Voltage and frequency regulation to support synchronous generators operation by grid feeding distributed energy resources

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Summary

Research on new grid topologies and control configurations to support distributed energy resources is being carried out in order to improve electric service reliability and better power quality to the end consumer. Besides, due to more restrictive environmental policies and economical incentives for the deployment of new renewable energy resources, the energetic scenario seems to be moving towards a more sustainable one. With the increasing proliferation of renewable energies and distributed energy resources, however, the challenges that future grids will have to confront can only escalate.

Before dealing with these new challenges, it is first necessary to fully comprehend how a standard grid is regulated and to embrace the fundamentals on grid operation and management from a technical perspective. By understanding how current grids function, the effect of these new actors on the grid namely distributed energy resources can be isolated and addressed either individually as a new phenomenon never encountered before or extrapolated from a well-known challenge of the mains.

In this thesis, the operating of the standard grid is depicted together with these forthcoming technologies such as microgrids and distributed energy resources. The synchronous generator together with its regulator and its excitation system prove to be key actors in terms of frequency and voltage regulation thus special emphasis is given to them. Simulations regarding the control of the synchronous generator and its influence on the grid stability are performed to support the many literature that attribute the synchronous generator as the par excellence regulator of the grid. Finally, the interaction between an inverter-based distributed generation and a diesel-based distributed generation is studied to identify its effects on both the dynamic response of the grid and its stability.

The realized simulations provide scenarios in which to test the importance of the synchronous generation inasmuch as the regulation of the grid is concerned. In addition, the introduction of an inverter-based distributed generation in the simulations is particularly interesting to present the benefits that the support from distributed generation on the grid can bring about.

Resum

Actualment es realitza molta recerca en relació a noves tipologies de xarxa i configuracions de control per donar suport als recursos d'energia distribuïda amb la finalitat de millorar la fiabilitat del servei elèctric i millorar la qualitat de l'energia que rep el consumidor. A més a més, a causa de les polítiques per combatre la contaminació ambiental i els incentius econòmics per al desplegament de noves fonts d'energia renovable, l'escenari energètic sembla estar dirigint-se cap a un futur més sostenible. Tanmateix, amb l'augment de la proliferació de les energies renovables i els recursos energètics distribuïts, els reptes que les futures xarxes hauran d'afrontar només poden fer que créixer.

Abans d'abordar aquests nous desafiaments, però, cal primer tenir un bon coneixement de la regulació d'una xarxa elèctrica estàndard i introduir els fonaments que regeixen el funcionament i la gestió de la xarxa des d'un punt de vista tècnic. Entesa la funcionalitat de les xarxes en la seva configuració actual, l'efecte d'aquests nous actors a la xarxa elèctrica pot ser desacoblat i afrontat de forma individual com un nou fenomen o extrapolar-se a partir d'un repte actualment conegut de la xarxa elèctrica tradicional.

En aquest projecte de final de grau, s'il·lustra el funcionament de la xarxa juntament amb totes aquestes noves tecnologies com ara són les microxarxes i els recursos energètics distribuïts. El generador síncron juntament amb el seu regulador i el seu sistema d'excitació resulten ser els actors principals en quant a la regulació de la freqüència i tensió de la xarxa i, per tant, se'ls dóna un èmfasi especial. Simulacions pel que fa al control del generador síncron i la seva influència sobre l'estabilitat de la xarxa es duen a terme per avaluar i contrastar la literatura que sovint atribueix el generador síncron com el regulador per excelůlència de la xarxa. Finalment, la interacció entre una generació distribuïda basada en un inversor i una generació distribuïda basada en un equip dièsel es visualitza per identificar els seus efectes tant sobre la resposta dinàmica de la xarxa com la seva estabilitat.

Les simulacions realitzades proporcionen escenaris els quals verifiquen la importància de la generació síncrona en relació a la regulació de la xarxa. A més, la introducció d'una generació distribuïda basada en un inversor en les simulacions és particularment interessant per presentar els beneficis que el suport de la generació distribuïda a la xarxa pot proporcionar.

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Preface

Centralized generation where long transmission lines attempt to reach end-users regardless of the electrical losses due to energy transmission is, slowly but gradually, coming to an end. The apparition of inexpensive and reliable power converters have triggered the emancipation of renewable distributed energy resources which are spreading at a fast pace.

None the less, new challenges that arise from the use of these state-of-the-art technologies require an in-depth comprehension of the grid regulation strategies. The motivation of this thesis, thus, rises from the wish to understand the new challenges that these cutting-edge technologies will carry along without neglecting the current controls and regulations of the grid which may prevail for still some time. Furthermore, the current regulation of the grid may well serve as a benchmark for upcoming microgrids regulations, distributed energy resources control schemes and so forth.

All in all, the progressive study of the synchronous machine aids at understanding at length how traditional and not so traditional grids are regulated. In turn, the operating principles of grid regulation allow the introduction of distributed generation to enhance grid dynamic performance and stability as a whole.

Hopefully, this thesis might serve as a cornerstone for future studies that attempt to further into microgrids and their multiple challenges

Introduction

Objectives of thesis

- To present the notions of a microgrid and distributed energy resources.
- To comprehend how an electrical grid is regulated in terms of frequency and voltage control from a theoretical point of view.
- To present the working principle of the synchronous generators together with its regulator and excitation system.
- To verify the importance of the synchronous generator and its governor and excitation system when regulating the electrical grid by monitoring the effect of such elements on the frequency and voltage of the grid.
- To analyse the dynamic response and stability of a microgrid with a synchronous generator operating as a grid-forming distributed generation and an inverter-based distributed generator operating as a grid-following one to support the grid by outputting a constant and variable power

Outline of thesis

Chapter 1 introduces the main theoretical background to provide solid ground in order to comprehend the main challenges that grids and microgrids need to confront and to motivate the diverse simulations performed in this thesis.

Chapter 2 introduces the elements employed in the upcoming simulations such as the parameters of the generator, which regulator and excitation system are employed and the characteristics of the inverter-based distributed generation among others. Moreover, the chosen software to carry out the simulations is depicted among other possible softwares that are currently being used in both the academia and the private sector.

Once the simulation environment has been set, the several simulations performed are then introduced in chapter 3. On one hand, the synchronous generator is studied with and without the governor and the exciter system. On the other hand, the coexistence of a grid-following distributed generation together with a synchronous generator is simulated. The realisation of the simulations along with their principal results are commented throughout their course. Finally, a small summary of the simulation is included to wrap up the results.

This thesis concludes by commenting on the time-planning and cost estimation of the realization of this thesis as well as its environmental impact.

At the end, the conclusions of this project and future lines of work are presented

Chapter 1

Theoretical Background

1.1 Microgrids

1.1.1 Distributed Energy Resources (DER)

Distributed energy resources (DER) which are composed of distributed generation (DG) and distributed storage (DS) are sources of energy located near local loads that can provide a variety of benefits including improved power quality and reliability [5][6][7].

Contrary to traditional generation where large electrical station such as nuclear powered or coil-fired plants are used to provide great amounts of power which are transmitted over long distances in a centralized manner, DER tend to use renewable energies namely bio mass, geothermic energy, wind power, solar power and so on as the main energy sources [8]. By using distributed storage systems together with distributed generation, it is possible to reduce the environmental impact, improve the overall electrical security system and allow a certain degree of flexibility and autonomy [9].

DERs can be classified into two different groups depending on their operating role towards the AC grid to which they are connected. These are grid feeding DERs and grid forming DERs [10][11].

- Grid feeding DER: In the grid feeding scenario, the DER is operated at its Maximum Power Point (MPP) controlled by a power converter. The output power is then delivered to an intermediate DC-link where the energy is stored. From there, an inverter transforms the DC power to AC power suitable to feed the operating grid. By controlling the DC voltage of the DC-link, the DER is capable of delivering a constant power to the grid regardless of the state of the grid. In short, grid feeding DER's can be seen in electrical terms as ideal current sources connected to the grid along with paralleled high-value impedances.

- Grid forming DER: In the grid following topology, the inverter responsible to interconnect the DC-link to the grid utilizes a control loop to set the voltage amplitude and frequency of the grid at which the DER delivers its power. Ideally, a grid forming DER can be seen as an ideal voltage source with a low-output impedance which, as its name implies, can be used to form the grid if operating isolated from other electrical networks.

1.1.2 Definition of a Microgrid

A microgrid is a localized small-scale energy grid with control capability which can disconnect from the utility power grid and operate autonomously as an electric island [12]. Likewise, they can be reconnected to the area or local electric power system with minimal disruption to the local loads by using a point of common coupling. Microgrids are systems that have at least one distributed energy resource and associated loads. They usually are low-voltage AC systems which utilize an array of distributed energy resources such as photovoltaic panels or wind turbines to provide power and, in most of the cases, heat to the community or area that they serve. Another particularity of microgrids is its bidirectionality of power flow [13]. When connected to the grid, they are able to either supply energy to the utility grid or consume it by storing it or distributing it to their connected loads.

All in all, microgrids feature interesting characteristics which motivate their future deployment and justify further research in the field [14].

Microgrids could be utilized in developing countries to provide power to remote areas where expanding the national grid would be extremely expensive [7]. In rapid industrialized economies, microgrids could support the utility grid when and where the electric demands are particularly high. Lastly, in developed countries, microgrids turn to be an attractive way to address climate change whilst maintaining or even increasing power quality and reliability. In spite of the appealing perks of using microgrids, there are several handicaps that prevent its expansion as cutting-edge technology. Most of the impediments that constrain the extensive use of microgrids can be linked to the coupling and decoupling of the microgrid with the utility grid and the management of all distributed energy resources that take part in it [15][8].

Microgrids are made up of several elements which shall be described in the following paragraphs [9]. These are DG, DS, interconnecting switches and control systems/strategies.

Distributed Generation

DG units can be divided into two main categories. The first group consists of conventional rotatory machines which generate AC at the frequency desired without needing to implement a power converter to modify its output. The second group includes distributed energy resources such as PVs which require power electronic converters as the interface medium between the source and the microgrid. These converters may transform AC to DC, DC to DC or DC to AC depending on the parameters that need to be monitored such as output voltage, frequency, active and reactive power and so on. DG units can also be classified in terms of energy flow whether the units are dispatchable or nondispatchable [13]. The output power of nondispatchable units such as intermittent renewable energies like PV or wind turbines are not controlled or modified to adapt, for instance, to the power demand but instead they usually work under the principle of the maximum point of power tracking (MPPT) in order to maximize the output power regardless of atmospheric conditions or the electric demands. In contrast, dispatchable units can adjust their output power accordingly to what the power system necessitates. A diesel generator, a clear example of dispatchable unit, can increase or decrease the output power by controlling the amount of fuel that is fed to the generator by using a governor [16][17].

Distributed storage

Distributed storage technologies are essential to balance out when the energy generated does not match with the energy consumption [18]. Similarly, DS reserve energy for a future demand, can stabilize the whole system, damp energy disturbances and, on the whole, permit certain flexibility in front of generation and load fluctuations. The most used DS consist of supercapacitors and flywheels for short term storage and banks of batteries for mid/long term storage [9].

Interconnecting switches

The interconnection switch is basically the point of common coupling between the microgrid and the utility grid. It covers all the devices necessary to carry out such operation including relays, protective components and communications [9][8].

Control systems

Finally, the control systems must ensure the safely operation of the microgrid when it is connected to the utility grid but also when operating in stand-alone mode [19][20]. There are several parameters that the control system needs to monitor and control when disconnected to the grid. First of all, it needs to maintain a constant frequency which might be a challenge since wind turbines and fuel cells have slow responses to control signal and are almost inertia less. To cope with this issue, big inertia rotating machines can be used to stabilize the grid frequency and operate as a reference to make sure that the current frequency does not deviate substantially from the desired value [21]. Secondly, voltage needs to be regulated to ensure reliability and stability of the grid [3]. Overvoltages may overheat and damage certain electrical apparatus whereas voltages that are too low can cause stalling or dropout of motors, flickering or dimming of lights or even high currents in constant-power devices such as compressors [1]. There are several control strategies that can be carried out to confront these issues which can be divided into four categories [13]. An interactive control method uses a power consign as an input command to control the power output given the energy demands of the moment. On the other hand, a non-interactive control method is used in certain DG to take advantage of atmospheric conditions and therefore output the maximum amount of energy finding the optimal point in terms of voltage vs current values by using MTTP technology [22]. Moreover, a DG can also be differentiated in whether voltage and frequency are controlled at the point of connection or not [13]. According to these definitions the control system will follow a grid-forming control or grid-following control approach respectively.

1.1.3 Benchmarks for Microgrids

According to [6] with the increasing proliferation of DERs, it becomes necessary to elaborate techniques and methodologies to validate and simulate microgrids that include these cutting-edge technologies. However, it makes no sense to think of a unique microgrid model to which one can use as a benchmark for all future deployable microgrids. On the contrary, each microgrid is a particular case study. Their main differences, for instance, may consist of the energy resources that feed the grid, the overall power to be handled, the electrical consumption/loads and amongst others. In order to cope with such inconveniences, several microgrids benchmarks have been design so as to deal, to a certain extent, with the diversity of cases and to be used as a reference for future deployments.

First off, it is fundamental to look into the different elements that make up the grid and identify the mathematical model that will simulate its real behaviour. The hierarchy of the elements that compose the grid can be seen in 1.1

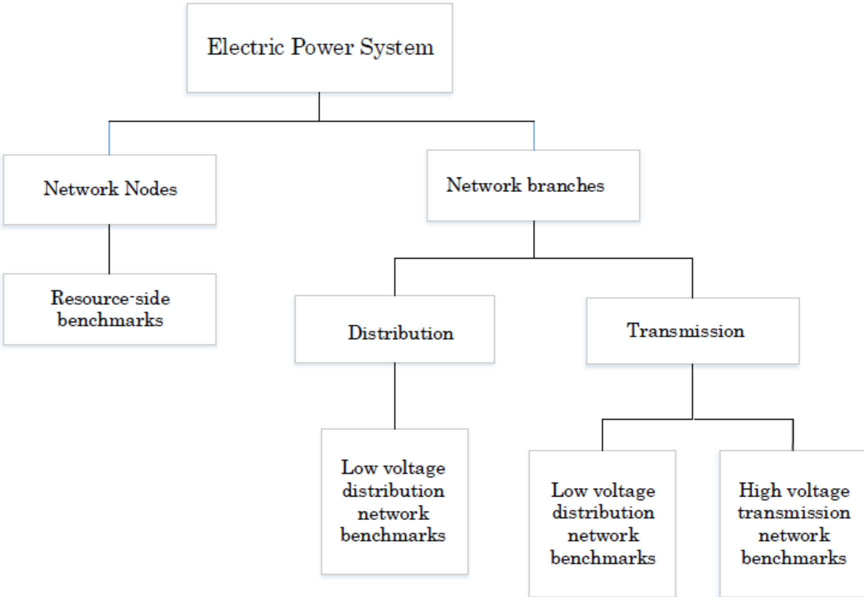

Figure 1.1: Breakdown of the electrical grid

Depending on whether it is a distribution or transmission line and whether it is a high, medium or low voltage line, the diverse characteristics and potential issues that may arise or that one desires to study will be different [6].

In addition, the characteristics and restrictions of the case study will be determinant when designing the power converter and its corresponding filters which link the DER with the operating grid. Besides, micrograds add new challenges and complexities that do not exist or that are not of such relevance in the macrogrid, and that need to be tackled in this scenario [23]. It is worth mentioning, for example, power quality as one of the paramount issues that microgrids need to focus on. Since these typologies of grids more often than not lack of a powerful synchronous generator which derives into a poor system inertia, it results harder to compensate for sudden connections and disconnections of loads that may alter voltage and frequency values. Other phenomena that require special attention are harmonic content in the point of common coupling, protection from electrical hazards in general and stability in the low-voltage context. In Figure 1.2 the main challenges are named classified by context and an example of each one is attached.

1.2 Axis orientation

The direct-quadrature-zero transformation, abbreviated as dq0 transformation or also known as Clarke's or Park's transformation is a mathematical transformation that rotates the stationary reference frame of three-phase systems to simplify the analysis of three-phase circuits. In particular, dq0 transformation is vastly used in three-phase synchronous machines where it transfers three-phase stator and rotor quantities into a single rotating reference frame to eliminate the effect of time varying inductances.

Any spatial vector with its three components can be broken down into a base of three independent vectors [24]. In particular, if an orthogonal system is chosen and if it is taken

Context	Issue	Example study
Operation and control	Energy management	Managing local storage
	Power electronic control	Maximum power tracking
Planning and design	Converter selection	Impact of multi-level inverters
	Sizing	Design of filters for DER interfaces
Power quality	Harmonics	Measuring harmonics
Protection	Fault current	Assessing fault current contributions of DER
	Fault voltage	Impact of terminal overvoltage on DG
Stability	Low voltage ride through	Impact of terminal short circuit on DC bus voltage

Figure 1.2: Main challenges that arise in current microgrids

into account that the sum of the three voltages and currents must be zero for an equilibrated system; a surface with a normal vector defined by $k{\cdot}[1,1,1]$ named π can be defined. These three orthogonal axis projected on the aforementioned plane constitute a three coplanar axis called a,b,c shifted 120 degrees from each other. Since it is quite intricate to control a power converter using three sinusoidal wave, the spatial vector concept is employed instead. Any three-phase magnitude can be represented as a spatial vector on the a,b,c reference that rotates on the plane. Its expression will be the following one:

$$x(t) = x_a(t) + x_b(t)e^{\frac{2\pi}{3}i} + x_c(t)e^{\frac{4\pi}{3}i} \tag{1.1}$$

Where $x_a(t)$, $x_b(t)$ and $x_c(t)$ are the instantaneous values of their respective vectors. Note that the obtained vector spins at the electrical frequency. In the second place, three new axis are defined. “α" also called “D" (direct axis) coincides with the axis “a". “β" also called “Q" (quadrature axis) corresponds to the perpendicular axis of "a" on the π plane using the "right-hand rule". Finally, “γ" or “H" (homopolar component) or “O" (zero component) is the perpendicular axis of “α" and “β".

If $x(t)$ is now expressed in the new axis reference:

$$x_{\alpha\beta}(t) = k(x_a(t) + x_b(t)e^{\frac{2\pi}{3}i} + x_c(t)e^{\frac{4\pi}{3}i}) \tag{1.2}$$

$$x_{\gamma}(t) = \frac{k}{\sqrt{2}}(x_a(t) + x_b(t) + x_c(t)) \tag{1.3}$$

Where k is a proportional constant which is $\sqrt{\frac{2}{3}}$ if the power is wished to keep constant. It is also worth noticing that in an equilibrated three-phase system x_γ would be zero. If no further transformation were made, the vector would still be variant in the time domain. To avoid such hassle, an additional transformation is made to rotate axis DQ with the angle of the grid (θ):

$$\begin{pmatrix} 0 \\ d \\ q \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta) & \sin(\theta) \\ 0 & -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} O \\ D \\ Q \end{pmatrix} \tag{1.4}$$

Combining all the transformations described, it is possible to transform any three-phase magnitude into a dq0 system magnitude useful for control purposes.

1.3 Power-Frequency Control

It is paramount to keep the frequency level of a grid within strict values. Its importance lies in the fact that certain electric appliances require a concrete frequency level in order to function correctly [25][26]. For instance, devices such as electric motors depend on the electric frequency to spin at the velocities to which they have been designed for. Also, automatisms and clocks usually use the electric frequency to determine how time passes by. A severe alteration of the frequency may, therefore, deteriorate electric devices or make them operate in an unexpected and undesired manner.

As a result of this, a frequency control system is required in order to avoid substantial changes in the frequency value and, if changes occur, to quickly return its value to the nominal one [27].

Frequency is determined by the speed of rotation of the generators that provide power to the system. Its value is tightly correlated with generation and demand of electricity [1]. If a system were generating and consuming the same amount of energy, an additional load connected to the grid would demand and extra amount of energy that would have to come from the kinetic energy stored in the supplying generators. Without an adequate frequency control scheme, such over-demand would gradually slow down the generators' rotational speed and, consequently, cause a drop in the frequency level. Conversely, a disconnection of a load would accelerate generators and, thereby, increase the frequency of the grid.

To cope with such dilemma, three frequency control schemes have been designed to regulate the frequency value. The primary control scheme aims at balancing the electric demand and generation. It is the fastest acting scheme operating every 2-20 seconds. It acts locally upon the synchronous generators modifying its rotating speed.

The second control scheme aims at keeping the frequency at its nominal level. It operates after the primary control has resolved, every 20 seconds to 2 minutes. It acts upon the control system, regulating frequency and power fluxes between neighbouring areas.

Finally, the third control scheme triggers last, every 10 or more minutes. It takes into account the electric grid in a much broader sense. Its goal is to optimize the load-sharing between different areas and to guarantee that enough energy reserves are available throughout the grid.

In the coming sections, the three control schemes will be explained making a special emphasis on the primary scheme.

1.3.1 Primary control scheme

The primary control scheme, in a few words, consists of correcting the instantaneous disequilibriums between generation and consumption. It varies the output power of synchronous generators by acting on the speed regulators of their turbines in respond to frequency variations.

Response to a frequency deviation without external control

In order to illustrate how the primary control scheme works, it is necessary to introduce how the pair shaft-turbine is modelled in control dynamics. A synchronous generator rotates under two different torques. In the first place, the mechanic torque tends to accelerate the turbine whereas the electromagnetic torque opposes to the rotation of the turbine generating an induced electric current that will eventually be injected to the grid. The basic equation that describes the mechanical movement is the following one

$$J\frac{d^2\theta_r}{dt^2} = T_m - T_e \tag{1.5}$$

where J is the inertia of the turbine, θ_r is its rotational speed and T_m and T_e are the mechanical and electrical torque respectively. Substituting the time derivation of θ for its angular frequency ω and moving J to the other side of the equation, it is possible to write

$$\frac{d\Delta\omega}{dt} = (T_m - T_e)\frac{1}{J} \tag{1.6}$$

where $\Delta\omega$ is the rotors rotational speed minus its reference rotational speed. The per-unit equivalent expression can be written taking the apparent nominal power of the generator as the base apparent power and the reference frequency as the base frequency

$$\frac{d\Delta\omega_r[pu]}{dt^2} = (T_m[pu] - T_e[pu])\frac{1}{2H} \tag{1.7}$$

The coefficient H is defined as the inertia constant which is a widely common terminology in control of electric systems. It represents the kinetic energy stored in the shaft at synchronous speed divided by its power base

$$H = \frac{\frac{1}{2}J\omega_b}{S_b} \tag{1.8}$$

From now on, all the following equations in this chapter will be per unit hence the $[pu]$ notation will be eluded to ease the reading.
If a small deviation from the original value of torque and rotational speed occurs and taking into account the formula of the active power $P = T\omega_r$.

$$P_0 - \Delta P = (T_0 + \Delta T)(\omega_0 + \Delta\omega_r) \tag{1.9}$$

Where the subscript 0 refers to the initial state. If the second order increments are now neglected

$$\Delta P = \omega_0\Delta T + T_0\Delta\omega_r \tag{1.10}$$

$$\Delta P_m - \Delta P_e = \omega_0(\Delta T_m - \Delta T_e) + \omega_r(T_{m0} - T_{e0}) \tag{1.11}$$

However, since $T_{m0} = T_{e0}$, and ω_0 is obviously 1, since we are still operating in per unit system, the previous equation can be rewritten as

$$\Delta P_m - \Delta P_e = \Delta T_m - \Delta T_e \tag{1.12}$$

Finally, for small deviation from the permanent working state the equation 1.7 turns into

$$\frac{d\Delta\omega_r}{dt} = (\Delta P_m - \Delta P_e)\frac{1}{2H} \tag{1.13}$$

This last equation is known as the oscillating equation of the synchronous machine and its equivalent block diagram can be seen in figure 1.3

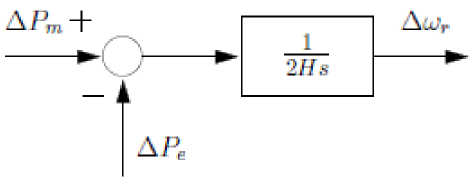

Figure 1.3: Transfer function between power and frequency[1]

All the stated so far would be entirely true if all loads connected were frequency independent. That is to say that the value of their load would not correlate with the frequency of the grid thus implying that all load were of a resistive character. Indeed, there are several loads that increase their value proportionally with the electric frequency of the grid that supply them. As a result, the new increment of electric demand can be rewritten as a function of the frequency

$$\Delta P_e = \Delta P_l + D\Delta\omega_r \tag{1.14}$$

where ΔP_l represents the increment of active power that does not vary with the frequency whereas D represents a constant that accounts for the increase of the electric power with the frequency. Such constant can be seen as a damping factor in terms of control system which opposes to the variation of frequency hence preventing an infinite decay of frequency in the case that a new load is connected or an abrupt increase of the same if a load is removed. Such damping effect, however, is not large enough to prevent sever alteration on the frequency that can, under no circumstance, be acceptable in a modern electric grid. Because of that, a frequency control must be employed.

The equivalent block diagram can be seen in 1.4, after the damping constant has been taken into consideration, is a first order transfer function where the dynamics of such depend solely on the inertia H and the damping constant D

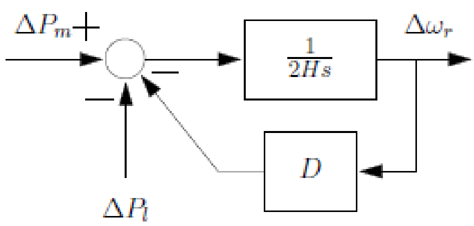

Figure 1.4: Frequency effect over electric demand[1]

Frequency regulators

So far, modifications on the load that feeds the generator have been performed to motivate the use of a certain control or regulation to prevent huge variations in the frequency of the grid.

The isochronous regulator 1.5 in is now introduced as a regulator that, in spite of the fact that it cannot be deployed in practical terms, it embraces the most basic concept of frequency regulation

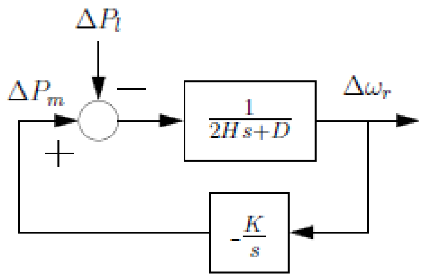

Figure 1.5: Isochronous Regulator [1]

The synchronous regulator consists of an integral controller fed with the frequency variation. The variation in mechanical power which is the output of the controller is compared with the frequency-independent increment of active power. If a negative frequency variation is detected, the regulator will respond by increasing the mechanical power applied on the shaft thus trying to reduce that error. Steady state is then attained when the frequency error is finally zero.
For instance, if a load is connected when the previous demand and generation are matched, there will be an exceeding electrical power. This extra demand will then be provided by the rotational kinetic energy from the shaft. This loss in kinetic energy will be seen as a diminishing mechanical frequency that will, in turn, trigger the isochronous regulator so that the mechanical power is risen to match the electrical demand.

This regulator would work perfectly as long as there were no other units in charge of regulating the grid. If this regulator were to be implemented in two or several units, the generators would start competing with each other to stablish their own speed frequency eventually causing the system to fall into instability. Taking into account that the electric system counts with several individuals that help regulate the grid, regulators with droop speed control are the ones used in practice.

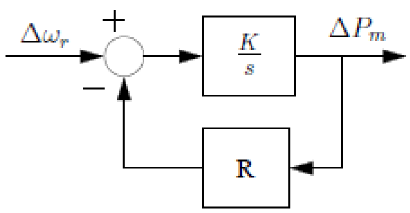

Figure 1.6: Block diagram of a droop speed control [1]

Otherwise, the droop speed control can be simplified in the block diagram in 1.7 that will be later utilized

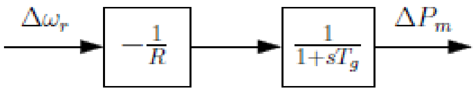

Figure 1.7: Simplified block diagram of a droop speed control [1]

To allow several units to participate in the power-frequency regulation of the grid, a negative power-frequency feature is added with the corresponding additional closed-loop that can be seen in the block diagram. The R constant is the droop of the generator and is equal to the relation between the relative increment (per unit) of angular speed (ω_r) and the relative increment of output mechanical power (per unit) of the unit.

$$R = -\frac{relative\ increment\ of\ frequency}{relative\ increment\ of\ power} = -\frac{\omega_v \cdot \omega_{pv}}{\omega_0} \tag{1.15}$$

where ω_v is the angular frequency at no load, ω_{pv} is the angular frequency at full load and finally ω_0 is the nominal angular frequency. Consequently, a 10% droop means that a 10% frequency increment would bring about an increment of a 100% of output power. If the active power versus frequency is plotted in the graph 1.8, it can be noted how a drop in the frequency triggers the output power

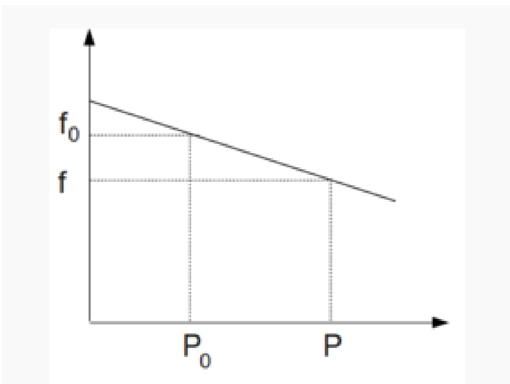

Figure 1.8: Frequency-Power droop relation [1]

The frequency droop, in fact, determines the slope of the relation between frequency and power. The greater the R droop value is, the flatter the curve will be and the unit will contribute more proportionally to its nominal power. Therefore, the greater the droop in a unit, the more it participates in the primary regulation in respect to its nominal power.

The droop control, as effective as it may be at permitting several units to cooperate to achieve frequency stability, does not guarantee that the steady state frequency remains the same as the original one. On the contrary, every perturbation in the system induces a steady-state permanent error in the resulting frequency as it can be seen in Figure 1.9

Because of that, the reference power of the generators will then need to be adjusted so that the steady-state frequency is shifted upwards or downwards to match the desired frequency value. Such change in the reference power will be later on discussed in the secondary control scheme of this section.

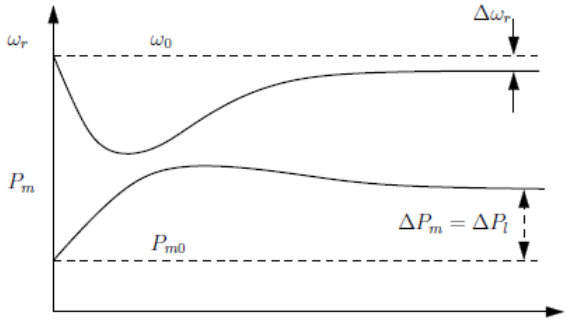

Figure 1.9: Steady state frequency error after a perturbation in the system [1]

Lastly, if frequency-dependent loads are considered and n generators participate in the primary power-frequency control, an equivalent generator with a constant inertia of H_{eq} can be considered. H_{eq} is equal to the sum of all constant inertias of the n generators referred to a unique power base. Then, the relation between the incoming power generated and the demand and frequency can be represented in the block diagram in figure 1.10.

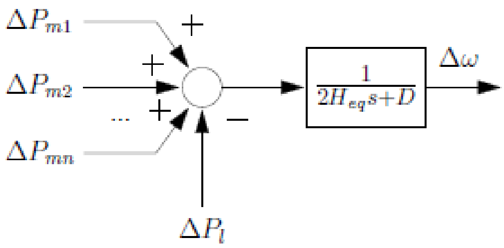

Figure 1.10: Primary power-frequency control with n generators [1]

Taking into account that in steady-state each generator fulfils $\Delta P_l = -\Delta\omega/R_i$, a load increment of ΔP_l will result in the following frequency variation

$$\Delta\omega = \frac{-\Delta P_l}{(\frac{1}{R_1} + \frac{1}{R_2} + ... + \frac{1}{R_n}) + D} = \frac{-\Delta P_l}{\frac{1}{R_{eq}} + D} \tag{1.16}$$

Where

$$R_{eq} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + ... + \frac{1}{R_n}} \tag{1.17}$$

The relation between frequency variation and power variation is finally given by

$$\beta = -\frac{\Delta P_l}{\Delta\omega} = D + \frac{1}{R_{eq}} \tag{1.18}$$

To sum up, the primary regulation, without taking into account losses due to electromechanical energy conversion amongst other possible associated losses, is responsible to match generation and demand and to make sure that the frequency of the system stabilizes. When an additional load is connected, the frequency shrinks due to the droop control and the generation is risen to match the increased demand minus the frequency-dependent part.

1.3.2 Secondary control scheme

It has already been observed that once the primary control acts upon the system, generation and demand are matched and the frequency value is stabilized at a certain value. However there are several challenges that the primary control does not solve and need to be addressed by means of complementary regulation. These issues consist mainly of the frequency deviation due to the droop control and the fact that the load increments are not distributed evenly nor will be in accordance with the programmed power fluxes between areas. The secondary control schemes is designed to cope with these two problems.

Correction in the frequency reference

In order to fix the fact that the eventual frequency does not match the original desired frequency, the reference power is tilted accordingly to ensure the desired frequency. A change in the reference frequency can be represented as a shift upwards or downwards of the P-f curve keeping the slope constant since that only depends on the droop factors of each unit. The shifts are restrained to the power capabilities of the units of the system meaning that there will be upper and lower boundaries at which the curve may never surpass.

If the system is isolated from neighbouring areas operating as an island, the restoration of the frequency reference can be carried out with a supplementary control action in one of the generators. There is a unique regulating loop that measures the system frequency and delivers the new increment of active power to all units that participate in the power-frequency regulation of the grid. The block-diagram in figure 1.11 depicts this scenario:

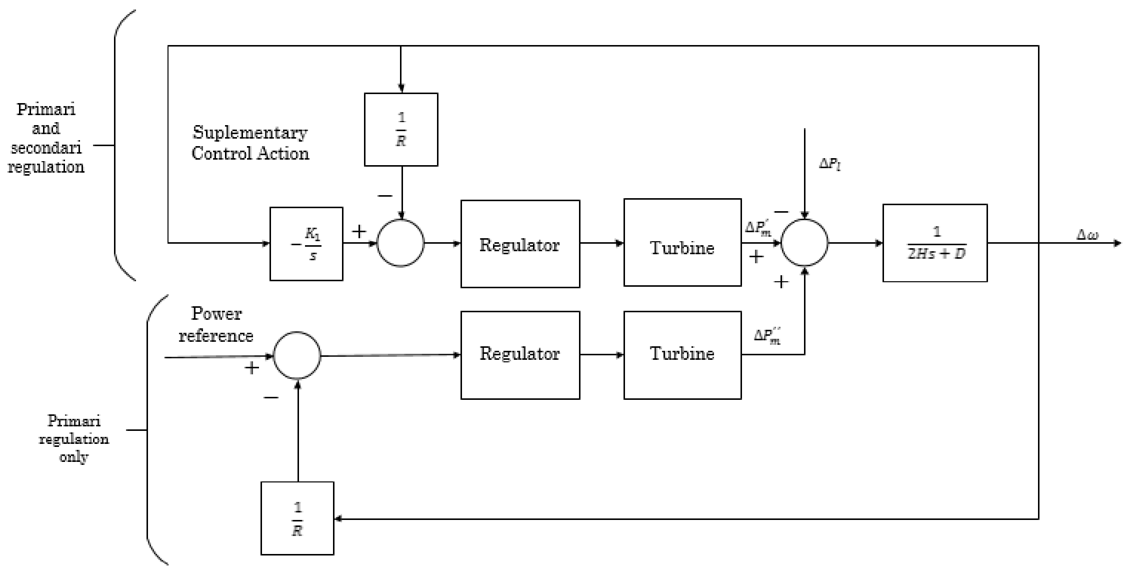

Figure 1.11: Supplementary control action to restore original frequency value [1]

Generation of a two-area system

If an electric system is divided into two areas interconnected through a single line, in control terms, each area can be reduced to a single generator that embraces the effect of all generators and all the corresponding control systems within it. Each generator can be modelled as an ideal voltage source with a characteristic source impedance. Such impedance can be considered to be mainly inductive thus only considering the impedance as a single reactance. If the line is considered to be lossless (No resistance nor dissipation of energy of any kind), its impedance can also be simplified to an inductance. The power transferred between the two areas is

$$P_{12} = \frac{E_1 E2}{X_t} sin(\delta) \tag{1.19}$$

Where δ is the relative phase angle between the two equivalent generators phasor.

$$\delta = \delta_1 - \delta_2 \tag{1.20}$$

Finally, X_t comprises both the line impedance and the two equivalent Thevenin impedances of each area

$$Zt = X_t = (X_1 + X_2) + X_l \tag{1.21}$$

Its equivalent electric schematic can be seen in figure 1.12.

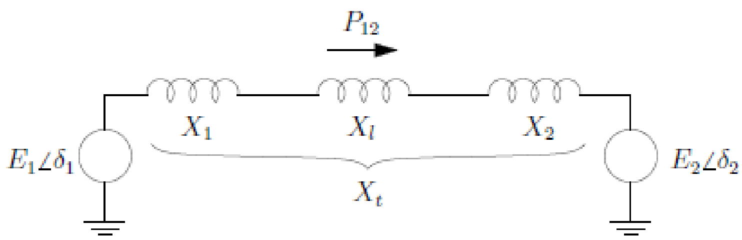

Figure 1.12: Power transferred between two areas connected through a lossless line [1]

If there is a small variation around the original phase angles (δ_{10} and δ_{20}) then

$$\Delta P_{12} = T_0 \Delta\delta_{12} \tag{1.22}$$

Where T_0 is called the synchronizing torque of the system and is defined as

$$T_0 = \frac{E_1 E2}{X_t} cos(\delta_{10} - \delta_{20}) \tag{1.23}$$

Then, the whole system can be finally simplified into two areas with a single generator composed of the inertia constant H of its turbine, a speed regulator and a damping coefficient D. The line's effect is represented by ΔP_{12} which accounts for the power flux between the two areas. If $\Delta P_{12} > 0$, then a power flux from area 1 to area 2 will occur. In conclusion, the secondary control scheme will have to compensate for $\Delta\omega_1$, $\Delta\omega_2$ and ΔP_{12} as it can be seen in the block diagram of figure 1.13.

An example may clarify the working principle of the secondary regulation. If there is an increment in the demand ΔP_{l1} and taking into account that in steady-state $\Delta\omega_1 = \Delta\omega_2 = \Delta\omega$ the power balance in area 1 will be

$$\Delta P_{m1} - \Delta P_{12} - \Delta P_{l1} - D_1\Delta\omega = 0 \tag{1.24}$$

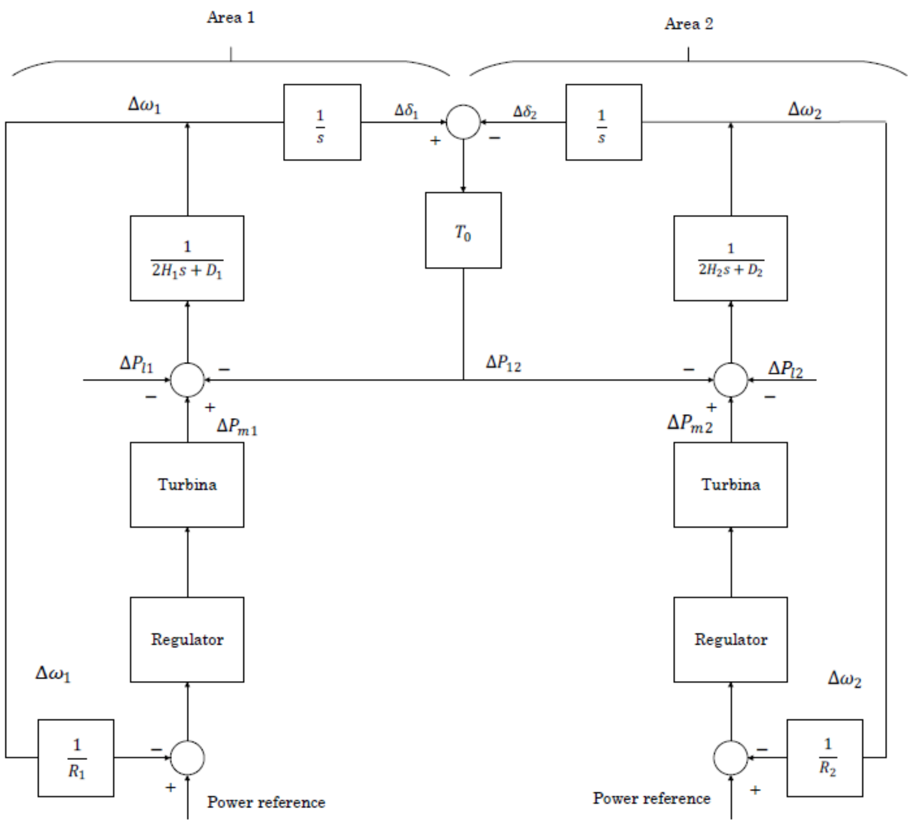

Figure 1.13: Two area system with no secundary control [1]

Similarly, in the area 2 the power balance will be

$$\Delta P_{m2} + \Delta P_{12} - D_2 \Delta\omega = 0 \tag{1.25}$$

On the other hand, it has been mentioned in the primary control that the variation in the mechanical power depends on the droop of the generators

$$\Delta P_{m1} = -\frac{\Delta\omega}{R_1} \tag{1.26}$$

$$\Delta P_{m2} = -\frac{\Delta\omega}{R_2} \tag{1.27}$$

If the variations in the mechanical power are substituted in the power balances of area 1 and area 2

$$-\Delta P_{12} - \Delta P_{l1} = \Delta\omega(\frac{1}{R_1} + D) \tag{1.28}$$

$$\Delta P_{12} = \Delta\omega(\frac{1}{R_2} + D) \tag{1.29}$$

If ΔP_{12} is isolated from the previous equations it can be seen that

$$\Delta\omega = \frac{-\Delta P_{l1}}{\frac{1}{R1} + D1 + \frac{1}{R2} + D2} = \frac{-\Delta P_{l1}}{\beta_1 + \beta_2} \tag{1.30}$$

$$P_{12} = \frac{-\Delta P_{l1}(\frac{1}{R2} + D2)}{\frac{1}{R1} + D1 + \frac{1}{R2} + D2} = \frac{-\Delta P_{l1}\beta_2}{\beta_1 + \beta_2} \tag{1.31}$$

As it had already been pointed out in the primary control, a variation in the demand in the area 1 leads to a frequency error due to the droop control system. If ΔP_{l1} is positive, the frequency error will be negative and so the working frequency will be smaller than the original one. Besides, there will be an increment in the power flux between areas. In particular, the increment of power flux will flow from area 2 to area 1 which makes sense since it is the area 1 demand that has risen.

In order to compensate for these errors, the secondary control scheme applies an integral control action on the combination of both frequency and power flux error in each area. A constant B allows the "mixture" of both errors and these are introduced to the integral control. These errors are called ACE (Area Control Errors) and can be defined as

$$ACE_1 = \Delta P_{12} + B_1\Delta\omega \tag{1.32}$$

$$ACE_2 = \Delta P_{12} + B_2\Delta\omega \tag{1.33}$$

Any positive values in the parameters B results in cancelling the aforementioned errors. However, their values determine the dynamic response such as the time required to perform the error-cancelling. In other words, parameters B will size the area control errors that feed the integrators. The block-diagram in 1.14 illustrates the whole principle of the secondary regulation:

In addition, error filters and power limiters are used in practice to delimit and prevent sudden and abnormal changes in the frequency or power fluxes. Last but not least, it pays to remind that the secondary control scheme will not act upon the system continually but rather every 2-4s so that the power commands are rectified accordingly.

1.3.3 Third control scheme

The last control scheme monitors the energy reserves available in each area. Its main functionality is to restore the energy reserves that the secondary control scheme utilizes. It acts upon the system every 15 minutes approximately [13].

Finally, since some electric appliances keep track of time through the electric frequency of the grid, if there is a deviation of 20 or more seconds in comparison with the UTC (Universal Time Coordinated), the reference frequency is shifted to 49.99 Hz or 50.01 Hz for 24 hours (if 50 Hz is the nominal frequency). This is the slowest control scheme of any electric grid [25].

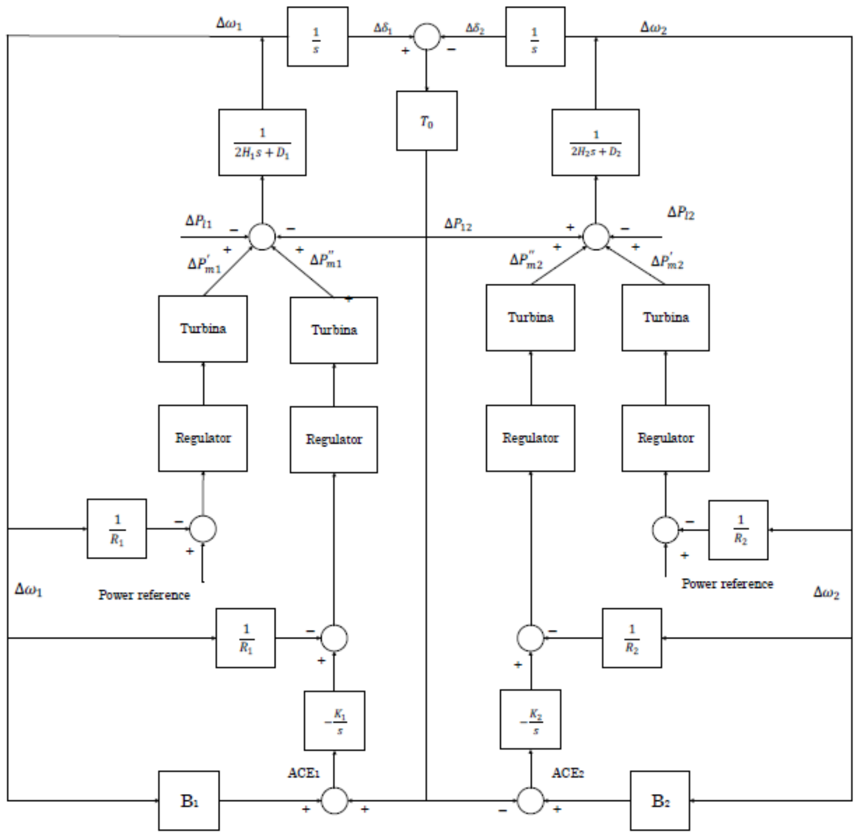

Figure 1.14: Two area system with a holistic secundary control [1]

1.3.4 Control in microgrids

When microgrids function in parallel with the utility grid, the voltage and frequency are controlled by the main grid in a master/slave topology. Depending on the load of the main grid, it will either supply or absorb power and act as either a controllable load or a controllable source [5][28]. If any fault or disturbance occurs in the main grid, a microgrid can always disconnect and operate autonomously following the three control schemes commented before.

1.4 Reactive Power-Voltage Control

The terminal voltage of a generator is controlled in a similar way that the power droop regulates the frequency of the grid. When the voltage drops, the reactive power that the synchronous generators deliver is increased [12][25]. Synchronous generators are the main and more versatile elements to control the voltage of the grid. However, there are other elements that may participate in the regulation of it [25]:

- Synchronous compensators: Indeed, these are synchronous machines working at no load. Since they have no load attached, they neither consume nor provide any active power save for attributed losses. Nonetheless, they can consume reactive power if subexcited or generate it if over excited. Its connection is generally done through transformers.

- Arrays of capacitances or inductances: They can be connected through concurrent switches.
- Static var control (SVC): Made of capacitors and inductances switched at a very high speed. They are made of electronic power devices such as GTO or IGBT transistors.
- Regulating transformers: These are transformers with several transformation relations a part from the nominal one.

1.5 Synchronous generators

1.5.1 Description

Based on [29] and [30] a synchronous generator or alternator uses the electromagnetic induction principle to generate a single-phase or three-phase AC current.

The excitation of the generator can be attained by two different methods. On one hand, a series of permanent magnets can be attached to the rotor in order to obtain a rotating magnetic field of constant intensity. Alternators that use this kind of excitation are called magnetos or permanent magnet alternators. On the other hand, the excitation can be accomplished by connecting a DC generator fixed on the same shaft that the alternator uses or, alternatively, direct current from a separate DC source can be passed through the windings on the rotor by means of slip rings and brushes.

When DC current passes through the excitation windings, a magnetic field that rotates at the rotor's speed is induced in the stator. This magnetic field extends outward and cuts through the armature windings embedded in the surrounding stator. As the rotor turns, alternating voltages are induced in the windings of the stator feeding the grid to which is interconnected. This rotating magnetic field mirrors the effect that a rotating magnet attached to the shaft would have on the stator windings. Yet, as it has been pointed out before, the strength of such magnetic field can be varied by modifying the exciting DC current.

Figure 1.15 depicts the electromagnetic principle of the most basic synchronous generator with a sole pair of poles:

In the three phase synchronous generator, three windings shifted $\frac{2\pi}{3}$ rad (120ï£¡) from each other are placed in the stator. Due to the rotating magnetic field of the rotor, the three windings of the stator see a variation of its magnetic flux which, in turn, induces a sinusoidal voltage (AC) as can be seen in 1.16.

The frequency of these induced voltages is directly related with the mechanical speed of the rotor $\omega_m = \omega_{rotor}$ and is also proportional to the number of poles of the machine.

$$f_s = p\frac{\omega_m}{2\pi} \tag{1.34}$$

Since the frequency of the utility is set at a particular value, 50 Hz for most European countries including Spain and 60 Hz for USA and Canada, the speed at which the rotor ought to rotate is fixed. Even for microgrids that operate autonomously from the mains,

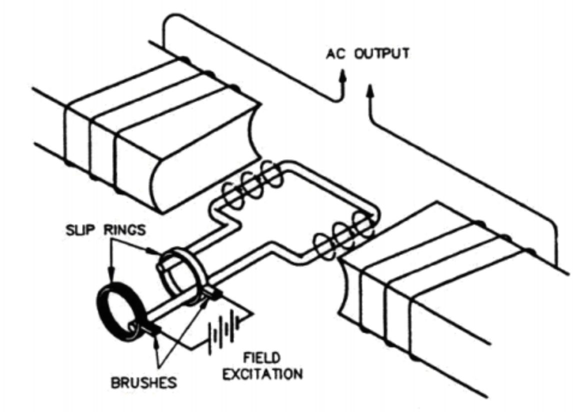

Figure 1.15: Electromagnetic principle of a basic synchronous generator with a sole pair of poles

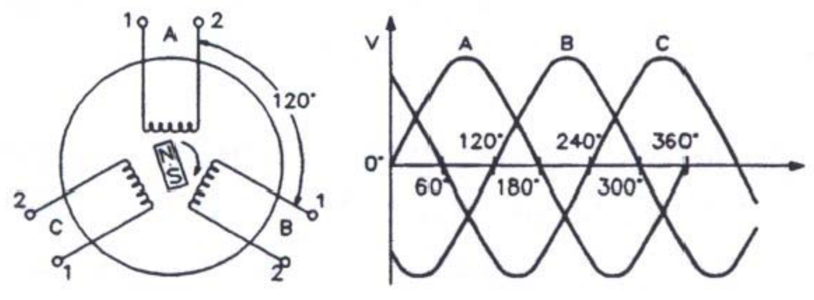

Figure 1.16: Simplified three-phase synchronous generator and its corresponding output voltage curves

electric appliances have been designed to work within strict frequency margins thus forcing once again the speed at which synchronous generators should rotate.

All in all, the synchronous machine is based on the principle of two magnets in which one chases the other without ever catching up. In the case of the machine working as a generator, the stator's magnet chases the rotor's at the same speed but lacks δ degrees ($\delta < 0$). In this working mode, the resultant torque is negative resulting in an influx of active power from the machine to the grid. The rotor's magnet overtakes the stator's depending on the power demand of the grid. The larger the demand, the greater the mechanical input power of the machine which results in a higher mechanical torque. This new mechanical torque can only be accomplished by increasing the load angle (δ). Naturally, if the synchronous machine were to operate as a motor, it would be the stator's magnet that would drag the rotor's thereby having a positive load angle ($\delta > 0$). The maximum torque is attained when $\delta = 90°$ if the machine has a sole pole or $\delta = \frac{90°}{p}$ if several poles exist. If the maximum torque is exceeded, the magnets of the rotor and stator will lose their synchrony and will liberate from each other. The machine will then slow down until it stops even if the load is reduced [29].

1.5.2 Steady-state equations

In stady-state, the study of the synchronous machine can be carried out through examining the phase-neutral equivalent circuit [29]. In a synchronous machine with "cylindrical generator rotor" the shematic of the circuit can be seen in 1.17:

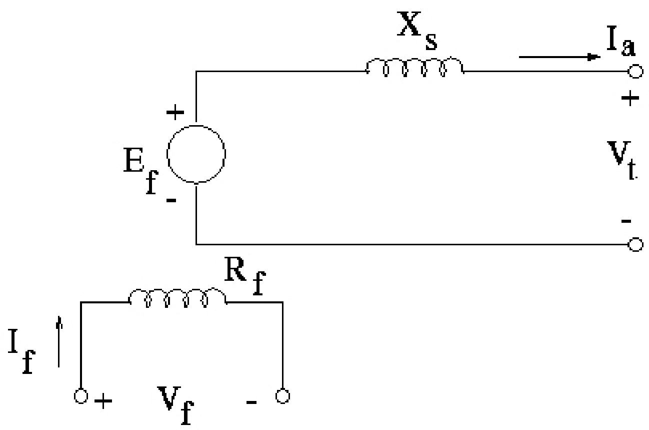

Figure 1.17: Phase-neutral equivalent circuit of the synchronous machine

The rotor which acts as the exciter is governed by the equation

$$U_f = R_f I_f \tag{1.35}$$

where R_f is the equivalent resistance of the rotor's windings and I_f and U_f are the current that circulates through the resistance and the DC voltage that excites the machine respectively. In the stator, Us represents the phase voltage $U_a = \frac{U_L}{\sqrt{3}}$ taking U_L as the line-to-line voltage of the three phase system. R_s and X_s are the synchronous resistance and reactance of the induced stator respectively, being R_s generally negligible for the majority of calculations. E_f is the induced voltage in each phase of the stator's winding [29].

$$E_f = K_f I_f \frac{\omega_s}{p} = K I_f \tag{1.36}$$

As it can be noted in the equation 1.36, the induced voltage is proportional to the excitation current. The parameter K_f depends solely of geometric and physical characteristics of the machine and can also be written as $\frac{K}{\omega_s}$. This K parameter is often used since in steady-state working condition neither the electric or mechanical frequency change [29].

Two representative parameters that need be mentioned are the angle shift ϕ between U_a and I_a. The cosine of such shift angle accounts for the power factor of the machine. Additionally, the angle between U_a which is the phase voltage and E_f being its corresponding induced voltage, accounts for the fact that a synchronous machine has the capacity of working as a capacitive or inductive load regardless of its active power output [29].

If we fix the active power that a particular synchronous machine releases to the grid, it can generate or consume reactive power depending on the excitation of the machine. If the machine is subexcitated ($E_f < U_a$) it will consume a positive reactive power ($Q > 0$) or, in other words, it will generate a negative reactive power. The contrary also applies, if the machine is overexcitated ($E_f > U_a$) then the machine will consume a negative reactive power ($Q < 0$) as in a capacitive load [29]. The consumption of reactive power is

$$Q = 3U_a I_a sin\phi = \sqrt{3} U_L I_L sin\phi \tag{1.37}$$

and if E_f is expressed as a function of U_a

$$E_f = U_a - I_a(R_s + jX_s) \tag{1.38}$$

The fact that alternators provide power to the grid at a constant frequency makes them the main kind of generator that nowadays feed the electric grid [2]. Moreover, since both their active and reactive power can be easily tuned to match the requirements of the grid, it makes them even more appealing for they effectively contributing to the regulation of the frequency and voltage of the grid.

When the behaviour of synchronous machines is to be simulated accurately in power system stability studies, it is essential that the governor and the excitation systems of the synchronous machines be modelled in sufficient detail [31].

1.5.3 Governor

The governor of the synchronous generator controls the torque and therefore also the mechanical power input to the generator according to the governor control characteristics [1]. Since the angular speed is fixated by the system frequency and cannot be changed by varying the power input, the governor settings determine the load level at which the machine operates.

The governor of the machine is responsible for the droop power-frequency control. As it has already been explained, when the frequency levels drop, the regulator will increase the mechanical power input of the machine resulting in an increasing electrical power output. In brief, the governor allows the possibility to control the frequency levels of the grid when variations on the overall load or power generation occur.

1.5.4 Excitation system

The excitation system is responsible to set up the magnetic flux in the magnetic circuit of the machine [2]. The excitation of the synchronous machine will determine its power factor operation point which can be leading, lagging or unity. When the synchronous motor is working at constant applied voltage V, the resultant flux remains substantially constant. This resultant flux is established by the relation between AC supply of armature winding and DC supply of rotor winding. Three cases can be noted:

- The field current is sufficient enough to produce the flux, as demanded by the constant supply voltage V, then the magnetizing current or lagging reactive VA required from the AC source is zero and the motor operates at unity power factor. The field current, which causes this unity power factor is called normal excitation or normal field current.

- If the field current is not sufficient enough to produce the required flux as demanded by the load, additional magnetizing current or lagging reactive VA is drawn from the AC source. This magnetizing current produces a deficient flux. Thereby in this case the motor is said to operate under lagging power factor otherwise said to be under excited.
- If the field current is more than the normal field current, motor is said to be over excited. This excess field current produces excess flux that must be neutralized by the armature winding. Hence the armature winding draws leading reactive VA or demagnetizing current leading voltage by almost 90 degrees from the AC source. Hence in this case the motor operate under leading power factor.

The excitation system also called automatic voltage generator (AVR) is essential to the machine performance under steady-state and transient conditions and controls terminal voltage and reactive power output of the generator [31].

According to [2]The synchronous machine excitation model can be broken down into several subsystems namely a terminal voltage transducer and load compensator, excitation control elements, an exciter, and, in many instances, a power system stabilizer. Figure 1.18 shows the block diagram of a general synchronous machine excitation control system:

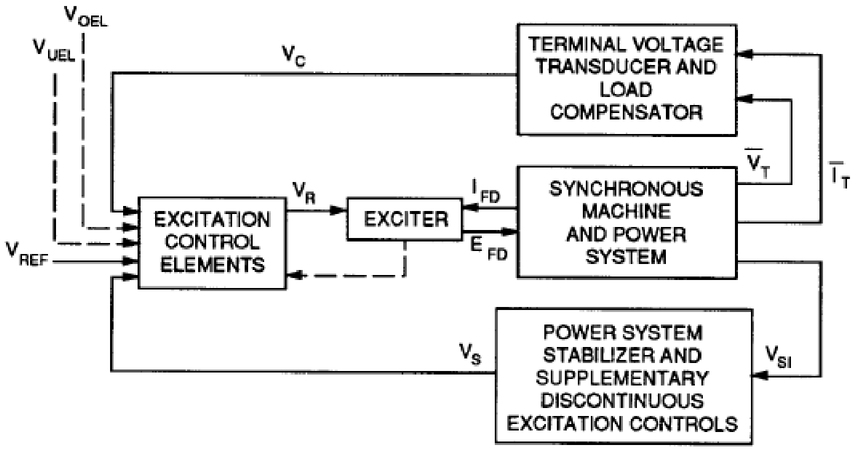

Figure 1.18: General synchronous machine excitation control system [2]

So as to simplify the excitation model, neither an underexcitation limiters nor a terminal voltage limiter will be used thus not using V_{UEL} nor V_{OEL} as excitation control inputs.

Three distinctive types of excitation systems are identified on the basis of excitation power source:

a) DC excitation systems: A direct current generator with a commutator is utilized as the source of excitation system power.

b) AC excitation systems: an alternator and either stationary or rotating rectifiers are used to produce the direct current needed for the synchronous machine field.

c) ST excitation systems: Excitation power is supplied through transformers or auxiliary generator windings and rectifiers.

Terminal voltage transducers with or without a load compensator are common to all excitation system models 1.19. The terminal voltage transducer output consists of the terminal voltage plus a load compensation corrector value reduced to a single DC quantity which passes through an associated filter that accounts for the transducer time lag. The load compensation corrector value is particularly interesting when the unit is connected through a significant impedance to the system. For example, this impedance may be due to a step-up transformer impedance that couple a source with a point at which voltage needs to be regulated. Alternatively, if several units are bused together with no impedance between them, the compensator can be used to create an artificial coupling impedance so that the units share reactive power appropriately.

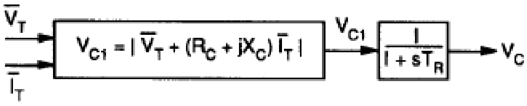

Figure 1.19: A terminal voltage transducer with load compensator [2]

1.6 Voltage-Source Inverters

The rapid rise of distributed generation and renewable energies has created the need to develop power electronic converters that permit to exploit their possibilities and improve their performance [20].

1.6.1 Definition

An inverter traditionally draws power from a DC source such as a battery or an array of solar panels [32]. It employs an electronic circuitry to transform that DC power into a sinusoidal AC power which can be at any required voltage and frequency as long as the characteristics of the converter allow it. Furthermore, inverters are also utilized to indirectly transform AC to AC by converting AC to DC and then back to AC by using an appropriate inverter. The latter is used, for instance, in some wind turbines where the air speed does not remain constant and neither does the frequency at which initially outputs. After the AC-DC-AC conversion, the frequency and voltage of the power can be adjusted to fit the one of the mains.

According to [33]An inverter is a static power converter composed with different controlled semiconductor devices that work as power switches. The output waveforms, therefore, are made up of discrete values that require a certain filtering to smoothen its shape and to reduce its harmonic content in order to make it a purer sinusoidal wave of desired frequency. The capability of the converter to attain a sinusoidal waveform as pure as possible at the fundamental frequency depends on the control scheme that controls the opening and closing of its switches. The modulation technique chosen in a particular scenario depends on the quality of the wave required for the application or load in question. However, the most common modulation techniques consist of the pulse-width modulation(PWM), space vector modulation(SVM) and carrier based techniques amongst others.

Inverters are generally divided into two principal topologies: voltage source inverters(VSIs) and current source inverters(CSIs) [34]. VSIs use a diode rectifier to convert AC voltage to DC. This DC power is delivered to a DC-link composed of capacitors that regulate the DC bus voltage ripple and store energy. An inverter made of insulated gate bipolar transistors

(IGBT) or other power transistors is then used to convert the DC power into utility/line AC power at the voltage and frequency desired. In the CSI topology, the DC link uses inductors to regulate current ripple and store the energy. Then an inverter is again used to produce the DC/AC conversion.

Most common inverters that use VSIs are single-phase half bridge inverters, single-phase full bridge inverters and three-phase full bridge inverters to name but just a few [32]. Multilevel inverters are also getting more and more popular since they notably reduce harmonic distortion and hence improve overall power quality.

Finally, applications of inverters include uninterruptable power supplies (UPS), adjustable speed drives (ASD), active filters, Flexible AC transmission systems (FACTS), voltage compensators and photovoltaic generators [32].

1.6.2 Control schemes

Two of the most common control schemes for an inverter-based DG are the power control scheme (P& Q) 1.21 and current injected control scheme 1.20 [3].

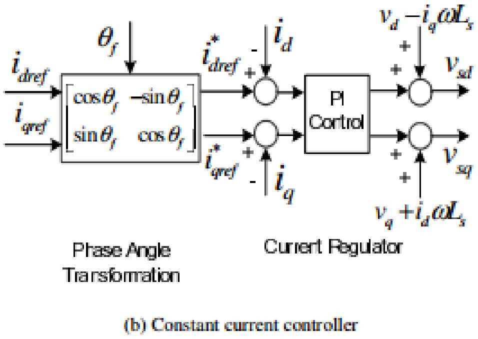

Figure 1.20: Current injected control scheme [3]

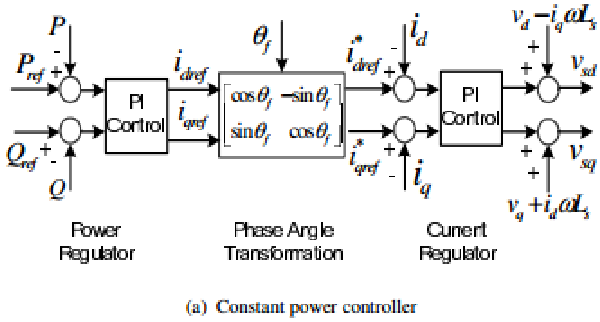

Figure 1.21: Power control scheme [3]

Where the angle that is fed into the phase angle transformation comes from a three-phase PLL (Phase-locked-loop oscillator). A PLL is a phase detector commonly found in power converters. It calculates the phase angle of the first harmonic of the input signal. Then, the

output signal is oscillated at the fundamental frequency of the input and takes into account the calculated phase angle of the input signal to maintain phase synchronism with the input [35].
For the constant current controller, i_{dref} and i_{qref} are transformed and compared with the real i_d and i_q that have been obtained by converting the currents from the *abc* coordinates to the dq. The current errors are fed in a Proportional-Integral controller (PI) and finally led to a sum block required to decouple i_d from i_q. The output voltage is then transformed from Cartesian to polar coordinates to control a PWM module. For the power controller, the same principles apply. However, the i_{dref} and i_{qref} references are computed through another PI controller. P_{ref} and Q_{ref} are compared with the actual P an Q delivered to the grid and the outcome error is then fed into this additional PI controller. From there the the i_{dref} and i_{qref} are defined and given to the rest of the controller.

Chapter 2

Main Case Study

2.1 Introduction to the Case Study

The purpose of this thesis is to investigate the stability and regulation of a microgrid using high dynamic converters and a synchronous generator to regulate the frequency and voltage of the grid. To do so, the synchronous generator is thoroughly studied. The study focuses on the stability of frequency and voltage of a diesel-based generator and its implementation in a microgrid, alone and along with an inverter-based distributed generator. The loads utilised are PQ loads and the impedance of the line is taken into account.

When the synchronous machine is investigated, the diesel generator is first tested under no regulation, secondly it is examined with an adequate governor to carry out the frequency control of the grid and finally, both governor and excitation system are implemented so as to regulate both voltage and frequency.

Once the synchronous generator is successfully modelled, an inverter-based distributed generator is included in the microgrid. The inverter-based DG is modelled as an ideal three-phase current source and as a non-ideal current source. The control implemented to manage both distributed generators is a master-slave topology where the synchronous generator forces both frequency and voltage (grid-forming DG) of the grid whereas the inverter-based DG follows along (grid-following DG).

2.2 Softwares utilised for microgrid simulations

With regard to the study of the stability of microgrids, it is of paramount importance to investigate the behaviour of the grid in front of discrete variations in the electric demand. Additionally, other aspects that can be investigated are transient faults and subsequent islanding conditions. Some articles and studies have dipped into these topics in order to find out how different kinds of loads might alter the stability and time response in front of the aforementioned events.

For the purpose of this project, it has been researched the variety of softwares that are currently being utilized to simulate microgrids. One of them is the well-known Matlab/Simulink which is a multi-paradigm numerical computing environment and a high-level programming language that excels in terms of control analysis such as time and frequency response amongst other features. The particular modules that were run consist mainly of the Matpower and

PSAT [36][37]. Secondly, it was found that PSS from Siemens was widely used in different formats such as the PSS/E, PSS-R-NETOMAC and SINCAL [38][39]. PSS is a power system planning and data management software which contains tools to accurately analyse different sorts of systems. Thirdly, other alternative softwares were used to simulate microgrids at different levels namely Eurostag which performs accurate simulations of the dynamics of electric power systems [40]. EMTP was also found in certain studies such as [17] and has been the software chosen for this study as it will be commented in the following section. Last but not least, Anylogic was also employed which supports discrete events, agent based and system dynamic simulation [41] and other particular software [42].

2.3 EMTP/EMTPWorks

The software that has been used to carry out the simulations is the EMTP/EMTPWorks. EMTP is a professional graphical user interface(GUI) that allows the creation of sophisticated electrical networks. EMTP has a powerful GUI called EMTPWorks which is also its simulation environment. It is designed to efficiently create and maintain small circuits as well as very large scale networks. It has automatic subcircuit creation methods, similar to the one that uses Matlab/Simulink, with unlimited levels of hierarchy which resulted particularly useful for the drawing of the simulated microgrid [35].

Differently from Matlab, EMTP is power-based orientated which makes it ideal for the case study. Nonetheless, it features a comprehensive set of control blocks that have been used to control the two distributed generations of the design.

EMTP is own by POWERSYS, a consulting and software company providing global solutions of engineering software and services for industry, research and education in the field of Electrical and Electromechanical power systems.

2.4 Synchronous Generator

2.4.1 Introduction

The diesel generator used as a distributed generator consist of a typical synchronous generator [43][16][44].

The fact that alternators provide power to the grid at a constant frequency makes them the main kind of generator that nowadays predominantly feed the electric grid. Moreover, since both their active and reactive power can be easily tuned to match the requirements of the grid makes them even more appealing for they effectively contribute to the regulation of the frequency and voltage of the grid.

The parameters of the machine have been inspired from a Canadian microgrid with a similar generator [4]. All these parameters have been used for all simulations:

- General parameters:

  Frequency: 60 Hz
  Number of Poles: 4
  Line-to-line voltage: 0.48 kV
  Armature winding connection: Wye grounded
  Rated power: 0.75 MVA

Phase A angle: 0°

- Mechanical parameters:

  Number of masses: 1
  Index of rotor mass: 1
  Index of exciter mass: 0

  For the shaft system its parameters are:

  Fraction of external torque: 1
  Inertia constant [H(s)]: 5 pu
  Speed deviation damping: 0

- Electrical parameters:

  Armature resistance (R_a): 0.0003 pu
  Zero sequence reactance (X_0): 0.1 pu
  Reactance in d axis (X_d): 1.305 pu
  Armature leakage reactance (X_l): 0.18 pu
  Reactance in q axis (X_q): 1.374 pu

  It has been included one damper in the d-axis windings:

  Sub-transient reactance in d axis (X'_d): 0.296 pu
  Sub-subtransient reactance in d axis (X''_d): 0.252 pu
  Transient short-circuit time constants (T'_d): 0.3 pu
  Subtransient short-circuit time constants (T''_d): 0.01738 pu

  One damper has been included in the q-axis windings:

  Transient reactance in q axis (X'_q): 0.243 pu
  Transient time constants in open-circuit in q axis (T_{q0}): 1.79 pu

When the behaviour of synchronous machines is to be simulated accurately in power system stability studies, it is essential that the excitation systems and the government of the synchronous machines be modelled in sufficient detail to comprehend how its outputs change depending on certain parameters of the grid [2].

2.4.2 Woodward Diesel Governor

The governor used for the diesel generator consists of a Woodward diesel governor. It's block diagram is 2.1

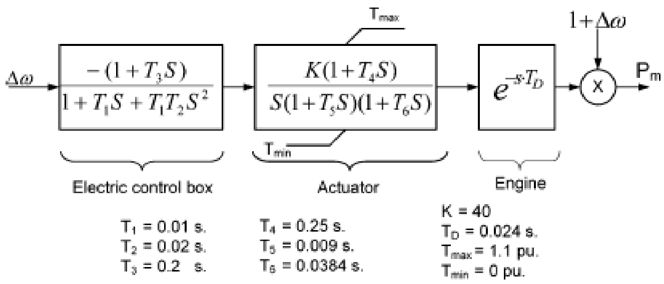

Figure 2.1: Block diagram of the Woodward diesel governor and its parameters [4]

The block diagram performed in the EMTP model can be seen in 2.2

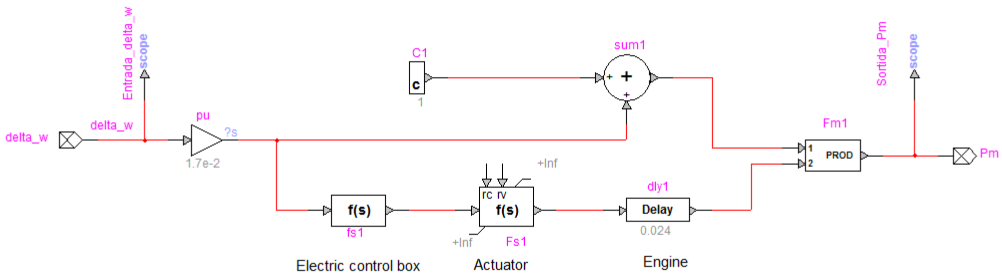

Figure 2.2: Block diagram of the Woodward diesel governor in EMTP

The governor input consists of the difference between the reference mechanical angular speed that has been set at $\frac{2\pi 60}{2} = 188.5$ rad/s and the actual angular speed of the machine. Such error is introduced to the first depicted diagram block. From there, the input signal is converted in per-unit and introduced to the electric control box and the actuator which has been modelled as the two transfer function that can be seen in the first diagram block. Finally, the engine is modelled as a pure delay and its output, the applied mechanical torque, is then multiplied by the actual angular velocity in per-unit. The governor output, then, is the mechanical power in per-unit that is wished to apply to the machine. Such increment of mechanical power will modify its electrical output power thus altering the mechanical frequency of the machine and thereby also modifying the frequency of the microgrid.

It is important to remark that the saturation of the actuator has been removed in these first simulations since the purpose of them were to visualize the dynamic behaviour of the control utilised.

According to this control scheme, an increment of 0.1 Hz will imply an input to the governor control of

$$\Delta\omega[pu] = \frac{\omega_{ref} - \omega_{real}}{\omega_b} = \frac{f_{ref} - f_{real}}{f_b} = \frac{60 - 59.7}{60} = 0.005 \tag{2.1}$$

where $f_b = f_{ref} = 60Hz$.

If the aforementioned variation in the frequency is introduced as an impulse input (δ) of module 0.005 the response obtained is the behaviour of the transfer function of the governor 2.3.

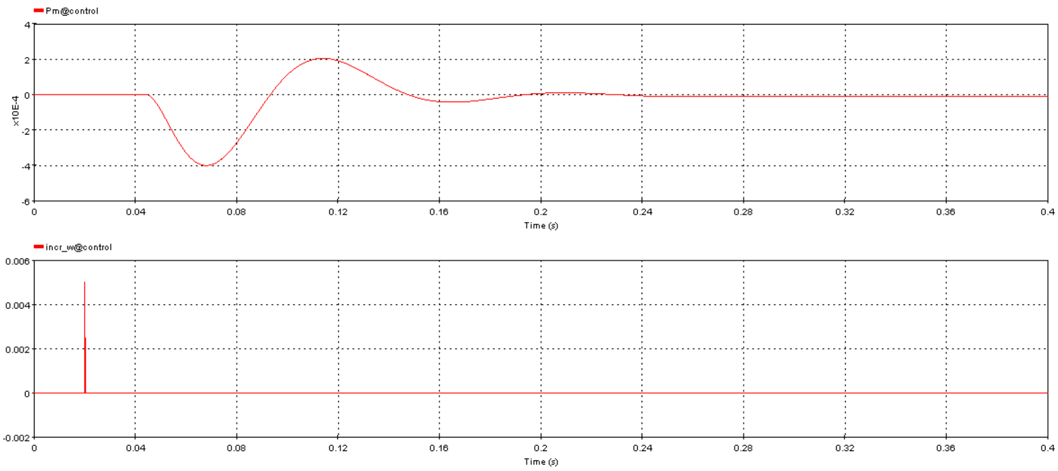

Figure 2.3: Dynamic response of the Woodward diesel governor in front of an impulse

The input impulse has been approximated as a step of an amplitude of 0.005 and a width of 0.05 ms. The gain of the transfer function is then

$$G = \frac{Pm}{\Delta\omega} = \frac{-2.4 \cdot 10^{-6}}{0.005} = -4 \cdot 10^{-4} \tag{2.2}$$

An output of 0.0025 signifies a drop in mechanical power of $\Delta Pm = -2.4 \cdot 10^{-6} \cdot S_b = -2.4 \cdot 10^{-6} \cdot 0.75 \cdot 10^{6} = -1.8$ W This decrement of power, however, depends on the amplitude of the step, tending to 0 when we decrease the amplitude of the step to make it closer to a real delta.

Finally, the step response has also been carried out in 2.4.

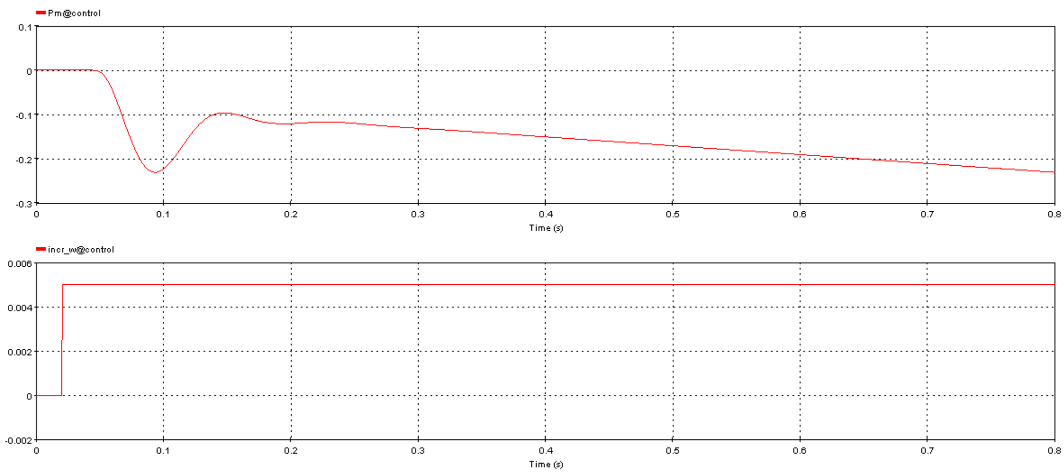

Figure 2.4: Dynamic response of the Woodward diesel governor in front of a step

After the transitional waving due to the step input, the mechanical power will keep on falling since the deviation from the nominal frequency does not get corrected. The control keeps decreasing the mechanical power in an attempt to compensate for the abnormally high angular speed.

2.4.3 DC1A Excitation System

The excitation system which controls the diesel generator of the microgrid under study is a DC IEEE type 1 excitation system also known as Type DC1A Excitation System Model [31]. The block diagram that describe its model is can be seen in figure 2.5.

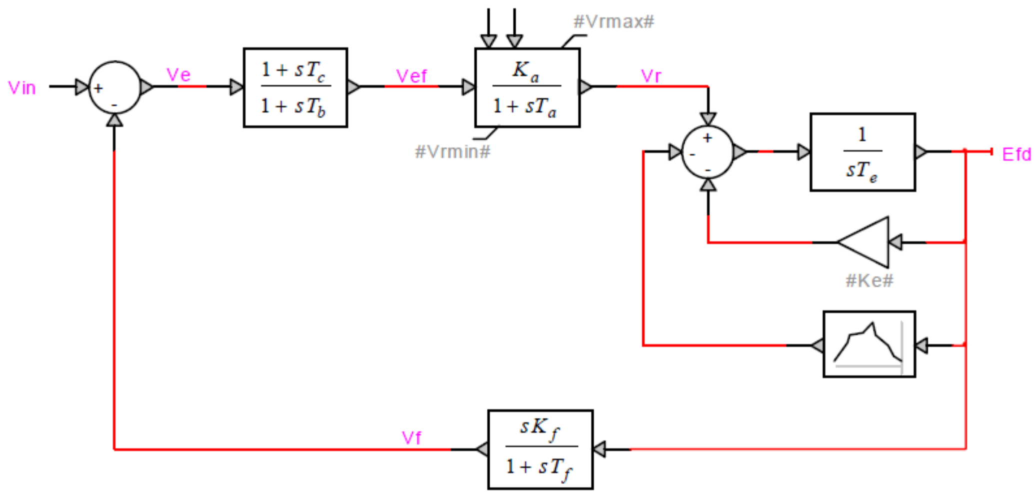

Figure 2.5: DC1A Excitation System Model in EMTP

Where the input signal is

$$V_{in} = V_{ref} - V_{meas\_RMS} - V_{aux} \tag{2.3}$$

which consists of the output signal that exits the terminal voltage transducer with load compensation described above. Feedback signal V_f is substracted from V_{in} to obtain the voltage error. This, in turn, passes through a transient filter which has a "lead" time constant T_c that is negligible and a “lag" time constant T_b. The output signal is then fed to the voltage regulator where it is amplified by a constant K_a with a certain time constant T_a. This regulator includes a voltage limiter that restricts its range. Finally, V_r is used to control the exciter.

The values of the aforementioned parameters have been extracted from the typical parameters stated for a Brushless Excitation System also known as IEEE type 1 [2]. The parameters can be seen in table 2.1.

2.5 Inverter-based distributed generation

Different active and reactive power management strategies can be included to enforce frequency and voltage or power factor regulation [38][45][15]. In this case, a master/slave control strategy has been deployed. The inverter-based distributed generator delivers a constant amount of active and reactive power regardless of the frequency and voltage of the grid. The fact that the inverter (slave) does not get involved in the regulation of these parameters, it requires another master DG unit to dictate them. The synchronous generator, therefore, will be responsible to ensure the frequency and voltage of the grid whilst the inverter-based DG will dedicate itself purely at injecting power.

Voltage Regulator	gain	400
	time constant	0.02 s
Exciter	gain	1
	time constant	0.8 s
Damping Filter	gain	0.03
	time constant	1 s
Output Limits	upper	3.9 p.u.
	lower	0.0 p.u.

Table 2.1: Typical Parameters for the Brushless Excitation System DC1A [4]

The inverter-based distributed generator has been modelled as an ideal and non-ideal three-phase current source. The power output of the current sources is 0.75 MVA with a unity power factor. To output such a constant active power, the voltage at the bus at which the inverter delivers is constantly observed in order to compute the current output required.

2.6 Loads

The loads used in the simulations consist of a series of P-Q loads. These loads defined by their apparent power and power factor could be modified so as to observe how different kinds of loads could affect the stability of the microgrid mainly the frequency and voltage of it.

2.7 Control Schemes

A master/slave control with frequency and voltage droop has been performed.

The synchronous diesel generator uses a frequency and voltage droop control that permits to control the frequency and voltage of the microgrid regardless of the loads connected and other existing distributed power sources. The synchronous generator fixates the frequency and voltage value of the microgrid whereas the other distributed sources are therefore forced to only inject power that is align with the set frequency and voltage premises of the diesel equipment.

Chapter 3

Simulations

Several simulations have been performed to illustrate several issues in relation to, firstly, the control of the synchronous machine and the stability of the microgrid and, secondly, in relation to its interaction with a distributed generation and the resulting dynamic response of the grid. EMTP has been utilised to draw the schematics as well as to simulate. Additionally, Matlab/Simulink has been occasionally used to find a particular transfer function. All plots in this thesis (except for the one computed with Matlab) have been obtained using ScopeView, the default plot viewer that EMTP offers.

3.1 Synchronous generator as regulator of the grid

It has been thoroughly investigated the behaviour of a diesel-based synchronous generator when it has no control at all, when a frequency control is implemented and when a full control where both frequency and reactive power are being controlled. These implementations provide an initial framework to work with and to build on afterwards.

3.1.1 Synchronous generator uncontrolled

In order to illustrate the importance of controlling the mechanical input power and the voltage field, two scenarios have been simulated. In both cases the synchronous generator was not controlled in terms of neither mechanical power nor voltage field. The loads utilised have been mainly resistive loads of sensible values (The generator was capable of providing the demanded power within its nominal power output). No other distributed source has been utilised so as to point out the causes of the following dynamic behaviours. This methodology permitted decoupling potential factors that could affect the results of the simulations (Whatever should happen in the frequency values or power flows, only the synchronous generator is to be responsible)

To begin with, the diesel generator and a load of unity power factor of 500 kVA have been interconnected taking into account a reasonable line impedance of 8 mΩ and 0.01 mH. The active and reactive power have been monitored and so has been the frequency .

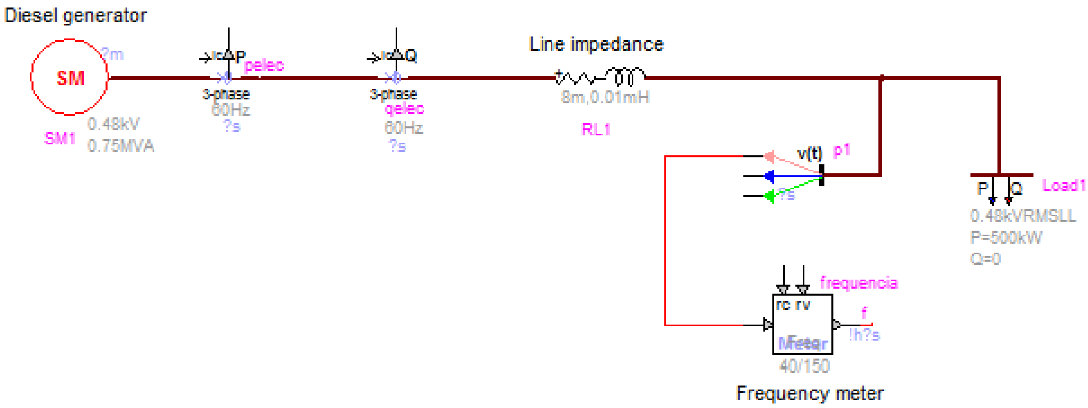

Figure 3.1: Diesel generator connected to a single resistive load with no regulation in EMTP

The behaviour of the circuit 3.1 is quite straight forward. As soon as the generator speeds up to its nominal frequency the system reaches steady-state. The simulation lasts 200 ms and the main time-step is 1 μs which will be repetitively used from this point onwards.

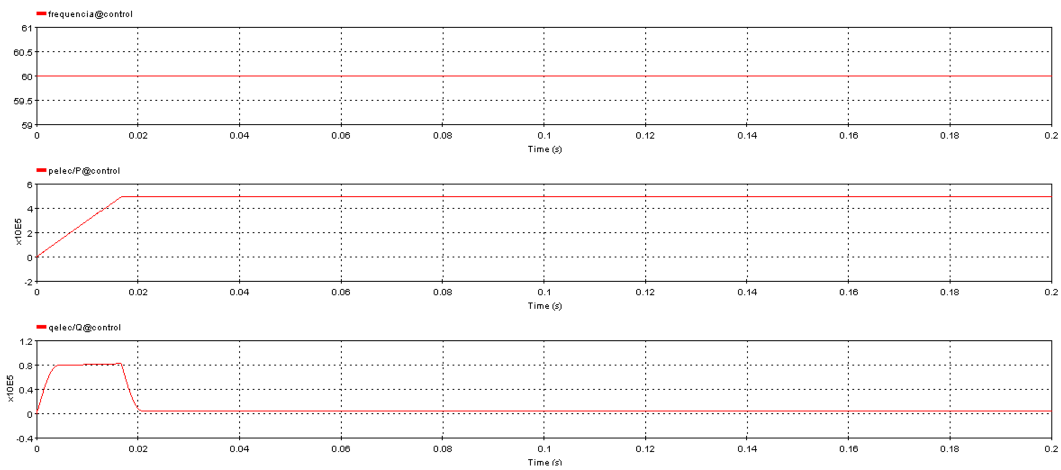

Figure 3.2: Evolution of the electrical frequency, active power and reactive power in the diesel generator connected to a single resistive load with no regulation scenario

According to the results in 3.2, the diesel generator is capable of maintaining the pre-set frequency constant at its expected 60 Hz. The active power increases until the demanded power is matched. It is worth noting, however, that the generated power is slightly smaller than the 500 kW set at the load. This difference is due to the fact that the load sees a voltage slightly smaller than the nominal voltage expected of 480 V. Since the load sucks a fixed current at a reduced voltage, the power consumed and thereby also the generated power shrink. Finally, the reactive power falls to almost null value since there is no inductive nor capacitive load but for the existing in the line.

In the second scenario, an additional load of 200 kW of active power has been connected through an ideal switch of no impedance. Such switch is closed at the start of the simulation and it is triggered after 200 ms when steady-state has already been reached. Such sudden connection illustrates the idea of a end-user connecting an electric device to the (micro)grid. This study is particularly worthy in order to remark the consequences of an alteration of the aggregated load when there is no control whatsoever of the generated power. The schematic of the scenario can be seen in 3.3

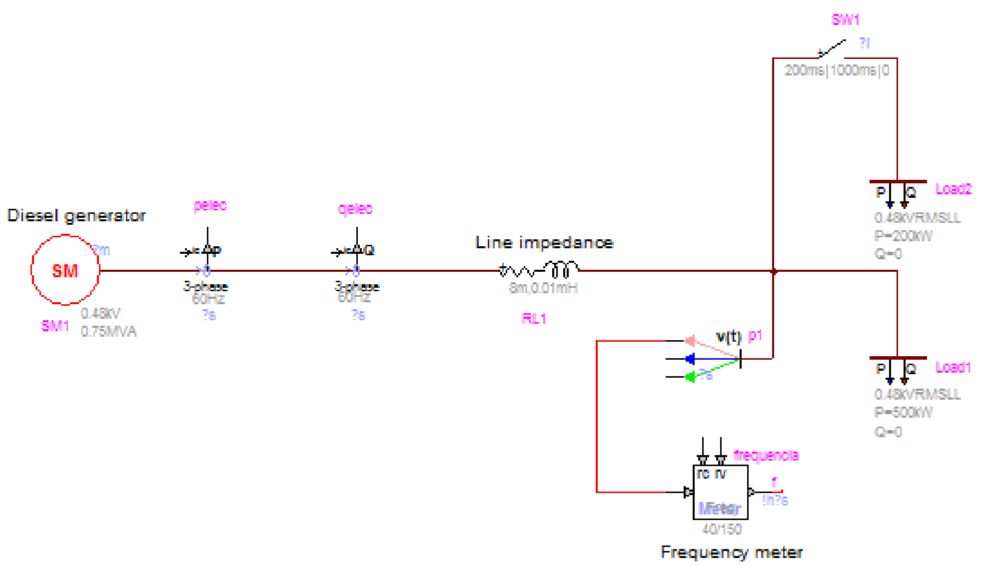

Figure 3.3: Diesel generator connected to a variable resistive load with no regulation in EMTP

Once again, the frequency and both the active and reactive power have been tracked. The length of the simulation have been extended to 800 ms so as to visualize the initial steady-state that could be found in the first simulation plus the reaction of the system after the second load has been plugged.

It can be seen in 3.4 how the electric power rises at the time when the load is connected. From that point on, the frequency drops steadily since there is no control that regulates it. Likewise, the reactive power augments since there is no control over the voltage field of the generator.

This hypothetical situation would be catastrophic. In fact, protection equipments would surely trip to avoid any electrical damage. The results act as a motivation towards the use of an exciting system and governor and demonstrate that control over both frequency and reactive power are of obliged nature.

3.1.2 Synchronous generator with frequency control

Once the governor control scheme has been tested and verified, it has been implemented in the previous scenario where the diesel generator was incapable of keeping the frequency of the grid with no control at all. The new scenario is depicted in 3.5.

Reproducing the two previous scenarios, a single load of a unity power factor has been connected with the generator (The switch of the second load has been closed throughout the whole simulation). The angular velocity of the machine has been observed and compared with the initial angular velocity in the frequency comparator. At all times, the mechanical

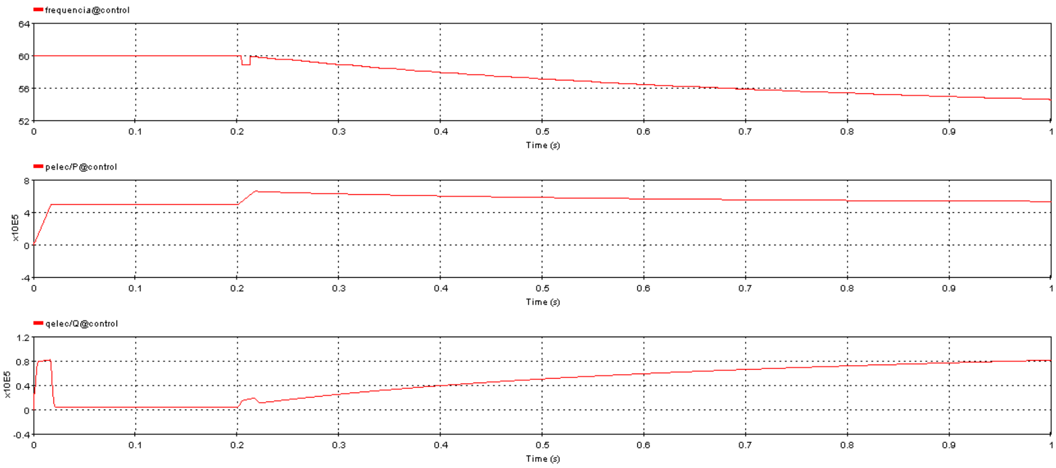

Figure 3.4: Evolution of the electrical frequency, active power and reactive power in the diesel generator connected to a variable resistive load with no regulation scenario

angular speed is twice the electrical angular velocity since the machine contains 4 poles or 2 pairs of poles. In the per-unit system, a variation in the electrical frequency is the same that the variation of the electric angular speed or the mechanical angular speed. Therefore, only mechanical rotational speed has been scoped.

The block-diagram of the "angular speed comparator" can be seen in 3.6. The output of this module is fed into the named "diesel-controller" which is in fact the frequency-control droop that has been previously tested in open-loop. The output of the "diesel-controller" is automatically introduced as a control parameter to the synchronous generator.

It can be seen in 3.7 the active and reactive power through the line plus the angular velocity of the machine.

It should be reminded, the aimed/original angular frequency is 188.5 rad/s. In the 3.7 graphs it is depicted how, after a considerable transient state, the angular frequency of the machine stabilizes at the original value of 188.5 rad/s which corresponds to the 60 Hz of the grid. Moreover, the active electric power seems to match the load and so does the reactive power that is close to null value (The reactance of the line accounts for the small difference).

In the light of the results, it can be affirmed that with no load variation the system is stable and works at the desired frequency.

The second scenario includes the connection of the second load at a time when the system has reached steady-state. The loads used for this study have been of 300 kW and 400 kW and the connection of the second one has been made at 3 seconds. The consequences of such event are shown in the graphs in figure 3.8.

To begin with, the system is clearly stable. In fact, it is even capable of maintaining the frequency at 188.5 rad/s in the given conditions. Both active and reactive power also converge and so the system seems to be able of dealing with variations in its load as long as the variation comes from unity power factor loads. However, the steady-state active power given by the generator is actually not the expected. The aggregated nominal active power of both loads should scale up to 700 kW. However, taking a closer look at the generator output, it does only supply an amount of 355 kW 3.9. To understand such irregularity, a phase voltage has been plotted 3.10

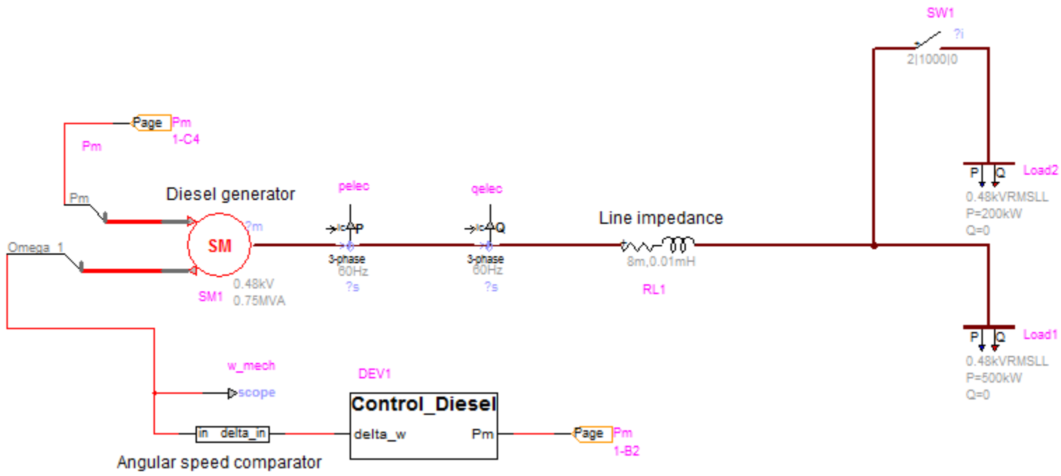

Figure 3.5: Diesel generator connected to variable resistive load with frequency regulation in EMTP

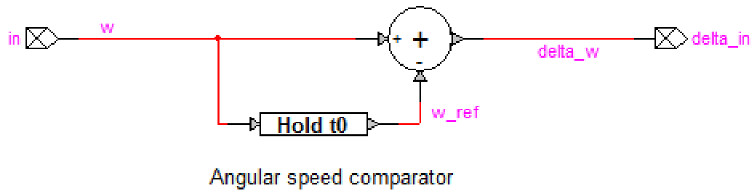

Figure 3.6: Angular speed comparator in EMTP

The graphs indicate that when the load is connected at time t= 3 s, the power supplied and thus the active power consume decline. Such reduction is suspected to be due to a drop in the terminal voltage of the machine.

If the whole thing is analysed, in the beginning of the simulation the phase voltage is

$$V_{RMS_a}(t < 3s) = \frac{390}{\sqrt{2}} = 275.77 \text{ V} \tag{3.1}$$

therefore the module of the line-to-line voltage will be $\sqrt{3}V_{RMS_a}(t < 3s) = 478$ V which is approximately the nominal line-to-line voltage. Once the second load is connected and once the transient effect dies out, the final phase voltage becomes

$$V_{RMS_a}(t > 3s) = \frac{275.8}{\sqrt{2}} = 195 \text{ V} \tag{3.2}$$

And the line-to-line voltage will become $\sqrt{3}V_{RMS_a}(t > 3s) = 337.8$ V. Since in this case there are only active loads, the power transferred by a phase would be.

$$S = P = \frac{V_{RMS_a}^2}{R} \tag{3.3}$$

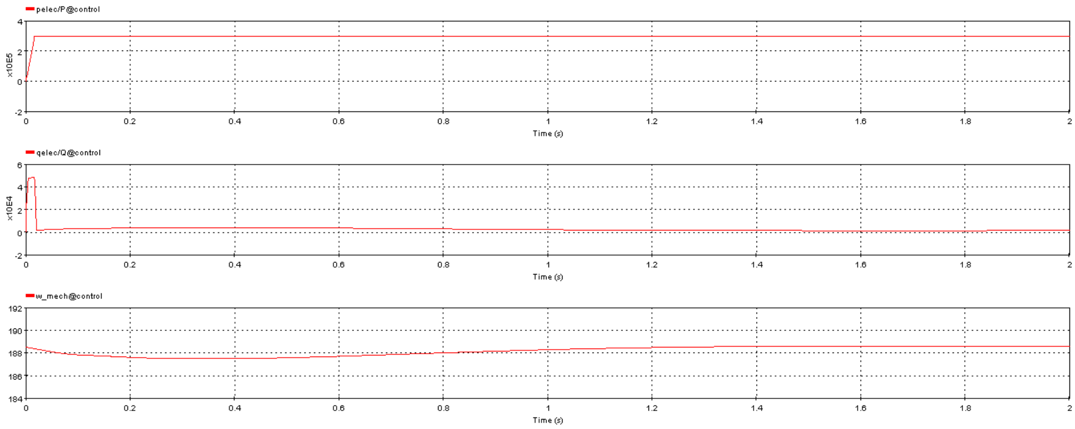

Figure 3.7: Evolution of the active power, reactive power and mechanical frequency in the diesel generator connected to a single resistive load with frequency regulation scenario

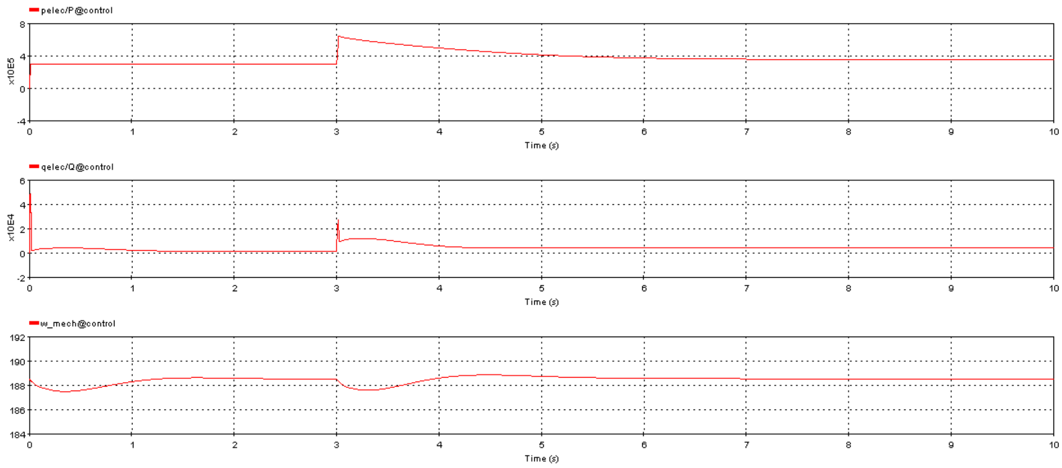

Figure 3.8: Evolution of the active power, reactive power and mechanical frequency in the diesel generator connected to a variable resistive load with frequency regulation scenario

Now, taking into account that the voltage has reduced by a factor of $\frac{337.8}{480} = 0.7$ the generated power will, in principle, reduce by a factor of $0.7^2 = 0.49$. If the validity of such statement is examined, the active power that the generator outputs ought to be $0.49 \cdot 700 = 343$ kW which is the steady-state output of the diesel generator in the simulation with a 3% of error

All in all, a second control scheme is required to adjust the field voltage that will permit to maintain the terminal voltage and thereby create the necessary excitation to provide for both loads.

3.1.3 Synchronous generator with both frequency and reactive power control

In this section, the governor of the machine and the exciter voltage regulator are implemented in the control of the generator. As for the loads, three scenarios have been studied. To begin with, the already studied case where one load of a unity power factor is connected from the

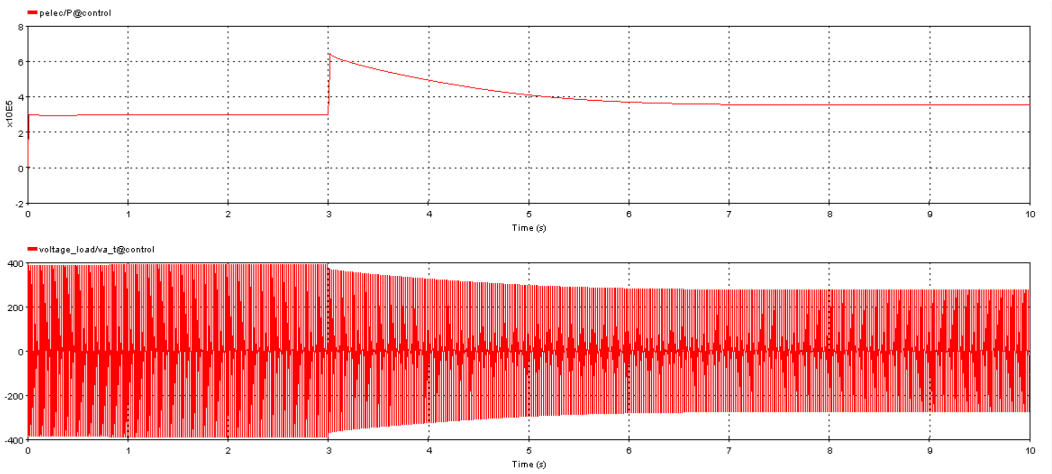

Figure 3.9: Evolution of the active Power and line voltage when the diesel generator is connected to a variable load

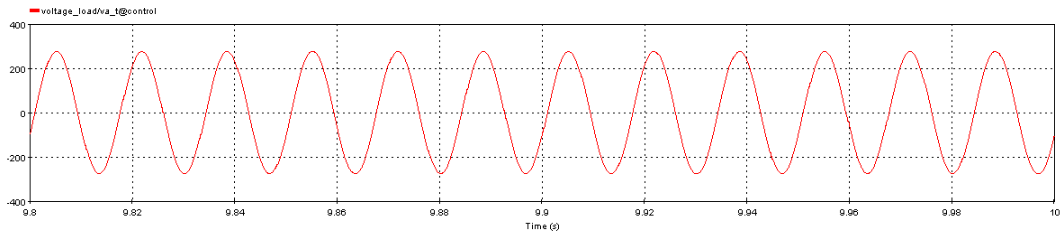

Figure 3.10: Close-up of the line voltage from at time 9-10 s when the diesel generator is connected to a variable load

beginning and later on a second active load is connected has been performed. Mirroring the loads used in the previous section, the first load consists of 300 kW whereas the second load accounts for 400 kW. The schematic 3.11 depicts this new scenario

The second load is introduced at time t= 6 s and the simulation time is 20 s. It can be seen the active power, the reactive power and the mechanical frequency in per-unit in figure 3.12

As in the previous case, the mechanical frequency and thus the electrical frequency successfully converge at the nominal frequency. In addition, the active power delivered by the generator almost reaches the 700 kW that would be generated should the line be lossless and with no line impedance in general. On the whole, both active and reactive power converge at desired values hence the control of the generator functions correctly controlling both frequency and reactive power delivered to the grid.

In the graphs in 3.13 the control signals in the excitator can be observed:

The E_{fss} symbolises the initial induced voltage that will logically remain constant as it is precisely defined at initial state. E_f represents the output of the excitator which is fed to the Diesel generator as a control input. Last but not least, V_t represents the terminal voltage of the generator. V_t was defined as the square root of the two components V_d and V_q consisting of the two components of the Clarke/Parks transformation of the terminal voltage (there is no homo-polar voltage component because it is an equilibrated three phase system with equal linear loads in all phases). The plots show a considerable deviation in the terminal voltage of the generator that slowly recovers its nominal value after about 5

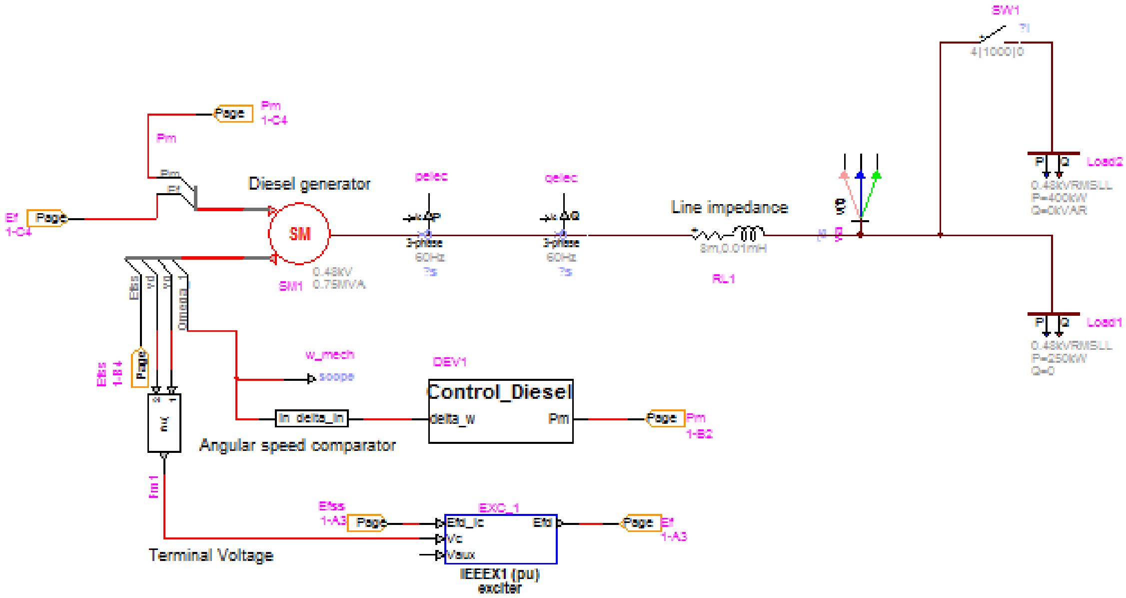

Figure 3.11: Diesel generator connected to a variable resistive load with both frequency and voltage regulation in EMTP

seconds. Likewise, the E_f signal increases to respond to the drop of field voltage. E_f is automatically stepped-up until the terminal voltage has been corrected.

The second scenario includes two loads, one initially connected and the other plugged after some time, with a power factor smaller than unity. That is to say that both loads consume a constant active and reactive power independently of the grid's frequency. The apparent power of both loads is kept constant for the sake of comparison and power factors is set at 0.8 implying that both loads are of inductive nature. Maintaining the schematic of the beginning of this section, the results are plotted in the graphs in 3.14

To briefly comment on the plots in 3.14, it can be seen how both active and reactive power plus frequency are regulated efficiently even though it takes a considerable time to reach steady-state. It is worth pointing out the increase in reactive power in comparison with the previous scenario and, similarly, a decrease in active power. More interesting is what happened with the excitation system inputs and outputs 3.15

The initial field voltage is notably greater in spite of the fact that the apparent power has not changed. Analogously, when the load is connected the increase in the field voltage output of the excitation system is much more pronounced as a result of the fact that extra reactive power is being demanded.

To wrap up, a disconnection of a load has been carried out to ensure that the control system also functions when a load is tripped or simply disconnected from the grid. To do so, both loads with power factor 0.8 have been initially connected and, after 8 seconds, the 400 kVA load has been removed from the grid. Its effect can be seen in plots 3.16

Once again the system is able to stabilize given enough time. The maximum frequency when the load is tripped goes up to 1.0085 pu or 60.51 Hz of electrical frequency, a deviation of 0.51 Hz.

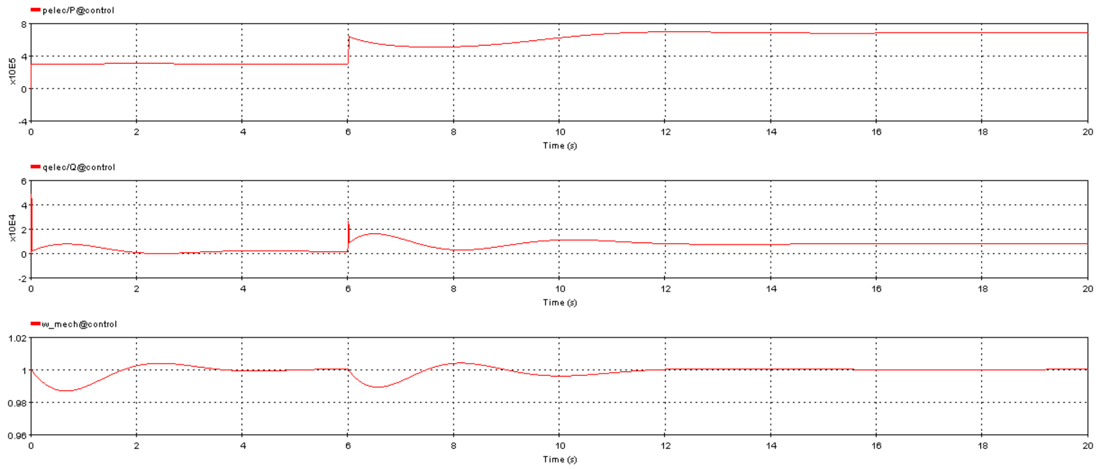

Figure 3.12: Graphs of active power, reactive power and frequency(p.u) of the diesel generator connected to a variable resistive load with both frequency and voltage regulation scenario

3.2 Isolated Microgrid with Synchronous-based and inverter-based DGs

Once the synchronous-based DG has been modelled along with its governor and excitation system and successfully been tested under several loads, an inverter-based DG unit is now introduced to the system in order to evaluate what may occur when notably large loads are suddenly connected or disconnected from the grid. The stability of this microgrid topology is examined including time responses.

As it has already been mentioned, different active and reactive power management strategies can be included to enforce frequency and voltage or power factor regulation. In this case, a master/slave control strategy has been deployed. The inverter-based distributed generator delivers a constant amount of active and reactive power regardless of the frequency and voltage of the grid (grid-following). The fact that the inverter (slave) does not get involved in the regulation of these parameters, it requires another master DG unit to dictate them. The synchronous generator, therefore, will be responsible to ensure the frequency and voltage of the grid (grid-forming) whilst the inverter-based DG will dedicate itself purely at injecting power.

3.2.1 Ideal inverter-based DG

The inverter-based DG contains a three-leg voltage source inverter followed by a filter on the AC side. The inverter-based DG is assumed to be dispatchable and, hence, the DC side is connected to a constant voltage source. From a control perspective, the inverter active and reactive powers can be controlled with various control schemes like the constant power and constant current controllers previously mentioned in the subsection 1.6.2. However, from an electrical point of view, the inverted-based DG can be simplified to a three phase controlled current source which output would depend on those internal control schemes. Ideally, if the control scheme were extremely fast the reaction time of the inverter-based would be negligible. Consequently, the three phase controlled current source could be able to provide the desired power output or current output at all times regardless of the current condition

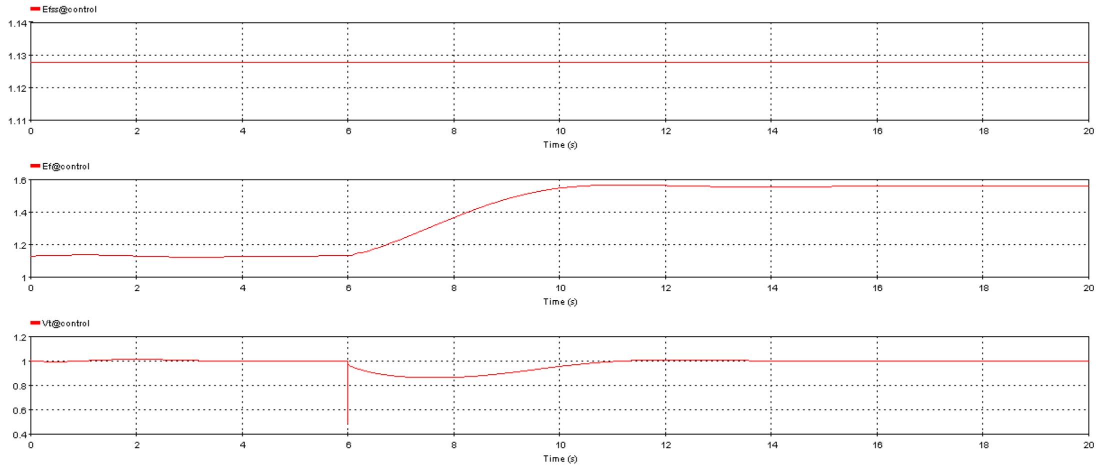

Figure 3.13: Graphs of the initial induced voltage (p.u), output of the exciter (p.u) and terminal voltage (p.u.) of the diesel generator connected to a variable resistive load with both frequency and voltage regulation scenario

of the grid at which it injects.

Such scenario has been carried out to investigate the interaction between the two DG and the effects on the microgrid when the grid's load is altered.

The control scheme of the current sources, if the output power is to be kept constant, can be seen in figure 3.17.

The control of the inverter-based DG modelled as an ideal three-phase current source consists of several elements. First, and most importantly, an ideal PLL which ,as it was described previously, is used to output a sinusoidal wave of phase and frequency matched with the voltage scoped. The output sinusoidal wave of the PLL is then multiplied by the desired current's peak to obtain the desired current to be injected. Since current and voltage will be in phase, only active power will be delivered. The inverter-based DG has been set to be of 0.75 MVA and delivering its total apparent power as real power.

$$S = P = 3 \cdot V_{phase} \cdot I_{phase} \tag{3.4}$$

then

$$I_{phase} = \frac{750,000}{3 \cdot V_{phase}} \tag{3.5}$$

and finally

$$I_{peak} = \sqrt{2} \cdot I_{phase} \tag{3.6}$$

To obtain I_{peak} of each phase, the RMS voltage of each phase is observed and sent to a mathematical module where the calculation of I_{peak} is computed taking into account the constant power output of 0.75 MW. With the inverter-based DG modelled, it is then

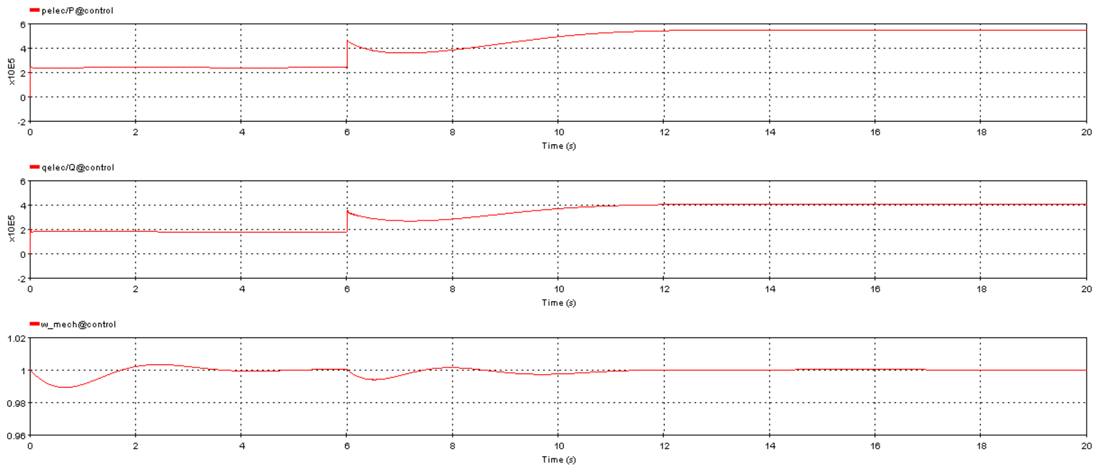

Figure 3.14: Evolution of active power, reactive power and frequency(p.u) of the diesel generator connected to a variable PQ load with both frequency and voltage regulation scenario

connected with the loads as it has been done with the diesel generator. The resulting schematic can be seen in 3.18.

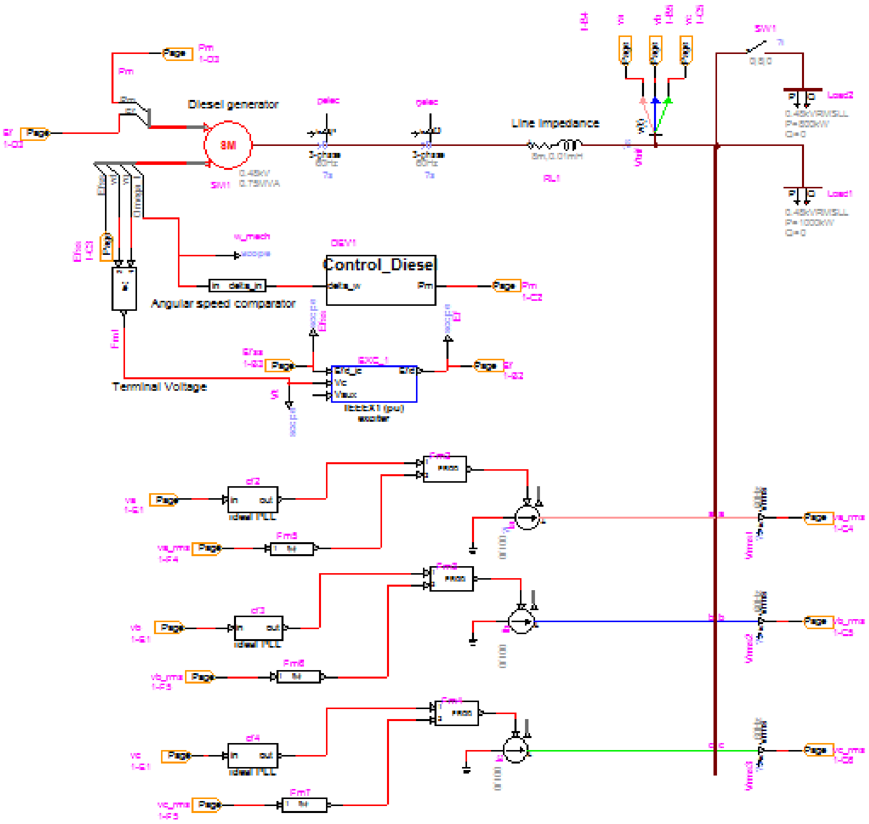

Figure 3.18: Microgrid with a grid-forming synchronous generator along with an inverter-based DG with an ideal current control scheme in EMTP

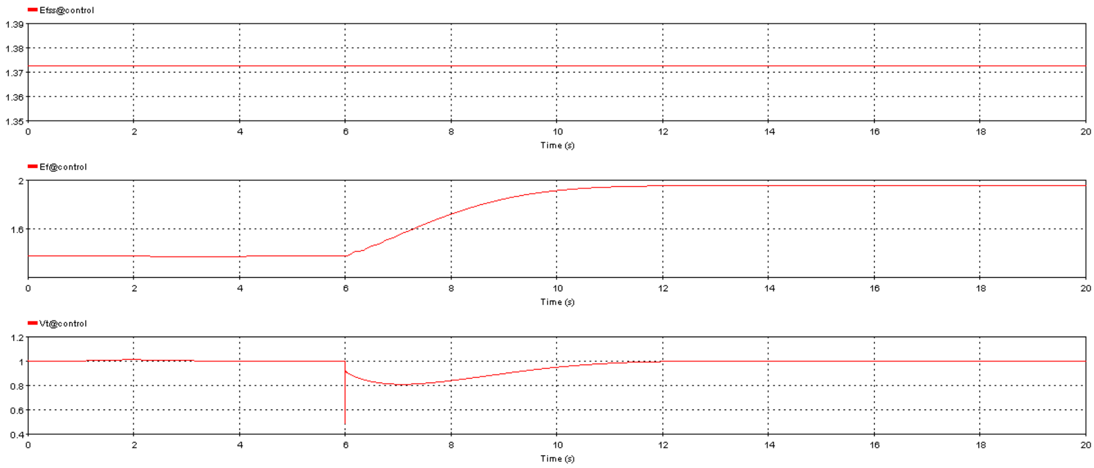

Figure 3.15: Graphs on the initial induced voltage (p.u), output of the exciter (p.u) and terminal voltage (p.u.) of the diesel generator connected to a variable PQ load with both frequency and voltage regulation scenario

The scenario simulated begins with two loads of 0.85 MVA and 0.6 MVA respectively with a power factor of 0.9. The latter is tripped at time t=8 s and the output powers of the diesel generator are scoped together with the mechanical frequency which, indeed, coincides with the electrical frequency if measured in per-unit. Notice that the values of the loads are greater than in the previous simulations in order to better match the power outputs of the generators. Only time period 8-20 seconds has been plotted to focus on the transition from having two loads connected to solely one.

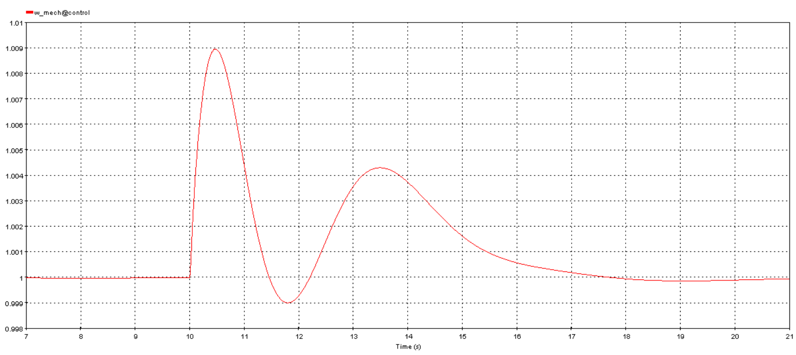

Figure 3.21: Frequency of the grid [p.u.] when the inverter-based DG is controlled by an ideal current control scheme

There are several features in the plots 3.19, 3.20, 3.21 worth pointing out. To start with, both power and frequency converge to a particular value with no oscillations whatsoever once the observable transients in the plots have died out. Secondly, the output real power of the generator is 500 kW before the load is disconnected and 12.5 kW afterwards. Likewise, the reactive power is 0.51 Mvar prior to the disconnection and 0.35 Mvar in the end. If the active and reactive power that demand the loads at nominal voltage are calculated:

$$P_1 = S_1 \cos(\alpha) = (0.85 + 0.6) \cdot 0.9 = 1.305 \text{ MW} \tag{3.7}$$

$$Q_1 = S_1 \sqrt{1 - \cos^2(\alpha)} = (0.85 + 0.6)\sqrt{1 - 0.9^2} = 0.63 \text{ Mvar} \tag{3.8}$$

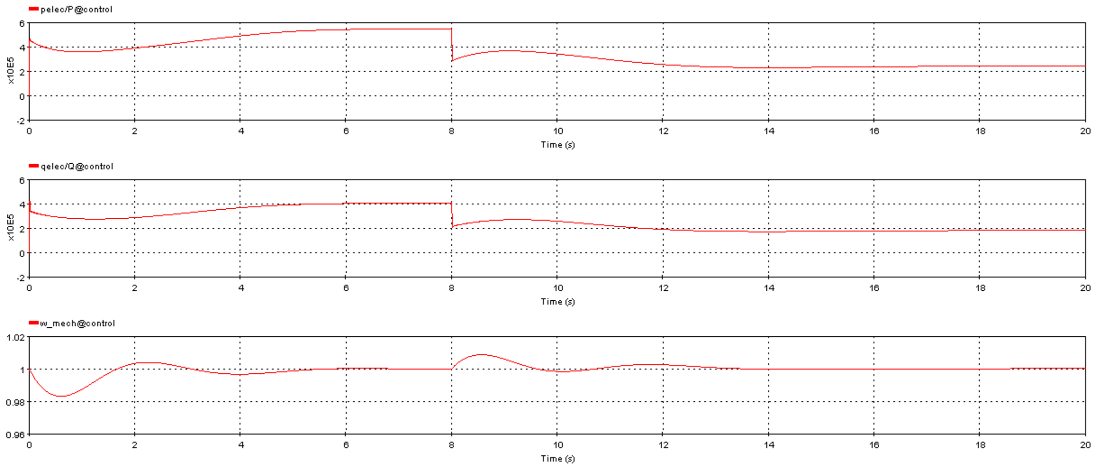

Figure 3.16: Graphs on active power, reactive power and frequency(p.u) of the diesel generator connected to a variable PQ load (Disconnexion case) with both frequency and voltage regulation scenario

And the power fluxes of the synchronous device when the load is disconnected:

$$P_2 = S_2 \cos(\alpha) = 0.85 \cdot 0.9 = 0.76 \text{ MW} \tag{3.9}$$

$$Q_2 = S_2\sqrt{1-\cos^2(\alpha)} = 0.85\sqrt{1-0.9^2} = 0.37 \text{ Mvar} \tag{3.10}$$

Taking into account that the inverter-based distributed generator provides 0.75 MW and 0 Mvar, the diesel generator ought to provide with the remaining part. It is clearly so when the load is disconnected since $0.75+0.0123 \simeq 0.76$ MW and $0+0.35 \simeq 0.37$ Mvar. The small difference can be accounted for the line impedance which slightly drops the load's terminal voltage. As for the initial state, the error gets amplified since the current drawn from the synchronous generator and thus the power dissipated in the line impedance increases. This error could be corrected if a load compensator were to be implemented in the excitation system as it has been described in the theoretical background.

If the transient oscillating frequency is inspected, the major deviation from the nominal value accounts for a 0.0088 pu which corresponds to 0.5 Hz in the electric frequency.

As a last point, the current peak of the inverter-based DG is plotted 3.22

This curve confirms that the output power of the inverter-based DG is always constant regardless of the voltage and the frequency of the grid. When the load gets disconnected, the voltage on the output terminal of the inverter and thus also the voltage of the grid temporally rises. In order to maintain a constant power output the converter delivers a smaller current inversely proportional to the voltage peak.

3.2.2 Non-ideal inverter-based DG

So far, the voltage source inverter of the inverter-based DG has been idealised as if it could react to variations of the grid with a null time response. In other words, the response in front of a variation in the input has been in real time with no delay at all.

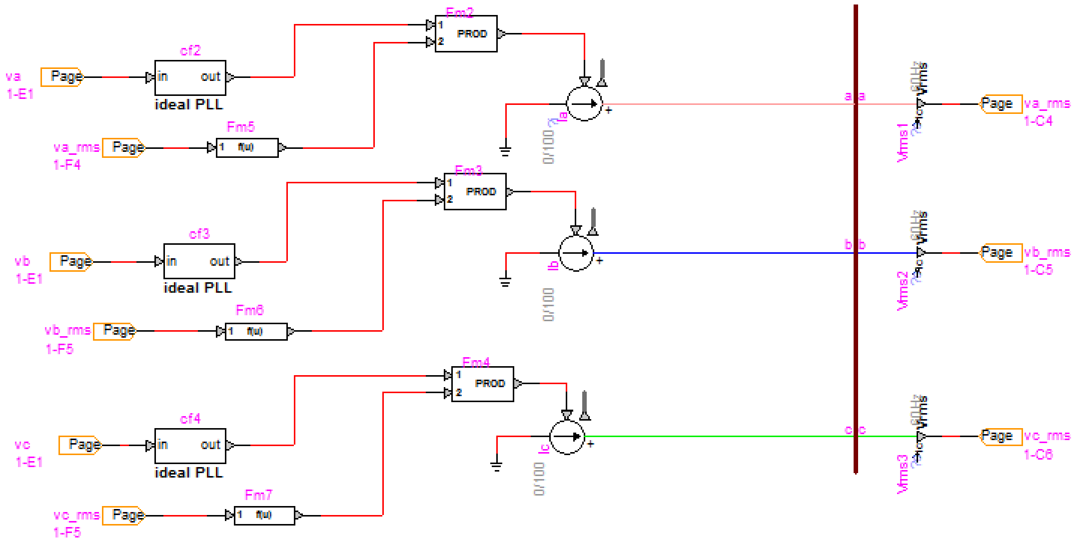

Figure 3.17: Ideal current control scheme in EMTP

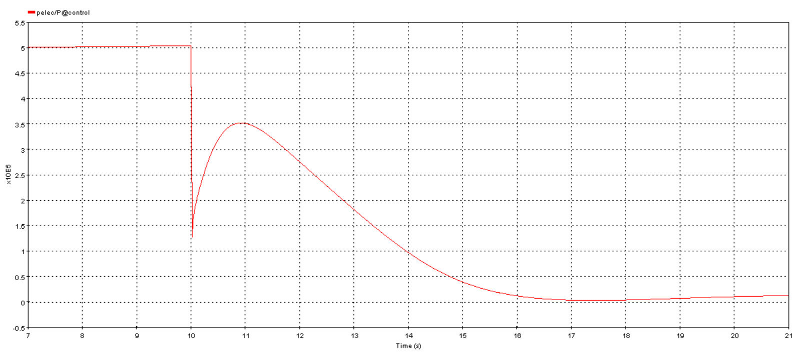

Figure 3.19: Active power output of the synchronous generator when the inverter-based DG is controlled by an ideal current control scheme

A more realistic approach consist of considering an ideal current feedback with a power control that has a certain time constant due to the PI controller and the transfer function of the filter utilised in the point of connection.
The parameters of the PI has been set at $K_p = 5.25$ and $K_i = 0.175$ and the coupling filter consists of an inductor that allows the interconnection between two voltage sources (The inverter-based DG and the grid). The impedance of the inductive filter in this case is $Z_f = 0 + j0.25$ p.u. The controller transfer function in the Laplace domain is

$$G_c(s) = K_p + \frac{K_i}{s} = \frac{K_p s + K_i}{s} \tag{3.11}$$

and the filter's transfer function is obtained from the electrical laws that rule the inductor

$$v_L(t) = L\frac{di_L(t)}{dt} \quad \rightarrow \quad V_L(s) = LI_L(s)s \quad \rightarrow \quad I_L(s) = \frac{1}{Ls}V_L(s) \tag{3.12}$$

Taking into account that $I_L(s)$ is the output of the transfer function that models the inductor and $V_L(s)$ its input, the filter's transfer function will be

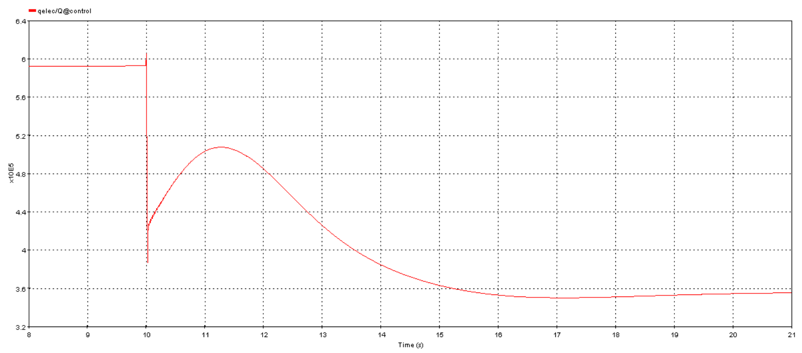

Figure 3.20: Reactive power output of the synchronous generator when the inverter-based DG is controlled by an ideal current control scheme

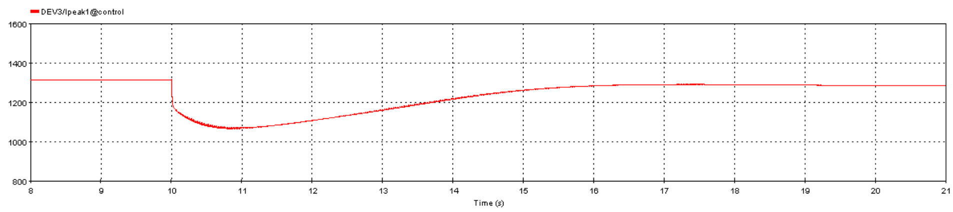

Figure 3.22: Current peak of a phase of the inverter-based DG when controlled by an ideal current control scheme

$$G_f(s) = \frac{V_L(s)}{I_L(s)} = \frac{1}{Ls} \tag{3.13}$$

Now, if the inductance is calculated from the reactance of the filter

$$X_f[\Omega] = x_f[pu] \cdot Z_b = 0.25 \cdot 0.0768 = 0.0192\ \Omega \quad \rightarrow \quad L = \frac{X_f}{2\pi f} = 50.9\ \mu\text{H} \tag{3.14}$$

Such control has been studied in Matlab to determine the time response and the time constant of the system. Prior to that, the equivalent transfer function has been calculated

$$G_{eq}(s) = \frac{\frac{K_p + K_i s}{s} + \frac{1}{Ls}}{1 + \frac{K_p + K_i s}{s} + \frac{1}{Ls}} = \frac{LK_p s + LK_i + 1}{Ls + LK_p s + LK_i + 1} = \frac{2.674 \cdot 10^{-4} s + 1}{3,183 \cdot 10^{-4} s + 1} \tag{3.15}$$

Such equivalent first order transfer function has a zero and a pole. It's time constant appears to be $3.183 \cdot 10^{-4}$ s which is checked using the command "step" from Matlab as can be seen in figure 3.23

The command “step" plots the output of the transfer function under study when a unity step at t= 0 s is applied. Because the transfer function is of first order, no oscillation can be found. It has a unity gain since the output of the transfer function tends to the amplitude of the introduced step. The time constant can be deduced by looking at the time when the output reaches 0.63 (63% of the input's step amplitude). The corresponding time, as it has been calculated previously through the equivalent transfer function, is $3.183 \cdot 10^{-4}$ s. Such fast response makes total sense considering the fact that inverter-based DG usually have a much faster response than synchronous generators since synchronous generator need to deal

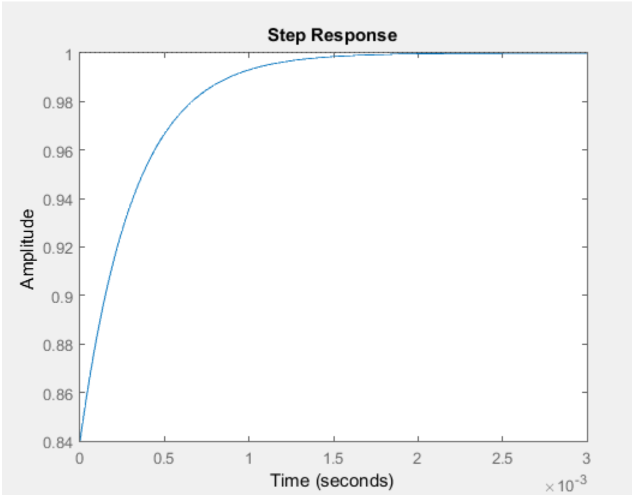

Figure 3.23: Step response of a real current control scheme that uses an inductor as coupling filter using Matlab

with their high rotational inertias.

Finally, this equivalent transfer function which, indeed, accounts for the converter's delay; is implemented in the current sources of the EMTP model 3.24

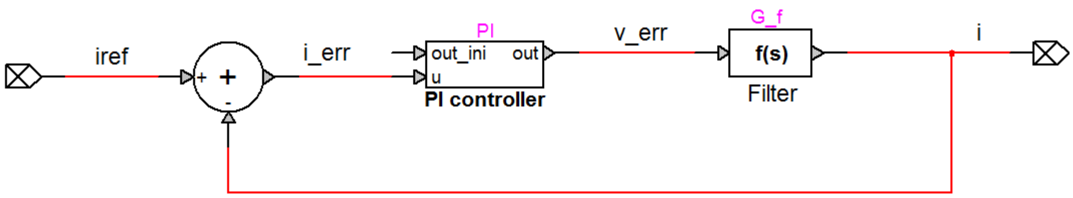

Figure 3.24: Equivalent block diagram to account for the control time delay in EMTP

Where the "out_ini" input of the PI controller refers to the initial value of the PI controller which is set to 0 since no value has been assigned. This control is implemented inside a box called "Power_ control" and connected between the three output "ia", "ib" and "ic" to recreate the intrinsic delay that accounts for the PI and the filter. The resulting circuit after all parts are included is shown in figure 3.25

As it can be seen, there is a large block called "i_ controller" prior to the "Power_ control" block. Such black box includes the ideal current control utilized in the previous simulation.

The scenario simulated mirrors the last few simulations as load is concerned. Two loads of 0.85 MVA and 0.6 MVA with a power factor of 0.9 are initially connected to the grid. At time t=10 s, when the initial transients die out as it will be shown, the smallest load is disconnected from the grid by opening its corresponding switch. A simulation of 30 s is performed and the powers of the generator together with the frequency are scoped. Since the steady-state of both the ideal and non-ideal converters are the same, only the transient comprised between 8 and 20 seconds have been included 3.26, 3.27, 3.28.

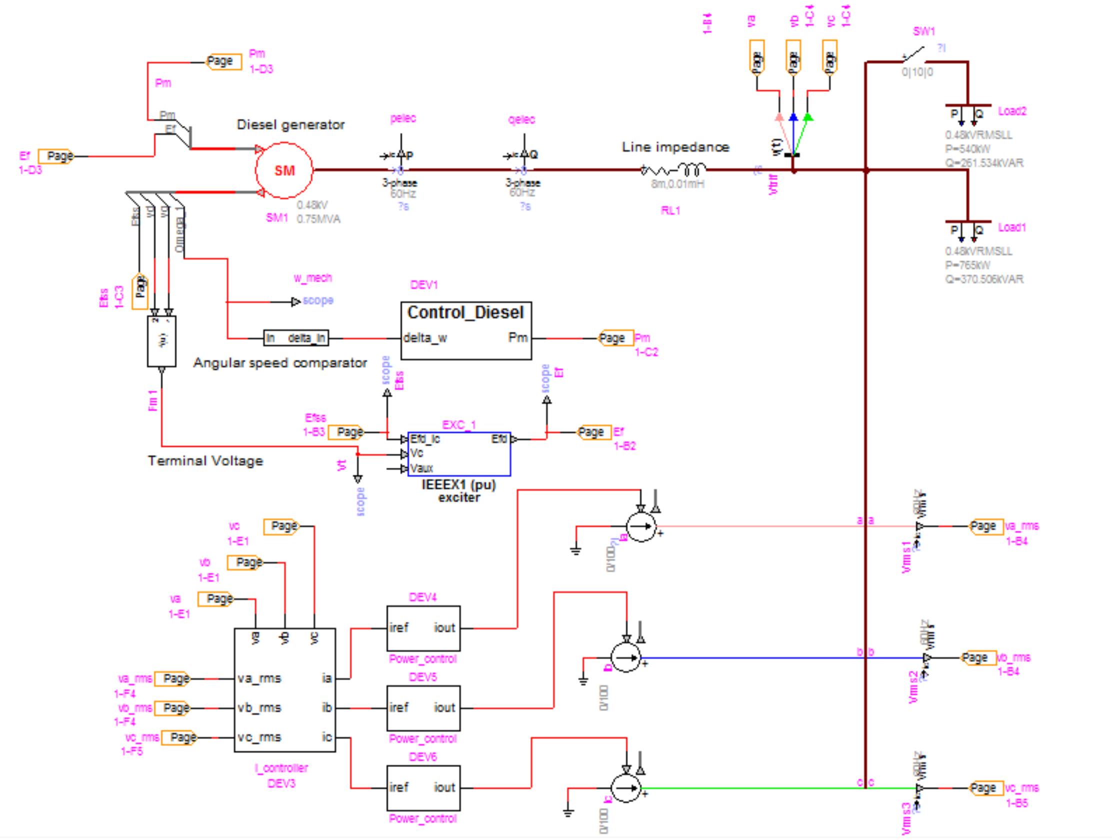

Figure 3.25: Microgrid with a grid-forming synchronous generator along with an inverter-based DG controlled by a real current control scheme in EMTP

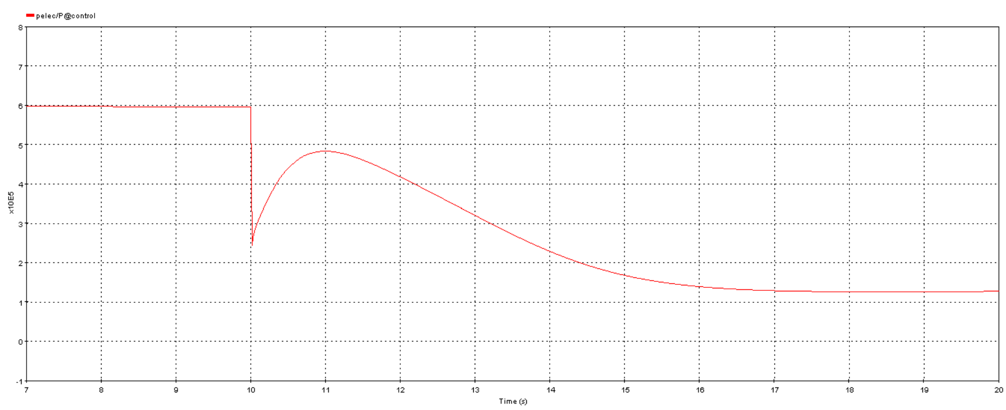

Figure 3.26: Active power output of the synchronous generator when the inverter-based DG is controlled by a real current control scheme

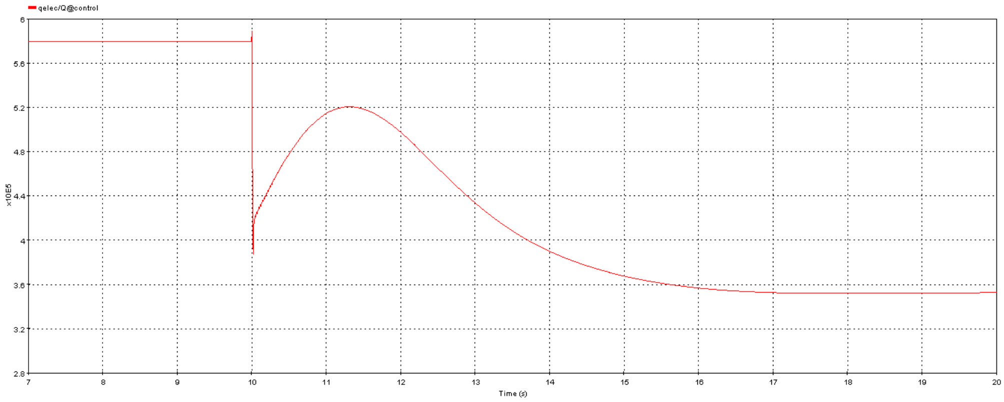

Figure 3.27: Reactive power output of the synchronous generator when the inverter-based DG is controlled by a real current control scheme

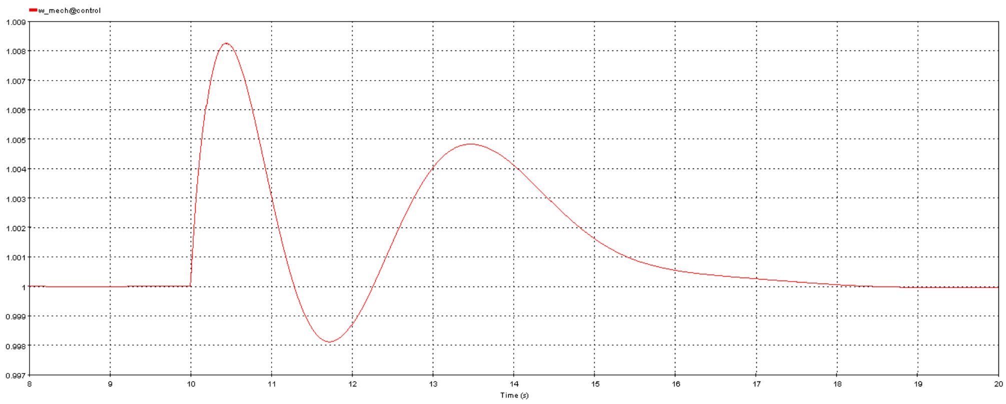

Figure 3.28: Frequency of the grid [p.u.] when the inverter-based DG is controlled by a real current control scheme

The plots 3.26, 3.27, 3.28 resemble quite a lot to the ideal-inverter ones. The reason lies in the fact that the converter is really fast at regulating itself and because the voltage drop due to the disconnection is not that significant the power plots and frequency plot do not change enormously. However, if a closer look is taken at both the active and reactive power curve, it can be seen that the peaks after the disconnection have exacerbated. Since the converter has a certain time constant, when the load is disconnected the voltage temporally peaks as in the ideal inverter-based DG. Yet, the converter takes a certain time to notice it thus injecting a constant current even when the voltage doesn't remain constant and thereby injecting more than the expected 0.75 MW of power. To verify such statement, the current peak of the inverter-based DG is scoped in figure 3.29

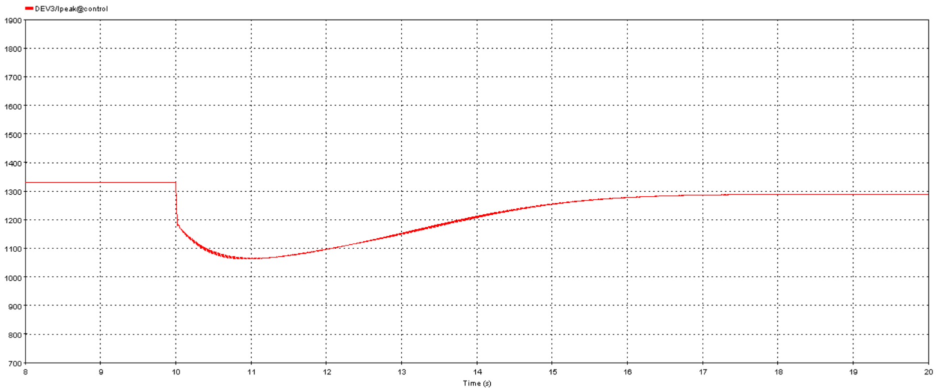

Figure 3.29: Current peak of a phase of the inverter-based DG when controlled by a real current control scheme

3.2.3 Inverter-based DG as supporter of the grid

In the previous two simulation, the inverter-based distributed generation has attempted to inject a constant power flow to the grid in order to contribute in the load feeding. The inverter-based DG, however, has to no extent been involved in the regulation of the grid since its power output was constant regardless of the load condition at any time.
A last scenario is now proposed where the inverter-based DG support the synchronous generator in terms of regulation of the grid. The main idea consists of varying the power output of the inverter-based DG depending on the load that needs to be supplied. In reality, a control system is responsible to ensure that the three power-frequency control schemes and reactive power-voltage control schemes function properly and, in addition, to take into account market prices and demand and renewable production forecasts to optimize production and to set the production points for the DERs [13].

Such scenario is motivated by the fact that since inverter-based DGs have really low inertias, they can modify their power output much faster thanks to their fast power converters. In contrast, synchronous generators are optimal to regulate the frequency of the grid in detriment of having slow responses to changes in the system.

In this case, the time when the load gets disconnected is known (t= 10 s) thus the inverter-based DG can act upon such event by decreasing its power output proportionally to the reduction of power. Since the load to be tripped is $S = 540 + 261.5$ KVA and taking into account that the inverter-based DG only supplies active power, the power coming from the inverter-based DG will be reduced from 750 kW to 250 kW. Such reduction in the power supply will be carried out instantaneously as if, once again, the inverter was ideal and no time delay existed.

To accomplish so, the "i_controller" module has been slightly modified to deliver the current necessary to output the 750 kW during the first 10 seconds and a power output of 250 kW after the tripping of the load. Figure 3.30 depicts the new control applied in one of the phases. Similarly, control of "i_b" and "i_c" consist of the same block-diagram substituting inputs with sub-index "a" for sub-index "b" and "c" respectively

The selector in the controller determines the current and therefore also the power that will be drawn from the inverter-based DG. While the signal generator outputs 1, the current is computed by forcing a power output of 750 kW and scoping the line voltage to determine

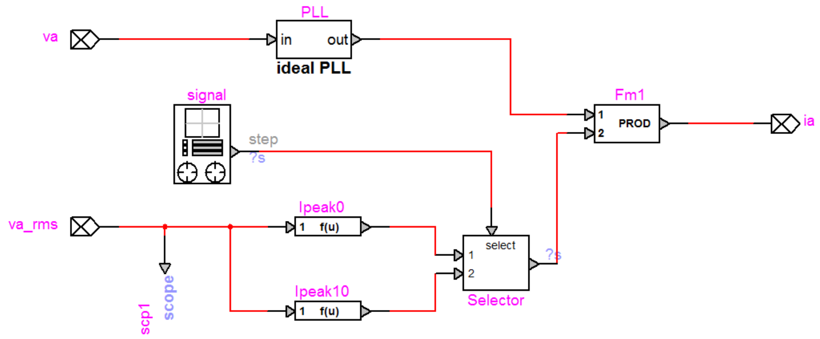

Figure 3.30: Control applied to determine the current of one single phase

the current to be output (computed at block function “Ipeak1"). At t= 10 s, a step of amplitude 2 is output at the signal generator. Such input in the selector alters the output of the selector letting pass “Ipeak10" which is the function that computes the current necessary for the inverter-based DG to deliver 250 kW.

The graphs in 3.31 show the real power output of the diesel generator and the frequency of the grid in per-unit during time period 10-16 s.

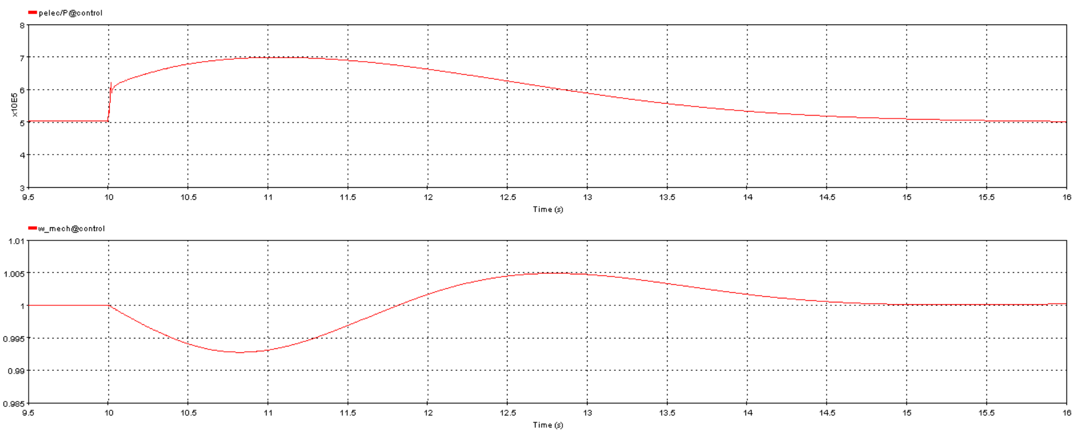

Figure 3.31: Real power output of the synchronous machine and frequency of the grid

To begin with, both the power and the frequency curve diverge from the ones extracted when the inverter-based output a constant power. The peak in the active power is $P_{peak} = 7$ kW which is 2 kW above the steady-state active power after the disconnection. In percentage it accounts for

$$\text{Percentual peak} = 100 \cdot \frac{P_{peak} - P_{steady-state}}{P_{steady-state}} = 100 \cdot \frac{7-5}{5} = 40 \ \% \tag{3.16}$$

and the frequency peak is

$$\text{Percentual peak} = 100 \cdot \frac{f_{peak} - f_{steady-state}}{f_{steady-state}} = 100 \cdot \frac{1.0048-1}{1} = 0.48 \ \% \tag{3.17}$$

which accounts for a frequency deviation of 0.288 Hz.

Since the inverter-based DG did not participate in the supplying of reactive power, such curve did not alter significantly and, therefore, has not been plotted.

In conclusion, the change in the power command of the inverter-based DG has smoothened the transition from one load-state to another by decreasing both power peak of the synchronous generation and the frequency of the grid.

3.3 Results of the simulations

A small summary of the results of the simulations performed and their conclusions are outlined:

The necessity of a governor and exciter system to control the grid-forming synchronous generator and thereby the grid itself has been verified through simulations. In addition, neither whether the load was increased or reduced nor the power factor of the load spared the diesel generator from requiring both the governor and the exciter system to regulate both the frequency and voltage of the grid

The incorporation of the inverter-based DG controlled by a current control scheme did not affect the stability of the microgrid although it affected its dynamic response. The inverter-based DG permitted to share the electric load between the two generator thus reducing the output current of the diesel generator. Finally, the modification of the power output of the inverter-based DG has proven beneficial to smoothen the transition from two different load-states.

Chapter 4

Time-planning and cost assessment

4.1 Time-planning and scheduling

In order to develop this thesis, a proper scheduling was carried out. A Gantt Chart was drawn to find out which activities should be done first and to quantify the amount of time that they would likely take. The 4.1 chart illustrates the planing

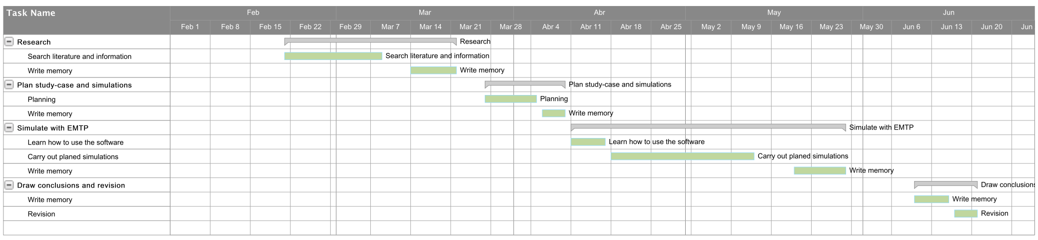

Figure 4.1: Gantt Chart of the project scheduling

In the research part, information and literature regarding microgrids in terms of what they are, which elements compound it, what the benefits that they can bring and so on were examined. Similarly, information on the working principles of the synchronous machine was gathered as well as information on its governor and excitation and topologies of these. Finally ,literature was read on how a standard grid was regulated in both frequency and voltage terms. Next, the planing of the cases to simulate was thought. Before doing so, however,articles were searched in order to find out which softwares were used to simulate grids and microgrids in particular. Having decided on which software to use and the different scenarios to focus on, the simulation part began. Some tutorial exercises were done to get familiarised with EMTP before getting down to the simulations analysed in this project. Once all simulations had been carefully studied, conclusions were drawn. Along with these four clear stages, the writing of the memory was progressively done so as to keep track with everything done up to that point.

Needless to say, this planing was not followed to the detail since the simulations ended up taking a bit longer consuming a small portion of the research time. On the whole, however, the order of the activities prevailed untouched throughout the project and the time assigned for each activity remained fairly accurate.

4.2 Cost assessment

Taking into account that the thesis has mainly focused on theoretical analysis and computer-based simulation, there has been no acquisition of any physical material that would have increased the cost of the project. Because of that, the whole budget of the project has been assigned to human resources, research and investigation, and to the purchasing of the softwares licenses utilised for the simulations. Finally, the physical computer-based equipment such as the laptop and its attached hardware can be added to the budget.

4.2.1 Human Resources

The Human Resources takes up the majority of the budget. It includes all the hours employed to develop the project including planning, research, investigation, learning how to use the EMTP software, the simulations carried out and finally the processing of results and conclusions of this thesis. For the sake of simplification, a reference price per hour has been taken as reference in order to compute the human-resources-based expenses 4.1.

Concept	Price per hour [€\hour]	Total Time [hours]	Total cost [€]
Research and study	20	130	2600
Learn how to use EMTP	10	25	250
Perform the simulations	30	205	6150
Writing the thesis	20	125	2500
Subtotal			11500
IVA 21%			2415
Total			13915

Table 4.1: Human Resources budget

4.2.2 Tangible and intangible assets

To compute the expenses due to tangible and intangible assets, both the computer-based equipment needed to realise the simulations and the licenses of the software have been taken into consideration 4.2. The price of the EMTP license corresponds to the industrial license which is the one that would have been used had this thesis been done in a private company. The Matlab license works slightly different. Its price depends on the number of toolbox that the user requires for its task. The price set is then a very rough approximation of its cost although it serves well enough to draw up a budget.

4.2.3 Final budget

Taken into account both the costs associated to human resources and the tangible and intangible assets, the total cost is:

$$13915 + 21901 = 35816 \text{ €} \tag{4.1}$$

Concept	Total cost
EMTP license	10300
Matlab 2016	7800
Subtotal	18100 €
IVA 21%	3801 €
Total	21901 €

Table 4.2: Tangible and intangible assets

Chapter 5

Environmental impact

As it has already been mentioned, the thesis has been based on computer simulations thus having no or little impact on the environment. Since no tangible material has been used but for the computer itself, no pollution at all has been emitted. Were this thesis carried out in reality to visualize and validate the results of the simulations performed, the emissions of the synchronous generator plus the environmental cost of the manufacturing of the distributed generators should be taken into account. Likewise, the cabling and measuring equipment should be taken into consideration when quantifying the environmental impact of the study. The components to be used should be picked intelligently so that the environmental impact could be minimised thus performing a sustainable project.

On the other hand, it is worth mentioning that the inclusion of renewable-based distributed energy sources permit to reduce carbon dioxide emissions which are responsible for the exceeding green-house effect that partially causes the well-know climate change [7]. Therefore, further investigation on feasible integration of these units into both the utility and microgrids can favour the reduction of carbon footprint. All in all, all advances towards the inclusion of renewable energies to our generation system will, in the long run, undoubtedly be beneficial for a more sustainable future.

Chapter 6

Conclusions

6.1 Main conclusions

Microgrids together with its components such as distributed energy resources have been researched and defined and its benefits and their main technical challenges have been exposed.

The regulation of a grid in both frequency and voltage terms has been studied to comprehend the main challenges that grid regulation hold and how to cope with them.

The understanding of how the grid is regulated through its three control schemes has given place to the synchronous generator as the de facto regulator of the grid. It has been studied along with its regulator and excitation system which proved essential in order to guarantee the mains stability. The regulator proved to be essential in terms of frequency regulation as it had been commented in the literature and later on tested through simulation. Likewise, an excitation system was examined to realise its direct influence on the voltage and reactive power of the grid. It was shown that without the existence of both regulator and exciter system, the synchronous generator was incapable of properly regulating the grid when a change in the load occurred.

Finally, a microgrid composed by a diesel-based DG and an inverter-based DG was simulated to comprehend how their interaction could alter the dynamic response and the stability of the microgrid. A master-slave topology was undertaken where the diesel generator acted as a grid-forming DG and master of the control scheme whereas the inverter-based DG operated as a grid-following DG and slave. The inverter-based DG contributed in the load feeding in all cases and resulted useful to smoothen the transition from two different load-states and thereby avoiding the synchronous generator to substantially change its power consigns.

6.2 Future work

Future research and work could be carried out since microgrids offer multitude of challenges and issues that need to be addressed. To mention just a few, these are some possible research lines that could be undertaken to proceed with this thesis:

- Different regulators and excitation systems could be employed in the synchronous generator and see how it may affect the dynamic response and stability of the grid

- Multiple synchronous generators could be included to involve the second control scheme in the frequency regulation
- The study could be extended by delving into the effect of other kinds of loads on the stability of the grid such as inductive motors or the use of some kind of distributed energy storage such as supercapacitors.
- Other control schemes apart from master-slave topology could be utilised to see if the results diverge from the ones with master-slave topology. It could be discussed cons and pros of each control scheme and differences in the dynamic response.
- A microgrid with no synchronous generator could also be tested to investigate the technical feasibility of such since synchronous generator are nowadays the de facto option when regulating the grid.
- The microgrid could be interconnected with a macrogrid through an appropiate three-phase transformer to visualize power transfer between the two areas. Furthermore, scenarios such as sudden isolating-faults could be performed to further analyse potential issues with microgrids.

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