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"Voltage control on active networks under adverse conditions."

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Figure 6.6.5. Inrush current when energizing the transformer.

Table 6.1.1. Fuzzy Rule base.

ANM - Active Network Management.
ATP - Alternative Transient Program.
BSP - Bulk Supply Point.
CHP - Combined Heat & Power.
CVPP - Commercial Virtual Power Plant.
DER - Distributed Energy Resources.
DG - Distributed Generation.
DN - Distribution Network.
DNO - Distribution Network Operators.
DR - Demand Response.
FC - Harmonic filter (Fixed Capacitor).
Hh - Harmonic percentage.
IDS - Interconnected Distribution System.
LTC - Load Tap Changer.
LV - Low Voltage.
MATLAB - Matrix Laboratory(Program).
MES - Massive Electrical Storage.
MMC - Modular Multi-level Converter.
MPPT - Maximum Power Point Tracking.
MSC - Mechanically Keyed SVCs and Capacitor.
MSR - Mechanically Keyed SVCs and Reactors.
OLTC - Operations to Change Tap Under Load.
PCC - Point of common coupling.
PFC - Power Factor Control.
PSO - Particle Swarm Optimization.
RMS - Root Mean Square.
SCC/LCC - Auto or online switched converter.
SR - Saturated Reactor.
STATCOM – Static Synchronous Compensator.
SVC - Static Var Compensator.
SVS - Static Var System.
TCR - Thyristor Controlled Reactor.
TCT - Thyristor Controlled Transformer.
THD - Total Harmonic Distortion.
TSC - Capacitor Keyed by Tiristors.
TSR - Reactor Keyed by Tiristors.
TVPP - Technical Virtual Power Plant.
UPS - Uninterruptible Power Supply.
VPP - Virtual Power Plant.

List of Symbols

Symbol	Description
Ac	Central cross-sectional area
B(t)	Magnetic induction time
C	Capacitance
D	Distortion
E	Amplitude of output voltage
$H(t)$	Magnetic field measurement of the core
Hh	Level of harmonic percentage
i	Time interval
I	Current
I_C	Capacitor Current
I_L	Inductor Current
I_S	Current of the Static Var System
K_S	Slope characteristics of the SVS
kω	Angular frequency
L	Inductance
m, n and p	Constants determined for any kind of steel rolling of the core
N_1	Turns number
P	Active Power
Q	Reactive Power
R_1	Resistance
S	Apparent Power
T_1	Time constant
THDI	Total harmonic distortion (where I stands for current.)
THDU	Total harmonic distortion (where U stands for voltage.)
u	Opponent value in the system under attack
U_k	k represents the harmonic order of the effective value U
V	Voltage
$V_t^{(k)}$	k^{th} harmonic voltage magnitude
ω	Frequency
X	Reactance
X_{SL}	Slope characteristics of the SVS
$Y^{(k,k)}$	Array containing partial derivatives of the k^{th} harmonic of injection currents
$\theta_t^{(k)}$	Phase angle at the t^{th}

Summary

Due to the inclusion of new loads and the predominant increase in electricity demand associated with the limitations of new environmental projects to minimize carbon emissions, such as pollution resulting from the energy generated by fossil fuels, the incorporation of electrical systems with distributed generation attributes to the energy planning, plans greater efficiency for various sectors of energy consumer groups worldwide.

To maintain the effectiveness and reliable operation of the entire power system interconnected between grids and intelligent microgrids of electricity supply, standards must follow the established voltage levels in all terminals of the electrical power supply equipment supply, keeping them within limits. Both power utilities and distributed generation and consumers maintain the required design specifications for a reliable range of variation. The need to maintain a standardized voltage level is summed up in the treatment of possible failures that can occur when there is a voltage level acting beyond the limits established in extended equipment operating times.

Due to the failure to maintain constant voltage levels along the electrical power grids several voltage control methods are applied, mainly controlling absorption, production and reactive power flow at all levels of the system, as well as when adverse system conditions where levels can achieve loss of system stability and voltage collapse.

This research aims to characterize the appropriate methods for voltage correction and stability in active electrical networks under the influence of adverse conditions, whether natural influences or disasters, to influences related to the conditions of electrical energy systems, such as contingencies and distortions in other factors of the system that influence the level of voltage, to which some scientific publications relate [1-4], analyzing in an equationally calculated experimental way and simulations in MATLAB and ATPDRAW to prove the results.

Index Terms – Voltage Control, Smart Grid, Microgrid, Statcom, Renewable Energy, Voltage Quality.

1. Introduction

About a hundred years ago when the first electricity systems were introduced the control systems used were still very old-fashioned and inappropriate. As these systems were very small, and the requirements regarding the quality standards of stability were less high as they appear today; thus, control system had manual resources in most cases. In a short time, end consumers have developed the ability to demand high demands on supply standards, that is, in the voltage and frequency profile provided. Therefore, automatic controllers and regulators had to be introduced into the power electrical system in order to meet these supply requirements. In addition, the stability margins of the systems were quite wide, and to ensure safety and reliability in most cases of operation no type of control was required.

As soon as systems networks increased in their size, and installed load grew, stability safety margins decreased substantially, and automatic control systems had to be deployed in essential services in order to improve stability. The installation of high-gain controllers, which, brought instability to the system, aimed to resolve the consequence of higher demands of the system to maintain the effectiveness and quality of electricity services, so controllers had installed to restore the desired stability [5].

The main reason for voltage control is in load variation. Being attention influenced by system loading. The daily load forecast makes up the basis for pre-dispatch of generators, in many current systems, through the price of selected markets, but the load variation must be balanced through automatic control. These control actions can also be obtained by a set of the auxiliary services market [6].

Simultaneous control of the voltage profile and power flows can minimize losses in the system and, consequently, improve economic performance [7,8,9]. Thus, the main reasons for power control are: quality, safety and economy.

Local controllers were the first controllers of electrical power systems. This means that a locally measured signal enters the controller, and the controlled quantity is also available in the same location. When systems grew in size, and interconnection lines between different subsystems were built, local controllers became obsolete for safe and cost-effective systems operation.

Currently in the world as a whole, the widely used electricity system presents itself with a serious of the problems of gradual depreciation of fossil fuel resources, inadequate energy efficiency and environmental pollution [10]. In order to operate the system in the face of these types of problems, there was the inclusion of locally energy generation at an acceptable level of distribution using generally unconventional energy sources or renewable energy, generation sources such as: natural gas, biogas, wind power, photovoltaic solar generation, fuel cells, cogeneration, microturbines and integration into the energy distribution network [11]. Thus, the term distributed generation was designated for this type of generation and the electrical energy sources called distributed energy resources (DERs).

Around the world some strict and country-specific definitions have been developed and have availability for distributed generation at the technological level, depending on the plant generation system, generation voltage level, etc. However, the contribution of distributed generation to the power system remains unchanged, regardless of all different definitions. Recent research results have defined some universally recognized common attributes in distributed generation as: central planning by the electric utility does not occur or centrally dispatched; normally with installation power less than 50 [MW]; distributed generators are connected in most of the installations to the distribution system.

The electricity system with distributed generation integration appears in the focus of technological research describing several characteristics in the face of the influencing diversity attributed to traditional energy systems, so the highlight of topics that lead to the constant development and integration of distributed generation energy systems, such as: technological innovation, better in scalability to the referred systems and the improvement of environmental certification. The concept of alternative energy sources is justified due to the need to implement electricity combined with the reduction of conventional energy resources already implemented.

With constant concern about environmental pollution and the growing threat of the greenhouse effect influencing climate change resulting in global warming the conclusions regarding the applicable resources tend to include sources of renewable energy with advantages over fossil fuels. The development of global environmental standards for reducing gas emissions and minimizing the greenhouse effect in order to stabilize climate change and global warming. The main work involves the creation of energy generation and use policies for the implementation of new energies and renewable sources. Thus, the inclusion of distributed energy resources (DER) appear to generate clean and ecologically correct energy thus reducing environmental impact.

Over the years in the past century, we have witnessed the development of technological innovation in the electric power system incorporating the generation of fossil fuel distant from its end users, complemented by high voltage transmission lines supplying the electricity demand needed to supply through a low voltage power distribution network to thousands of consumers. This aspect has supported several scientific and technological developments directed to the evolution of specific norms, imposing a diversification in the generation of electric energy with electric power plants destined to attend the decentralized or “distributed” (DG) generation.

Distributed generation (DG) guides the production of electricity to places with a short supply distance from consumers, representing a significant and comprehensive improvement in terms of electricity produced in the expectations of several countries. As a result, the possibility of a total evolution in the electricity system has transformed the end users of electricity consumers into producers and managers. The term “Distributed Energy Resources” (“DERs”) recognizes that distributed assets are presented in various ways. This includes demand response (DR), all forms of distributed generation and even storage, if it can be reasonably priced, and commercially extended. This form of generation provides a better margin for the implementation of cogeneration, trigeneration or CHP plants for the use of residual heat in industrial, domestic, or commercial applications. DERs are generally presented as modular units of small capacity, a characteristic imposed by the lower energy density and dependence on the geographical conditions of a given region.

Greater reliance on DER would be a significant deviation from the current structure of the electrical industry. DERs help the network by increasing the network’s reliability and resiliency, making the network less vulnerable to prolonged power outages. A more diversified, distributed, and renewable electric power system has widely known benefits, which influences the location of deployment and provides a reduction in construction time and capital investment. The load being close to the source reduces transmission and distribution [12] (T&D) losses. With electrical energy generated at low voltage (LV), it is possible to connect a DER separately to the distribution network of public services or they can be interconnected in the form of Microgrids.

In recent years, there has been another important trend in the electricity sector: the emergence of the “Intelligent Network”. Broadly speaking, this involves two different objectives: smart technologies [13] to reform the electrical system [14,15] and provide consumers with new applications [16] for the manufacture, use and conservation of electricity. The relationship between Smart Grid [17,18] and DERs involves all domains of the electricity transmission and distribution system [19].

Power plants with renewable energy sources appear as a magnificent idea that involves the aggregation of DERs to provide an amount of resources that can serve as a functional equivalent of a traditional power plant. The relationship with DERs makes plants with renewable energy sources a significant energy potential, acting as a resource equivalent to a conventional plant, and can reduce the demand for fossil fuel plants, a directive that avoids the generation of electricity or the purchase less economically attractive markets [20].

The imposition that virtual power plants operate only to meet economic [21] requirements has been widely questioned. The virtual plants are referred to in two reference activities: technical and commercial plants [22], and those of the first type seek to meet the standardization of electrical energy systems, supplying the necessary energy demand for each load requested, implementing the quantitative and qualitative requirements imposed by incremental variations. To meet technical flexibility seeking scalability in the electric energy market, the concept of Plants with Renewable Energy Sources was also applied to microcogeneration clusters, overlapping massive electrical storage (MES) and providing benefits between systems and systems shareholders.

The growing concern with environmental issues and the advancement of electronic energy technology has resulted in the rapid development of energy production using renewable energy sources (RES). These natural resources play an important role in the generation of aggregate energy systems for virtual plants and wind and solar energy stands out as one of the most promising energy resources today. Wind energy represents one of the optimistic sources of energy generation among all RES. Now, the daily demand for energy is increasing rapidly due to population growth and the economic development of the world, leading to a greater environmental impact in conventional power plants. Therefore, RES must be used to meet energy demand and have community development and prolong growth.

One of the main systems directly related to distributed energy resources (DER) is formed with the implementation of energy systems with energy cogeneration, where it provides increased energy rationality, becoming a set of engaging aspects that constitute an alternative production in the generation plant. Having with one of the differential factors the economy of energy resources directly influencing the feasibility of implementation. When defining the distributed generation systems of electricity, it has as greater conditions for the implementation of generation plants with the installation of cogeneration plants or cogeneration for use of residual heat (CHP) in installations with industrial, domestic, or commercial applications. Thus achieving a significant increase in the overall energy efficiency of the plant, as well as the reduction of thermal pollution of the environment, which brings extremely negative effects on the ecosystem, such as : decreased oxygen levels in water verified in reducing the solubility of oxygen (O_2) in water, which causes a diffusion of gas into the atmosphere, thereby reducing availability in water. With the increase in temperature, algae, for example, grow on the surface of water, a determining factor in reducing oxygen in water from their plant respiration; there is also the loss of biodiversity provided by temperature changes in the environment and may cause the displacement of certain species to the destination of a more conducive environment, or certain species can move to the warmer environment.

Properly planned and operated DG facilities have many benefits, such as savings due to reduced energy losses, greater reliability and better power quality. However, the increased penetration of DG without harmony between the generating units can lead to greater losses of energy from the grid, undesirable voltage profiles, unreliable operation of the protection devices and imbalance between actual consumption and production. Therefore, in order to achieve optimal economic operation of the main network, DER units must be visible to the system operator. According to the distribution and planning operations lines, where the local electricity utility has the defined function to maintain safety, quality and reliability for all customers, there is a spectrum between fully accommodating and integrating. The extent to which an energy distribution utility has a certain level of visibility, control and orientation of the location of the site determines the point in the spectrum that a specific resource will be. A resource in which an energy distribution utility guides the implementation and has a certain control visibility, such as a DER operating in coordination with a distribution operator through a DER management system, falls at the extreme of the spectrum integration.

A customer-driven DER, over which the electricity utility has no visibility or control, resides in the final capacity with accommodation characteristic. A feature installed and controlled by a third party but visible to the utility, such as a storage unit connected to the distribution being employed for mass system services (e.g. frequency regulation), needs to be accommodated at the distribution level, but the distribution utility with visibility means that the resource would be slightly towards the end of the spectrum integration, in an intermediate sector between accommodation and integration. The negative aspects of increasing the uncoordinated penetration of the DG are the basic motivation for the introduction of the concept of VPP [23,24]. VPP originates in the aggregation of DG units, controllable loads and storage devices connected to a given cluster in a single imaginative entity responsible for managing the flow of electricity within the cluster and in exchange with the main network. Previously, DER was installed with a “fit and forget” approach and they were not visible to system operators [25]. The VPP aggregated all DERs into a single entity through which the Distributed Energy Resources (DERs) [26] would have visibility and controllability of the system and impacts on the market as generators connected to the transmission. Different studies have analyzed the concept of VPP in three main directions: First direction related to the classification of DGs in the structure of the VPP according to their capacity and ownership. Another DG classification was presented according to its operational nature; stochastic or dispatchable. Second direction focused on the VPP structure, both technically and commercially; Technical VPP (TVPP) and Commercial VPP (CVPP) [27], and their functionalities. Inclined third direction for the optimization of VPP operation [28]. Some of these studies focused on optimizing the VPP structure, selecting the ideal size and location of the VPP components. On the other hand, other studies have highlighted the maximization of VPP profit [29].

In the quality aspect of electrical energy, the supply voltage stands out in relation to the level of harmonic distortion imposed on the electrical system, introspecting the energization procedure of the distribution transformers.

The voltage waveform measured at any node in an electricity distribution network due to harmonic distortions is almost always a non-sinusoidal function. The degradation of the network voltage is generated mainly by the multiplicity of non-linear loads (industrial and domestic), which arise currents with a high level of harmonic distortion, as well as renewable energy sources with inverters. These non-linear load currents flow throughout the plant and, due to the finite (non-zero) value of the upstream network impedance, they also pollute the supply voltage waveform. This voltage affected by the harmonic distortion will be applied to any other device connected to this point in the installation network.

In addition, during a highly demanding energy process (starting a motor, energizing a transformer or electric arc welding machine), the voltage waveform additionally suffers from severe harmonic distortion. Thus, power transformers are being affected by the presence of harmonics, but they also generate low power quality when connected to the grid. The energization current consumed by a discharged power transformer, known as inrush current (IC), is characterized by high amplitude and harmonic level content in its waveform spectrum.

The capacity to generate distributed energy resources (DER) has their quantitative formation influenced by the energy density linked to the means of generating electricity and defining available means related to the geographical conditions of the defined region. Thus, the aspects define the geographical diffusion of the installation, a factor that largely determines the most efficient location close to the load. The technical and economic viability of electric power generation plants depends entirely on these previous definitions. When analysing the cogeneration plants, it is verified that the effective deployment location is defined close to heat sources, avoiding the transport of residual heat over long distance, a factor that can economically derail the implantation. The reduction of deployment time, as well as capital investment, can be improved along with the location of local ideas through specific analysis.

Losses in transmission and distribution of electricity, which can reach around 30[%] of the total energy generated by the source, are eliminated through the implementation of generation in physical proximity of the load. According to the voltage level generated, which usually has the low voltage level, a DER can be connected independently to the power distribution network of the power utility or being interconnected in the form of microgrids. The microgrid has the characteristic of being able to be connected back to the electricity utility network as a separate autonomous or semi-autonomous unit and, in some cases, to assign the form of distributed generation integrated to the electric utility’s main network, the which improves the overall quality and reliability of the electricity supplied. Completing the context, in a deregulated environment, where it practically revolutionizes the electricity industry in which it has electricity as part of a business, rather than public service, with the highlight of traditional monopolies being deregulated and fractionated in specific business units, with electricity supplied as a product and subject to competition, as well as open access to the distribution network can also provide greater connectivity factors for the integration of distributed generation. With regard to the specific characteristics of each country, the form of integration of distributed generation can be classified with valuable in places with intense diversity of energy generation, or in countries with economic growth where there is a shortage of electricity supply and it can enable numerous forms of generation to meet the demand required for the inclusion of the load.

With the inclusion of more viable innovative technologies and with the improvement of the energy efficiency of the insigne electric power system, the definition of electricity networks contract the characteristics arising from the adaptation phase of distribution networks of Passive electric power stable with the conduction of directable electricity in a single direction in active distribution networks [30] with the conduction of electricity in both directions assigned in the electricity system. By definition, electricity distribution networks are considered passive if in their constitution, the installation of distributed generation systems has not been considered, therefore it is defined that the supply of electricity comes only network system. The same will be defined as active when the installation of distributed generation systems is integrated into the distribution system, thus driving the flow of electricity in both directions in the networks. In today's global context, countries considered developing in technology [31] therefore aim to include in energy planning of networks the infrastructure needed for deployment, while countries that already demonstrate structural development in advancing the implementation of systems, focus efforts on effective the best operating conditions and better results due to the diversity of generation attributed and obtain more advantages over the systems of distribution of previous energy. The inclusion to the installation of the system of distribution of flexible and intelligent control systems in conjunction with distributed intelligent systems, as well as autonomous control and maintenance systems, become differentities in the evolution of active distribution networks.

With the tendency to increase energy efficiency by integrating renewable electricity generation sources, active networks also evolve to the inclusion of more advanced technological control systems in order to perform the said use of electricity, thus being defined with the characteristics of smart grids and microgrids. The dissemination of the system to active network management, where the incorporation of the distributed generation into distribution networks and in the management of the system to be supplied energy, results in greater possibility of distributed generation connections, characterizing greater advantage over systems without active management. As a fundamental distinctive quality in view of the upward inclusion of renewable energy generation as well as distributed generation in an electric power distribution system, Active Network Management (ANM) describes itself as a preference of considerable value for the control of the distribution system to develop the operations of the safe provenance system and imposing greater scalability on the development analysis set regardless of inclusion of systems for greater reliability quantitative network [32].

This research has as main goals the characterization of voltage levels in electrical networks active under adverse conditions highlighted among external influences defined as disasters [33] of different types and distortions related to different sources and loads, as well as the variations of influences in the electrical power system parameters, specifying the appropriate methods for correction and voltage stability, using pre-defined resources and aiming at achieving acceptable levels of results in more economically attractive markets.

2. Microgrid control systems

The microgrid appears as the main premise for future electricity distribution networks [34]. As the use of technologies for microgrid deployment expands in traditional electricity distribution networks will imply the adequacy of traditionally utilizing control systems employed [35]. The structure of microgrid control system formation is based on control doctrines being categorized into three fundamental methods:

i. Centralized control

ii. Decentralized control

iii. Hierarchical control

i. Centralized Control

Characterized as common and traditional, centralized control represents a control method for microgrid. In centralized mode there are two types of control systems for microgrids. In the first form of control, a distributed generation system controls distributed energy (DER) resources. In the second form of control, a central unit of control and decision management controls the microgrid [36,37]. The centralized control system consists of all data from all instruments in the microgrid and determines the operation with databases in that data. Centralized control is convenient for the application of accurate optimization algorithms

[38,39,40] and a wider range of operation of the entire system. Some disadvantages stand out in centralized control, such as lack of flexibility and easy universality (not being a modular controller), as well as high costs of communication, design, and computing facilities.

ii. Decentralized Control

Uncoordinated control represents another control approach. Each unit performs a task independent of other drives in this type of control. In this mean, reducing interchangeable information will reduce demand for a high-cost communication network. In addition, its characteristic is to provide plug-and-play capacity for installing additional distributed power resource units and consumers on the microgrid. The probability of network instability increases in decentralized control because each inverter operates based on local measurements. In addition, your locations can change during the operation demand period and generation capacity. Because they operate independently of the system of the new network scheme, decentralized controllers make decisions that raise the likelihood of network instability. Therefore, decentralized control without cooperative control does not remain stable.

iii. Hierarchical control

As the electric power system receives improvement control system objects become less complicated at the operational point of view. The modes islanded and connected to the network in microgrid applications have always been considered by separate approaches. With this, there was a need to develop a microgrid operation system in both operating modes, connected to the network and islanded. The scalability and profitability of the micro-network became fundamental to the operation after deregulation. In this way, microgrid operations have changed completely [41]. It is necessary to implement hierarchical control as the best option in this situation, where its control objectives are organized in three levels:

a) Primary control

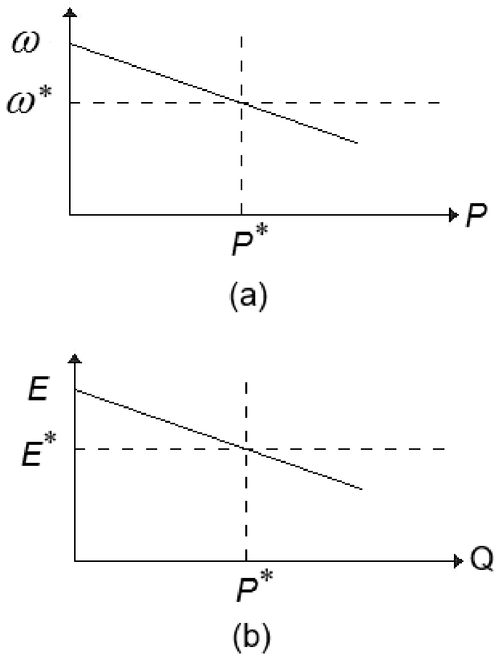
Frequency adjustment and voltage amplitude are the focus of this control level which are placed as the input parameters for the internal control loops of current and voltage. Changes in supply for cargo supply and changes in power supply are attended with faster responses guaranteed by primary control. The provision of the operational scope of this regulation is established in milliseconds, being paramount to maintain the operational stability of the network. The continuity of the performance of energy storage systems, such as batteries, has its features assisted by the use of primary control. The power availability and battery charge level for supply define the mode of operation for this purpose. The ideal settings for primary regulation in island mode are defined by the battery charge state.

In this respect, each inverter will have an external power loop based on a tilt control, defined as autonomous or decentralized control, whose purpose is to share active and reactive power between distributed generation units and impose the best system performance and stability, whose adjustments at the same time define the frequency and magnitude of output voltage.

$$\omega = \omega^* - m\,(P - P^*) \tag{2.1}$$

$$E = E^* - n\,(Q - Q^*) \tag{2.2}$$

Where ω^* e E^* represent the frequency and amplitude of output voltage, and the coefficients m and n define the corresponding inclinations (angular coefficients). P^* e Q^* are active and reactive power references, in connection island mode are set to zero value when connecting ups units in parallel autonomously. However, to share energy with constant energy sources, the active and reactive energy sources to be extracted from the units use the electricity grid. In this way, the performance of the system can be increased, allowing the autonomous operation of the modules. Thus, the amplitude and frequency output voltage can be influenced by P = Q sharing through a self-regulation system with active and reactive local energy provided from each unit.



$$\omega = \omega^{*} - m(P - P^{*}) \qquad (2.1)$$

$$E = E^{*} - n(Q - Q^{*}) \qquad (2.2)$$

Figure 2.1. – Voltage and frequency control.

In order to obtain a good energy sharing, the output voltage amplitude and frequency of being adjusted in the control circuit, in order to compensate for the imbalance of active and reactive power. The inverter can inject the desired active and reactive energy into the main network, defining the output voltage regulation [42] and matching linear load changes.

b) Secondary control

The bandwidth of the secondary control has a lesser amplitude than that of the primary control, because it thus dissociates the two dynamics, and also reduces the communication speed [43,44] and has sufficient time to perform all the necessary calculations [45,46]. Of course, it compensates for the voltage and frequency variations obtained by the primary control and performs network synchronization. In other overhand, secondary control can also act as the Power Management System, defining energy flow and energy quality within the microgrid, defining itself as the highest level of control when the microgrid is in island mode.

c) Tertiary control

In the third hierarchical control loop, the inverter references connected to the microgrid are adjusted even to generator MPPTs so that power flows are optimized. Power references provided to secondary control can be calculated based on an economic analysis structured by market prices, weather forecasting (as sources with stochastic behavior are employed, such as panels photovoltaics) and the agreement between the customer and the network operator. When deploying this level of control, some extra features can be obtained, with island detection or harmonic reduction of harmonic network voltage by harmonic injection. The implementation of the multilevel hierarchical approach will be related to communication infrastructure and future intelligent network codes [47,48].

3. Voltage Control Methods

3.1. Voltage Control Methods in microgrids

The main function of voltage control on the network bus (including active network management) stands out in maintaining the stability and total reliability of the network. Maintaining a specific voltage control prevents reactive power fluctuations [49] mainly due to the high number of micro-generation sources in microgrids. The microgrid voltage control function focuses on reducing relatively large circulating reactive currents between micro-sources components of the network, similarly to what happens in large synchronous generators. The problem of circulating current in the microgrid becomes relevant in because feeders are radially positioned in most interconnections, thus resulting in a small equivalent impedance between micro-sources, which occurs in a way that occurs differentiated in electricity utilities, where this circulating current is usually restricted by the great impedance between generators. Similarly, circulating currents in the networks may exceed the nominal currents of micro-sources in microgrid, although there are minimal discrepancies in their respective voltage adjustment points.

Voltage and reactive power drop (V-Q) controllers with fall characteristics are used for effective control of circulating currents.

In this type of controller stands out the characteristic of increasing the point of adjustment of the local voltage at the instant when reactive currents from micro-sources remain predominantly inductive and decrease the adjustment point when the current becomes Capacitive. Reactive power variation extremes have classification definition VA (VAR; S) inverter and active power output (P) micro-source according to the interface:

$$Q = \sqrt{(S^2 - P^2)} \quad (3.1.1)$$

3.2. Voltage Control Methods in networks

The control of voltage levels has been performed by control of production, absorption, and reactive power flow at all levels of the system [50,51,52]. Generating units provide basic means of voltage control; Automatic voltage regulators control the field excitation to maintain a scheduled voltage level at the generator terminals. Some additional means are required for voltage control in the system [53].

a) Reactive energy sources or absorbers, such as shunt capacitors, derivation reactors, synchronous condensers and static var compensators (SVCs);
b) Line reactance compensators, such as serial capacitors;
c) Transformer regulators, such as tap slat transformers and boosters;
d) Active Network Management;

Parallel capacitors and reactors, and series capacitors promote passive compensation. They permanently connected to the transmission and distribution system or are disconnected. Contributing to voltage control with the modification of network characteristics.

Synchronous compensators and SVCs promote active compensation; the reactive power absorbed/supplied by them has been automatically adjusted to maintain the voltages on the bars on which they are connected. Together with the generating units, they establish voltages at specific points of the system. Voltage levels at other system locations are determined by active and reactive power flow through various circuit elements, including passive compensating devices.

3.2.1. Shunt capacitors

The main advantage of using shunt capacitors is represented in low deployment cost and installation and operation flexibility. These are readily available at various points in the system, resulting in a contribution to the transmission of energy distribution. However, the reactive output power is proportionally related to the voltage square, appearing as the main disadvantage of using shunt capacitors. Consequently, the reactive output power is reduced to low voltages when it is probably most needed.

Shunt capacitors are used extensively in distribution systems for power factor correction and voltage control in feeders. Distribution capacitors are generally switched by automatic controls or current and voltage sensitivity.

The goal of power factor correction is to provide reactive power near the point where it is being consumed, rather than being supplied by remote sources. Most loads absorb reactive energy; that is, they have delayed power factors. Switched shunt capacitors are also used extensively for feeder voltage control. They are installed in appropriate locations along the feeder length to ensure that voltages at all points remain within the maximum and minimum limits allowed as loads vary.

Shunt capacitors are used to compensate for XI^2 losses in transmission systems to provide satisfactory voltage levels during heavy load conditions. They are typically distributed through transmission systems to minimize losses and voltage drops.

3.2.2. Shunt Reactors

Shunt reactors are used to compensate for the capacitance effects of the line, in particular to limit increased voltage in open circuit or light load.

3.2.3. Active Network Management

Active Network Management helps balance floating generation capabilities for a reliable power supply [54], especially when the amount of renewable energy in your energy portfolio increases. Through a range of analysis and evaluation functions, active network management provides reliable voltage regulation (figure 3.1) and helps to avoid overload situations, in addition to efficiently informing the direction of the load flow and providing updated load values [55,56,57,58].

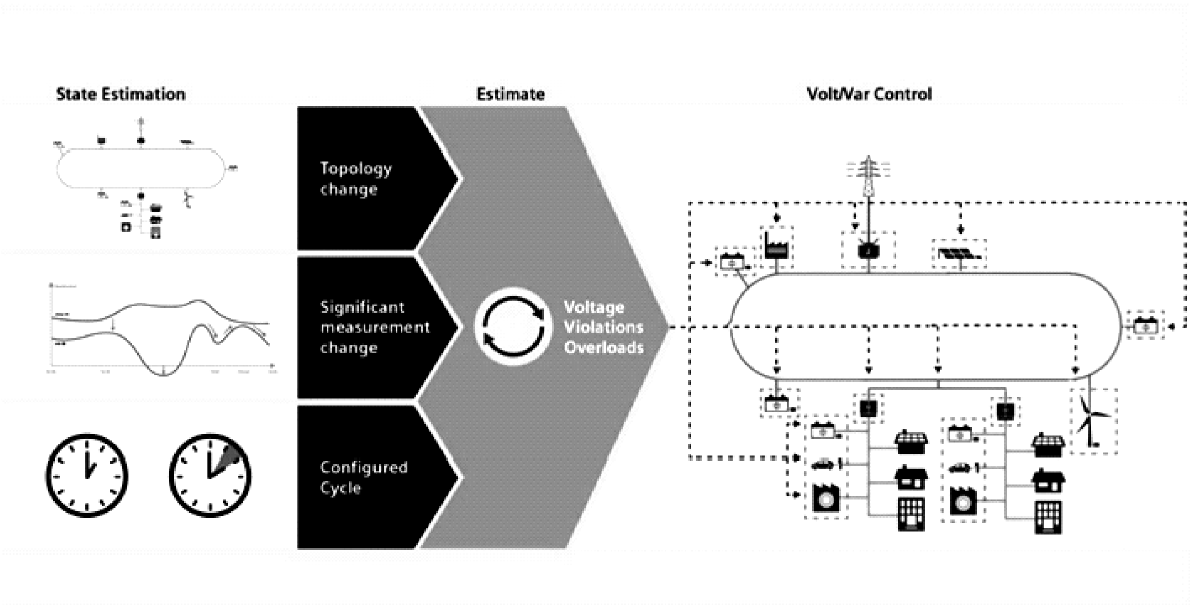


Figure 3.1. – High efficiency and reliable supply (smart microgrid).

3.2.4. Static var systems

Variable static var compensators (SVCs) are connected-parallel static generators and/or absorbers whose outputs are varied according to the specific controls of the parameters of the electrical power system [59].

The main differential aspects of Variable static var compensators (SVCs) devices include, among others, the ability to control line voltages reliably and effectively. Voltage regulation and control to the required set point under normal steady-state [60] and contingency conditions stands out as a characteristic of the SVC, thus providing dynamic reactive energy and effective resolution after system contingencies (such as, network short circuit, line ad generator disconnections). As well as, it contributes to increase the capacity [61] of transferring electric energy, reducing losses in the lines, mitigating oscillations of active power and avoiding voltage oscillations with over-voltages in the loss of load.

A var static system (SVS) consists of an aggregation of mechanically keyed SVCs and capacitors (MSCs) or reactors (MSRs) whose outputs are coordinated.

SVCs Types:

i. Saturated Reactor (SR)

ii. Thyristor Controlled Reactor (TCR)

iii. Capacitor keyed by tiristors (TSC)

iv. Reactor keyed by tiristors (TSR)

v. Thyristor Controlled Transformer (TCT)

vi. Auto or online switched converter (SCC/LCC)

vii. Harmonic filter (FC)

Static var systems have the ability to control the individual phase voltages of the bars to which they are connected. They can therefore be used to control negative sequence and sequence-positive voltage deviations. However, this type of systems focuses on problems in balanced fundamental frequency performance systems.

a) Features of an ideal SVS

From the point of view of operation of electrical power systems, an SVS is equivalent to a shunt capacitor and a shunt inductor, both of which can be adjusted for voltage control and reactive power in their terminals (or at a nearby point) in a prescribed way.

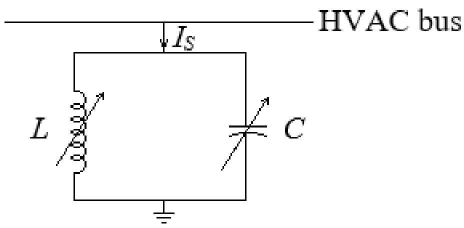


Figure 3.2. – Static var system (SVS).

This analysis considers an SVS composed of a controllable reactor and a fixed capacitor. Therefore, the resulting characteristics are sufficiently general and apply to a wide range of practical SVS configurations.

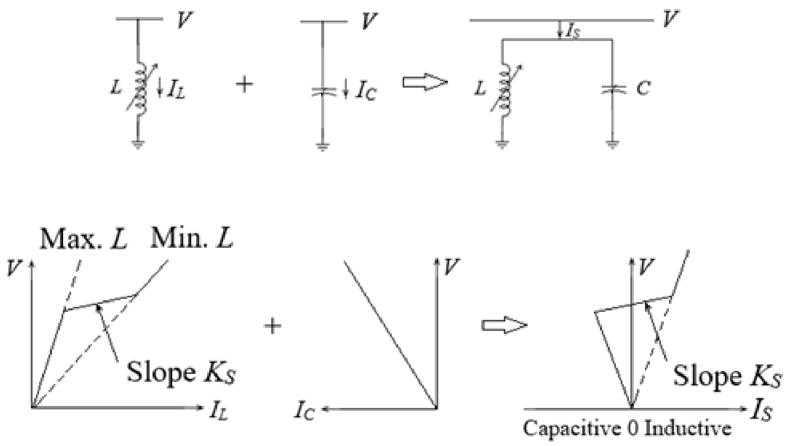


Figure 3.3. – Composite characteristics of an SVS[62].

b) Composite SVS - Characteristics of the power system

System characteristics can be expressed as:

$$V = E - X\,I \tag{3.2.4.1}$$

The characteristics of the SVS, in the control range defined by tilt reactance, are given by:

$$V = V + X\,I \tag{3.2.4.2}$$

For voltages outside the control range, the V/I_S ratio has a value equal to the slope of two extreme segments of Figure 3.4. These are determined by the ratio of the inductor and capacitor. The Solution of the SVS and the characteristic equations of the power systems are graphically illustrated in the figure below.

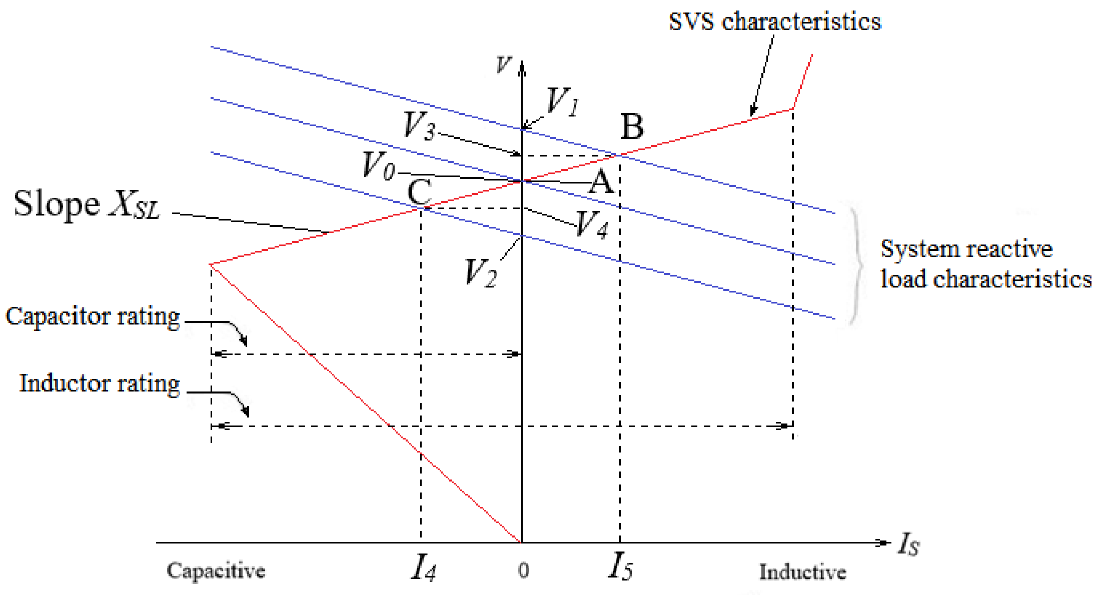


Figure 3.4. – Graphical solution of the SVS point of operation for system conditions.

The Figure 3.4. considers three characteristics of the electric power system, corresponding to three values of the source voltage. The central characteristics describe the nominal conditions of the system and it is assumed that they intercept the characteristics of the SVS at point V-V_0 and $I_S = 0$. If the system voltage increases by ΔE_{th} (due to a decrease in the system load level), V will increase to V_1, without an SVS. With the inclusion of SVS, however, the operational point changes to B; absorbing the inductive current I_3, the SVS maintains the voltage in V_3. Similarly, if the source voltage drops (due to an increase in the system's load level), SVS maintains the voltage in V_4, instead of in V_2 without SVS. If the slope K_S of the SVS characteristics were zero, the voltage would be maintained at V_0 in many cases considered.

3.2.5. Storage of electricity for voltage control

The storage of electricity has as its objectives to support a feeder with excess charging, provide power factor correction, reduce the need to restrict distributed generation, minimize operations to change tap under load (OLTC) and mitigate flicker, voltage sag and swells [63].

Voltage control using the ratio of real and reactive energy export voltage sensitivity is based on the optimization of the actual and reactive energy export of electricity storage, so that the size of the storage unit electricity can be minimized.

Conventionally, renewable energy sources are connected to the Distribution Network (DN) through electronic power converters and are responsible for modifying voltage profiles at the end of the customer. The voltage at the customer's connection point depends on the voltage drop along the grid, which, in turn, is related to the active and reactive energy exported from the renewable energy source connection bus (RES) to the bulk supply point (BSP).

The preferred mode of operation of the distributed generation is established in power factor control (PFC) mode, so that the P/Q ratio is maintained almost constant and the reactive power is proportional to the variation of the active power.

This requirement allows voltage profiles to be kept within legal limits, but with a high penetration of distributed generation, this mode of operation may tend to increase the voltage variation, especially in rural areas, and the increased voltage if makes a significant restriction for distribution network operators (DNO) and distributed generation owners (DG) in terms of network safety and reliability and maximization of production and energy, respectively.

The storage of electricity has as its function of local use the mitigation of increased voltage due to a wind generation park, absorbing reactive energy.

3.2.6. Current and emerging coordinated voltage control schemes

The latest voltage control devices have control performed locally to obtain a passive coordinated voltage control scheme on distribution networks. This passive coordinate voltage control scheme is characterized as the most suitable for most cases in current distribution networks.

Coordinated and optimized voltage control uses heuristic or metaheuristic algorithms and particle swarm optimization or PSO optimization [64,65]. The voltage control system is developed in with formulation in a mathematical optimization system, thus defining the control objectives and constraints [66,67,68]. The reduction of losses in the network and the leveling of the voltage profiles represent the control objectives, while the constraints may present the thermal and voltage limits in the network. In these types of control systems, it is necessary to analyze the online load flow structured by the network model to find the optimized solution. Organized skills for database-based control form the primary basis for having an application in coordinated voltage control schemes. In such schematics, the coordinated voltage control solution forms in a database, which contains historical operation control solutions or previously completed offline studies. The goal of deploying a database is to improve the overall performance of the controller and avoid risks of nonconvergence of load flow analysis resolution. However, there is a need for a database of solutions, developed from offline analysis, and intelligent algorithms [69] of self-learning database. In these control systems, only permanent regime voltage level problems at medium voltage level are considered [70].

4. Voltage control in adverse conditions

4.1. Voltage control for interconnected microgrids under cyberattack

The operation of electricity networks, specifically, microgrids currently face several challenges, thus, to touch the operation more effectively, making it safe and reliable, these need to be faithfully coupled to control systems supervision and data acquisition that monitor in real time and operate the entire electrical power system, gathering data from specific electrical installations and remote smart meters, as well as sending control and supervision commands. Among the new challenges, these systems act under susceptible malicious cyber threats through communication infrastructure connections. Thus, the safe and stable operation of electricity grids needs to be guaranteed under normal operating conditions and cases where cybersecurity is under constant threat of malicious attacks. Thus, it is essential to analyze possible vulnerabilities of the electricity system, through modeling and studies of different threats to this system, attributing the results for the development of resilient schemes with the objective mitigate security threats at high risk.

Some security systems propose threat detection algorithm to mitigate sparse attacks. Using the electrical power adjustment points to change the power inverter devices or even for deactivation, the objectives of cyber attacks can be achieved, in order to attribute this possibility in the attack scenario considered, cyber opponents build a specialized tool to perform intermediate attacks and manipulate sent to photovoltaic energy inverter, thereby affecting the physical energy system. In the specific attack, each subsection starts by determining the opposing model and thereby affects the tilt controller. Therefore, based on the properties of the linearized system stipulates the impact of the attack, such as stability and induced inlet and output standard. The sets of nodes attacked that produce possibly higher impacts have identification established through these characterizations, determining which threats pose risks to the system and the level of action.

a) Voltage reference attack

For this type of attack the current system considers for analysis an adversary that injects false data into the communication network that operates the control system.

In the clearance of a reference signal attack on bus j, the correlation of the reference signal occurs in the j bar, taking into account the analysis of the load flow for the electricity system in question, have:

$$V^*(t) = u\,(t), \tag{4.1.1}$$

Where the value $u\,(t)$ was defined as an opponent. Therefore, the resulting control signal in the j bar under an attack on the reference signal will be:

$$u_{V_j} = -k_j V_j^c \left(V_j^c - u^a(t)\right) - Q_{j.}^c \tag{4.1.2}$$

In Figure 4.1.(a), when a false data of $u_1^{a,1} = 3$ [V] is injected on the voltage sensor in agent I during event A, leads to an increase in the voltage observer output. Consequently, the voltage of agent II also increases from 48.1 [V] to 51.6 [V]. This results in an increase in C_1 from 0 to 0.2 [V], which guarantees the attack vector on agent I. After a certain moment, when the agent I link is deactivated, which interrupts the transmission of false data during event B, the agent II voltage returns to 48.1 [V]. However, the injected false data is still effective, which is evident from C_1 in Figure 4.1.(a). In the most critical case, the attacker can try to manipulate C_1 in the negative region so that the disabled link is restored. In event C, another attack vector $u_1^{a,2}$ = -1.2 [V] is injected into C_1, which does not affect its detection philosophy, as it is strategically oriented in the control system of each agent using the cross-coupling methodology.

Similarly, in Figure 4.1.(b), a sneak attack is modelled injecting a balanced set of zero sum vectors u^f_i = ±3 [V] in voltage sensors of both agents before event A. After the transient instant, both voltages return to their respective set points before the attacks. However, C_1 and C_2 increase from 0 to 0.2 [V], which suggests that the two agents are *attacked*. To avoid further damage, a corrective action disabling cyber links during event B in Figure 4.1.(b) results in local operation for each agent.

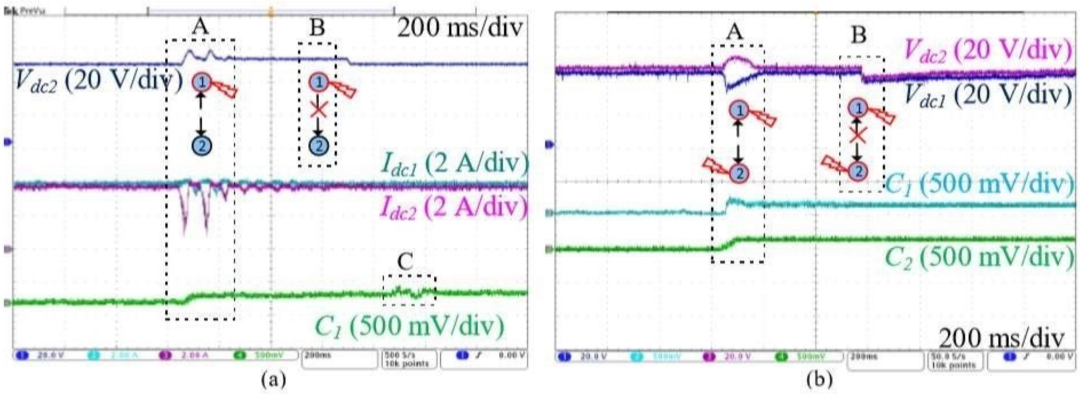


Figure 4.1. – (a) Experimental validation and (b) stealth attack on the voltage sensor (s) in a DC microgrid with M = 2 agents [71].

4.2. Voltage stability to Major disturbances

Among the main characteristics of electric power systems, the ability of this electricity systems to maintain voltages on a permanent basis soon after a major disturbance occurs, such as a lack, loss of generation or circuits. This capacity is related to and determined by the characteristics of the system and load, and also by the interactions of the various control systems (discrete and continuous), as well as the respective protections [72].

The dynamic behavior examination of the system determines the analysis of voltage stability at a great disturbance, in which it requires a sufficient period of time for capturing interactions and actions of devices such as engines, LTC and current limiters of generator field. Thus, the need for a nonlinear analysis of the system is formed in a period of time of interest for the complete definition of studies, ranging in a few seconds to a few minutes, and also the realization of simulations in the field of time, and modeling may be classified as transient or long-term.

4.3. Voltage stability to Minor disturbances

The voltage stability analysis to minor disturbances (small signals) is directly related to the system's ability to control voltages after minor disturbances, such as gradual changes in load. This form of stability has a direct influence with the determinations of permanent approximations using the linearization of the dynamic equations of the system in a given operating instant, allowing valuable sensitivity information in the identification of factors that influence voltage stability.

4.4. Long-Term Voltage Stability

Long-term stability analysis assumes that power fluctuations between synchronizations and power have attenuated, resulting in a uniform frequency of the system. The focus is on the slowest and smallest phenomena that accompany large-scale system disturbances and sustained disagreements resulting from the generation and consumption of assets and reactives. Long-term voltage stability involves in its characteristics the slow dynamics of certain equipment, for example, LTCs, thermostatic loads and actuations of generator current limiters. The period of interest may extend from some to many minutes and long-term simulations are required to evaluate dynamic system performance. Static analyses can be used to identify estimates of stability margins, as well as influence factors and examine different system conditions and many scenarios.

4.5. Short-Term Voltage Stability

Short-term stability presents characteristics related to the variation between transient responses and long-term responses. In the short-term stability the focus is on synchronizing the power fluctuations between machines, as well as on the effects of some of the slower phenomena. It also involves the dynamics of some loads, for example induction motors, electronically controlled loads and continuous current system converters. Dynamic load modeling is essential, and the study interest period is contained from the instant of a few seconds and the analysis requires the solution of differential equations related to the system, similarly the solution of the transient stability problem [73].

4.6. Severe weather conditions in microgrids

This analysis considers the load variation of the electricity system in a reduced way from some kind of untimely action with damage to the electrical power generation structure caused due to the insufficient time required for restoration of equipment, thus having to reorganize the types of loads demands in order to keep the microgrid operating in a defined mode of safety until the power generation is fully restored and with this the total storage established for a system with high reliability and higher economic return. The impacts caused by the damage of the structure are initially classified according to the installation site within the electrical power system, differentiated between the points of electricity generation and electricity distribution network connecting the generation system to differentiated consumer load systems.

Listing of loads to be included from the feeders of the electricity distribution system in the escalation of supply priorities:

a) Load 1: Consumption units directly related to the supply of electricity, which are not being attended by distribution and transmission networks and own generation of electricity;

b) Load 2: Facilities related to maintenance organizations of human health care units;

c) Load 3: Units specifically linked to Safety Systems, firefighting, health support, and emergency commercial transport;

d) Load 4: Service to the supply of commercial and industrial consumers;

e) Load 5: Residential Units and other consumers;

f) Load 6: Educational and Research Institutions.

Thus, a priority escalation system is defined due to the type of load in relation to the essential condition to maintain the quality of life of users, according to the type of service provided in each consumer the load falls into a concept of economic sociability, maintaining the essential and normal conditions in the purpose of maintaining a favorable environment until it has been returned to a state of normality of the grid’s electricity system.

Load escalation settings due to the type of operation of the microgrid:

Type of operation	Priority	Supplied load
Critique	High	Load 1 Load 2 Load 3

Emergency	Average	Load 3 Load 4 Load 2 Load 1 Load 5 Load 6
Normal	Low	Load 1 Load 6 Load 5 Load 2 Load 3 Load 4

5. Quality control of voltage levels

5.1. Harmonic Power Flow

Three-phase systems with nonsinusoidal and unbalanced conditions [74,75].

For each time interval *i*, the effective voltage and current are recorded; moreover, the fundamental component is separated from the total harmonics components [76,77,78], that is:

$V_{ei}^2 = V_{e1i}^2 + V_{eHi}^2$ and $I_{ei}^2 = I_{e1i}^2 + I_{eHi}^2$ (5.1.1) and (5.1.2)

Where $V_{eHi}=\sqrt{\sum_{h\neq1}^{\infty} V_{ehi}^2}$ and $I_{eHi}=\sqrt{\sum_{h\neq1}^{\infty} I_{ehi}^2}$ (5.1.3) and (5.1.4)

The total effective apparent Power squared is:

$$S_e^2= 9V_eI_e=\frac{9}{v^2}\sum_{i=1}^{v}(V_{ei})^2\sum_{i=1}^{v}(I_{ei})^2=\frac{9}{v^2}[\sum_{i=1}^{v}(V_{e1i}^+)^2\sum_{i=1}^{v}(I_{e1i}^+)^2+\sum_{i=1}^{v}(V_{e1i}^+)^2\sum_{i=1}^{v}I_{eHi}^2+\sum_{i=1}^{v}V_{eHi}^2\sum_{i=1}^{v}(I_{e1i}^+)^2+\sum_{i=1}^{v}V_{eHi}^2\sum_{i=1}^{v}I_{eHi}^2] \quad (5.1.5)$$

The first term is due to the contributions of the fundamental voltage and current and has exactly the same terms as Equation.

$$\frac{9}{v^2}\sum_{i=1}^{v}(V_{e1i}^+)^2\sum_{i=1}^{v}(I_{e1i}^+)^2=\left(\overline{P_1^+}\right)^2+\left(\overline{Q_1^+}\right)^2+(\overline{S_{1u}})^2+D_{1R}^2 \quad (5.1.6)$$

The second term is due to the interaction between the fundamental voltages and the harmonic currents,

$$\frac{9}{v^2}\sum_{i=1}^{v}(V_{e1i}^+)^2\sum_{i=1}^{v}I_{eHi}^2=(\overline{D_l})^2+D_{1R}^2 \quad (5.1.7)$$

With:

$$\overline{D_l}=\frac{1}{v^2}\sum_{i=1}^{v}3\,V_{e1i}I_{eHi} \text{ and } D_{lR}=\sqrt{\frac{9}{v}\sum_{1\leq n<m\leq v}^{v}(V_{e1m}I_{eHn}-V_{e1n}I_{eHm})^2} \quad (5.1.8)$$

Being the current distortion power and the randomness current distortion power, respectively. The third term is due to the interaction between the harmonic voltages and the fundamental currents,

$$\frac{9}{v^2}\sum_{i=1}^{v}V_{eHi}^2\sum_{i=1}^{v}I_{e1i}^2=(\overline{D_v})^2+D_{vR}^2 \quad (5.1.9)$$

With:

$$\overline{D_l}=\frac{1}{v^2}\sum_{i=1}^{v}3\,V_{eHi}I_{e1i} \text{ and } D_{VR}=\sqrt{\frac{9}{v}\sum_{1\leq n<m\leq v}^{v}(V_{eHm}I_{e1n}-V_{eHn}I_{e1m})^2} \quad (5.1.10)$$

Being the voltage distortion power and the randomness voltage distortion.

The fourth term is due to the interaction between the harmonic voltages and the harmonic currents,

$$\frac{9}{v^2}\sum_{i=1}^{v} V_{eHi}^2 \sum_{i=1}^{v} I_{e1i}^2 = (\overline{S_H})^2 + D_{HR}^2 \qquad (5.1.11)$$

With:

$$\overline{S_H} = \frac{1}{v^2}\sum_{i=1}^{v} 3\, V_{eHi} I_{eHi} \text{ and } D_{HR} = \sqrt{\frac{9}{v}\sum_{1\leq n<m\leq v}^{v}(V_{eHm}I_{eHn} - V_{eHn}I_{eHm})^2} \qquad (5.1.12)$$

The harmonic active power $\overline{P_H}$ and the non-active harmonic power $\overline{N_H}$ make up the total harmonic apparent power $\overline{S_H}$.

Finally, the apparent power squared can be resolved using the expression:

$$S_e^2 = \left(\overline{S_1^+}\right)^2 + (\overline{S_{1u}})^2 + (\overline{D_l})^2 + (\overline{D_V})^2 + (\overline{S_H})^2 + D_R^2 \qquad (5.1.13)$$

Where,

$$D_R = \sqrt{D_{1R}^2 + D_{lR}^2 + D_{VR}^2 + D_{HR}^2} \qquad (5.1.14)$$

In the total randomness power.

The harmonic generating loads impose a parameter of harmonic power flow formulation [79] that differs from the fundamental load flow [80]. Line switching circuits and nonlinear resistors are the focus of the detailed load models that are included. These models relate the non-linear load currents defined with the respective terminal voltages represented by their series [81].

Current sources connected to the power distribution system serve as the basis for the analysis of non-linear loads. From the model data based on specified loads and sources, the generation of harmonic distorted power generation for an initial prediction of injected currents and terminal voltages for non-linear loads [82] is defined. The dependence of the frequency on the reactances develops in the energy system autonomy and mutuality for the fundamental and also for each harmonic frequency of the injected current. The current injected at a different frequency may affect the system voltage response at a harmonic frequency, although these admittance matrices only relate the currents at a given frequency at the same frequency.

In addition, an iterative solution is required when it is verified that the distortion caused by harmonic currents will affect the injected current. The Newton-Rapson reformulated iterative method includes frequencies [83]. The resolution of the harmonic node voltages requires additional equations. Kirchhoffs' current law and conservation of apparent power, when appropriate, serve as the basis for equations.

These equations are extended by the harmonic power flow formulation to include non-linear devices and non-linear resistors, a variety of parameter combinations for line-switched circuits [84].

The general results are hereby stated by completeness, considering that the detailed formulation of the equations is beyond the scope of this study. The linear buses are numbered from a to m-1, for a node system n with non-linear buses. The oscillating bus represents the numbered linear bus. Numbered from m to n, the non-linear buses appear. The odd harmonics do not triple from five to L are considered.

The active and reactive power balance is:

$$[\Delta W]=[J^{(1)}\ J^{(5)} \ldots J^{(L)}][\ \Delta V^{(1)}\ \Delta V^{(5)} \ldots \Delta V^{(L)}]^T \tag{5.1.15}$$

Where $[\Delta W]=\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix}$, $[\Delta V^{(k)}]=\begin{bmatrix}\Delta\delta^{(k)}\\ \Delta|V^{(k)}|\end{bmatrix}$, and the superscript k indicates harmonic order. The Jacobian fundamental, $J^{(1)}$, is the same as the square matrix in equation.

$$P_n = \sum_{k=1}^{N} |V_n V_k Y_{nk}| \cos(\theta_{nk} + \delta_k - \delta_n) \tag{5.1.16}$$

$$Q_n = -\sum_{k=1}^{N} |V_n V_k Y_{nk}| \sin(\theta_{nk} + \delta_k - \delta_n) \tag{5.1.17}$$

Partial derivatives of equations (5.1.16) and (5.1.17) evaluated with k^{th} harmonic the values of the frequency components are used to construct the Jacobian harmonic $J^{(k)}$ [85].

The non-linear device models use two state variables, α and β. The change in state variables to an iteration are defined to be:

$$[\Delta\Phi]=[\Delta\alpha_m\ \Delta\alpha_{m+1} \ldots\ \Delta\alpha_n \mid \Delta\beta_m\ \Delta\beta_{m+1} \ldots\ \Delta\beta_n] \tag{5.1.18}$$

The k^{th} harmonic current injected at node t has real and imaginary parts $g_{t,r}^{(k)}$ and $g_{t,i}^{(k)}$, respectively, where $m \le t \le n$. The partial derivatives of nonlinear device currents with respect to nonlinear device state variables at the k^{th} harmonic are:

$$H^{(k)} = \text{diag}\begin{bmatrix} \frac{\partial g_{t,r}^{(k)}}{\partial \alpha_t} & \frac{\partial g_{t,r}^{(k)}}{\partial \beta_t} \\ \frac{\partial g_{t,i}^{(k)}}{\partial \alpha_t} & \frac{\partial g_{t,i}^{(k)}}{\partial \beta_t} \end{bmatrix} \qquad (5.1.19)$$

The harmonic jacobian that relates the k^{th} and J^{th} harmonics is indicated by $YG^{(k,j)}$ and is defined as:

$$YG^{(k,j)} = \begin{cases} Y^{(k,k)} + G^{(k,k)}, k = j \\ G^{(k,j)}, k \neq j \end{cases} \qquad (5.1.20)$$

where $Y^{(k,k)}$ is an array containing partial derivatives of the k^{th} harmonic of injection currents with respect to the k^{th} harmonic bus voltages derived from the system admittance matrix. The partial derivatives of the k^{th} harmonic device currents with respect to the J^{th} harmonic applied voltages are derived from the nonlinear device models and form the matrix: $G^{(k,j)} =$

$$\begin{bmatrix} O_{2(m-1),2(m-1)} & O_{2(m-1),2n} \\ O_{2n,2(m-1)} & diag\begin{bmatrix} \frac{\partial g_{t,r}^{(k)}}{V_t^j \partial \theta_t^{(i)}} & \frac{\partial g_{t,r}^{(k)}}{\partial V_t^{(i)}} \\ \frac{\partial g_{t,i}^{(k)}}{V_t^j \partial \theta_t^{(j)}} & \frac{\partial g_{t,i}^{(k)}}{\partial V_t^{(j)}} \end{bmatrix} \end{bmatrix} \qquad (5.1.21)$$

where, $V_t^{(k)}$ and $\theta_t^{(k)}$ are the k^{th} harmonic voltage magnitude and phase angle at the t^{th} bus, $O_{i,j}$ is an ixj matrix of zeros, and m$\leq t \leq$n.

If h harmonics in addition to the fundamental are considered, the set of 2n(l+h) + 3m nonlinear equations in matrix form is:

$$\begin{bmatrix} \Delta\overline{W} \\ \Delta\overline{I}^{(1)} \\ \Delta\overline{I}^{(5)} \\ \vdots \\ \Delta\overline{I}^{(L)} \end{bmatrix} = \begin{bmatrix} \overline{J}^{(1)} & \overline{J}^{(5)} & \cdots & \overline{J}^{(L)} & 0 \\ \overline{YG}^{(1,1)} & \overline{YG}^{(1,5)} & \cdots & \overline{YG}^{(1,L)} & \overline{H}^{(1)} \\ \overline{YG}^{(5,1)} & \overline{YG}^{(5,5)} & \cdots & \overline{YG}^{(5,L)} & \overline{H}^{(5)} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \overline{YG}^{(L,1)} & \overline{YG}^{(L,5)} & \cdots & \overline{YG}^{(L,L)} & \overline{H}^{(L)} \end{bmatrix} \begin{bmatrix} \Delta\overline{V}^{(1)} \\ \Delta\overline{V}^{(5)} \\ \vdots \\ \Delta\overline{V}^{(L)} \\ \Delta\phi \end{bmatrix} \qquad (5.1.22)$$

The resolution of the fundamental equations of charge flow of the previous section has the same form as the resolution of these equations. An initial guess is made at harmonic voltages and state variables of non-linear devices. From estimated values, power and currents are evaluated. Voltage changes and state variables are calculated from equation (5.1.22). Until the change in power and currents decay to the specified tolerance, with each iteration, the voltage and state variable estimates are updated with the calculated values [86,87,88].

Due to the large number of sparsely matched arrays, the speed of the solution and the memory requirements are highly system dependent.

5.2. Behavior of the transformer core under surge conditions

For an initial analysis, we almost ignore the transformer core [89], treating it as an equipotential earth surface, in which the winding has some capacitance. This is an excellent initial approximation because the parasite currents will initially prevent magnetic flux from penetrating the iron. However, we emphasize that, over time, the flux accumulates in the iron, and when this happens in the core of the transformer, we can expect it to modify our previous conclusions about the behavior of the winding under the conditions of the surge.

A problem of this type is solved in the solution of the Maxwell equations for the appropriate stimulus - a voltage surge applied to the winding in this case - consistent with the contour writhings applied by the lamination thickness. Christoffel [90] considers a waveform of step function and approaches the opposite end to what we have used so far. That is, it considers only the inductance of the winding and ignores all capacitances. When a voltage step function is applied to an inductance, we expect it to rise to a linear current ramp, to neglect the resistance, the inductive emf must balance the applied voltage. If the voltage is V_0, we would write:

$$V_0 = L\frac{dl}{dt} \tag{5.2.1}$$

Or,

$$I(t) = \frac{V_0}{L}t \tag{5.2.2}$$

Initially L will have a low value since the flux is all airborne. It will correspond to the inductance we have been using in our work so far. But as time passes and the magnetic flux penetrates the laminations, the inductance will increase considerably to some much higher value, L_∞. In practice, of course, the core would ultimately sature and the inductance would fall again. The expression that Christofell derives for the current is an infinite series:

$$I(t) = \frac{V_0}{L_\infty}\left\{t + \frac{\pi^2}{3}T_1\frac{\left[1-\sum_{n=1}^{n=\infty}(\frac{1}{n^2})\epsilon^{-n^2t/T_1}\right]}{\sum_{n=1}^{n=\infty}(\frac{1}{n^2})}\right\} \tag{5.2.3}$$

T_1 is a time constant, which gives a measure of the rate at which the flux moves into the iron. It is given by:

$$T_1 = \frac{\mu}{\rho}\left[\frac{d}{2\pi}\right] \qquad (5.2.4)$$

Where μ and ρ are the absolute permeability and resistivity of the core material, respectively, and d is the thickness of the laminations.

Equation (5.2.3) has been plotted in a dimensionless form in figure 5.1. It is seen that the current slope is initially high when the inductance is small but becomes asymptotic to a line of slope t/T_1 as time increases. Typically, the following values might apply for transformer steel:

$$d = 0.35\, mm\ or\ 3.5 \times 10^{-4} m$$

$$\mu = 10^3 \times 4\pi \times 10^{-7} = 4\pi \times 10^{-4}$$

$$\rho = 6 \times 10^{-7} ohm\ meter$$

Substituting these numbers in Eq. 5.2.4 $T_1 = 6.5\ [\mu sec]$, indicating that the core will influence the transient behavior of the winding in a relatively short time.

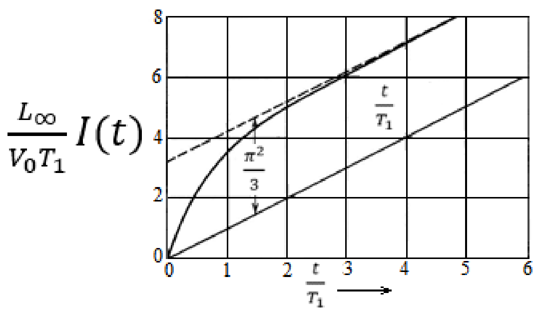


Figure 5.1. – Flux penetration into transformer core under surge conditions.

5.2.1. Inrush Current

During their operating time, the transformers undergo numerous switching processes. Consequently, the predetermination of the IC's resources is necessary in order to properly consider its instantaneous effects both on the transformer installation (normal operation of protection devices, overloading nearby equipment and other power quality problems).

For a better illustration of the procedure suggested by the calculation of the IC, a particular class of power transformers, commonly found in low voltage applications, is used for analysis.

The evolution of the current inrush time i(t) immediately after switching the transformer can be derived from the instantaneous equations of the electric circuit along with the law of the Ampère circuit applied to the magnetic core device. Thus, taking the primary winding with resistance R_1 and turns number N_1, and the magnetic mean path length lm of a central cross-sectional area Ac, the inrush current i(t) and induction of magnetic induction time B(t) can be expressed:

$$\begin{cases} u(t) = R_1 i(t) + N_1 A_c \frac{dB(t)}{dt} \\ N_1 i(t) = H(t) l_m,\ H = f\big(B(t)\big) \end{cases} \quad (5.2.1.1)$$

where u(t) is the supplied non-sine wave voltage and H (t) is the magnetic field measurement of the core.

To solve the system of equations above, a representation of the characteristic of the magnetic core in terms of H-B ratio is imposed. Various approach functions can be selected. Since the description of the accuracy of the heavy saturation core area is important for the IC generation phenomenon, Brauer's expression was selected here:

$$H = mB + nBexp(pB^2) \quad (5.2.1.2)$$

where m, n and p constants are determined for any kind of steel rolling of the core by a simple assembly procedure (restricting the expression to pass through at least three of the data points provided by the electric steel).

Finally, the system of nonlinear differential algebraic equations described by (5.2.1.1) is solved numerically using the method of Rosenbrock [91].

The magnetic flux density of the core before the energizing process B_{r0} represents the required initial value parameter, which is always taken as the remaining magnetization. Thus, the worst case scenario is considered.

Many transformer equipment protection devices discriminate the IC from different internal fault currents (e.g., short circuits) by investigating the current transient harmonic spectrum of the first cycle (over a period of time from the fundamental voltage source waveform T = 2π / ω). This principle is also known as the second harmonic restriction procedure [92, 93]. In this regard, a harmonic analysis on the first cycle waveform IC, which is based on the Fourier series [94, 95, 96], is also performed. Thus, the spectrum of the first cycle of the IC is evaluated according to [97] along with each level of harmonic percentage (Hh) with respect to the fundamental and its total harmonic distortion (THDI):

$$i(t) = \sum_{h=0}^{m} [A_h \cos(hwt) + B_h \sin(hwt)], \quad (5.2.1.3)$$

$$A_0 = \frac{1}{T}\int_0^T i(t)dt, \quad (5.2.1.4)$$

$$A_h = \frac{2}{T}\int_0^T i(t)\cos(hwt)\,dt, \qquad B_h = \frac{2}{T}\int_0^T i(t)\sin(hwt)\,dt,$$

$$I_h = \sqrt{A_h^2 + B_h^2}, H_h[\%] = \frac{I_h}{I_1}\cdot 100, THD_I = \frac{\sqrt{\sum_{h=2}^{m} I_h^2}}{I_1}\cdot 100. \quad (5.2.1.5)$$

In order to quantitatively describe the level of harmonic pollution of the supply voltage, the THDU indicator of total harmonic distortion was also adopted (derived from the Fourier series decay voltage signal):

$$THD_U = \frac{\sqrt{\sum_{k=2}^{n} U_k^2}}{U_1}\cdot 100, \; u(t) = \sum_{k=1}^{n} U_k\sqrt{2}\sin(kwt), \quad (5.2.1.6)$$

with k the harmonic order of the effective value U_k and angular frequency kω.

The IC evaluation described above can be easily implemented in any general-purpose computing environment, since all necessary data (for transformer voltage and applied) are available. The distorted voltage applied must be investigated before starting the energizing process. This can be achieved by using a high-performance metering and monitoring device such as a modern power quality analyzer capable of delivering a complete harmonic signal profile up to the 51st harmonic. This valuable information can lead to precise IC pre-determination parameters. In the following section, a case study will illustrate the flexibility of the computation procedure of the suggested IC. In addition, the influence of the harmonic voltage spectrum of the IC characteristics is revealed by the realization of specific quantitative parametric estimates.

6. Simulations

6.1. Fuzzy Controller for Smart Grid

The fuzzy smart grid controller has the ability to make automatic decisions [98] to define resource allocation [99,100,101]. It uses some predefined entries, and then relies on the parameters provided, selects the best font where it connects to a collector [102,103]. First, diffuse variables become identified. In the Smart-Grid model definition, the power generation capacity of the source, the price to generate the power unit, and the distance between the source-sink are defined as inputs for the fuzzy model [104,105]. These three parameters have their definition as power, price, and distance. After that, the junction functions are constructed. The junction functions are based on trapezoidal and triangular functions. The input parameters are described below [106,107,108].

Power: The power supply capacity represents the first input parameter. The power of the source was divided into three categories: Low, Medium and High (figure 6.1.1). The low power value starts at 0 and goes up to 500 units, starting at 300 units and continues to overlap the middle. Similarly, the medium starts at 300 and overlaps with high 500 units. After 700 units, all values are considered high. The power unit is represented by megawatts (MW), but the unit can also be designated as something else as well. All input power values are defined using the participation function in the range from 0 to 1. In order to maximize the amount of energy use, therefore, for power generation, a higher energy value will have more priority.

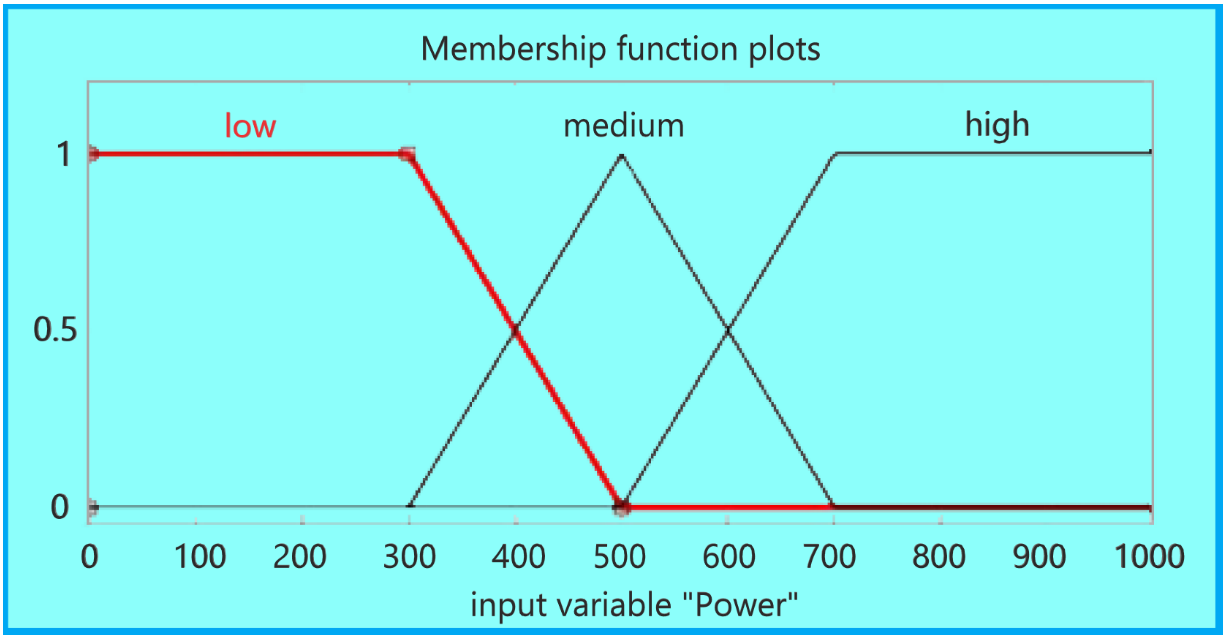


Figure 6.1.1. – Input variable Power.

Price: The second variable is represented by the energy generation price and is divided into three categories: low, medium and high (Figure 6.1.2). The low value starts at 0 and goes up to 6 units; starting in 3 units, begins to overlap in the middle. Similarly, the medium starts at 3 and overlaps with high in 6 units. After 9 units, all values are considered high. The unit is dollars/day. All input power values are set using this function in the range from 0 to 1. By prioritizing the source that is offering energy at a lower price, so that a lower price receives more priority.

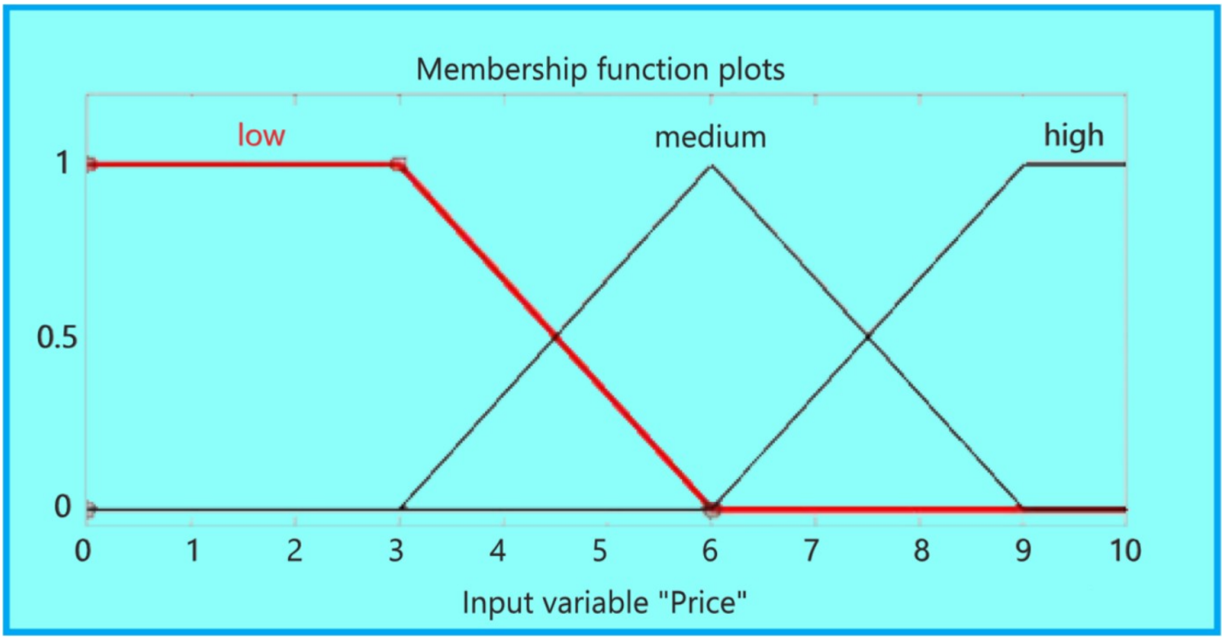


Figure 6.1.2. – Input variable Price.

Distance: The last diffuse variable is represented by the distance between the source and the collector. It is also divided into three categories: low, medium and high (figure 6.1.3). The low value starts at 0 goes to 5 units, starting in 3 units and begins to overlap in the middle. Similarly, the medium starts at 3 and overlaps with high in 5 units. After 10 units, all values are considered high. The unit is represented by miles. Power input values are defined using this function in the range from 0 to 1. Thus, a higher priority should be given to the source that is closer to the demand area, so that the shorter distance takes more priority.

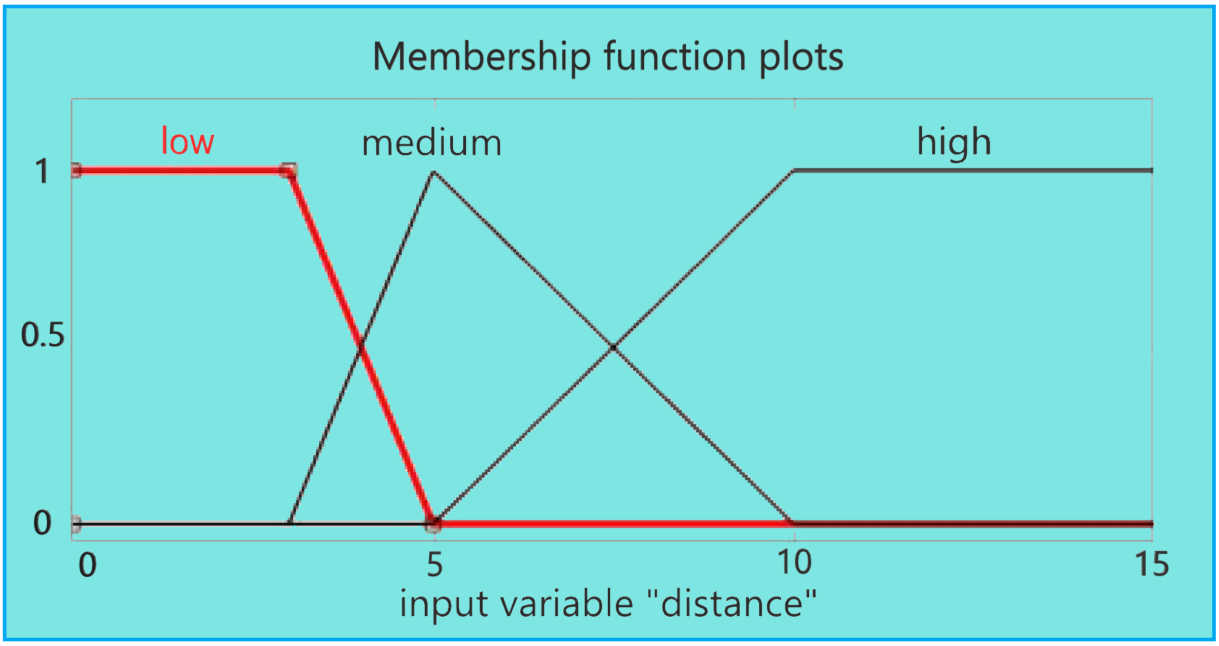


Figure 6.1.3. – Input variable Distance.

Inference mechanism: As there are three Fuzzy variables and because, for each variable, there are three different results, the total number of rules is 27. Table 6.1.1 lists all rules. These rules have the If-then feature. The result of the rules is considered between priority levels. This linguistic result captured the notion of entry in a complete and clear way. The high priority output would probably be preferred at low or medium priority. Detail the decision-making system, considering a situation where, based on user input, rule 1 is triggered; then the model would interpret the model as follows: if the power capacity is low, the price is low and the distance is low, the result is a low priority when signing that power source with the collector. Computational results were generated by the Matlab program [109].

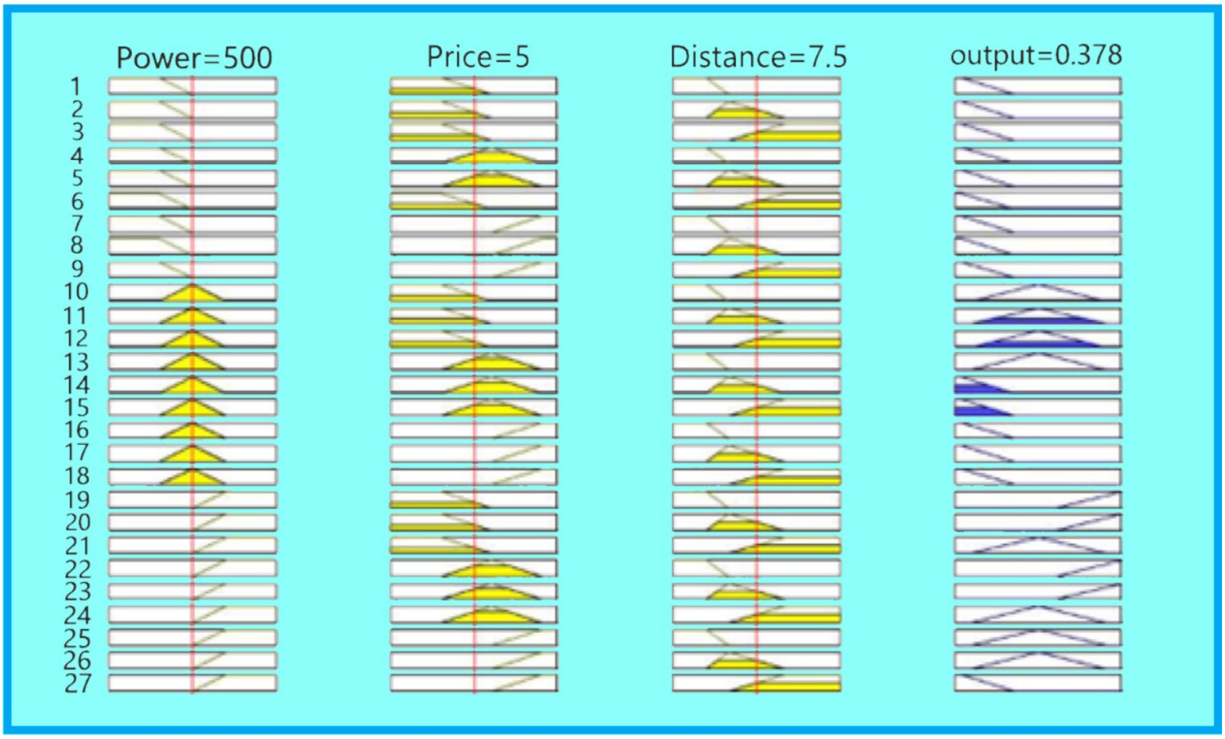


Table 6.1.1. – Fuzzy Rule base.

The surface chart shown in figures 6.1.4. and 6.1.5. demonstrates how the fuzzy smart grid controller can make automatic decisions to define resource allocation. It uses some predefined inputs: power and distance in figure 6.1.4. and power and price in figure 6.1.5, then it counts with the supplied parameters, selects the best source in which it connects to a collector described in the chart output.

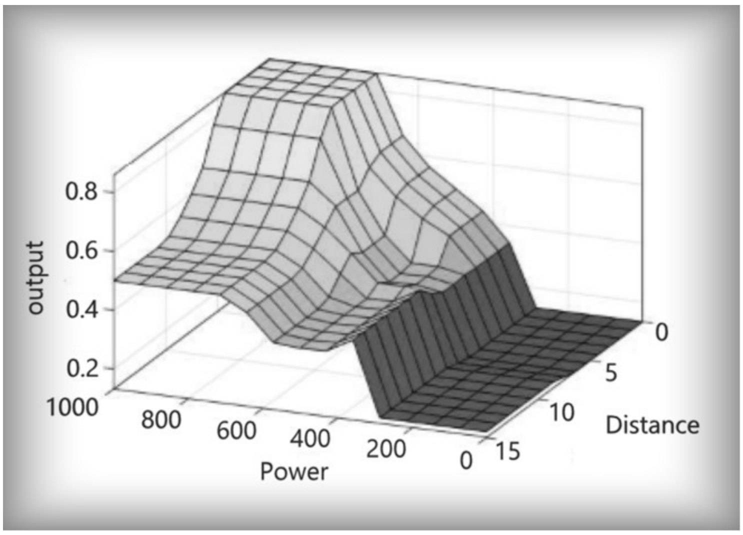


Figure 6.1.4. – Power and distance output graph.

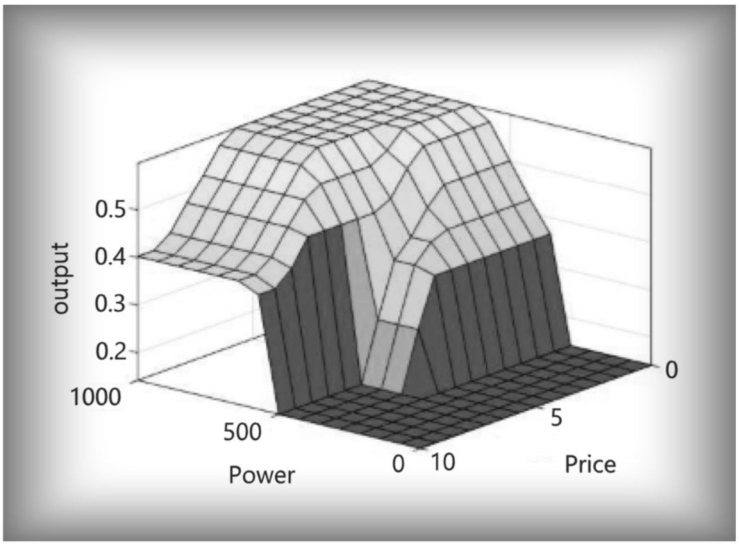


Figure 6.1.5. – Power output and price graph.

6.2. Simulation of the electricity system with SVC (Static Var Compensator)

In this simulation (MATLAB) a var static compensator (SVC) is being used to regulate the voltage at 500[KV], a system of 3000[MVA]. When the system voltage is low, the SVC generates reactive power (capacitive SVC). When the system voltage is high, absorbs reactive power (inductive SVC). The SVC is evaluated + 200 capacitive [Mvar] and 100 inductive [Mvar]. Var’s static compensating block is a fasor model representing the static and dynamic characteristics of SVC at the fundamental frequency of the system.

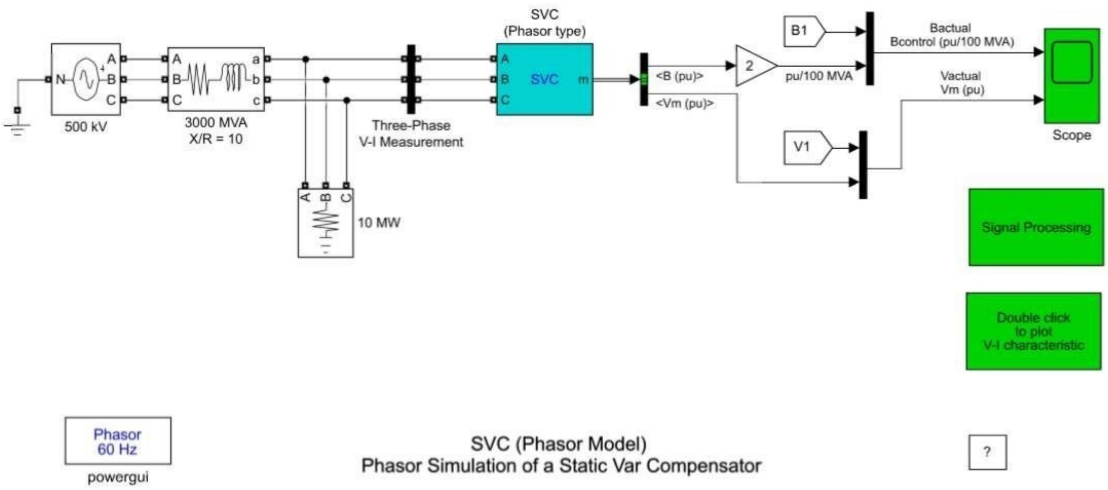


Figure 6.2.1. – SVC (Phasor Model).

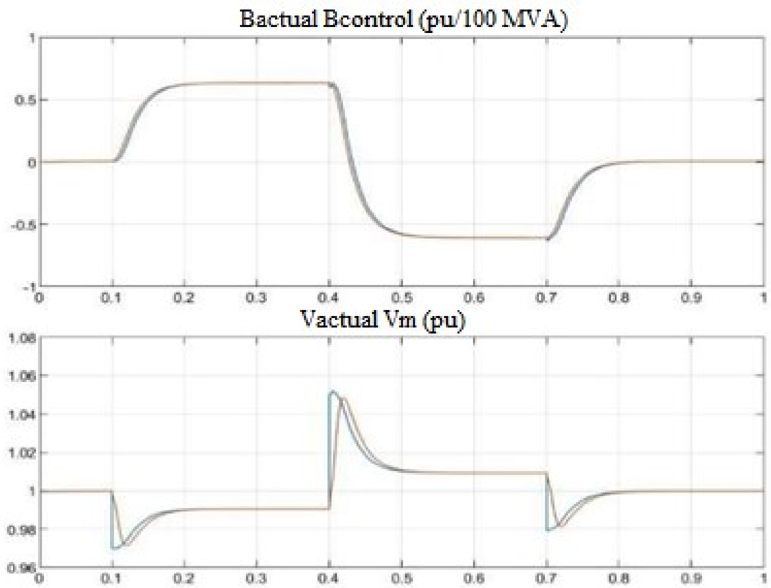


Figure 6.2.2. – Voltage variation.

The programmable three-phase voltage source has the function of varying system voltage and observing the performance of the SVC. Initially the source is generating nominal voltage. Then, the voltage is successively decreased (0.97 pu in t = 0.1 s), increase (1.05 pu in t = 0.4s) and finally returned to nominal voltage (1 pu in t = 0.7 s).

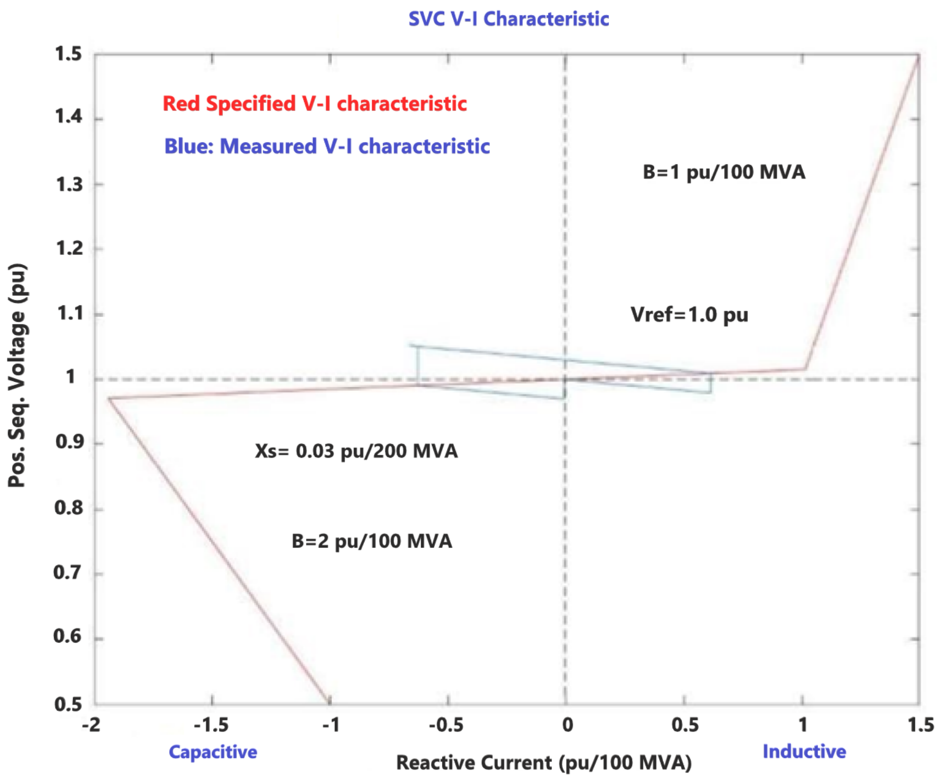
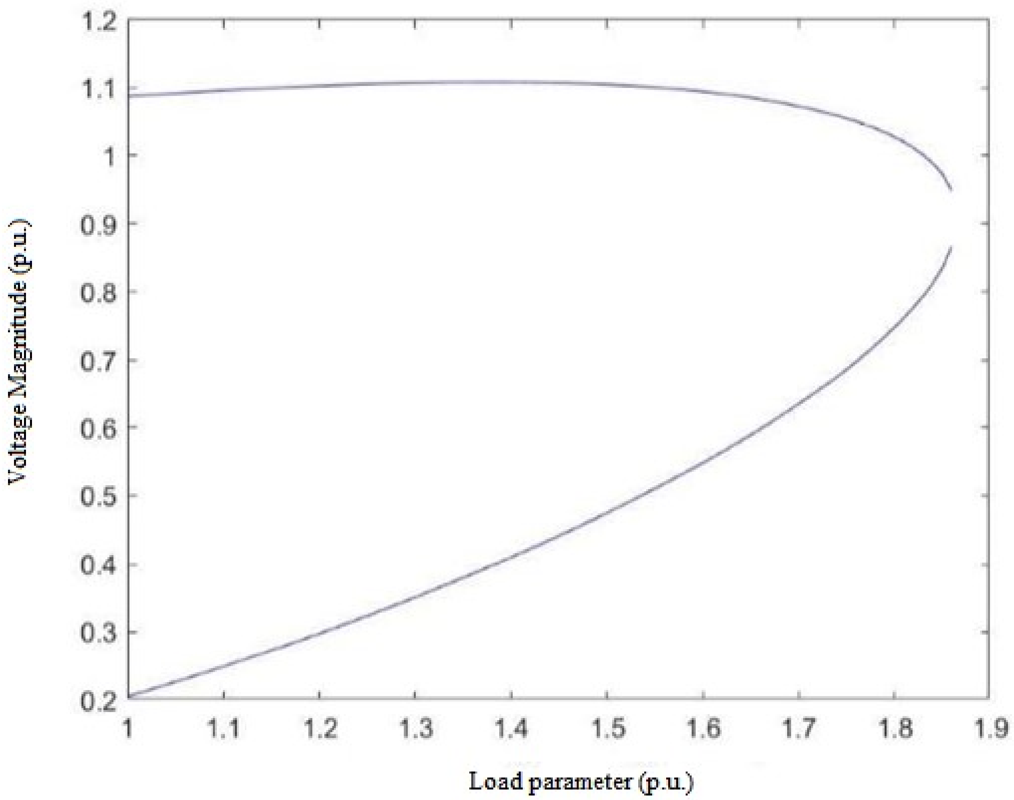


Figure 6.2.3. – Variation of voltage and reactive current.

In this type of controller stands out the characteristic of increasing the point of adjustment of the local voltage at the time when reactive currents from the sources remain predominantly inductive and decrease the adjustment point when the current becomes Capacitive.

6.3. Voltage stability analysis

When varying the load power factor (through the variation of the reactive energy installed in the load bar) the variation in the voltage stability margin is noted (figure 6.3.1.), increasing or decreasing due to the required need in the load variation of the system, that is, the direct influence of the load power factor on the voltage stability margin, determining one of the main alternatives of maintaining the stability of the system's voltage that is summarized in maintaining the load power factor, as well as, the inclusion of close to consumption.



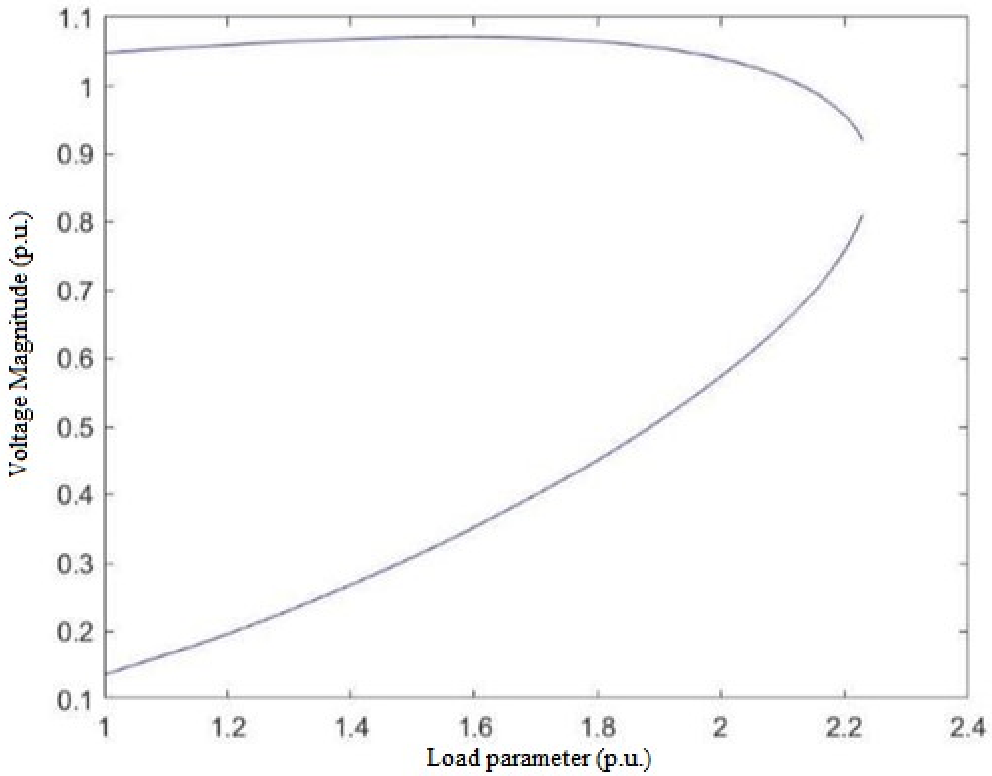


Figure 6.3.1. – Voltage stability margin.

6.4. Voltage control with STATCOM

The power control and reactive voltage system by shunt compensation is constantly used in active electrical networks. In this electrical power system analyzed (Figure 6.4.1), the modeling of a type of shunt compensation device widely found in updated networks: multi-level modular STATCOM (MMC).

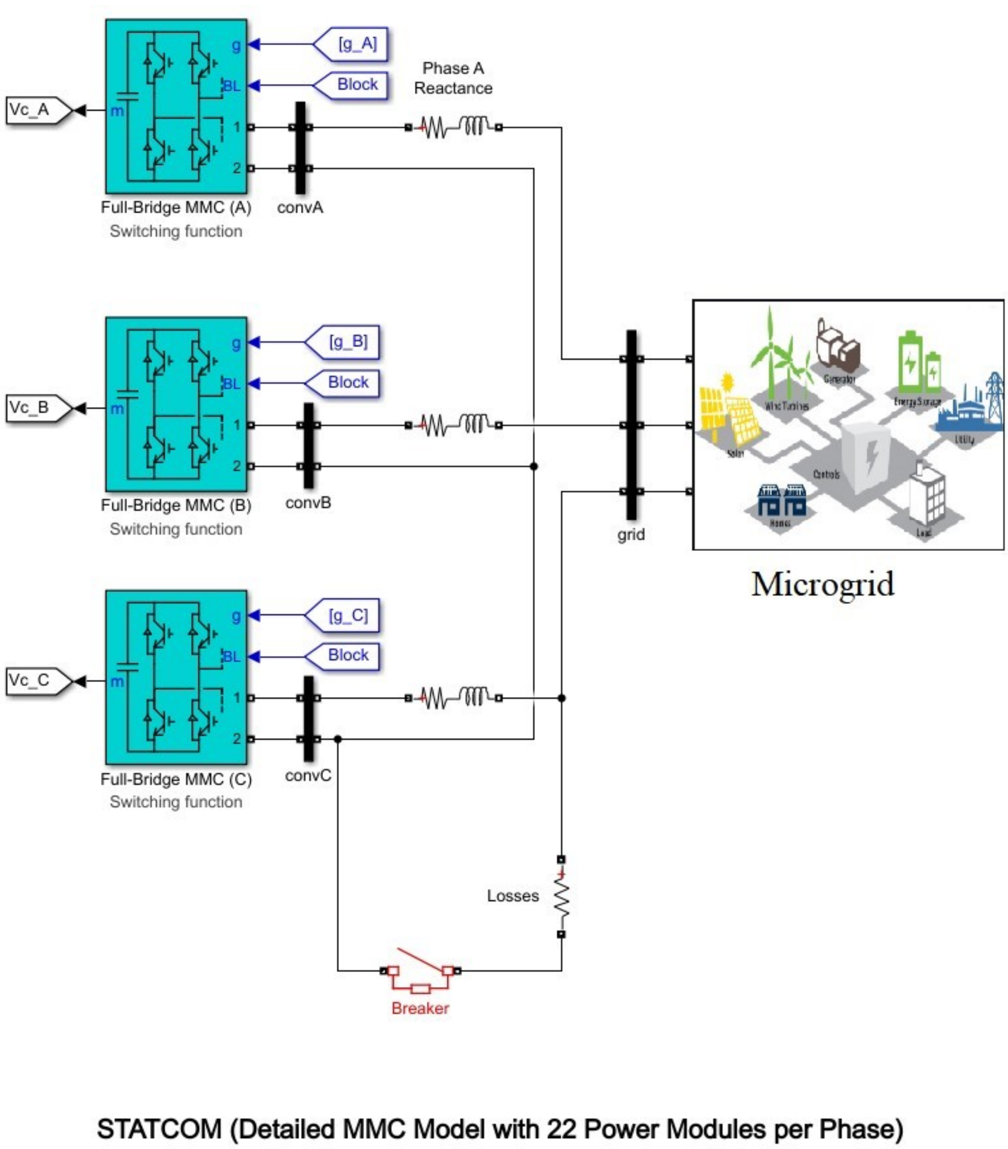


Figure 6.4.1. – STATCOM.

Multilevel STATCOM consists of a structure formed by serially connected power modules. The main objective of the use of these structural formations linked in submodules is to develop a better use of components, such as semiconductors. With this, the energy available with semiconductors will imply a new MMC to be developed to attend the new converter specifications. The number of modules is determined through the required output. The sum of all output voltages of the power module forms terminal attention. The reactive power supplied has established control through the amplitude of the converter voltage.

Among some advantages of the MMC is the continuity of the operation, where the MMC submodules are serial, so if some submodules stop working, the general MMC may remain functioning. Through its modular structure, the MMC has the characteristic of being sized to different levels of power and voltage. The MMC also has high efficiency.

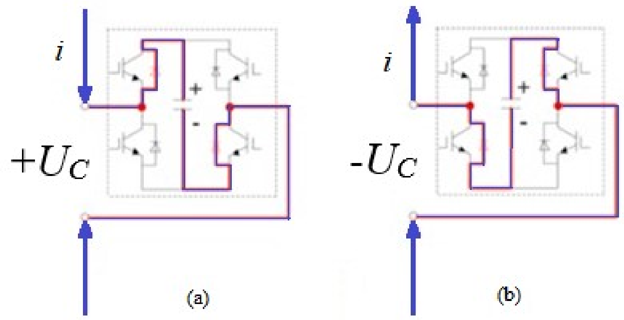


Figure 6.4.2. – Current path in full-bridge. (a) when the current is in the positive direction; (b) when the current is in the negative direction.

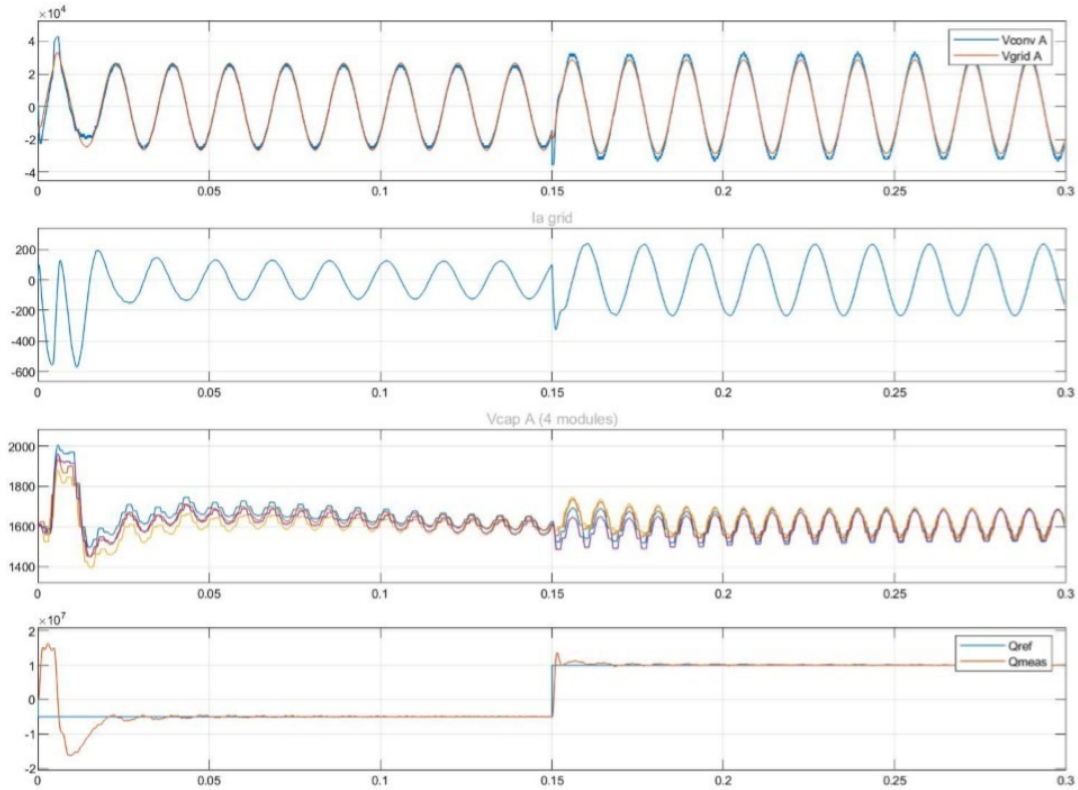


Figure 6.4.3. – Voltages and powers in the statcom.

Figure 6.4.4 describes the result of the measurement of the network voltage and current when the power and reactive voltage control system by shunt compensation (multilevel modular STATCOM (MMC)) operates in the active electrical network.

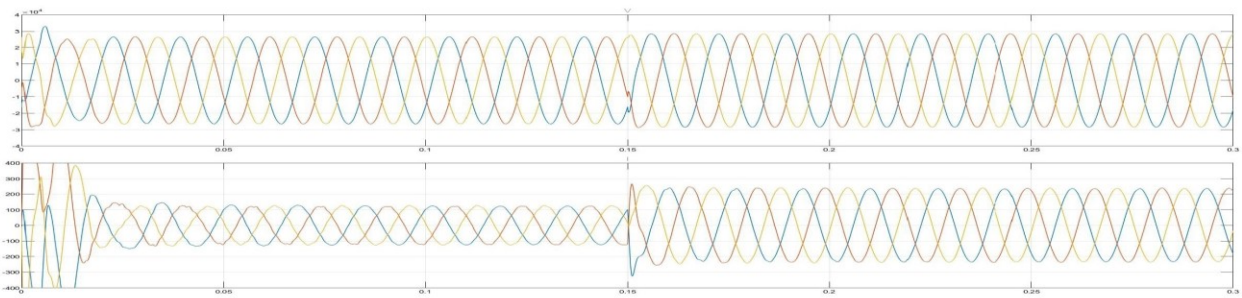


Figure 6.4.4. – Voltage and current in the network.

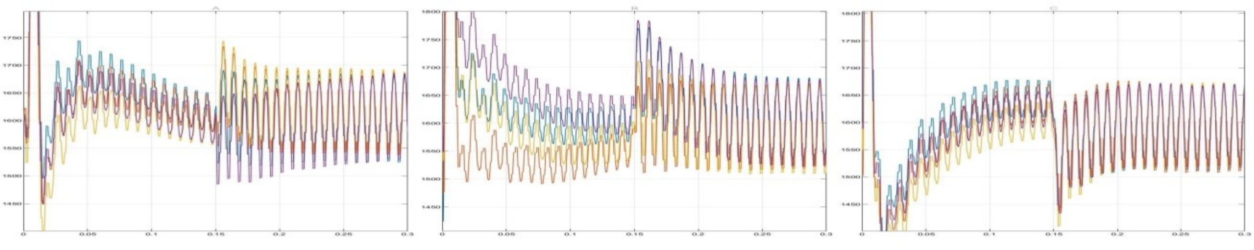


Figure 6.4.5. – Voltages in capacitors.

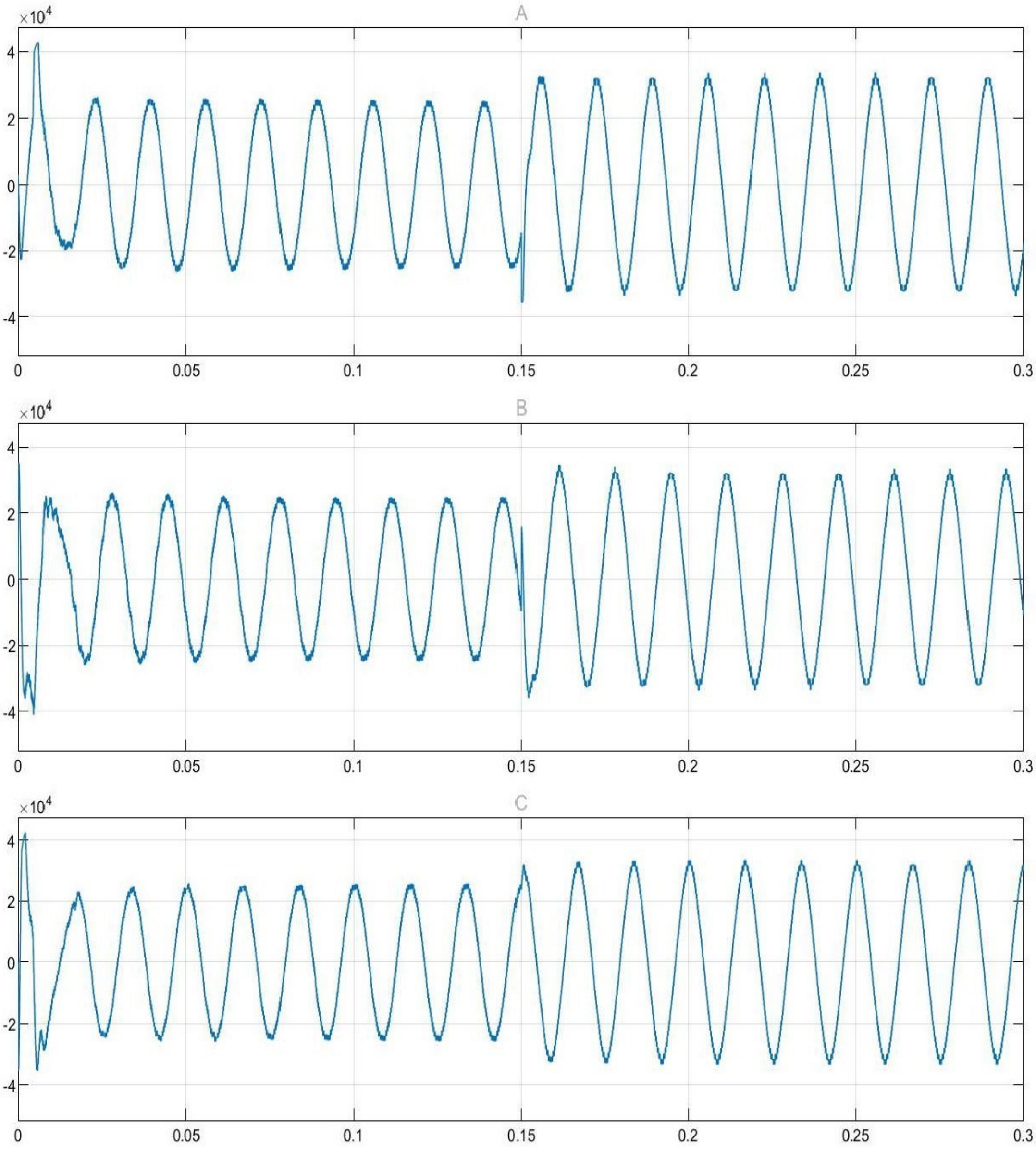


Figure 6.4.6. – Voltages at the exit of the statcom.

With the analysis of the responses presented, it can be verified that STATCOM can absorb or generate reactive energy. The recurrent phase reactance proportional to reactive power transfer. The converter generates a voltage in sync with the voltage of the network. When the voltage amplitude of the converter has a value lower than the voltage of the network, STATCOM acts as a reactive power that absorbs inductance. When the voltage amplitude of the converter has a higher value than bus voltage, STATCOM acts as a capacitor that generates reactive energy.

6.5. Voltage quality with incorporation of renewable generation

The impact of harmonic distortions [110] due to the integration of renewable energy generators (Figure 6.5.1.) with harmonic injection level equated to potentially disturbing loads that participate in the analysis of the harmonic flow of power and influences the evaluations considered in the management algorithm formation variables of the integrated electric power system, the virtual power plant can be measured at 13.8 [kV], which is a function of the connection of a new generation of renewable energy to an electric power system, considering the representation of the main connected loads to the Interconnected Distribution System (IDS) at 13.8 [kV] [111,112,113].

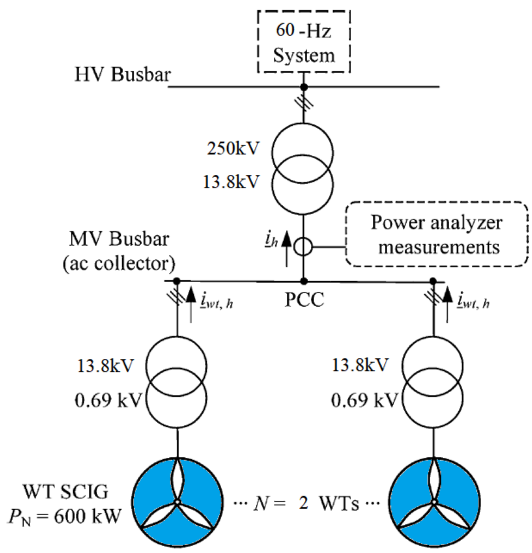


Figure 6.5.1. – Wind Turbines connected to the distribution system.

The figure 6.5.2. shows, respectively, the harmonic spectrum that results in the current shown in figure 6.5.3., observing the characteristic harmonic components, especially in the condition of full wind generation. The results of the simulation presented were performed by the electromagnetic transient program (system described in the figure 6.5.1. and simulated in ATPDRAW).

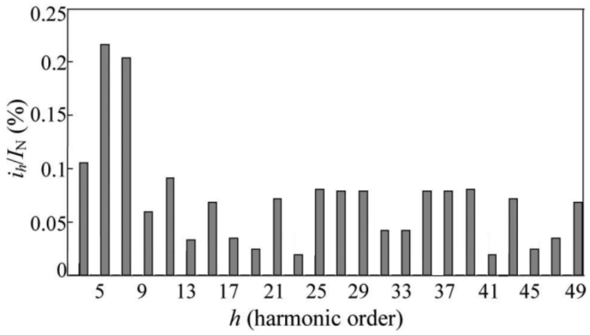


Figure 6.5.2. – Harmonic spectrum.

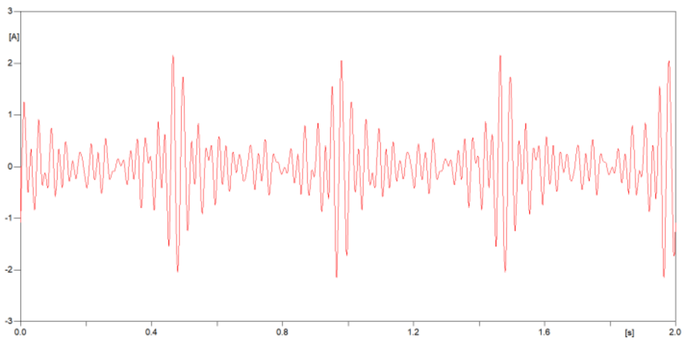


Figure 6.5.3. – Wind turbine harmonic current.

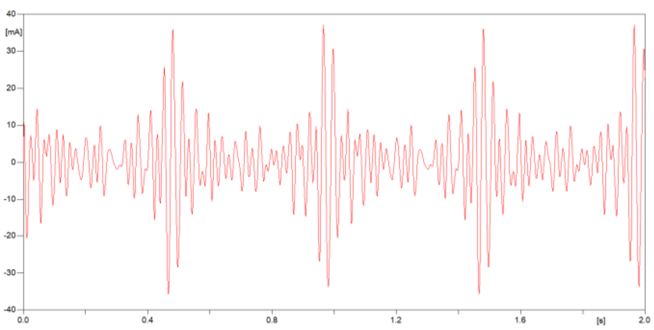


Figure 6.5.4. – PCC harmonic current.

The harmonic power flow analysis shows the variation of the harmonic distortion propagated at the common coupling point, which can reflect as the main influence of the wind turbines to be coupled in the virtual plant, being able to be quantified in function of variables and parameters available in the operations of the entire electric power system composed of various sources of harmonic distortion, such as these presented energy sources and inverters of energy in other renewable energy sources, allowing to include in the managers of computer systems the improvement through the best aspects of the quality of the available energy [114,115,116].

6.6. Voltage quality at power transformer energization under harmonic distortion

A single-phase, low-voltage transformer with nominal power of 2 [KVA], shall be energized at a given grid point of an electrical installation of the electricity distribution grid supplied by wind power generation sources potentially impacting the supply voltage demanded with a harmonic distortion spectrum (Figure 6.6.1.).

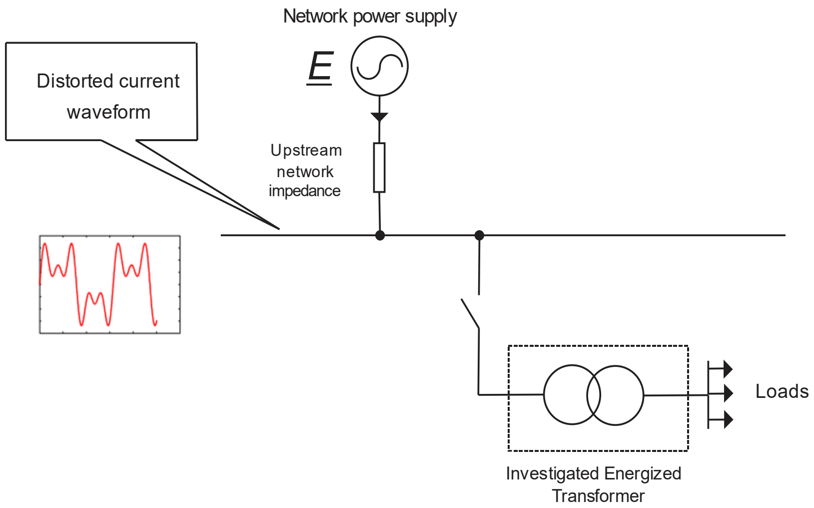


Figure 6.6.1. – The network energy degradation process and the transformer connection network point.

In this specific network node, several non-linear loads are already active (adjustable speed inverters, switched sources, unloaded lamps and others), but the focus of harmonic analysis is on distinguishing the impact of renewable sources. The characteristics of the supply voltage were investigated with an electromagnetic transient simulation software called ATPDRAW.

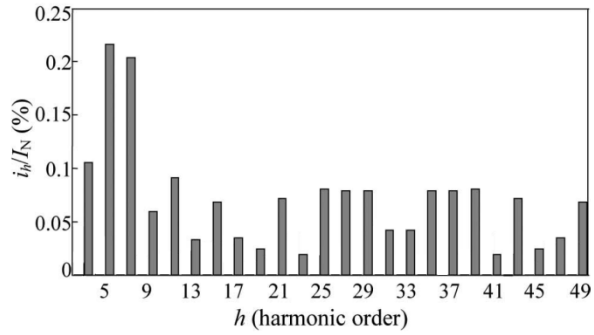


Figure 6.6.2. – Current harmonic distortion spectrum.

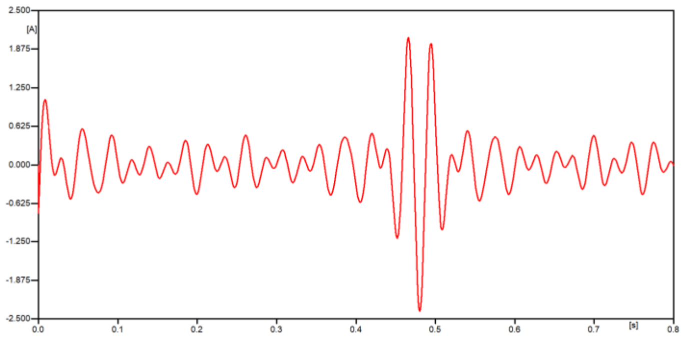


Figure 6.6.3. – Current harmonic distortion waveform.

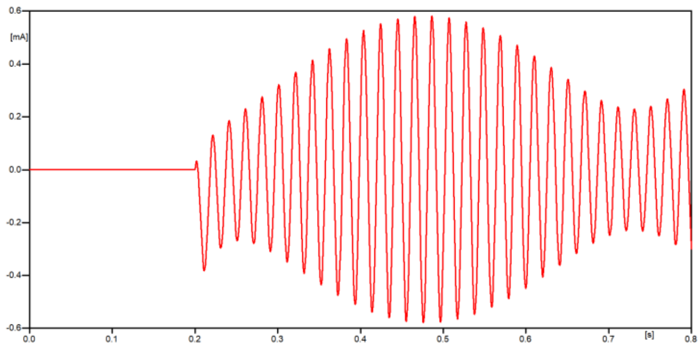


Figure 6.6.4. – Waveform of the harmonic distortion supplied in the inrush current.

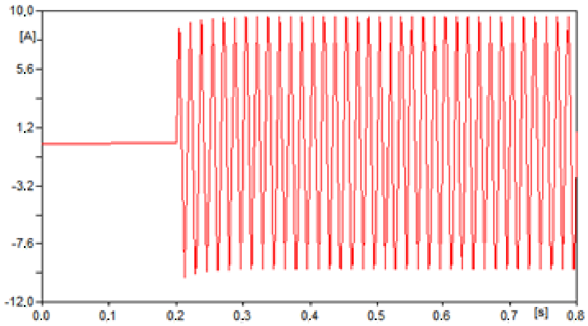


Figure 6.6.5. – Inrush current when energizing the transformer

7. Conclusions

The variation in the voltage profile characterizes the action scenario of appropriate methods for the correction and stability of voltage. The low and inappropriate voltage profile characterizes the voltage collapse [117] as a set of changes that precede voltage instability in the electrical power system. One with corrective measures is necessary to maintain an acceptable level of voltage in the networks and microgrids of the systems. The use of shunt capacitors in voltage control stand out with low deployment cost and installation and operation flexibility. These are readily leased at various points of the system, result in a contribution to power transmission and distribution. Shunt reactors are used to compensate for the capacitance effects of the line, in particular to limit increased voltage in open circuit or light load. Active network management appears as a very reliable solution for operation with network and microgrid stability, as the system remains constantly in terms of demand for electricity supply with the use of sources of renewable generation in a distributed manner implying a set of stabilization measures. Several adverse conditions can be created during the oscillations in the power provided to the feeders of the networks, and the concept of better use of the available potential, disturbances or overload situations of the electricity grid is designed. Today's networks more completely manage electricity demand, effectively including generation from renewable sources.

Large-scale disasters, from natural disasters such as earthquakes and tsunamis, to disruptions caused by humanity, such as cascading supply failures, generate enormous cost to local communities, businesses and societies in general. These costs are often caused by electrical interruptions often associated with widespread disasters. Unfortunately, the number of widespread electrical interruptions constantly grows. With the great modern dependence on electricity, it is clear that the current state of things needs to change. This is the case to create a way to strengthen the supply of electricity against disasters and, on the worst occasions, provide a rapid restoration of supply. The microgrid appears as a technology that can perform an important role in planning more resilient and reliable electricity supply systems, which is based on the principles of distributed generation. Distributed generators now stand out as an accepted means to improve the reliability of electricity supply on your site, acting as uninterrupted power supplies. As a recent technology, microgrids are not challenge-free. There is often a lack of standards that specify common control interfaces between microgrid devices, and other nontechnical challenges, such as appropriate business models to support the microgrid development system.

The study of the impacts of the penetration of renewable energy sources on the voltage buses, the values of harmonic distortion voltage and harmonic order are investigated for a virtual plant using the Newton Raphson method based on the harmonic energy flow. From the studied method, it can be observed that the addition of RES in the network directly affects the RMS value of the voltage, harmonic order and harmonic distortion factor. The fundamental voltage is improved and depends on the energy penetration of the RES system; also, the injection of RES has a significant impact on the harmonic evaluation and the value of the harmonic distortion.

Other research related to various renewable energy sources connected to the grid and added to the virtual plant are currently under investigation and preparation for future improvements in electrical energy systems that seek reliability and, above all, quality of electrical energy, to interact directly with the conditions of economic variation of the generating structures to be incorporated into the system, defining real parameters expressed in editable variables and adhering to the general algorithm of the system's control system a higher level of economic growth potential and with greater reliability to the generation system with energy quality plant formed by the Virtual Plant.

The exploration of the influence of the inrush current completes the main objective of analyzing an analytical procedure that predicts the IC parameters of a single-phase power transformer under a condition of distorted voltage. The evaluation method is based on the solution of the system of nonlinear differential algebraic equations derived from the transformer circuit model and on the characterization of the magnetic core. As the harmonic voltage content can now be accurately measured, the voltage distortion is modeled according to the Fourier series. The variations in IC resources corresponding to the level of harmonic voltage pollution (THDU) are the main reasons for this analysis. Thus, the amplitude of the IC and its zero harmonic component of the waveform of the first cycle are increasing along with the degradation of the voltage, while the distortion of the IC (THDI) and the amplitude of the second harmonic decrease.

These parameters are particularly important because they generate the thermal and electrodynamic voltages experienced by the transformer during the switching process (IC amplitude) and also lead to the appropriate selection of the equipment or protection method (for example, harmonic frequency discrimination procedure between the IC and short circuit). The level of voltage distortion that can be measured at different nodes in the common low voltage grid does not generate critical values for the transformer IC parameters. However, the constant demand for energy efficiency, operational flexibility and high levels of performance for home appliances requires the large-scale use of electronic energy equipment. Consequently, voltage distortion is expected to increase steadily. These harmonic distortions, especially when they influence the supply voltages in a power monitoring system integrated with the virtual plant, are characterized by being different in terms of monitoring the quality of the energy to be generated with the integration of the injected sources and loads in the energy system formed by this virtual plant, in order to minimize these harmonic distortions and, consequently, improve the system stability, economic viability and countless other advantages for the analyzed energy generation.

Cyber-attacks, currently defined as cyberterrorism, clearly describe an option for “modern” terrorists, who use anonymity, extreme potential to inflict massive damage, impose psychological impact and appeal from media sources. Cyber-attacks on key components of national infrastructure (electricity systems) may not be uncommon, but do not fit as attacks conducted by terrorist groups and are not defined as the types of damage in which terrorist qualification. But even though the fear of cyberterrorism has sometimes been manipulated and exaggerated by inopportune interests acquired, it is clear that one should not deny or ignore it.

Even if a reliable safety standard is determined based on autonomous voltage controls, electric power systems are always evolving and include new consumption loads and modern forms of electric power generation, thus, the development of research and technology to guarantee that all technical standards of safety and quality are fulfilled should remain ahead of this evolutionary time, whether with the inclusion of high computational performance systems to reduce response times and prompt contingency assistance, that is, including in future projects more next, the adaptation for the assembly and maintenance with robotic and autonomous systems aiming at greater economic growth and increasing the quality of the electric lines, activities planned for next research and technological incorporations.

8. Bibliography

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