DC bus capacitance makes difficult to manage the DC capacitor voltage, mitigating the voltage fluctuations on the bus.

Finally, it is possible to say that the output voltages are regulated by means of the injection of series voltages and the zero sequence current of the input terminal can be compensated using an additional shunt connected converter (which provides supplementary shunt compensation features). [37]

9. Simulation

In order to prove the positive influence of the smart transformer on the distribution network a proper simulation has been performed, by means of the software MatLaba – Simulink.

First of all a general distribution system is presented, connecting MV and LV networks by means of a common three phase transformer. In addition, dispersed generation in MV side and distorting loads in LV grid are introduced in the scheme. Then, the common three phases transformer is replaced with the smart transformer, observing the various advantages taken to the distribution network.

9.1. Simulation without Smart Transformer

The first part of this analysis consists of the simulation of a normal distribution network, combined with the presence of dispersed generation and distorting loads.

9.1.1. Distribution network

The first step of the simulation is to refer the analysis on a system which can exist in the actual distribution network. The overall scheme of the system is the following one.

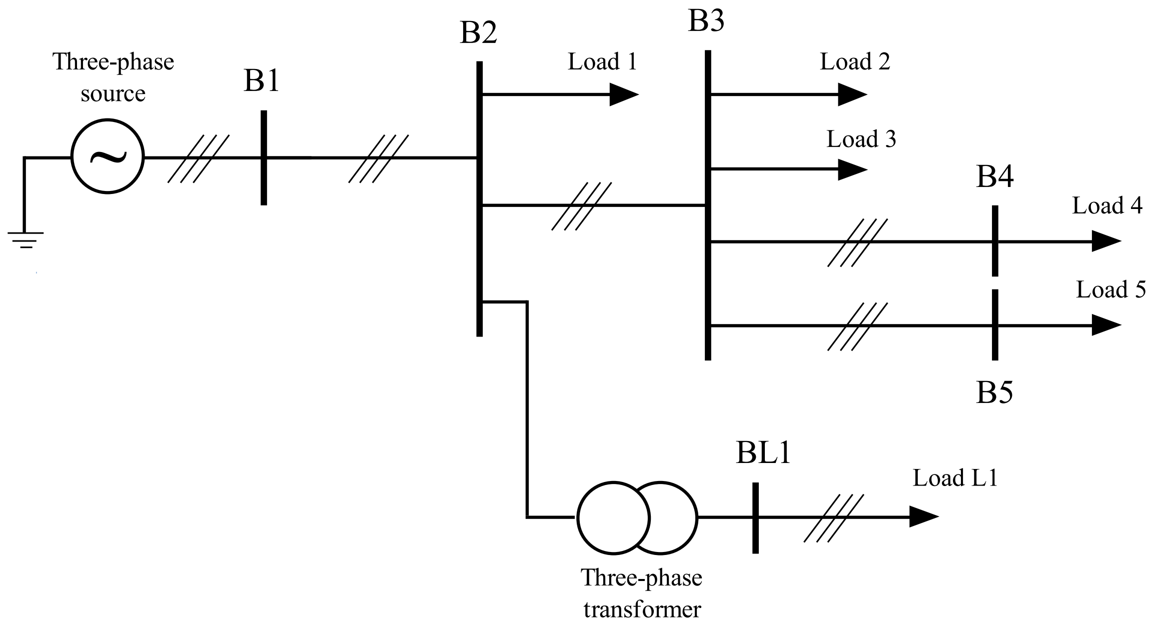

Fig 23. Electrical scheme of the network taken into account for the simulation.

In order to analyse properly this network the simulation has been performed in the software MatLab – Simulink. Using suitable blocks and features it has been possible to build the desired network.

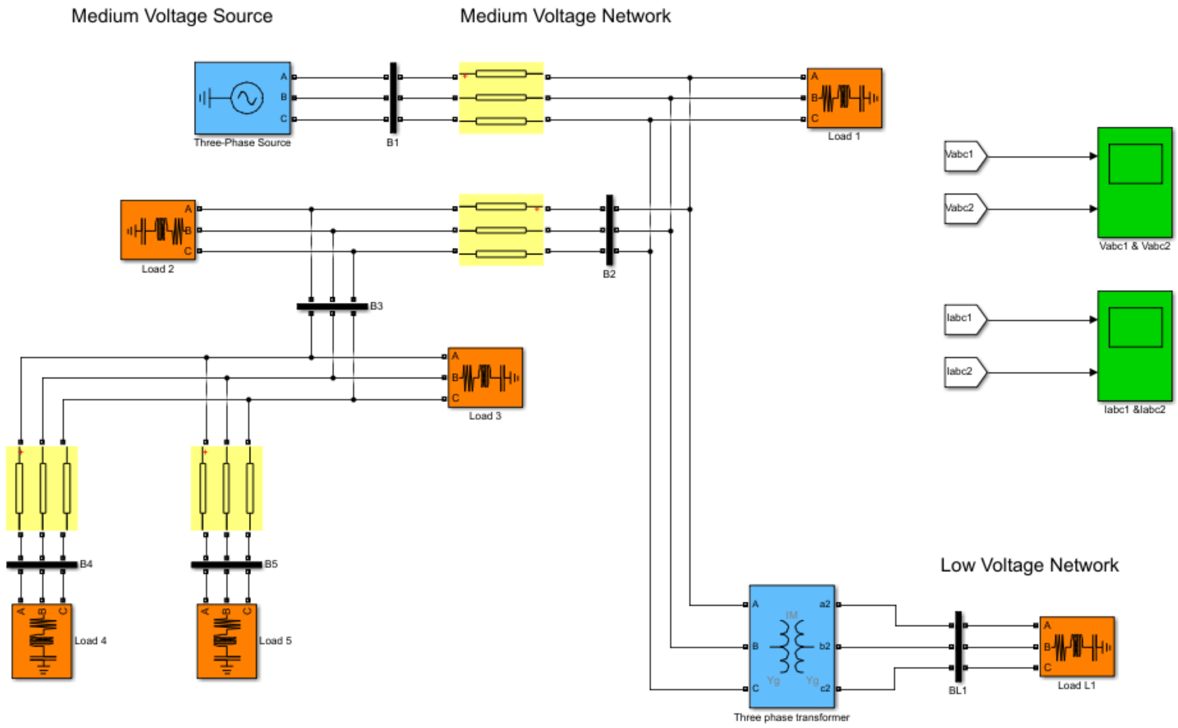

Fig. 24. Simulink scheme of the chosen distribution network.

To perform an appropriate simulation it has been necessary to use parameters of a real distribution network, in this case the ones belonging to an European MV distribution system.

Line segment	**Node from**	**Node to**	**R’$_{ph}$** [Ω/km]	**X’$_{ph}$** [Ω/km]	**B’$_{ph}$** [μS/km]	**R’$_0$** [Ω/km]	**X’$_0$** [Ω/km]	**B’$_0$** [μS/km]	**l** [km]
1	1	2	0.501	0.716	47.493	0.817	1.598	47.493	2.82
2	2	3	0.501	0.716	47.493	0.817	1.598	47.493	4.42
3	3	4	0.501	0.716	47.493	0.817	1.598	47.493	0.61
4	3	5	0.501	0.716	47.493	0.817	1.598	47.493	1.30

Tab. 2. Line parameters of the distribution network. [39]

The system is supplied by a three-phase generator with a nominal phase to phase voltage of 20kV at 50Hz, and the transformer decreases the voltage level to 400V (nominal industrial one). Each line connecting different loads is characterised by the same impedance parameters, but the lengths among the various section of the network are different.

On the other hand, the loads chosen are the following ones:

- Load 1: P = 50kW.
- Load 2: P = 50 kW.
- Load 3: P = 20 kW.
- Load 4: P = 20 kW, Q = 15 kVAr, (cosφ=0.8).
- Load 5: P = 20 kW, Q = 15 kVAr, (cosφ=0.8).
- Load L1: P = 10 kW.

As it is possible to notice, these loads are quite low for being in a MV network and present a low amount of reactive power as well. Moreover, the distribution network taken into account correspond in just a part of the European one and it is slightly modified. All these measured are adopted in order to simplify the simulation and make it more dynamic.

Therefore, in this particular system it has been possible to observe voltages and currents on bus 1 and on bus 2 by means of two scopes, and representing them in the following graphs.

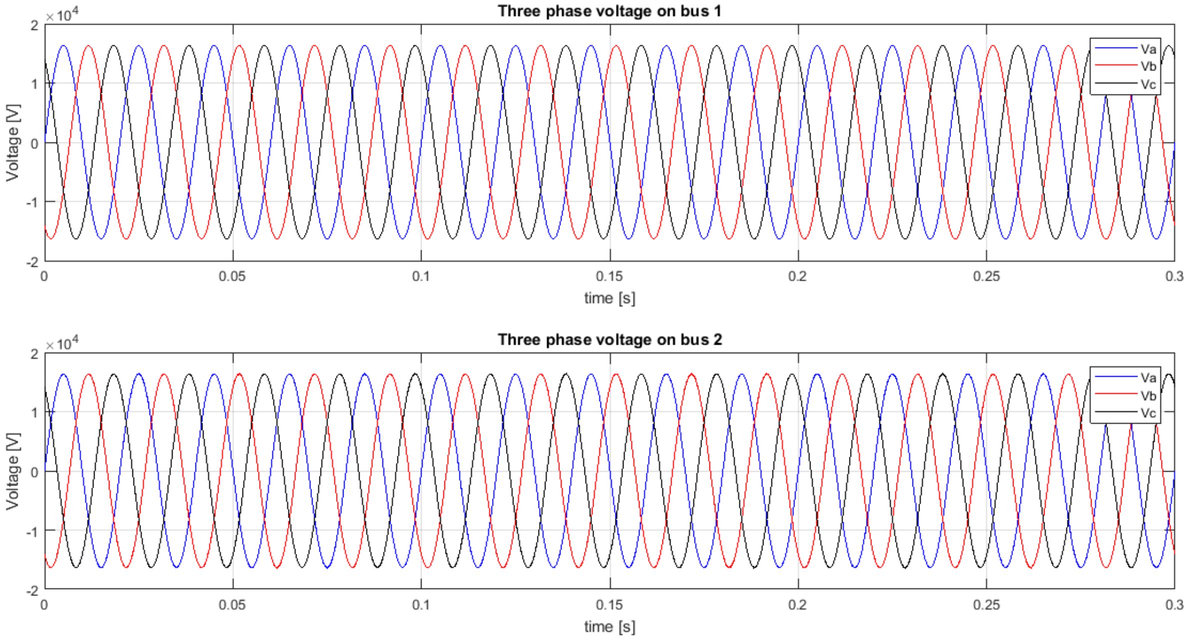

Fig. 25. Graph of voltages on bus 1 and 2 during the simulation.

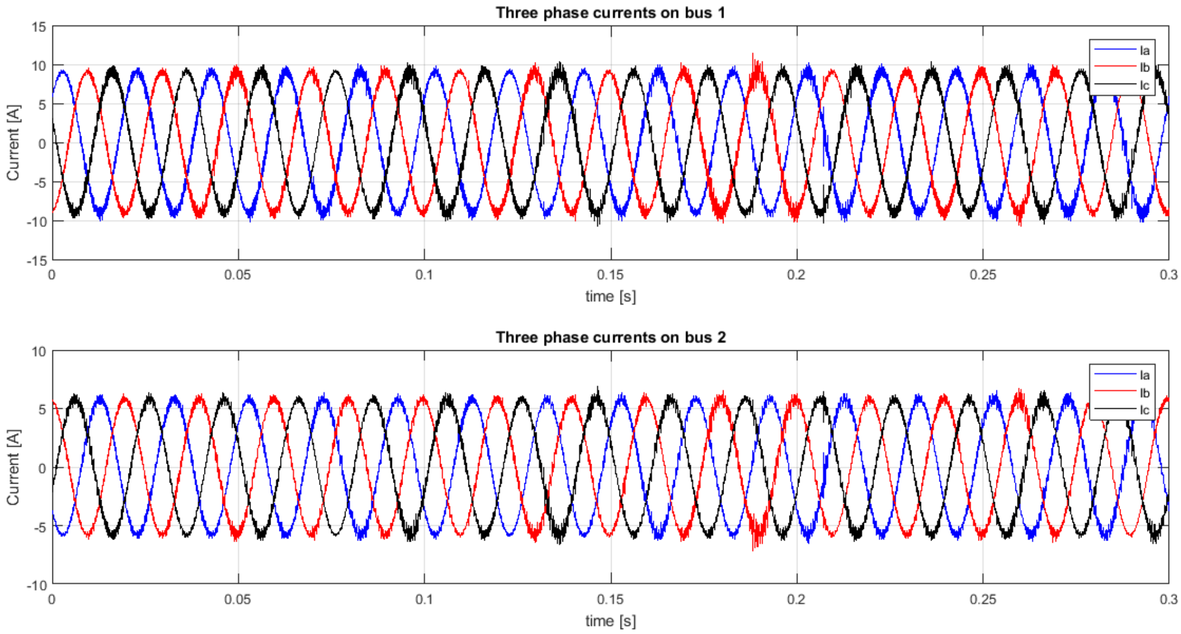

Fig. 26. Graph of currents on bus 1 and 2 during the simulation.

It is possible to notice that the three-phase voltages on the buses are perfectly sinusoidal and, as they are equal also in phase shift, this means that the parameters of the lines does not influence the voltages in the distribution network. On the contrary, three phase currents are still sinusoidal but present few distortions, possibly due to some disturbs caused by resonance with line parameters in the various sections and by the configuration change of the distribution network compared to the standard one.

9.1.2. Dispersed generation

The second step in the network analysis consists of the introduction of dispersed generation in the simulation of the distribution network.

To analyse this aspect it has been chosen a simple electrical system, composed of a three phase generator at 20kV at 50 Hz connected by two buses to a simple load characterised by an active power of 80 kW and a reactive one of 30 kVAr (cosφ=0.936). Besides, dispersed generation is introduced in the system between the two buses (in this case it is indifferent if to bus 1 or bus 2, because there are no line parameters) and its input current is calculated starting from the possible power which can be generated. Rms value of current is calculating dividing the power generated (P_G) by square root of three and the value of phase to phase voltage of the grid which the dispersed generation is connected (V_{ptp}), that in this case is 20 kV.

$$I_{rms} = \frac{P_G}{\sqrt{3} \cdot V_{ptp}}$$

Therefore, the peak value of the current, which it defined as I_{max} is calculated multiplying by square root of two its rms value.

$$I_{max} = \sqrt{2} \cdot I_{rms} = \frac{\sqrt{2} \cdot P_G}{\sqrt{3} \cdot V_{ptp}}$$

Consequently, choosing an input power of 100kW the rms current is equal to 2.89 A and the peak value correspond to 4.08 A.

The electrical scheme and the one implemented in the simulation are presented as follows.

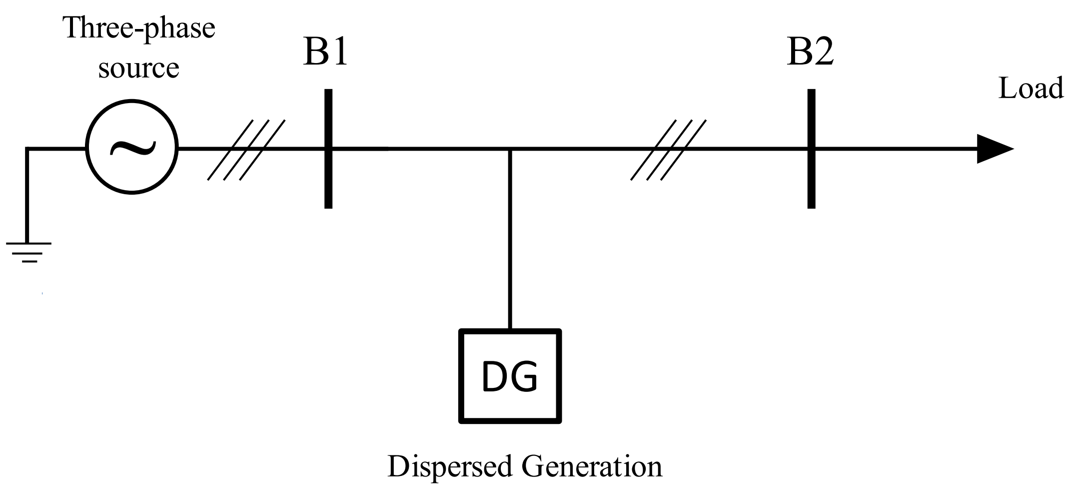

Fig. 27. Electrical scheme of the introduction of dispersed generation in the distribution network, in MV side.

As shown in Figure 28 it has been possible to test the introduction of dispersed generation in MatLab – Simulink using proper blocks and controls. Taking the exact phase shift between the two buses by means of a PLL (Phase Locked Loop, yellow block in the Figure) it has been possible to inject power, that is current, of the distributed generation in phase with the one already present in the network, without causing any imbalance and making the protection to act on the system. In this case just active power is introduced in the system, and simply changing the block phi_deg it is possible to inject a component of the reactive power as well. Transforming the reference system from alpha-beta to abc and giving as input the peak value of the generation current I_{max} (with a step input and a rate limiter, as to smooth the input current), it is possible to inject the desired current (and power) in the distribution network by means of three controlled current generators.

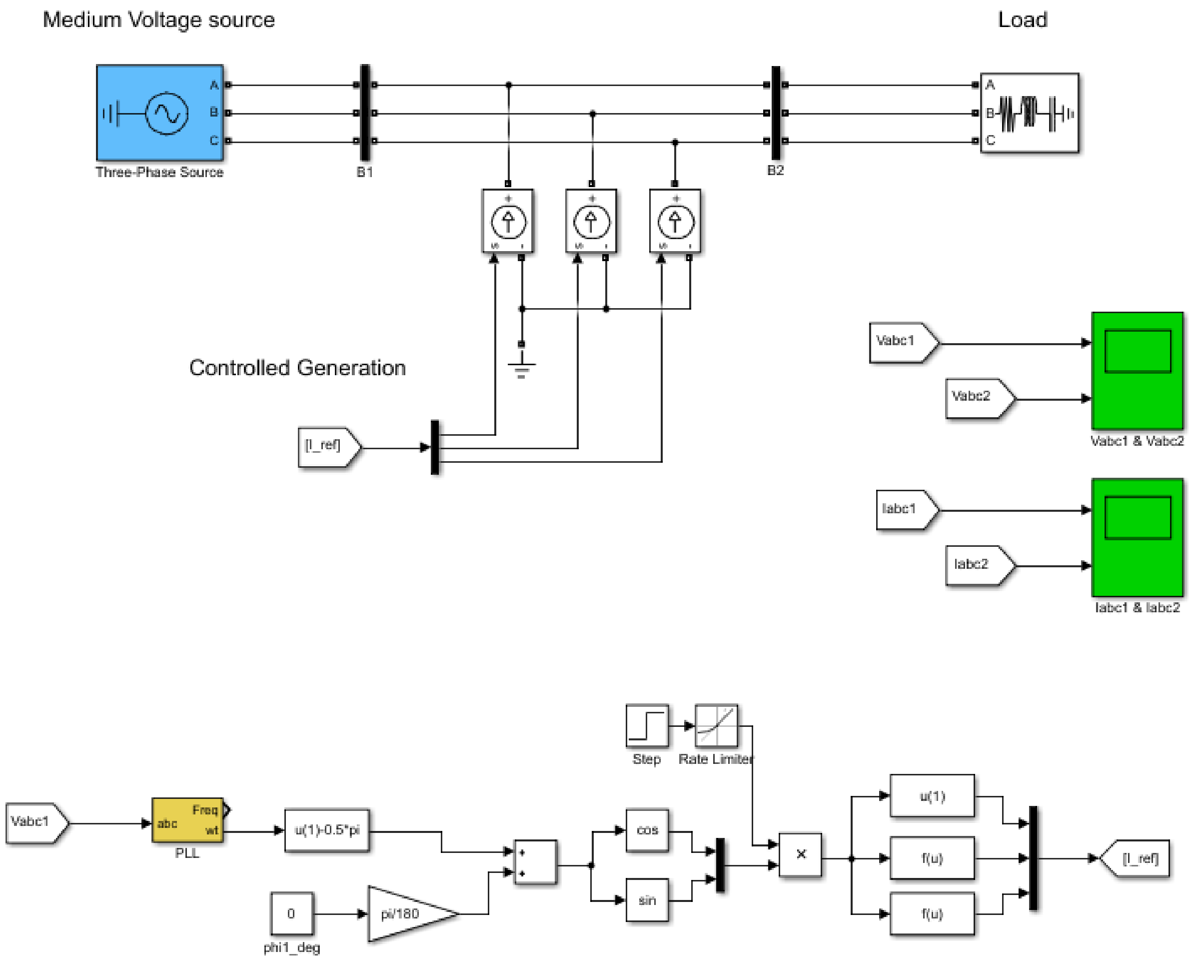

Fig. 28. Simulation scheme of the introduction of dispersed generation in the distribution network.

Therefore, it has been possible to analyse voltages and currents in the distribution network (on bus 1 and on bus 2) by means of the bus measurements and two scopes. The resulted graphs are shown in the following figures.

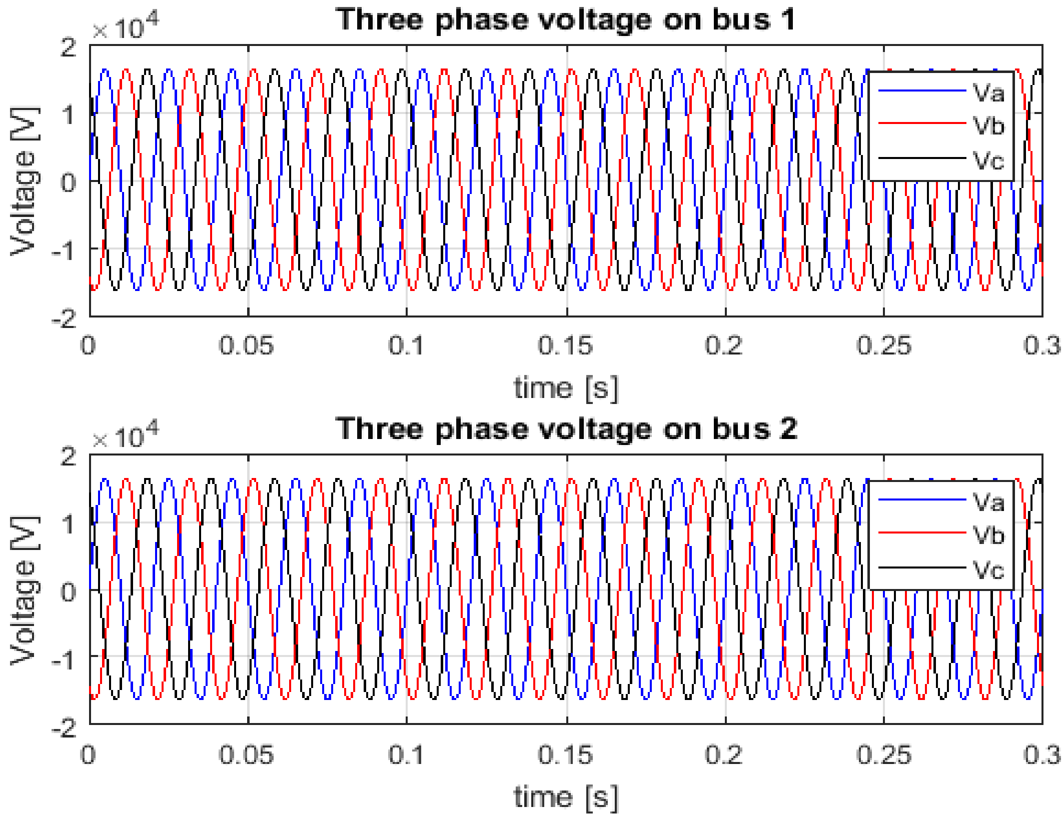

Fig. 29. Three phase voltages in the distribution network during the introduction of dispersed generation.

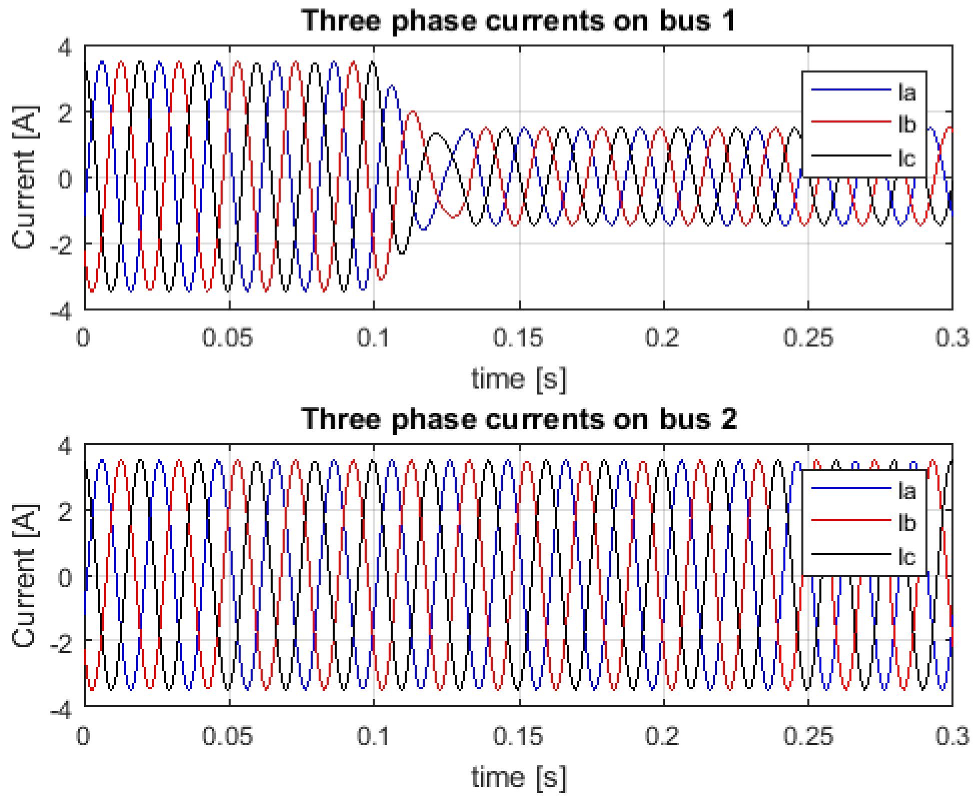

Fig. 30. Three phase currents in the distribution network during the introduction of dispersed generation.

As it possible to notice from the obtained graphs the introduction of dispersed generation in the distribution network affects just the currents in the grid, and just the ones in the bus 1. On one hand, the three phase voltages are stable during the whole simulation and are not affected by the introduction of extra power and current in the system. On the other hand, when the distribution energy sources are introduced (at 0.1s) the current on bus 1 decreases by a quantity equal to the injected one. Except a first transient state due to the rate limiter to smooth the changes in the system, then the three – phase generator has to supply less current (and power) to the grid, thanks to the help provided by the dispersed generation. In fact, the working principle of the grid is dictated by the voltage and the current has to adapt itself in function of the changes in the system. As a result, the powers on the load (then also voltages and currents) are the same during the entire simulation, while the current generated from the generator decreases.

9.1.3. Distorting loads

The third step in the analysis of the distribution system is the introduction of distorting loads in the low voltage side of the transformer together with the normal loads of the power grid.

It is possible to divide the distorting loads used in two types, and studying them separately one from another.

- ✓ ***Diode rectifier with RL load***

The first distorting load taken into account correspond to a diode rectifier with a load composed of a resistance and an inductance. The electrical scheme of the load is shown in the following figure.

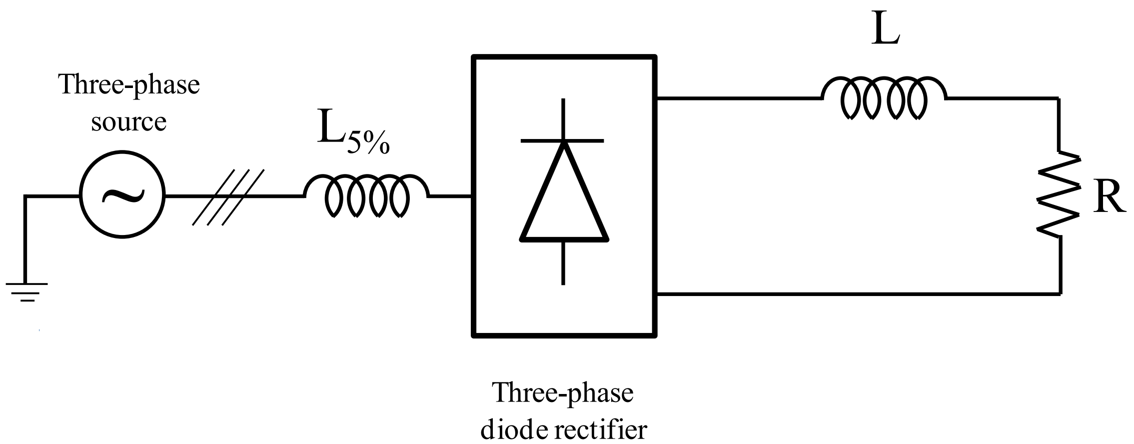

Fig. 31. Distorting load composed of diode rectifier and RL load

In this case three phase voltage imposed is always at 50 Hz but with a rms value phase to phase equal to 400V (LV system). The parameters of the load are calculated in function of its sizing power.

The root mean square value of current is calculated dividing the sizing power (P_L) by square root of three and the rms value of phase to phase voltage.

$$I_{rms} = \frac{P_L}{\sqrt{3} \cdot V_{ptp}}$$

The initial inductance, used especially to filter and smooth the rectifier input is calculated as the 5% of the phase voltage ($V_{ptp}/\sqrt{3}$) divided by the electrical pulsation ($\omega = 2\pi f$) times the value rms of current calculated in the previous equation.

$$L_{5\%} = 0.05 \cdot \frac{V_{ph}}{\omega \cdot I_{rms}}$$

Finally, the resistance load is calculated dividing the square value of output DC voltage in the rectifier ($\sqrt{6} \cdot V_{ph}$) by the overall power chosen for the load.

$$R = \frac{\left(\sqrt{6} \cdot V_{ph}\right)^2}{P_L}$$

Therefore, choosing a power of 10kW the parameters obtained are

- ✓ $L_{5\%} = 2.5mH$.
- ✓ $R = 32\Omega$.
- ✓ $L = 1mH$ chosen independently from the other parameters.

The further point performed is to simulate the circuit in MatLab – Simulink software. Using the three-phase generator, inductance parameters, resistance, diode rectifier, a current measurement and a scope it has been possible to build the proper scheme in order to study this type of distorting load.

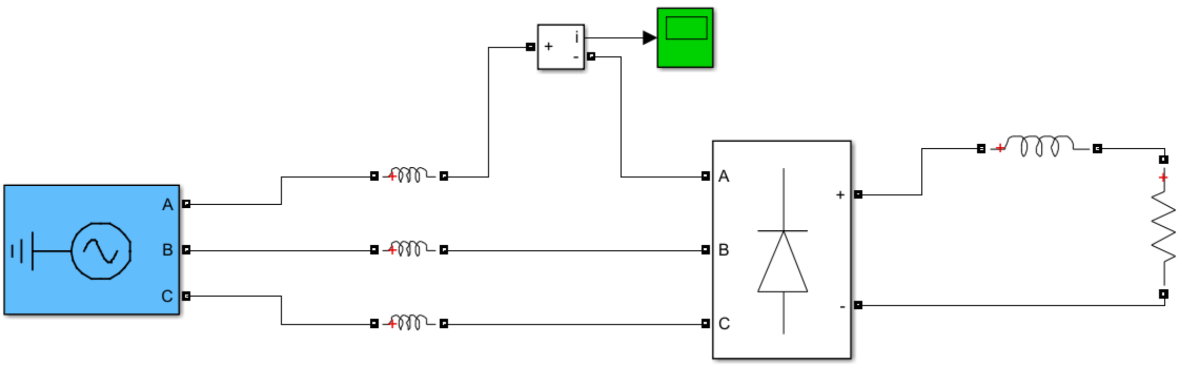

Fig. 32. Simulation scheme of the distorting load with RL parameters.

By means of the blocks presented above it has been possible to analyse the entire circuit, especially noticing the distorted current on one phase upstream the diode rectifier. This result is clearly shown in Figure 33. Each phase is subjected to a distortion, but for visual aspect just one phase has been represented in the graph below.

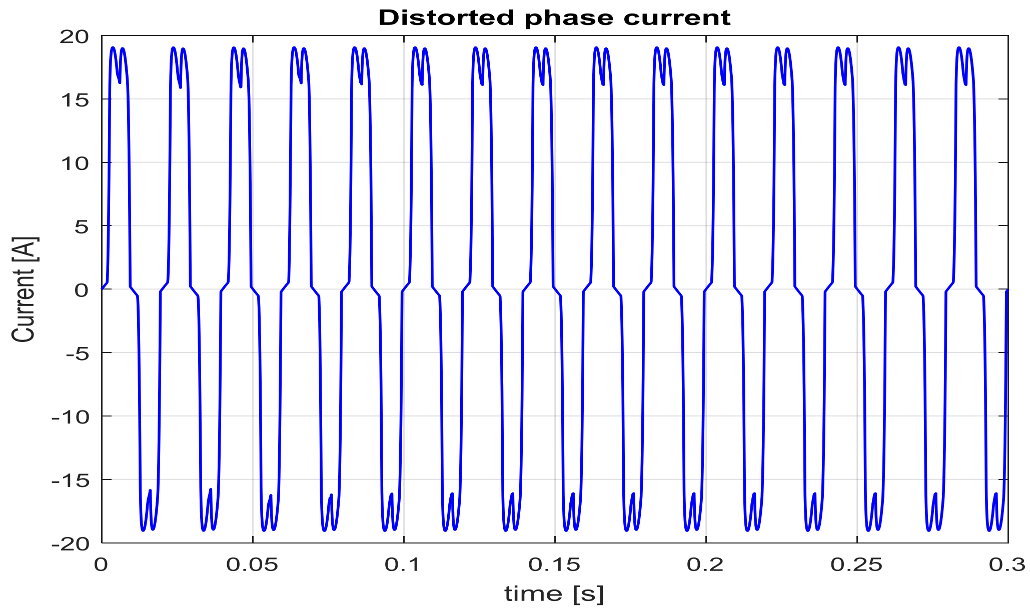

Fig. 33. Distorted phase current.

- ✓ ***Diode rectifier with RC load***

The second distorting load taken into account is a diode rectifier connected to a capacitor and a resistance. Its electrical scheme is shown in the following picture.

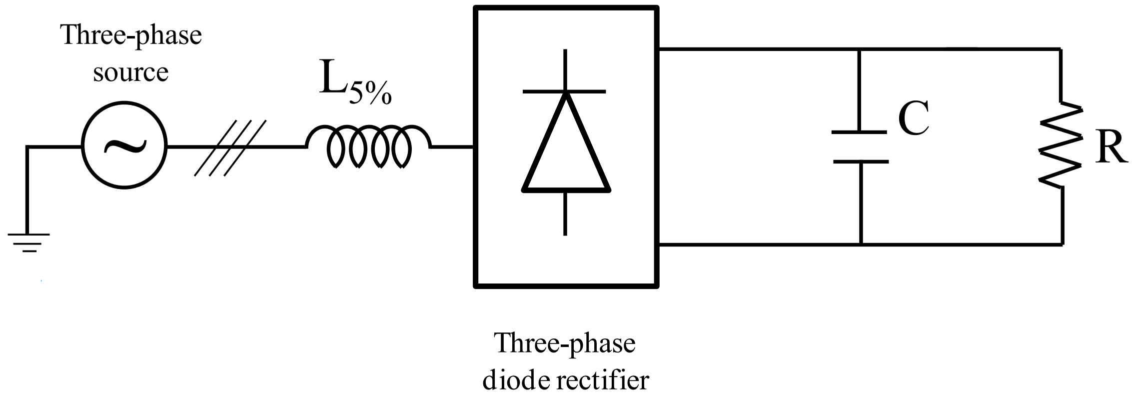

Fig. 34. Electrical scheme of a distorting load with RC parameters.

The procedure is very similar to the one concerning the first case. The source supply is always 400V phase to phase at 50 Hz and the parameters are calculated starting from the load sizing power. Parameters $L_{5\%}$ and R are calculated in the same exact way as before, but using the power of this particular case.

Therefore, choosing a sizing power of this distorting load equal to 10kW the parameters obtained are:

- ✓ $L_{5\%} = 2.5mH$.
- ✓ $R = 32\Omega$.
- ✓ $C = 20\ mF$ with a capacitor initial voltage equal to $V_{in} = 1.05 \cdot \sqrt{6} \cdot V_{ph}$; chosen both independently from the other parameters.

The following step in the simulation is the implementation of the parameters in Simulink – Matlab and, as before, using the proper blocks it has been possible to analyse this type of distorting load.

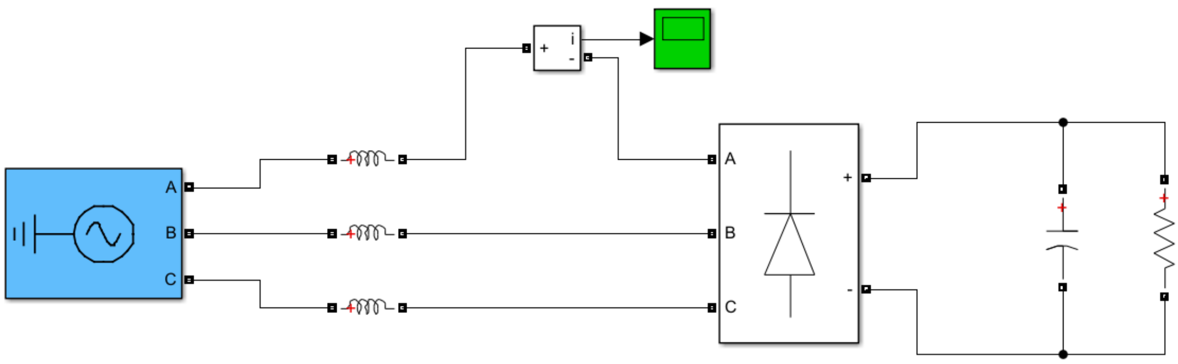

Fig. 35. Simulation scheme of a distorting load with RC parameters.

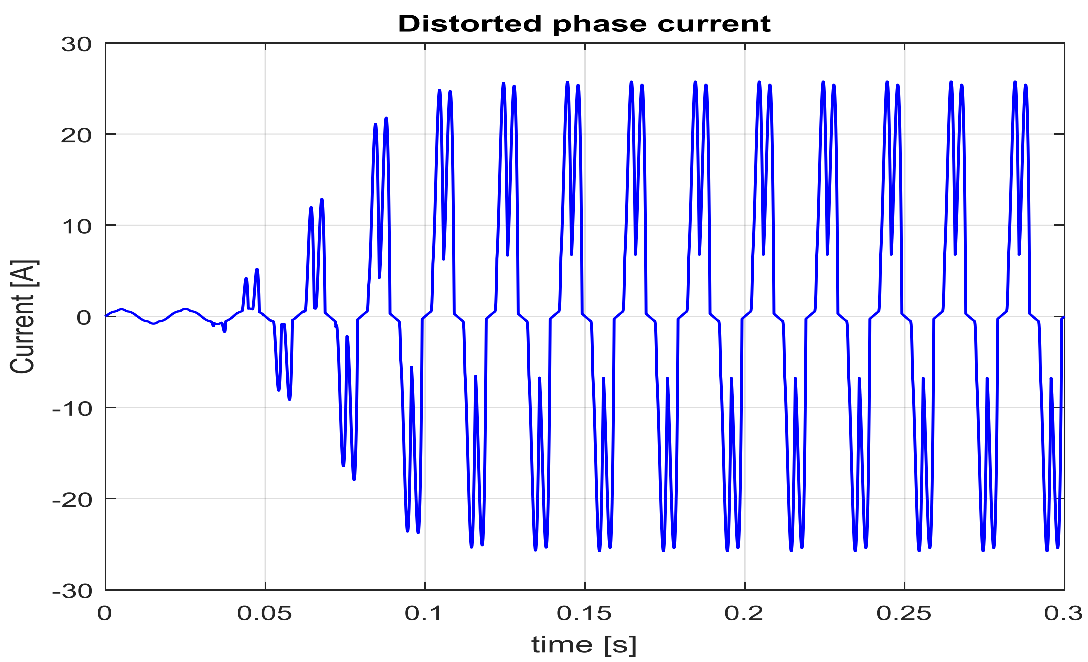

Fig. 36. Distorted phase current.

The last graph shows the distorted current in one phase upstream the diode rectifier. After an initial transient state of the load the distortions keep the same evolution during the entire simulation, causing a disturbed non – sinusoidal input current in the diode rectifier.

9.1.4. Overall simulation scheme

Combining all these elements presented (distribution system, dispersed generation and distorting loads) it is possible to construct the overall scheme of the distribution system, simulated with a normal three phase transformer between MV and LV grid.

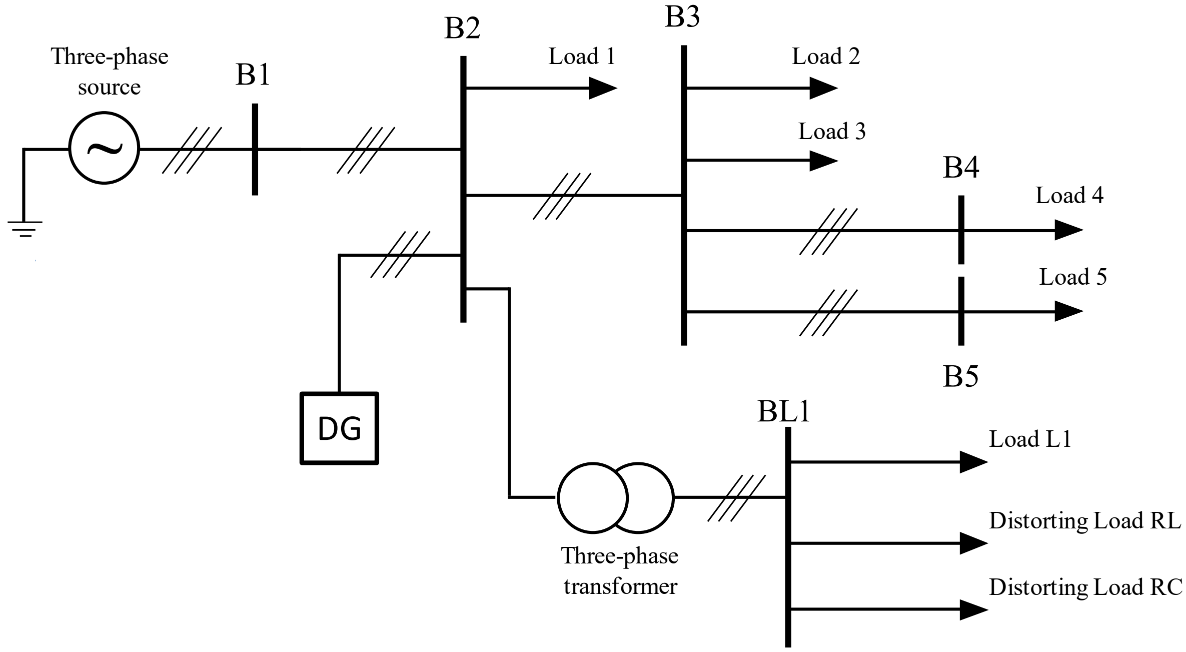

Fig. 37. Overall simulation scheme connecting dispersed generation and distorting loads to the distribution network interfacing MV and LV systems with a simple three phase transformer

The parameters used for this simulation are the ones already presented in the various elements: voltages, line parameters and loads are equal to the ones in the distribution system, dispersed generation input power is the same as the one in paragraph 9.1.2. and the distorting loads correspond to the ones just presented in the previous chapter.

Following these information and the electrical scheme taken into account it has been possible to implement the base distribution system with the extra elements of dispersed generation and distorting loads, achieving the final simulation scheme in Figure 38.

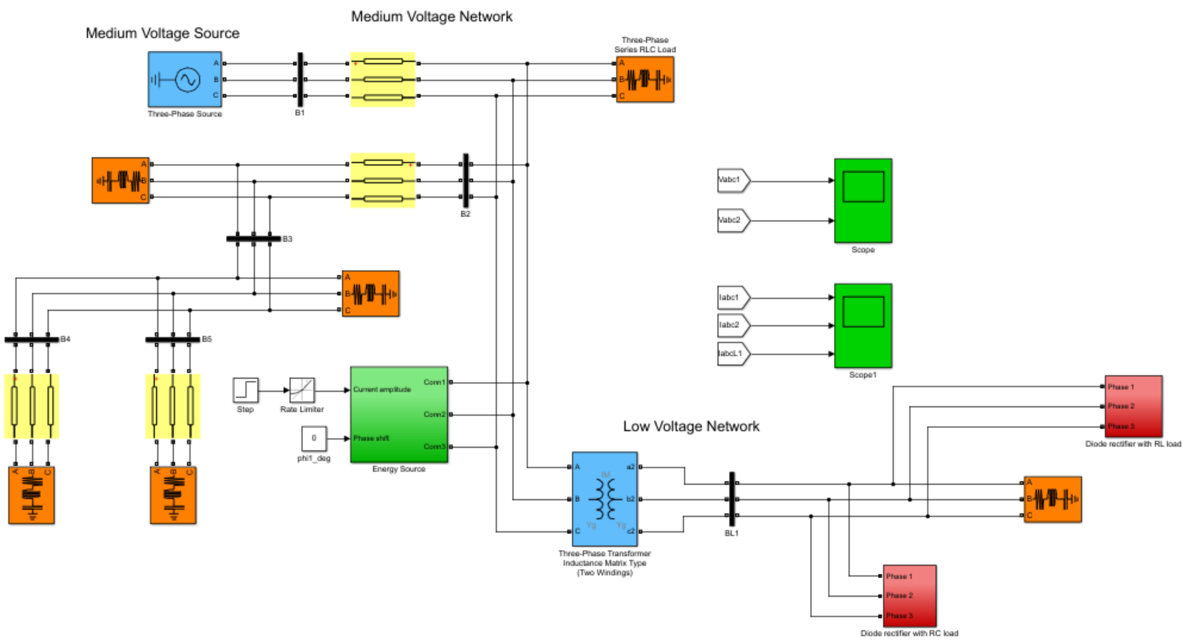

Fig. 38. Final scheme of the simulation without smart transformer, comprehending dispersed generation and distorting loads.

9.1.5. Simulation results

By means of the bus measurements and scopes present in the simulation it has been possible to analyse voltages and currents on the various point of interest of the distribution system.

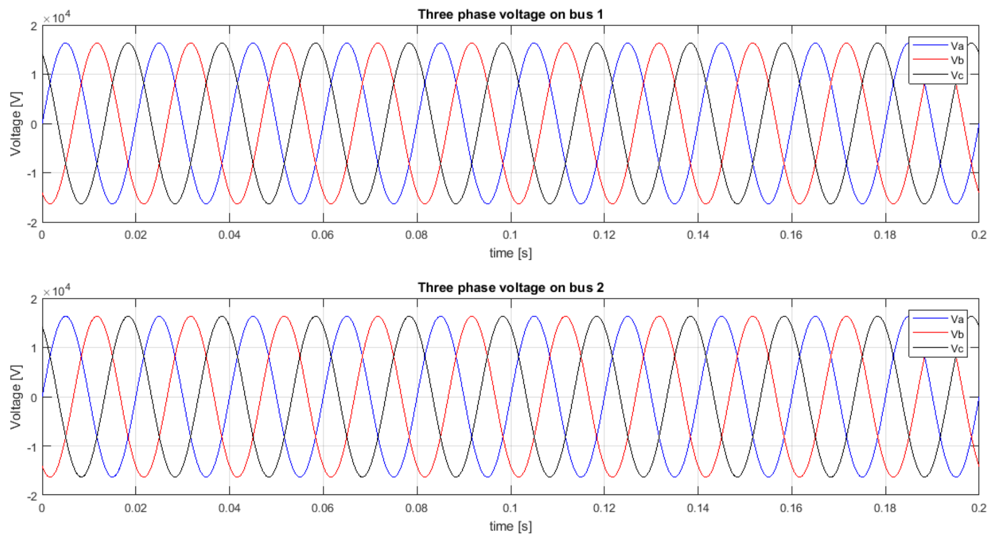

Fig. 39. Three phase voltages on bus 1 and 2 of the distribution network.

In Figure 39 it is possible to observe the evolution of the three phase voltages in bus 1 and 2: as the three phase generator dictates the voltage both voltage waveforms are perfectly sinusoidal and shifted by 120° in time. The introduction of dispersed generation and distorting loads does not affect the voltage waveforms in the distribution system. On the contrary, the same cannot be told regarding the currents. In fact, observing the currents on bus L1 (Figure 40) it is possible to notice that the currents in low voltage side are distorted because of the presence of both distorting loads with inductive and capacitive nature.

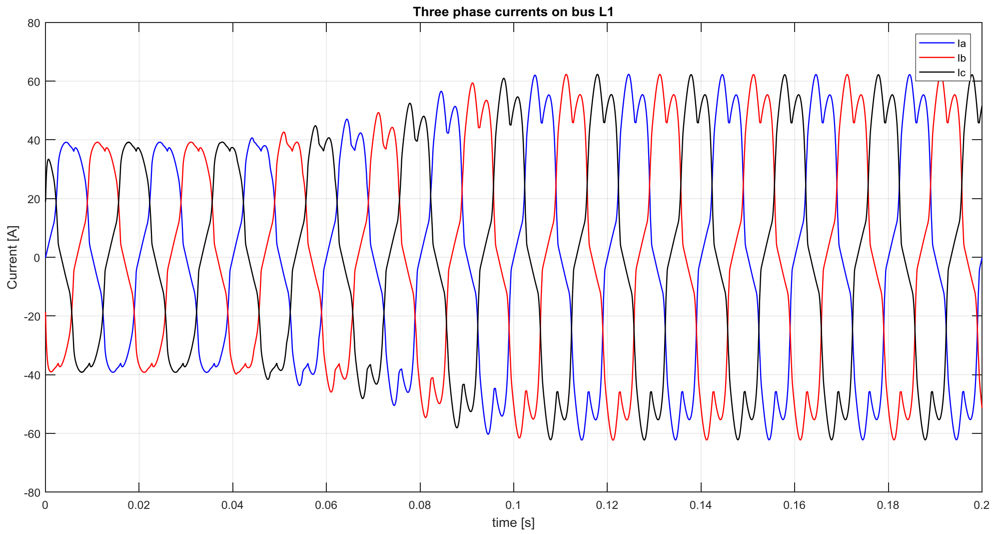

Fig. 40. Distorted current on bus L1 due to distorting loads.

These current distortions are the combination of the ones caused respectively by the distorting inductive and capacitive loads. Moreover, these distortions are transmitted in primary side as well, because the three phase transformer is not able to mitigate any disturb and separate the two side of the distribution network.

In addition, the primary side is affected also by the introduction of dispersed generation: at time 0.1s the distributed energy sources is turned on and the current supplied by the generator decreases as the case in paragraph 9.1.2. on bus 1. On the contrary, on bus 2 three phase current is always stable and sinusoidal (except of few unwilled resonant phenomena), in order to guarantee the proper supply to the network users. All these aspects can be observed in Figure 41.

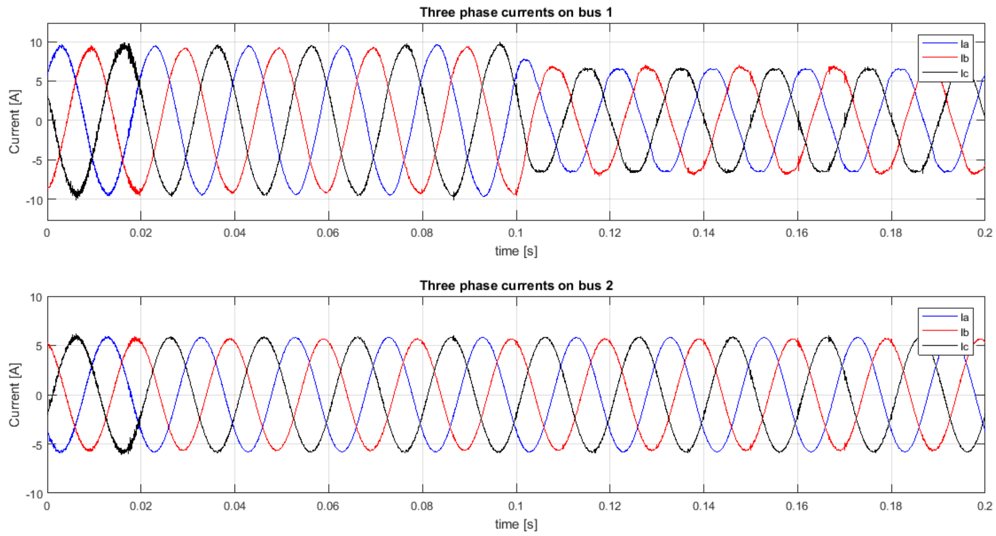

Fig. 41. Three phase currents on bus 1 and on bus 2 of the distribution network.

Three phase currents on bus 1 are affected by the distortions due to the distorting loads in LV side; especially after the introduction of dispersed generation.

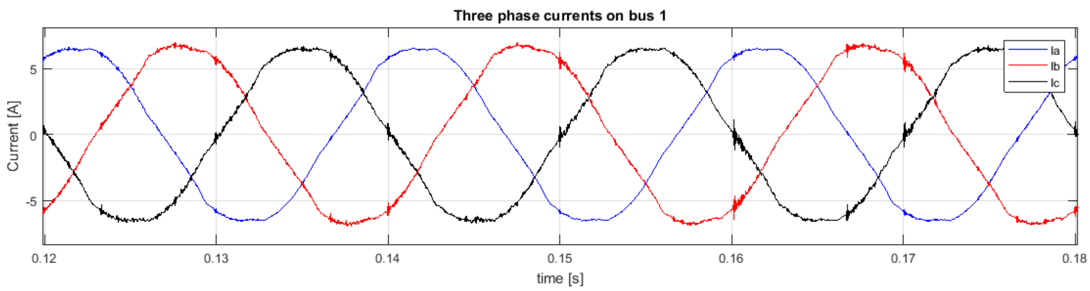

Fig. 42. A zoom of the distorted currents in bus 1 from 0.12s to 0.18s after the introduction of DG.

Focusing the attention in the steady state, it is possible to notice that the three phase currents are distorted because of the presence of distorting loads. Besides, the power introduced by dispersed generation is just the active one and without introducing also a reactive part the Total Harmonic Distortion of currents (THD_I) increases. Usually, the interfacing inverter of each decentralised generation is able to solve this problem and compensate the harmonics but when the sizing of the power plant change then all the operations have to be re-done. Therefore, to solve this problem and to improve the electric power quality the basic three-phase transformer is replaced with an intelligent solution: the smart transformer.

9.2. Simulation with Smart Transformer

The really important step of this simulation is the employment of the Smart Transformer instead of a normal three phase transformer. Three simulations have been performed with different loads at LV side and they are presented in the following chapters.

9.2.1. Simulation with linear load

The first simulation consists of a simulation implementing the basic scheme as before (paragraph 9.1.1.) with the smart transformer (ST) instead of the two windings three phase transformer.

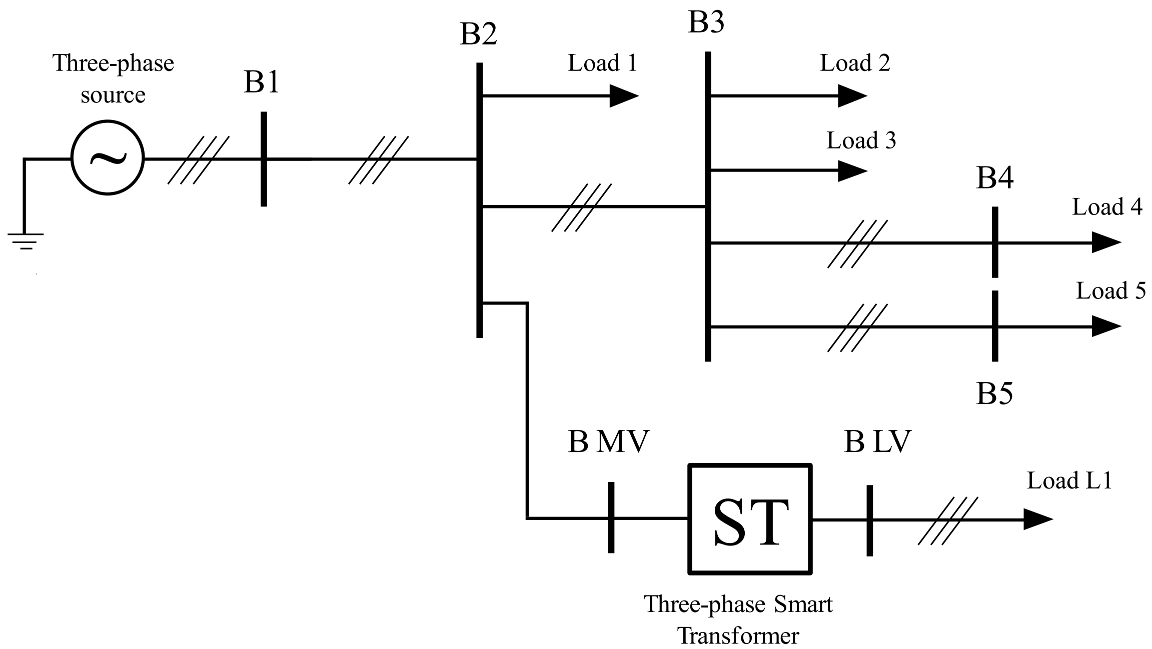

Fig. 43. Electrical scheme of the simulation employing the smart transformer

As already said, the simulation is just implementing the basic one, thus, impressed voltages, line parameters, network configuration and medium voltage loads do not change from the first case. The main difference is the introduction of smart transformer in the distribution system, followed by the presence of a linear load in low voltage side characterised by an active power of 10kW and a power factor of 0.9.

The following points in this chapter explain the simulation scheme and the control of the smart transformer in order to manage the distribution network in a proper way, achieving the advantages typical of this technology.

- ***Scheme of the distribution network***

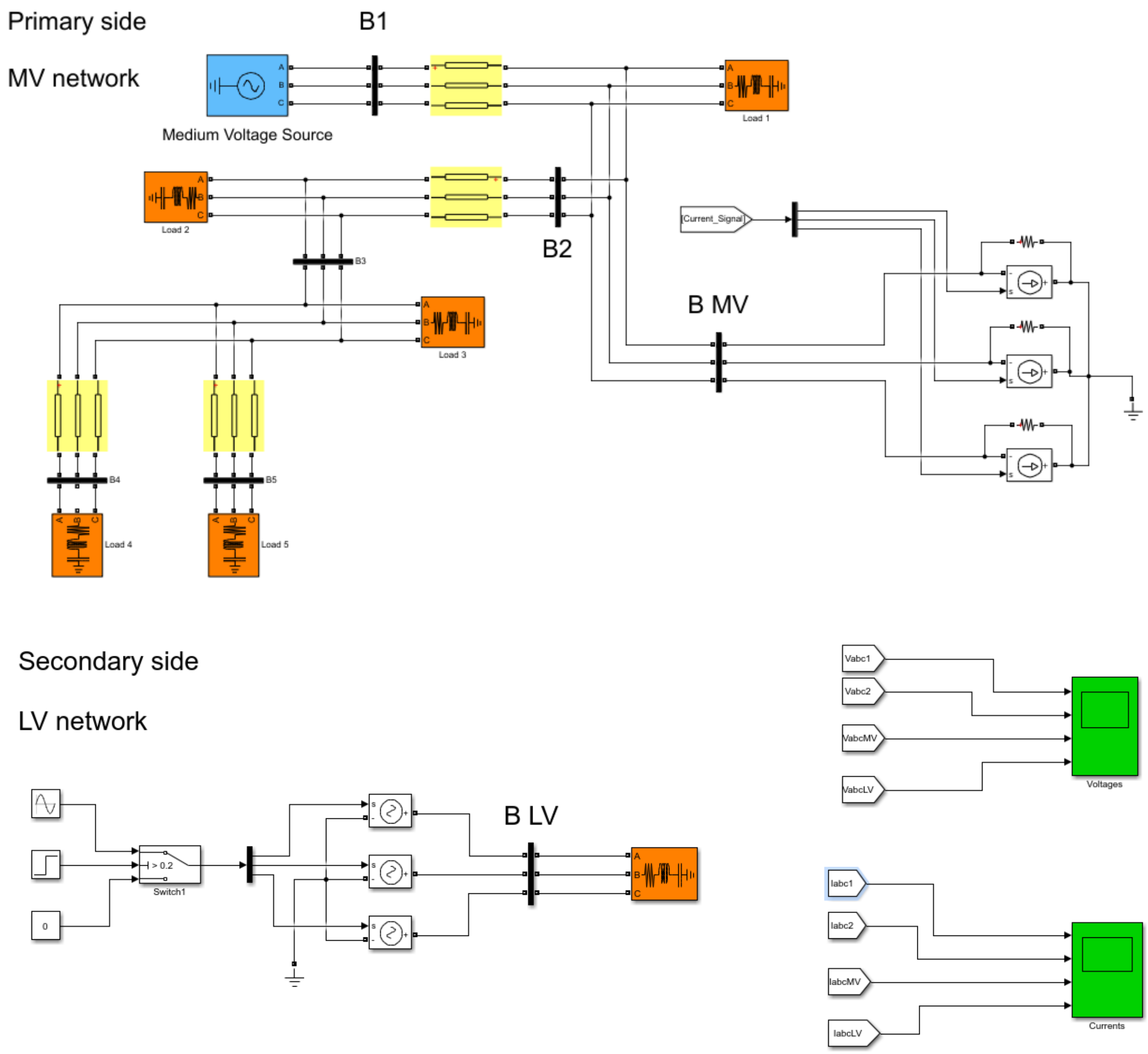

Fig. 44. Simulation scheme of the distribution system with smart transformer.

As it is possible to observe from this picture the smart transformer has been schematised as a combination of controlled generator, in particular three controlled voltage sources has been employed in the secondary side (LV network) and three controlled current sources on the primary side (MV network). In this way it is possible to guarantee a suitable voltage level in the LV system, varying just the current in MV system and keeping the same amount of voltage amplitude in the upstream MV network.

The input voltage in LV system is given by three sine wave signals shifted by 120° one another, dictating the three phase voltage of 400V phase to phase. This signal is given with a

step input activated after 0.1s from the beginning of the simulation, in order to observe the changes in the system due to the introduction of loads and smart transformer in the distribution network.
Moreover, with a few scopes it has been possible to observe voltages, currents and also powers in the distribution network and representing them in this chapter.

However, the most important part of the smart transformer consist of its control, and it is presented in the point below.

- ***Control scheme:***

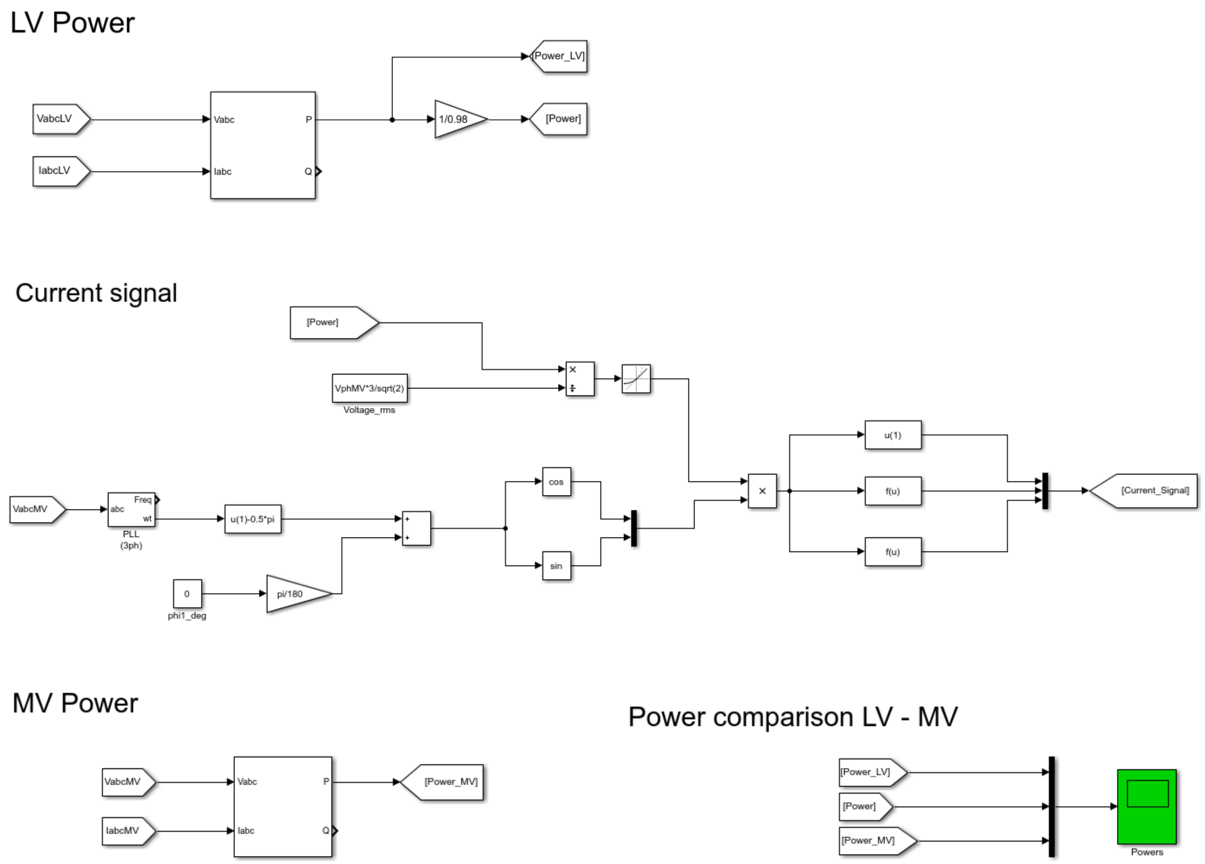

Fig. 45. Control scheme of the smart transformer in MatLab – Simulink sotware.

First of all it has been extrapolated the LV power (P LV) by means of a default block, and divided by an efficiency ($\eta = 0.98$) which summarises the possible losses of switches and passive devices inside the smart transformer. Consequently, it has been achieved the power that the primary MV side of the smart transformer has to transmit to the low voltage network, taking into account also possible losses. This power has been indicated with the input/output block “Power” (P).

Then, as the chapter 9.1.2. on the introduction of DG in the system, by means of a PLL it has been possible to detect the phase shift at which the currents in the primary side have to be introduced. Similarly to the mentioned chapter, the peak value of current has been achieved dividing the obtained power from before by square root of three times the voltage phase to phase (which in this case in MV side is 20kV) and multiplying everything times square root of two, passing from rms value to the peak one.

$$I_{max} = \sqrt{2} \cdot I_{rms} = \frac{\sqrt{2} \cdot P}{\sqrt{3} \cdot V_{ptp}}$$

Using these two information it has been possible to transform the reference system from alpha – beta to abc, obtaining the current signal to give to the controlled current generators on the primary side of the smart transformer.

To be sure of the control performed the power “P MV” on MV bus (B MV) close to the smart transformer has been measured as the LV one and both compared and observed on one scope.

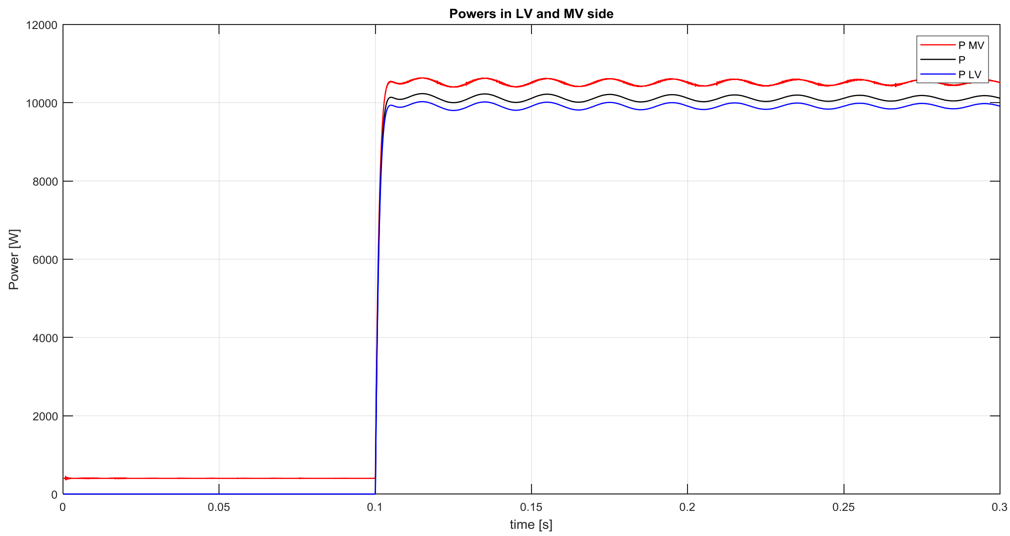

Fig. 46. LV and MV powers in the distribution system on the smart transformer sides.

In Figure 46 it is possible to observe the powers just discussed: the power transmitted as to control the MV current (P) is slightly higher than the LV one (P LV) and the one in MV side (P MV) contains also the power contributions of the upstream distribution system, staying in the difference between the red and black line.

- ***Simulation results***

By means of the scopes previously reported it has been possible to obtain voltages and current waveforms of the points of interest of the distribution network, that are B 1, B 2, B MV and B LV.

Firstly, it is possible to analyse three phase voltages around the distribution network and noticing that either in MV and LV network maintain a clear sinusoidal waveforms shifted by 120°.

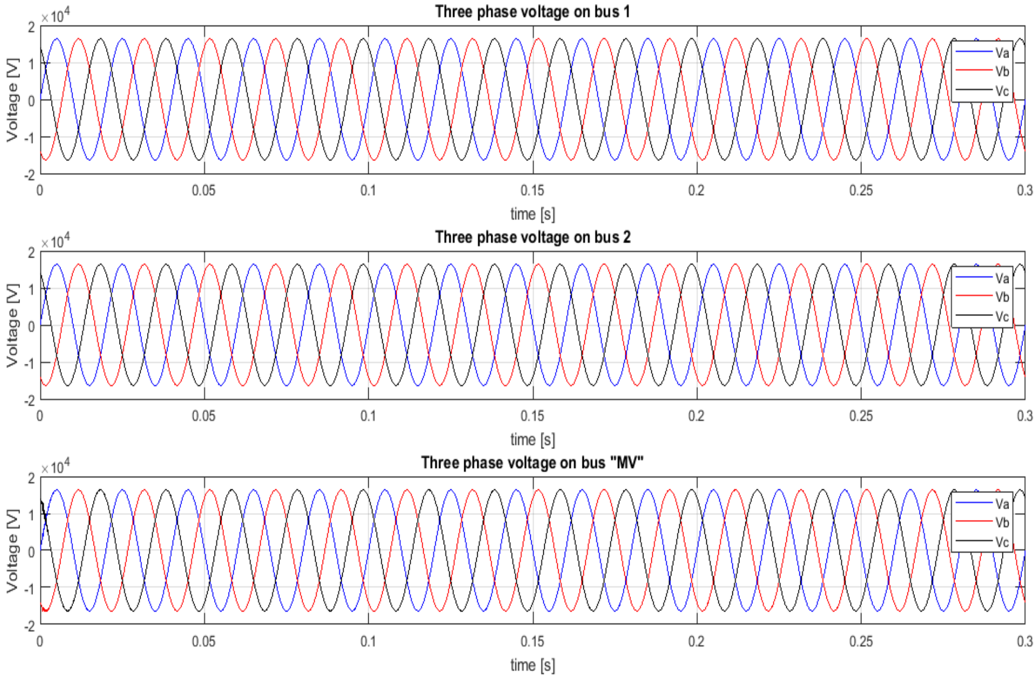

Fig. 47. Three phase voltages in MV network on bus 1, 2 and "MV".

These three voltages are continuous during the entire simulation because the three phase generator at 20kV phase to phase is always working. On the contrary, three phase voltages on LV side, represented in Figure 48, are activated at 0.1s because of the step signal input, but they are anyway perfectly sinusoidal with an amplitude phase to phase of 400V.

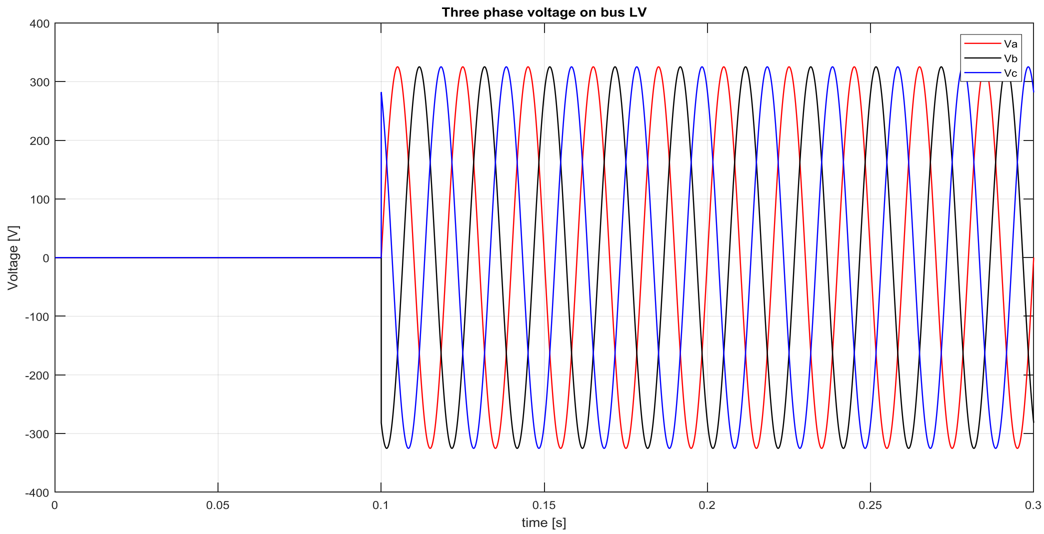

Fig. 48. Three phase voltages on LV network on LV bus.

Secondly, analysing the three phase current in the distribution network it is possible to observe that the currents inside the MV network are affected by the insertion of the load in the LV system.

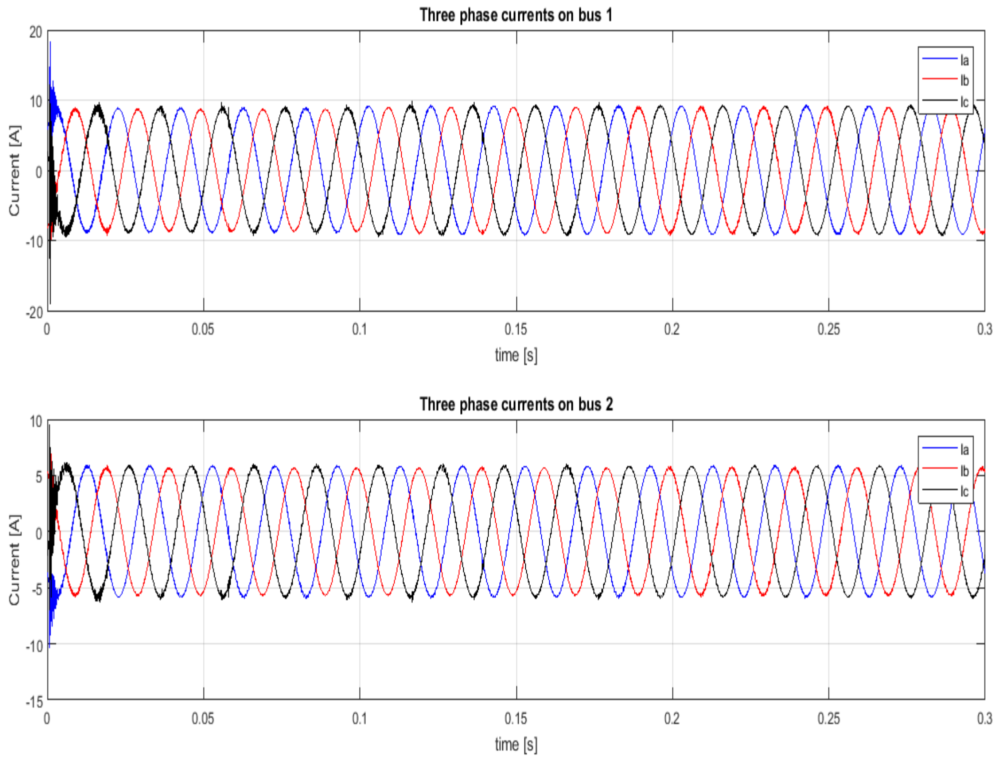

Fig. 49. Three phase current in MV network on bus 1 and bus 2.

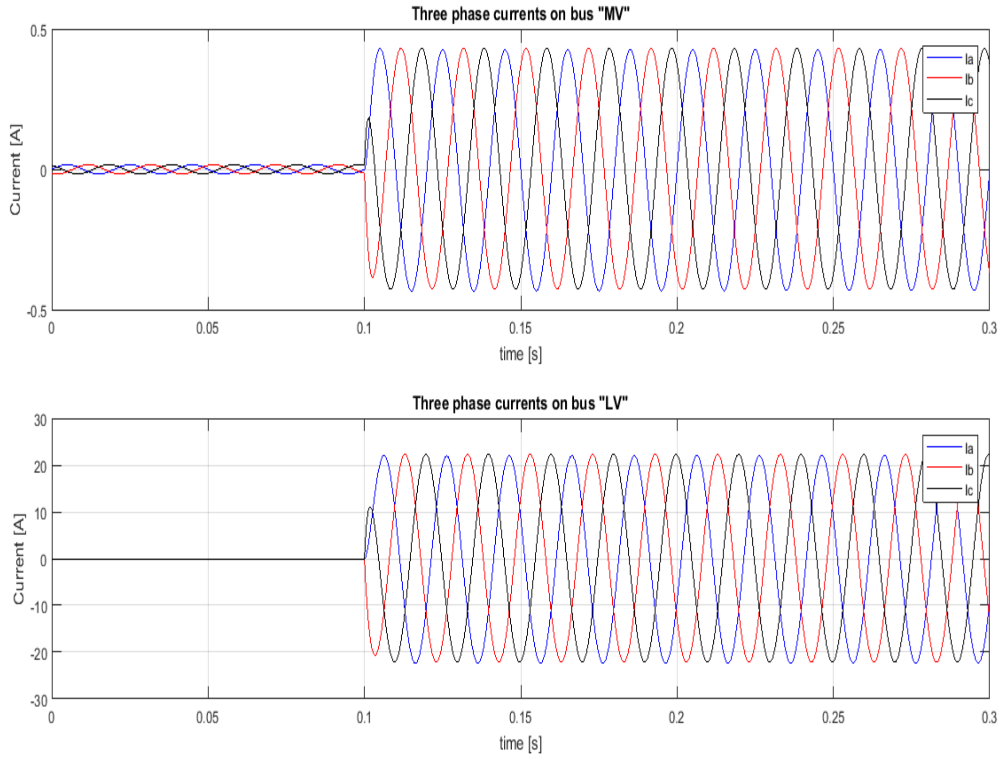

Fig. 50. Three phase currents on bus MV and bus LV.

At first, from these overall four graphs it is possible to notice that the low voltage current works as the relative voltage: until 0.1s there is no current in the LV network and after the command of the step input secondary current appears on the circuit. Then, this current is taken to the primary side of the smart transformer in MV network. In the primary side, as the voltage level is much higher, to have the same amount of power as the one present in the low voltage side (adding some losses), the current is lower, in fact it is possible to notice a LV current amplitude of 22A against a MV one of less than 0.5A. Therefore, from this graph it is not possible to notice the influence of the introduction of this load in the MV network on the bus 1, because the amplitude of current on this bus is 9A. However, the generator is anyway forced to supply more power (current) to the distribution system. On the other hand, MV currents on bus 2 maintain the same level during the entire simulation, in order to keep the end user of medium voltage system supplied with the same parameters.

To mark the effect of the load introduction on MV network (on bus 1) it has been changed the load on LV network from 10kW, cosφ 0.9 to a one of 100kW. The results obtained concerning the currents are presented in the following figures.

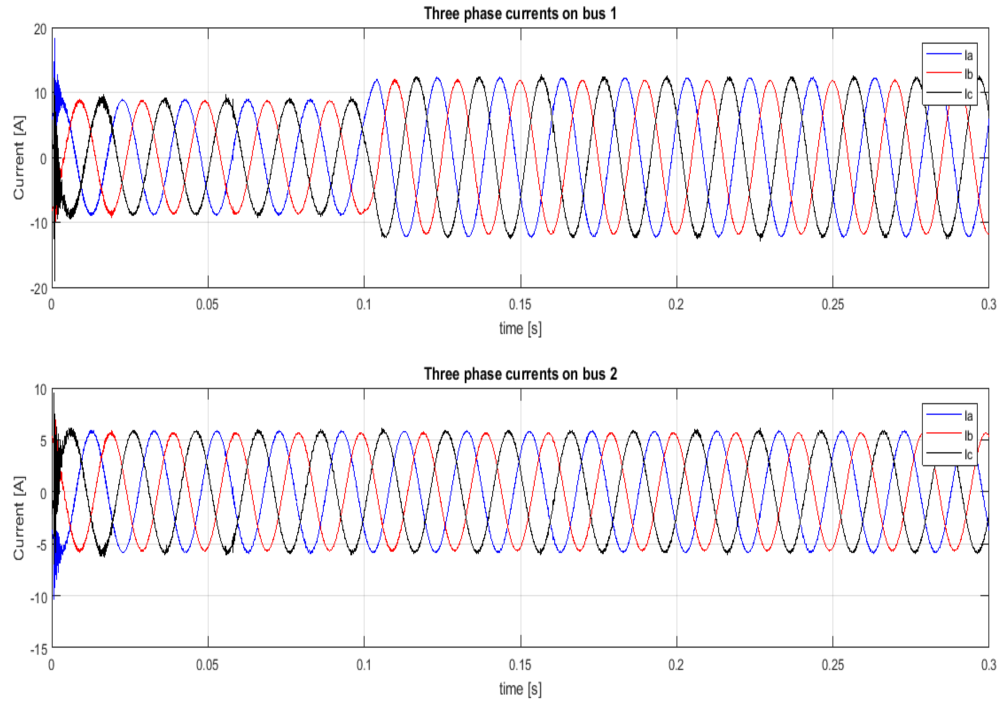

Fig 51. Three phase current in MV network on bus 1 and on bus 2, in case of a bigger load in LV network.

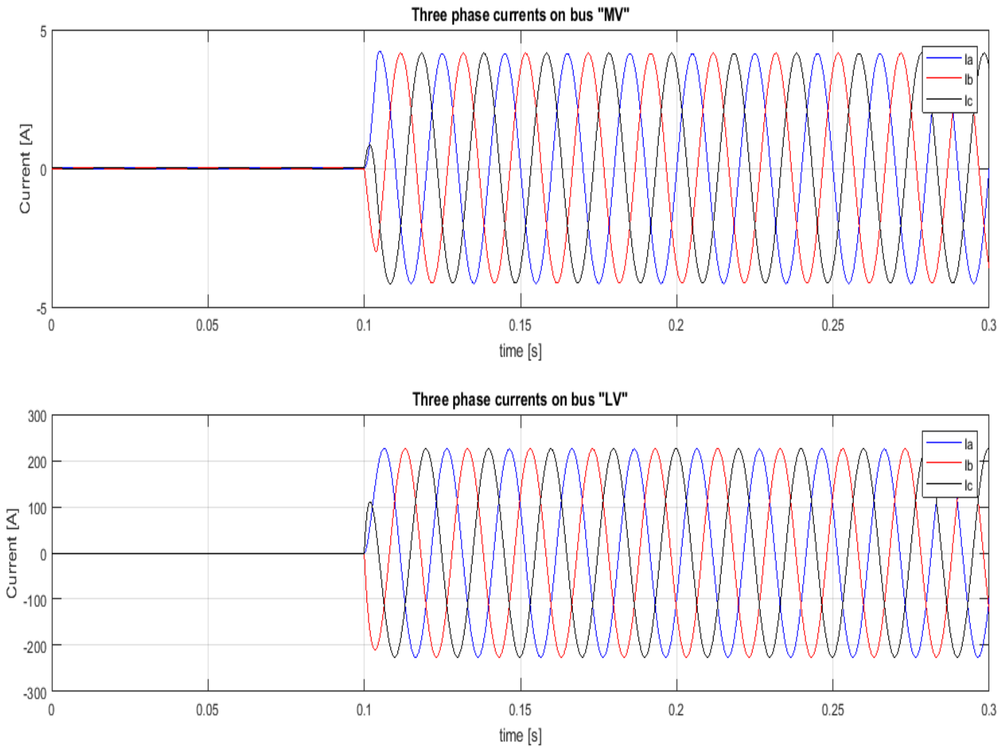

Fig 52. Three phase currents on MV and LV buses in case of a bigger load on LV side.

From these last four graphs it is possible to notice the influence of the loads on bus 1. This time LV current is higher and thus also the one on MV bus. Therefore, this current affects the bus 1, making the generator supplying more current to the distribution system, keeping in any case the current level on bus 2 stable.

The important point of this simulation is that it is possible to work on both side independently one from another, especially employing several loads characterised by completely different power factors.

9.2.2. Simulation with linear and distorting loads

The second analysis employing the smart transformer consists of adding to the basic simulation of before two distorting loads characterised by inductive and capacitive nature.

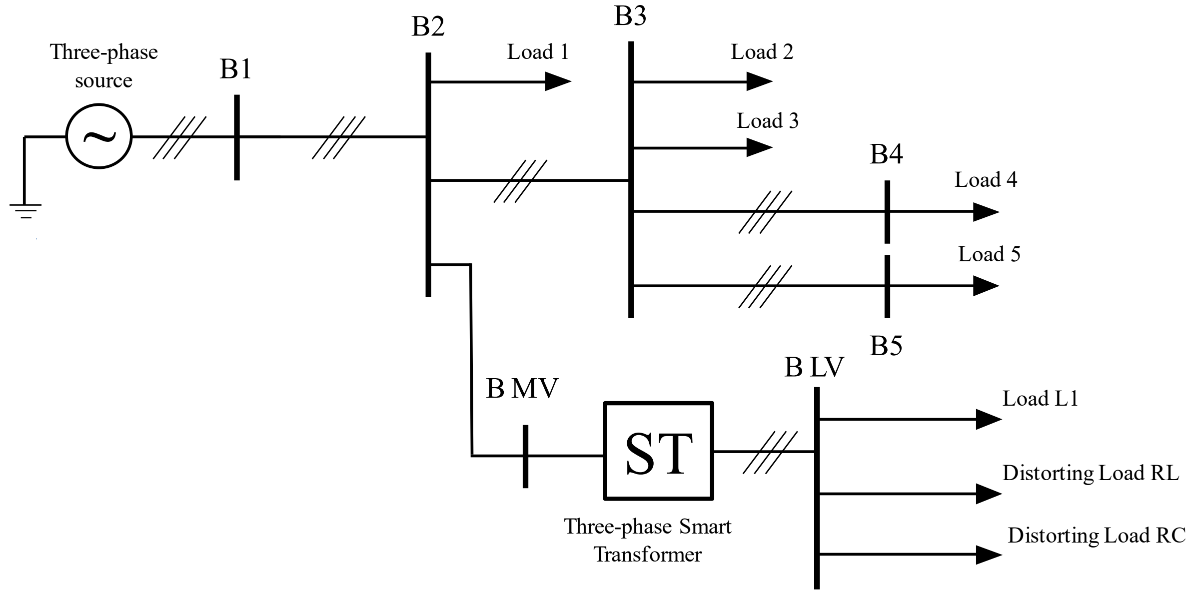

Fig. 53. Electrical scheme of the distribution network implementing the smart transformer with distorting loads on LV grid.

To solve the visual problems of before it has already been chosen a LV load higher than the 10kW one and equal to 50kW with a power factor of 0.9, leading to a reactive power of 24 kVAr.

- ***Scheme of the distribution network***

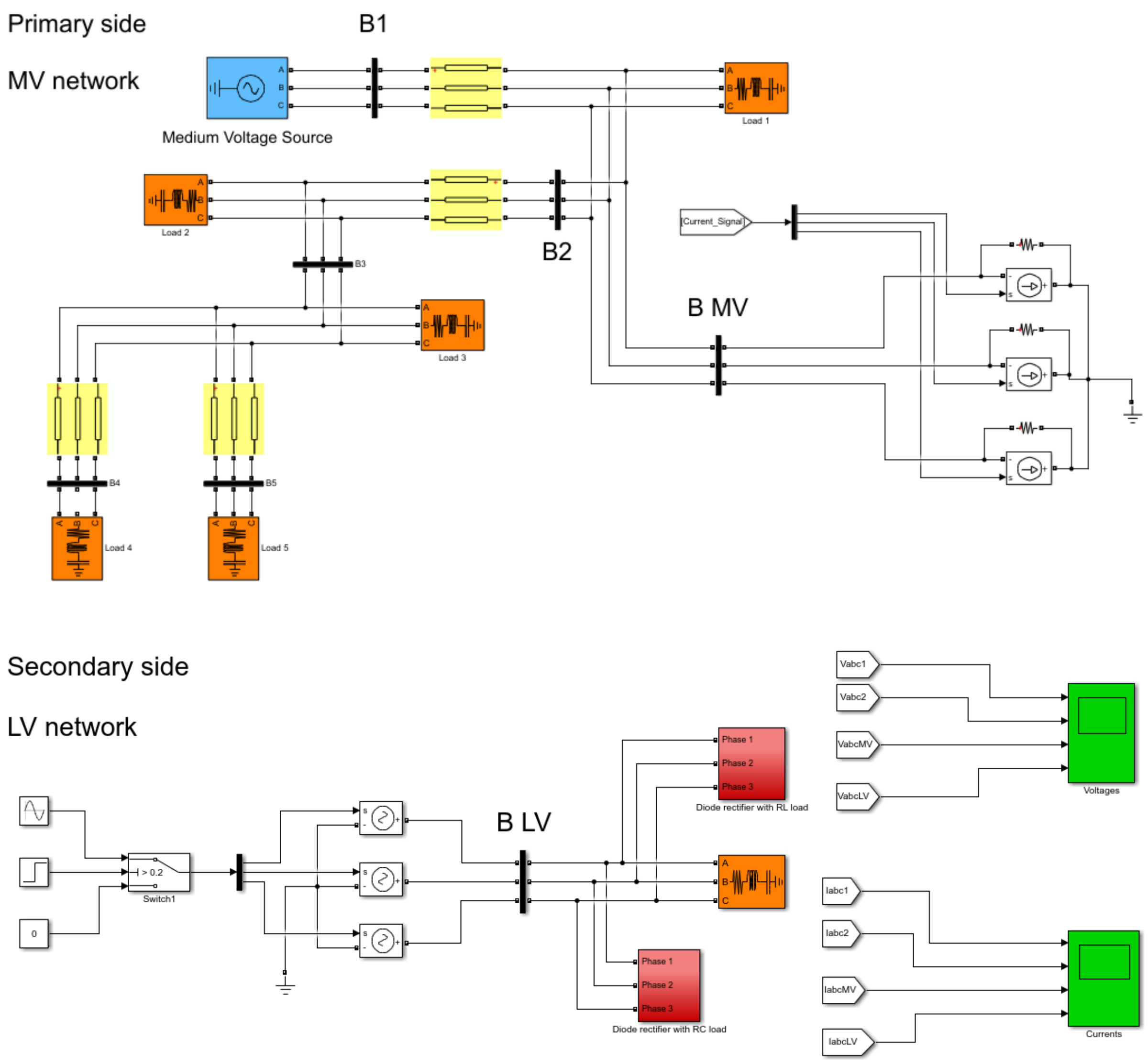

Fig. 54. Simulation scheme of the distribution network employing the smart transformer with two distorting loads on LV grid.

From the first simulation, except the increase of the power in the load in LV network, the only thing changed is the introduction of the two distorting loads (red blocks) characterised by a power of 10kW each in the LV grid. This fact takes not many changes in the network itself but the control of the smart transformer has to change, because the power requested from the overall LV load is not as smooth as the previous case. The implementation of the control system is shown in the following point.

- ***Control scheme***

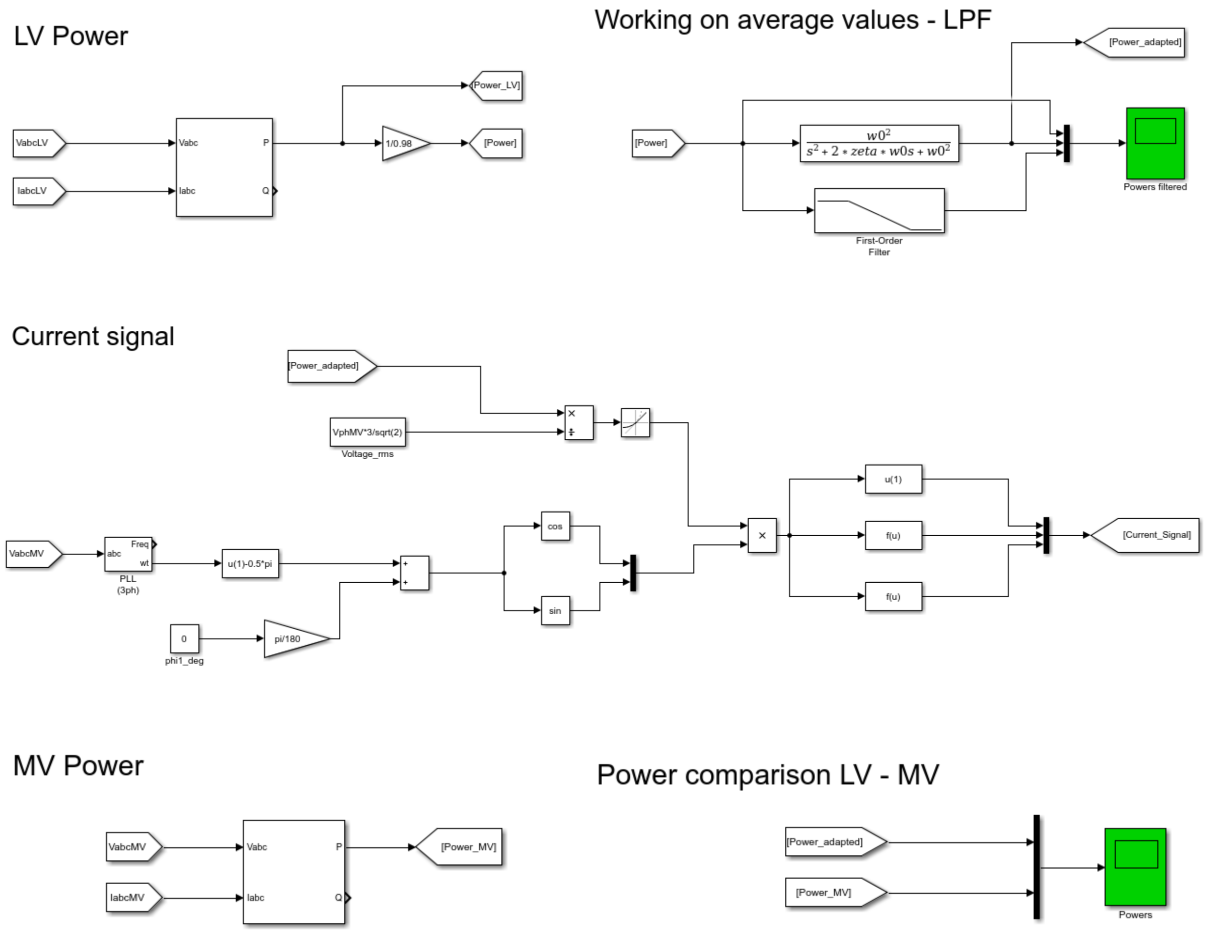

Fig. 55. Simulation control scheme of the smart transformer in the presence of distorting loads.

Regarding this simulation, the power of the smart transformer at LV side is a waveform composed of a sixth harmonic summed by a mean value. Therefore, it is necessary to not transmit all the signal to the medium voltage side, but just the mean value. To perform this action a Low Pass Filter (LPC) has to be adopted in the simulation. It is possible to employ a first order or a second order low pass filter: the choice is the consequence of their comparison in this specific case, shown in the part of blocks "Working on average values - LPF". As low pass filters parameters it has been used a cut off frequency (f_c) of 10 Hz, then a cut off pulsation of $\omega_c = 2\pi f_c$ equal to 62.83 rad/s and a damping factor (ζ) of $\sqrt{2}/2$. The results of this test are achieved by a scope and reported in the following figure.

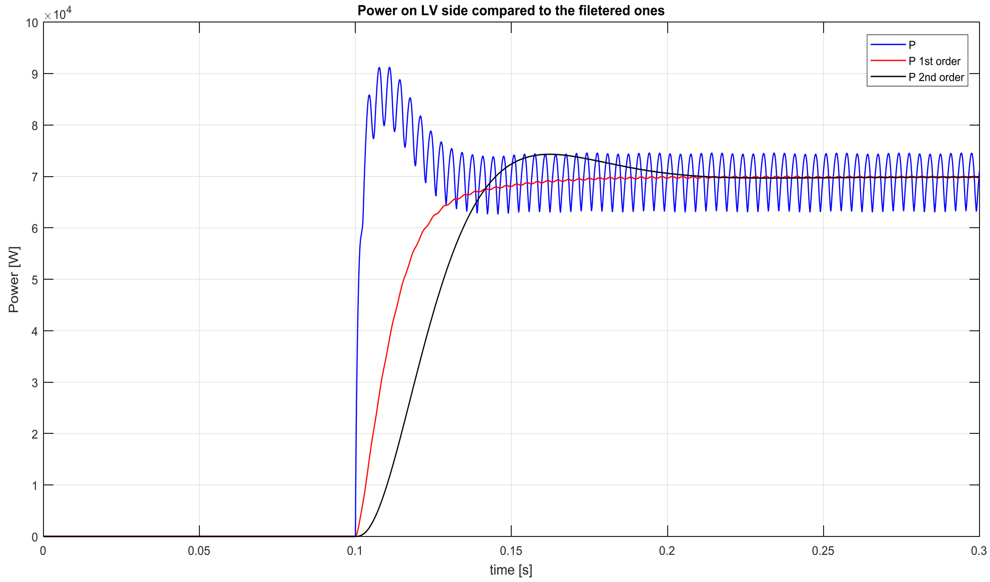

Fig. 56. A comparison between the power on low voltage side and the filtered ones.

Observing this graph it is possible to notice the sixth harmonic summed to the mean value as the power in LV network in blue, the filtered response with a first order low pass filter (in red) and with a second order one (black line). The response of the first order filter is fast but presents more oscillation during the following time. On the other hand, the response of the second order filter is slower than the first one but without oscillation in the steady state (Figure 57). As a result, the filter adopted is the second order one and particular attention has to be put in the steady state results.

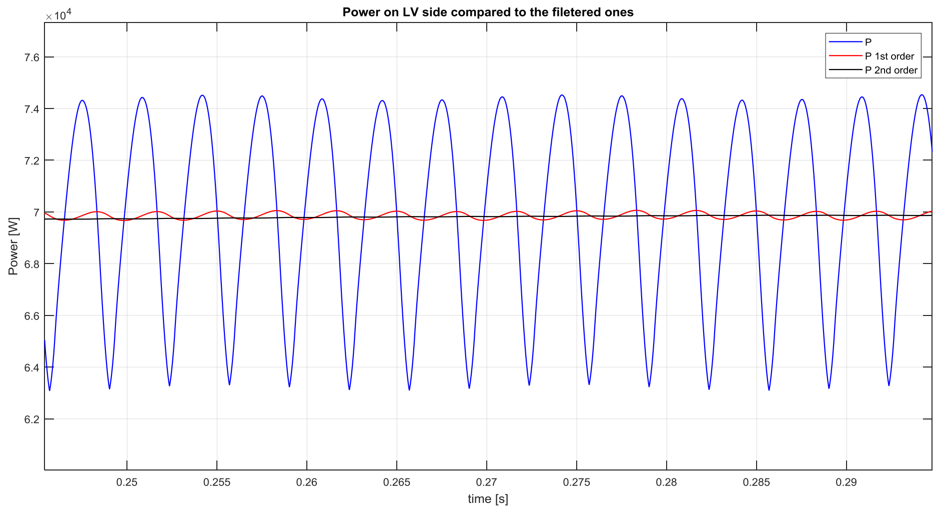

Fig. 57 A zoom on the steady state of the previous graph.

Therefore, adopting the second order low pass filter it is possible to obtain a suitable power signal called Power_adapted, instead of simply Power as before. Then, it is possible to transmit this indication to the next controller, which achieves the current signal to give as input to the controlled current sources on the ST primary side. Obtaining the peak current value from this power with the same procedure as the first case, combining it to the phase shift of the MV bus and transforming it to the abc reference system it is possible to acquire the current signal to control the primary side of the smart transformer. To conclude the argument about the powers in the system it has been possible to measure the power transmitted to the three controlled current generators and the one on MV bus close to the primary of the smart transformer.

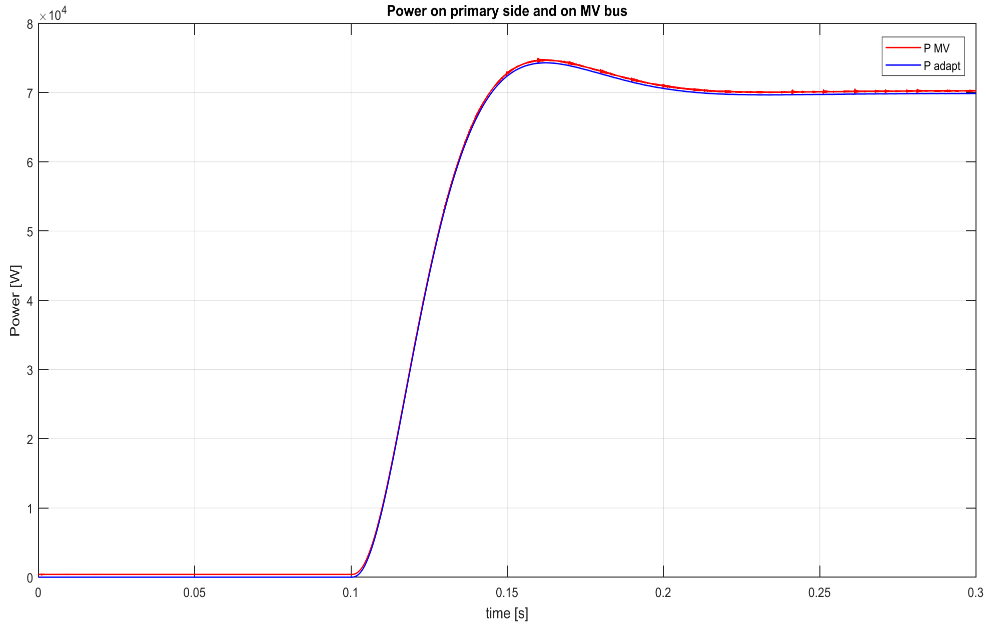

Fig. 58 A Power on MV bus and on primary side of the ST.

It has to be known that in this case, as the previous one, the power requested to the primary side of the smart transformer is the LV one added by some possible losses considered dividing this quantity by an efficiency of 0.98.

As shown in the graph, power requested on MV side and the one on MV bus differ from a quantity equal to the power on the other part of the MV network. In normal cases this power difference is higher, because the network is more loaded than this one taken into account.

Finally, the results of voltages and currents in the distribution network are presented in the following point.

- ***Simulation results***

Employing the various scope inside the simulation it has been possible to obtain the measurements of voltage and current in the distribution network, especially on bus 1, bus 2, bus MV and bus LV.

Starting with three phase voltage values it is possible to notice a case equal to the previous one with the absence of distorting loads in LV network. As shown in Figure 59, voltages in MV network on bus 1, bus 2 and bus MV keep the three phase sinusoidal shape for the entire simulation.

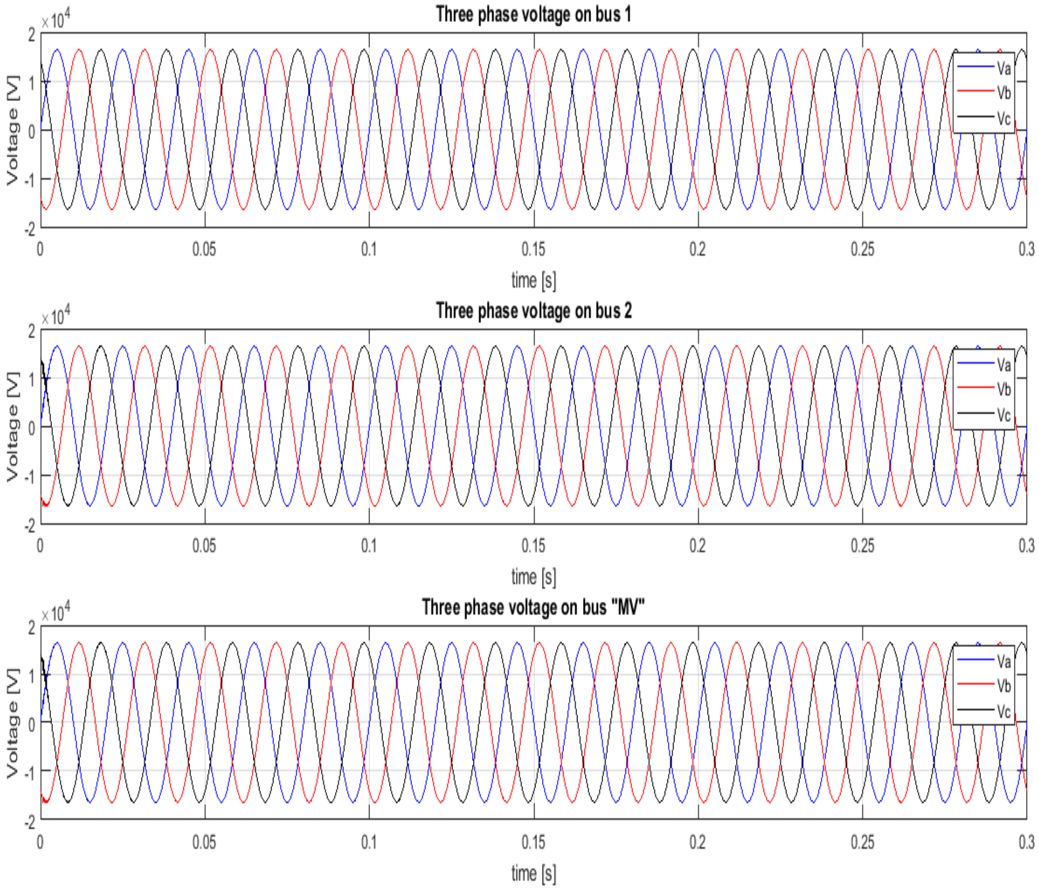

Fig. 59. Three phase voltages in medium voltage network.

In addition, three phase voltage on bus LV maintain the correct three phase waveform as well, but just after the activation of the source at 0.1s, before this time the network voltage is equal to zero (Figure 60).

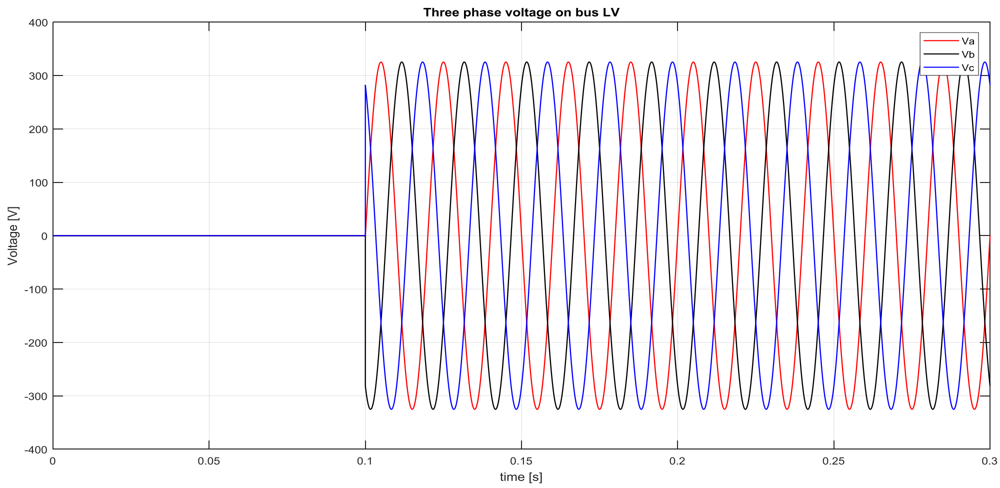

Fig. 60 Three phase voltage in low voltage network.

Regarding the network currents it is possible to observe on LV grid the distortions in all three phases due to the introduction of the distorting loads in the system. This phenomenon, visible in Figure 61, is subjected to a peak right after 0.1s when the source is activated and then decreases, keeping a stable level of distorted currents on LV bus. However, thanks to the control implementing the second order low pass filter, the distortions are not transmitted on MV network, which the currents maintain a sinusoidal shape shifted by 120°.

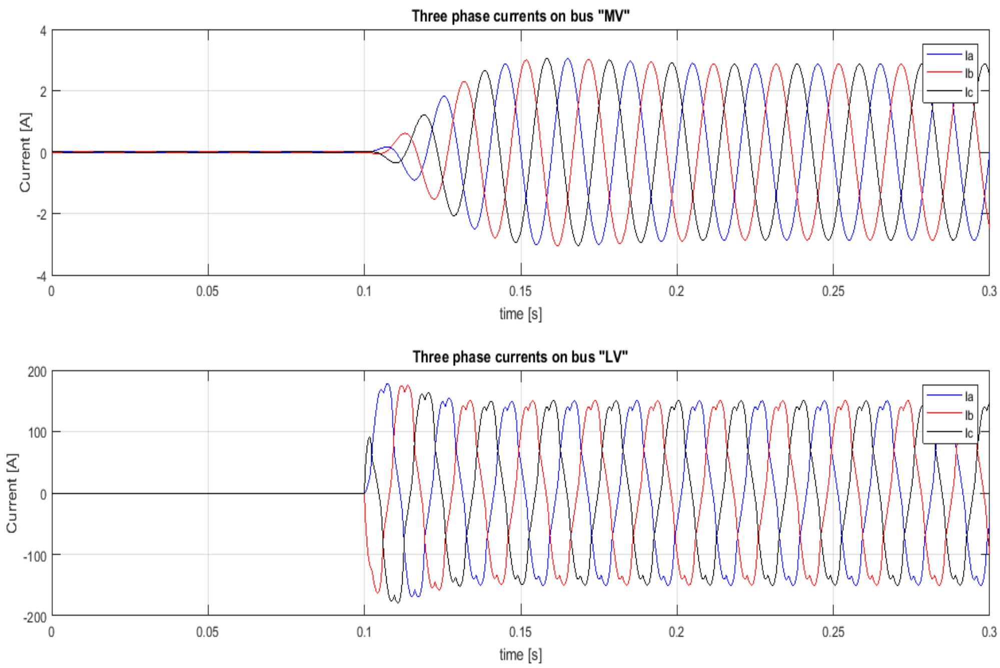

Fig. 61 Three phase currents on MV bus and in low voltage network.

Moreover, it is possible to observe that the initial peak of distorted current is damped by the control in the MV bus, but a minimal part is still present in the system. In fact, in the initial instants after the activation of the source, the current in MV reach a maximum value and then slightly decrease achieving the steady state value. The influence of the introduction of the load is visible also from the three phase current on bus 1 (in Figure 62), where the generator has to supply more current (power) after 0.1s in order to guarantee a proper working of MV and LV users.

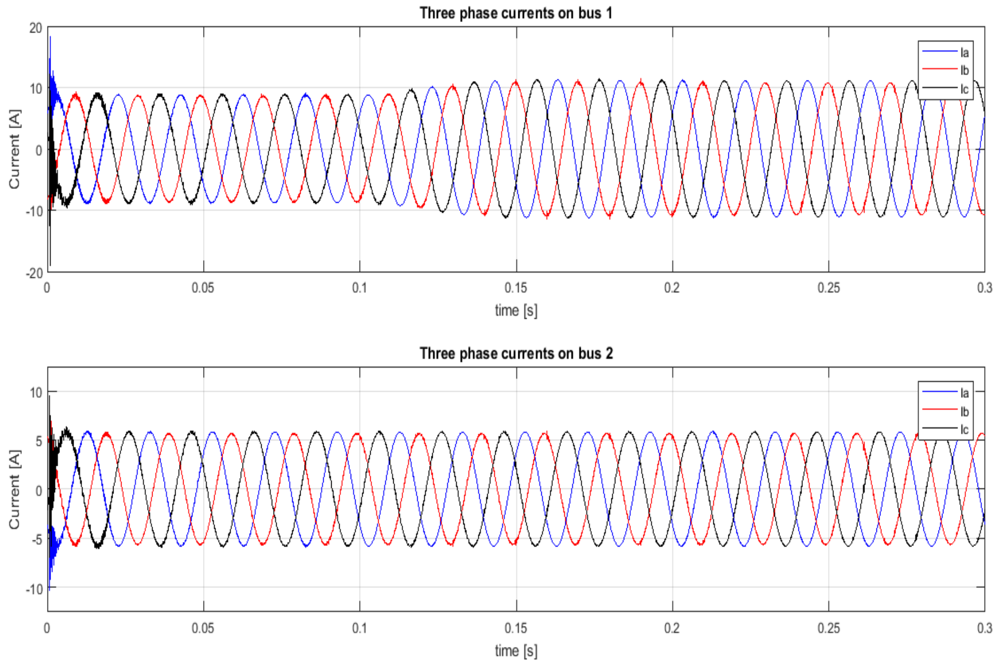

Fig. 62 Three phase currents in MV network on bus 1 and bus 2.

On the other hand, as any case studied until now, currents on bus 2 are not affected by the introduction of distorting loads in LV grid, and the currents keep the proper sinusoidal shape shifted by 120° one from each other.

9.2.3. Simulation with linear, distorting and unbalanced loads

The last analysis performed consists of the introduction of an unbalanced load in the LV grid, obtaining linear, distorted and unbalanced loads.

The only difference from the previous case is the presence in LV grid of a load between two phases (a and b) characterised by an active power of 20kW and a power factor of 0.928. The three phase generator, loads, line parameters and all the others features of the simulation are kept unaltered. Therefore, as presented in Figure 63, the only part slightly changed of the simulation is the LV network.

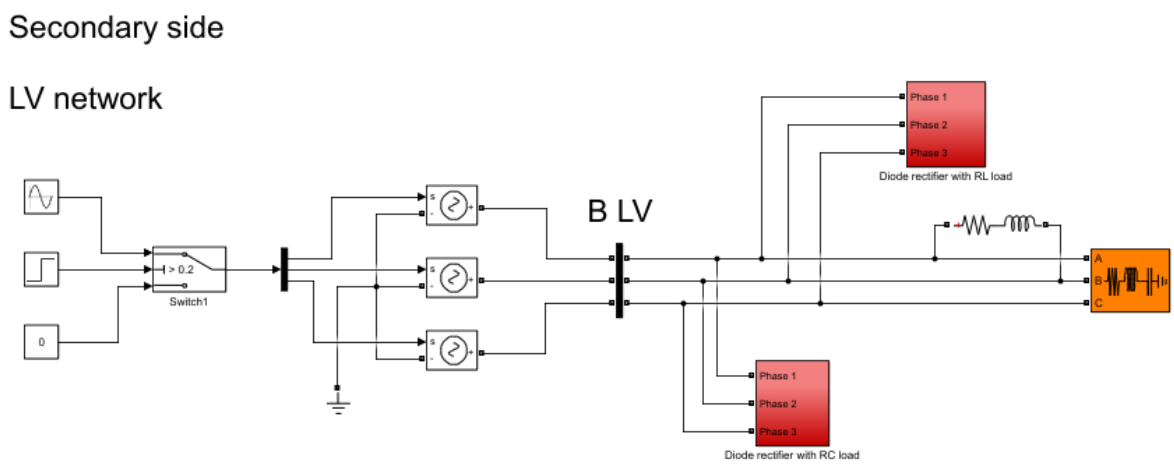

Fig. 63 LV network of the simulation, noticing the load between two phases of the system.

Besides, the control scheme does not change from the previous case as well: the power transmitted from LV network is adjusted by an efficiency and filtered with a second order low pass filter. This filter has to face more instability than before but it is able to carry anyway a proper current signal to manage the controlled generators in the primary side of the smart transformer.

In addition, three phase voltages around the entire distribution network are equal to the ones in the previous cases: voltage levels are kept stable and the currents have to adapt their values in order to guarantee the exact amount of power to the different loads connected to the grid.

Consequently, just the currents among the distribution network are presented, observing the differences with the other cases.

Due to the introduction of a load between two phases it is possible to notice the addition of an unbalanced contribution in current summed to the distortions caused by the two distorting loads (Figure 64).

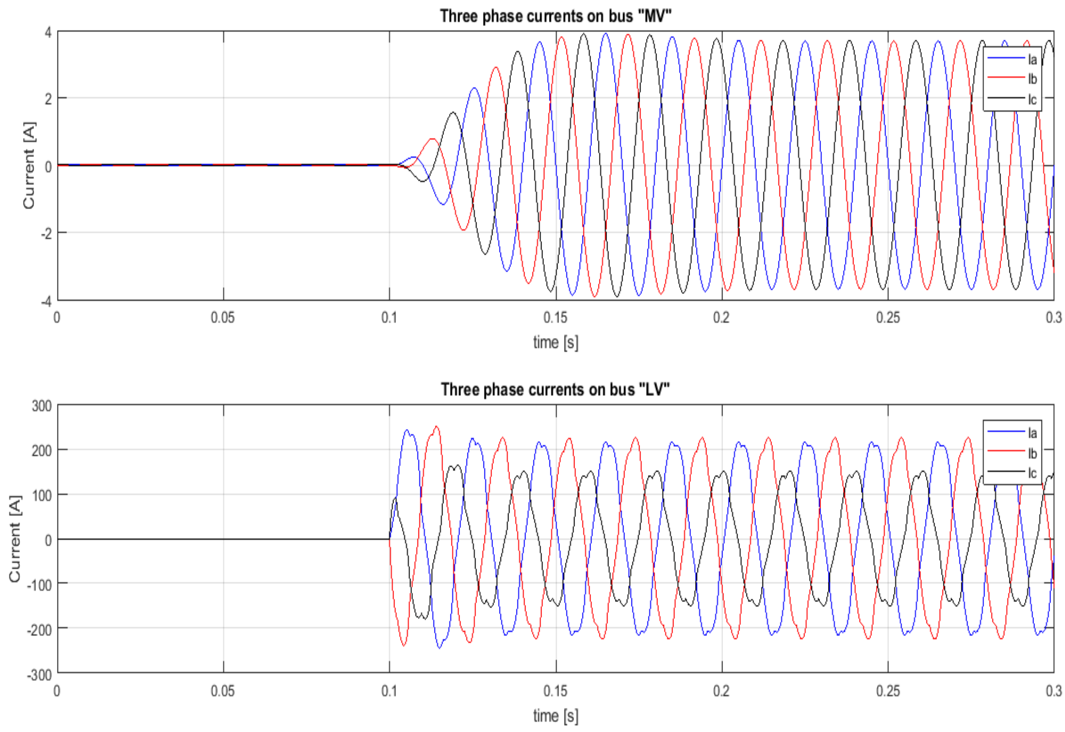

Fig. 64. Three phases currents on LV bus and on MV bus at both side of the smart transformer.

The extra load is connected between phase a and b, thus, phase c is less loaded and presents an amplitude lower than the other two (black line in the second graph). The currents are activated after 0.1s as the other cases and present an initial amplitude higher than the steady state one.

This first initial peak is also visible from the currents in MV bus, which increase at 0.1s from their first low values (as the LV side is unloaded) to the ones of almost 4A and slightly decreasing in the steady state. However, these currents are always perfectly sinusoidal and shifted by 120°: distortions and unbalances are not transmitted from LV side to the MV one.

Finally, observing Figure 65, it is possible to notice the influence of this current on the other buses in MV network. Bus 2 is not affected at all by the introduction of an unbalanced load in the LV network and it maintains its currents stable and sinusoidal, keeping its downstream users supplied with a reliable level of power.

On the other hand, bus 1 is subjected to an increase of the three phase currents flowing through it, equal to the one requested to feed the primary side of the smart transformer. As a result, the generator has to increase its supplying power and output current in order to guarantee the proper working of the loads of the distribution network.

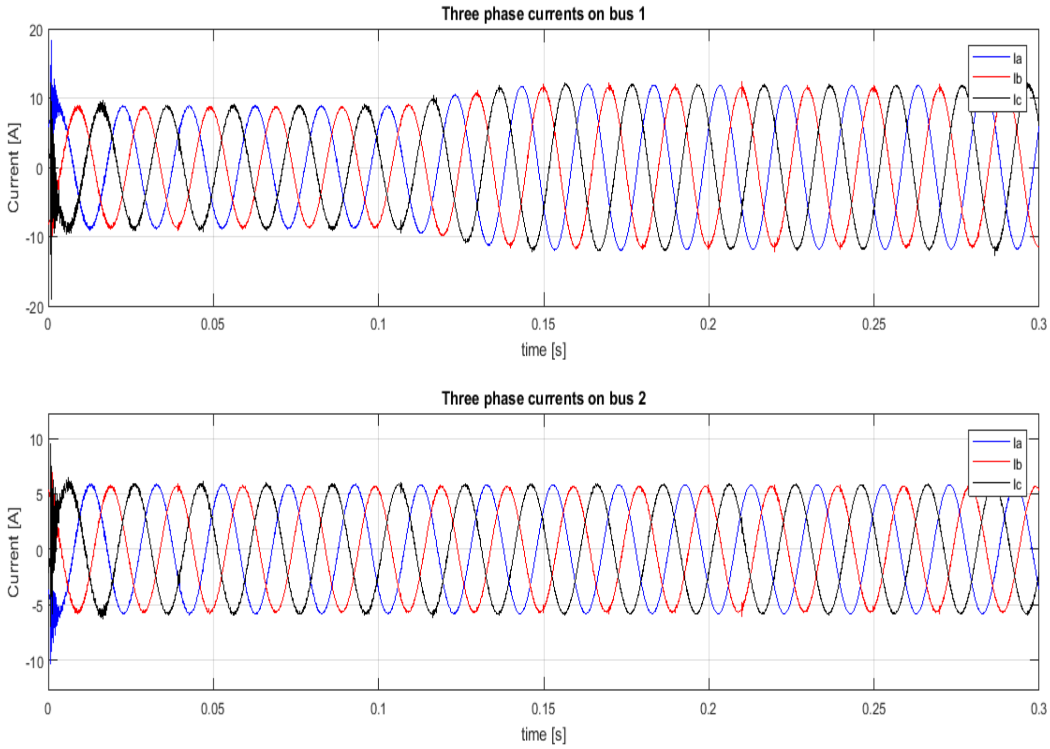

Fig. 6e. Three phases currents in MV network on bus 1 and on bus 2.

Even though it is not marked, a transient state causing the increase and decrease of the three phase current on bus 1 at around 0.15s is present. Therefore, the attention has to be focused in particular on the steady state of the various phenomenon, especially when distorting and unbalanced loads are introduced in the distribution system.

10. Conclusions

It has been analysed the possible features of a modern device: the smart transformer. Starting from dispersed generation and its influence on electric power quality it has been possible to present the topic of microgrids and smart grids, focusing in particular on smart transformer, the centre of this modern approach to manage distribution networks.

By means of smart transformer it is possible to separate low and medium voltage distribution networks, mitigating and compensating in this way any disturbances which affect both sides. Besides, smart transformer consists of having a control point between these voltage levels, improving optimisation of the entire grid. The ability to control voltage level, active and reactive power enable the possibility to work with a unitary power factor, filter voltage fluctuations and support voltage on medium voltage side. If loads characterised by high harmonics are present smart transformer act like an active filter, reducing dangerous conditions on the transformer and improving overall electric power quality of the grid.

It has been analysed three stage smart transformer, which is the most efficient configuration of this technology and these are just some of the several advantages which smart transformers can take on the distribution network.
In addition, it is possible to mark that on load tap changer (OLTC) and unified power flow controller (UPFC) have been taken into account as a technology similar to the smart transformer, but the three stage smart transformer topology is much more efficient and creates more possibilities for future developments.

In conclusion, simulating a distribution system employing a normal three phase transformer against a network adopting a smart device, it has been possible to notice the differences between the two cases. Focusing in particular on the smart transformer in general, and not to each single converter, it has been noticed and proved that the smart transformer act as an electrical separation between LV and MV grid. In fact, it permits to operate at different power factors at both sides and any distortion and unbalance present in the LV network can be mitigated and compensated, in order to not affect the MV network.

11. References

[1] Warsaw University of Technology, Faculty of Electrical Engineering, Institute of Power Engineering and High Voltage Technology, Electric Power Quality, slide from dr inż. Łukasz Rosłaniec.

[2] Warsaw University of Technology, Faculty of Electrical Engineering, Institute of Power Engineering and High Voltage Technology, Distributed Energy Sources, slide from dr inż. Łukasz Rosłaniec.

[3] https://en.wikipedia.org/wiki/Electric_power_transmission; "Electric power transmission".

[4] Guarnieri, M. (2013), "The Beginning of Electric Energy Transmission: Part Two", IEEE Industrial Electronics Magazine.

[5] http://www.electricalquizzes.com/electric-transmission-distribution/electric-transmission-distribution; "Electric Transmission and Distribution: Concepts".

[6] https://en.wikipedia.org/wiki/Electric_power_distribution. "Electric power distribution".

[7] Sathsara Abeysinghe, Jianzhong Wu, Mahesh Sooriyabandara, Muditha Abeysekera, Tao Xu, Chengshan Wanga. "Topological properties of medium voltage electricity distribution Networks". IEEE, 2017

[8] Prof. A.Lipsky, prof. A.Braunstein, N.Miteva, Prof. M, Slonim. "Electric power quality and efficiency of power supply". IEEE, 2000.

[9] J.Driesen, Member, IEEE, and R.Belmans, Fellow, IEEE. "Distributed Generation: Challenges and Possible Solutions". IEEE, 2006

[10] http://www.dg.history.vt.edu/ch1/introduction.html. "Introduction to Distributed Generation".

[11] http://www.cleanenergyresourceteams.org/get-answers/26/06/2008/what-is-DG. "What is Dispersed Generation". 2008

[12] https://www.frost.com/sublib/display-market-insight.do?id=27284029. "Dispersed Generation - Future Evolution of Distribution System". 2004

[13] https://www.eonenergy.com/for-your-business/large-energy-users/manage-energy/on-site-generation. "On Site Generation : Learn more about our onsite renewable energy generation technologies".

[14] Akash T. Davda, Member, IEEE, Bhupendra. R. Parekh, Manhar D. Desai. “Reduction of Losses and Improvement in Voltage Profile for a 2.8 MVA Distribution Network with Dispersed Generation”. 2012.

[15] Giuseppe Esposito, Dario Zaninelli, George C. Lazaroiu, Nicolae Golovanov. “Impact of embedded generation on the voltage quality of distribution networks”. IEEE, 2007.

[16] P.A.J. Freij, J.F.G. Cobben, J.G.J. Sloot, W. L. Kling. “Influences of dispersed generation on the performance of the electricity grid”. IEEE, 2005.

[17] J. Dolezal, P. S,mtarius, J. Tlusty, Member, V. Valouch, and F. Vybiralik, CIGRE members. “The Effect of Dispersed Generation on Power Quality in Distribution System”. IEEE, 2004.

[18] Goran Strbac, Member, IEEE. “Impact of Dispersed Generation on Distribution Systems: an European perspective”. IEEE, 2002.

[19] Nouredine Hadjsaid, Jean-Franqois Canard, FredCric Dumas. “Dispersed generation increases the complexity of controlling, protecting, and maintaining the distribution systems”. IEEE, 1999.

[20] Maurizio Delfanti, Davide Falabretti, Marco Merlo. “Dispersed generation impact on distribution network losses”. IEEE, 2013.

[21] Martin Kašpírek. “Voltage Quality in the Medium Voltage Distribution Grid with Connected Wind Power Plants”. IEEE, 2016.

[22] S. Monesha, S. Ganesh Kumar and M. Rivera. “Microgrid Energy Management and Control: Technical Review”. IEEE, 2016.

[23] Md. Ashib Rahman_ and Md. Rabiul Islam. “Different Control Schemes of Entire Microgrid: A Brief Overview”. IEEE, 2016.

[24] https://building-microgrid.lbl.gov/about-microgrids. “About Microgrids”

[25] www.siemens.com/transformersubstations. “Intelligent Transformer Substations for Future-Proof Power Distribution”. 2013.

[26] Maria Carmen Falvo, Luigi Martirano, Danilo Sbordone, Enrico Bocci. “Technologies for Smart Grids: a brief review”. IEEE, 2013.

[27] Mr. Gyula Hipszki, mr. Ronald Schmid, dr. Reinhard Maier, mr. Karsten Handt, mr. Gerhard Buchgraber. “Distribution transformers - ready for the smart grid”. CIRED, 2011.

[28] Wim Willems, Tine L. Vandoorn, Jeroen D. M. De Kooning and Lieven Vandevelde. "Development of a Smart Transformer to Control the Power Exchange of a Microgrid". IEEE, 2013

[29] Marco Liserre, Giampaolo Buticchi, Markus An dresen, Giovanni De Carne, Levy Ferreira Costa and Zhi-Xiang Zou. "The Smart Transformer: Impact on the Electric Grid and Technology Challenges". IEEE, 2016.

[30] Chandan Kumar and Marco Liserre. "Operation and Control of Smart Transformer for Improving Performance of Medium Voltage Power Distribution System". IEEE, 2015.

[31] Hiba Helali, Adel Bouallegue, Adel Khedher. "A Review of Smart Transformer Architectures and Topologies". IEEE, 2015.

[32] Markus Andresen, Levy F. Costa, Giampaolo Buticchi and Marco Liserre. "Smart Transformer Reliability and Efficiency through Modularity". IEEE, 2016

[33] N. Nila-Olmedo, F. Mendoza-Mondragon, A. Espinosa-Calderon, Moreno. "ARM+FPGA Platform to Manage Solid-State-Smart Transformer in Smart Grid Application". IEEE, 2016.

[34] Giovanni De Carne, Giampaolo Buticchi, Marco Liserre, Changwoo Yoon, Frede Blaabjerg. "Voltage and Current Balancing in Low and Medium Voltage Grid by means of Smart Transformer". IEEE, 2015.

[35] Josemar O. Quevedo, Rafael C. Beltrame, Mauricio Sperandio, Tiago Marchesan, Luciano Schuch. "Smart Distribution Transformer for Secondary Voltage Regulation and Load Modeling". IEEE, 2016.

[36] Josemar O. Quevedo, Julian C. Giacomini, Rafael C. Beltrame, Fabricio E. Cazakevicius, Cassiano Rech, Luciano Schuch, Tiago B. Marchesan, Maurício de Campos, Paulo S. Sausen, Jonatas R. Kinas. "Smart distribution transformer applied to smart grids". IEEE, 2013.

[37] M. Mejbaul Haque, Peter Wolfs. "A Four-Wire Reduced Bus Capacitance UPFC for LV Distribution Networks with High PV Penetrations". IEEE, 2014.

[38] Manas Kumar Jena, S.R.Samantaray. "Synchrophasor Measurement based Smart Relays for UPFC Compensated Transmission System". IEEE, 2014.

[39] Kai Strunz, Ehsan Abbasi, Chad Abbey, Christophe Andrieu. “Benchmark Systems for Network Integration of Renewable and Distributed Energy Resources”. Cigre, task force C6.04, April 2014. Page 34 – 63.