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An analysis of technical aspects related to intentional islanded operation by gensets of MV/LV networks with distributed generation

TESI DI LAUREA MAGISTRALE IN
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Author: **Edoardo Daccò**

Student ID: 10555035
Advisor: Prof. Davide Falabretti
Co-advisor: Dott. Andrea Vicario
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Abstract

The incidence of faults, the willingness to improve the system security and reliability of the distributed network, as well as the economical drawback related to the fees for the lack of service to end users brought considerable challenges to electricity supply industry, creating further constraints for Distribution System Operators (DSO). In this scenario, several measures have been taken to overcome these challenges or at least mitigate their effects; islanding a portion of distribution networks after a fault is now considered by DSOs as a way to improve the continuity of power supply. The intentional island is energized by means of GenSets (GS) that work as main power supplies for a portion of the distribution grid.

In the thesis, the operation of diesel engine-driven salient pole synchronous generator sets is studied. The first objective is to develop the modelling framework for such GSs to enable their operation in an islanded distribution system. The frequency and voltage of the island are controlled by the speed governor and the excitation system of the GS. Thus, proper modelling of both regulators has been performed. In addition, the aim of the project is to provide a set of technical guidelines for the usage of GS, highlighting the static and dynamic limits of each solution proposed. To examine the suitability of a GS for islanded operations, tests have been performed in two scenarios: i) a passive network employing just a single GS as power supply, ii) an active network where distributed energy resources (DER) are reconnected to the intentional island and multiple generators feed the system.

All numerical simulations have been conducted through DigSilent PowerFactory software.

In the first scenario, the dynamic stability of the system has been evaluated by varying different parameters of the network (the length and typology of the line, and load demand). In the second scenario, a key contribution is the development of DERs models. Regarding this aspect, DER models have been implemented according to the actual control laws of active and reactive power prescribed by technical standards currently in place in Italy. Possible interactions and instabilities caused by the presence of GS and Distributed Generation (DG) units have been evaluated.

Key-words: Gensets, Islanding condition, Dynamic stability, Distributed energy resources, DigSilent PowerFactory.

Sommario

L'incidenza dei guasti, la volontà di migliorare la sicurezza e l'affidabilità delle reti di distribuzione, nonché lo svantaggio economico legato alle sanzioni per la mancanza di servizi agli utenti finali hanno portato notevoli sfide al settore della fornitura di energia elettrica, creando ulteriori vincoli per i gestori del sistema di distribuzione (DSO). In questo scenario, sono state adottate diverse misure per superare questi ostacoli o almeno mitigarne gli effetti; il funzionamento in isola di una parte di rete di distribuzione è ora considerato da alcuni DSO come un modo per migliorare la continuità del servizio. L'isola intenzionale viene alimentata tramite gruppi elettrogeni (genset: GS) i quali fungono da alimentazione principale per una porzione di rete.

Nella tesi viene studiato il funzionamento di gruppi elettrogeni sincroni a poli salienti azionati da motori diesel. Il primo obiettivo è sviluppare la struttura di modellazione e controllo per tali gruppi in modo da consentirne il funzionamento in un sistema di distribuzione funzionante in isola. La frequenza e tensione dell'isola vengono verificate dal regolatore di velocità e dal sistema di eccitazione dei gruppi elettrogeni; pertanto, è stata eseguita un'adeguata modellazione di entrambi i regolatori. Inoltre, lo scopo del progetto è quello di fornire un insieme di regole tecniche per l'utilizzo dei GS, evidenziando i limiti statici e dinamici della soluzione proposta. Per esaminare l'idoneità di un GS funzionante in isola, due scenari sono stati proposti: i) una rete passiva che impiega un solo gruppo elettrogeno come sorgente della rete, ii) una rete attiva dove le risorse energetiche distribuite (DER) vengono ricollegate all'isola intenzionale e più generatori alimentano il sistema.

Tutte le simulazioni numeriche sono state condotte tramite il software DigSilent PowerFactory.

Nel primo scenario, la stabilità dinamica del sistema è stata eseguita variando diversi parametri della rete (lunghezza e la tipologia della linea, e la domanda del carico). Nel secondo scenario, un contributo chiave risulta lo sviluppo di modelli DER. In merito a questo aspetto, i modelli DER sono stati implementati secondo le vigenti leggi di controllo di potenza attiva e reattiva prescritte dalle attuali norme tecniche in Italia. Sono state valutate le possibili interazioni e instabilità causate dalla presenza di GS e generazione distribuita (distributed generation: DG).

Parole chiave: Gruppi elettrogeni, Funzionamento in isola, Stabilità dinamica, Risorse distribuite, DigSilent PowerFactory.

Contents

Introduction

The increasing energy demand, the decay of traditional energy resources and the growing concerns about environmental pollution brought considerable challenges on energy and electricity supply industry [1]. Many measures have been taken so far to overcome these challenges or at least mitigate their effect on electricity supply industry. The core of those measures are the deregulation of electricity markets across developed countries, the investments in renewable energy deployments, the developments in electricity distribution networks and the legislation of new energy policies.

The incidence of faults [2], the protection issues related to the increase of Distributed Generation (DG) units, as well as the willingness to improve the system security, efficiency, and reliability of the distributed network create further constraints for Distribution System Operators (DSO). In this scenario, innovative solutions are being increasingly adopted; the islanding of a portion of power system distribution network after a fault is now being considered by some utilities as a way of improving the continuity of power supply. The intentional island is energized by means of GenSets (GS) for the specific purpose to reduce the out-of-service period of time. The GS unit works as the main power supply for a portion of the distribution grid. For an island to be sustainable, there must be a sufficient generation to supply the load. Moreover, frequency and voltage quantities must be kept inside specified ranges by the speed governor and the excitation system of the GS.

The present study aims to validate regulatory practices and logics for the operation of the MV network through an intentional island condition by means of GSs. The analyses will deepen the stability of the island through numerical models and dynamic analyses developed in DigSilent PowerFactory.

In addition, the study is aimed at validating existing operating practices and operating procedures. If the approaches commonly adopted result to be not adequate, indications will be provided on how to solve the critical issues encountered.

For the purposes of the above analysis, case studies based on real distribution networks will be examined. Specifically, the study will include the analysis of the following aspects:

- Identification of suitable models for the GS, its regulators and all the parameters required to model an existing grid;

- verification of the dynamic stability of the island with a passive MV/LV network powered by GSs. The stability is also evaluated in presence of motors connected to the passive grid;
- evaluation of the effects of the automatic reconnection of the DERs on the islanded portion of network (parametric analysis aimed at evaluating the total share of DG that the GS is able to manage without creating instability of the island).

The aim of the project is to provide a set of technical guidelines about the usage of GS units, highlighting the static and dynamic limits of each solution proposed.

A brief summary of the project is hereafter presented.

First chapter

The first chapter describes different typologies of distribution system, and it states why GSs are more important than ever. A deep analysis of the standards and regulations for the quality of the service and resilience plans has been conducted. General concepts of islanding conditions have also been discussed. The aim is to provide examples in support of GS and islanding condition in the nowadays grid.

Second chapter

The second chapter deals with the state of the art of GSs. It presents the technical components mounted on a GS: different types of motors and alternators, the circuit breaker, and the electric control switchboard. In addition, the operating conditions in which a GS can work, as well as the capability curve, are described.

Third chapter

The third chapter introduces the theme of DG. After a brief introduction related to different regulations through the years, the chapter describes the current technical standards and control laws. In addition, the services provided by the DG to the grid are explained, considering one regulation for active and reactive power each. In particular, the first is related to the reactive power control with respect to the voltage profile; the second one to the active power control during over-frequency events.

Fourth chapter

The fourth chapter describes in detail the theory behind the speed governor and the voltage excitation system. In addition, the selected model of the speed governor and voltage excitation system are described.

Fifth chapter

The fifth chapter describes the implemented model of the network in DigSilent PowerFactory software. All the implemented parameters and characteristic curves are presented, as well as all the elements of the grid (lines, transformer, loads). By changing one parameter at a time, numerical simulations have been conducted to show the static and dynamic limits of the passive network powered by the GS.

Sixth chapter

The sixth chapter presents the study case of the DG unit implemented in the software. The reconnection ramp, and the other control logics of active and reactive power are considered in accordance with the third chapter. Tests have been conducted to check the correctness of each control logic. In addition, it provides the results of the simulations conducted on the network with or without the above-described regulations. With this network configuration, the load sharing approach is evaluated when both the GS and the DG unit feed the grid in islanded condition. The aim is to understand if the reconnection of DG units may cause instability issues, and if the above-described control laws provide benefits to the grid.

Eighth chapter

Conclusions are given in the last chapter, highlighting the criticalities and operations limits of GS in both the study cases analysed. Future developments are introduced.

1 New needs for the distribution networks

In this chapter, new needs of distribution networks are discussed; other than the configuration of these networks, the importance of the continuity of service and resilience are introduced. These aspects are introduced because if target levels of the quality of the service are not reached, the DSO must pay fees proportional to the quality of service reduction. These fees are expensive, and, in order to avoid them, GSs result more than ever important to improve the continuity of service and the resilience of the system. The main operating principle of the GS (the islanded condition) is explained as well.

1.1. The structure of distribution networks

The distribution system consists of all the infrastructures and services necessary for the transport of electricity from the primary substations to the end users. The most common rated operating voltages for overhead and cable networks are 15 and 20 kV; less common voltage levels range between 6 and 25 kV. Typically, in rural areas, MV networks consist mainly of overhead lines, while in urban areas of cable lines.

With regard to LV distribution networks, the most common rated operating line voltage is 400 V, which corresponds to a single-phase voltage of 240 V typical for domestic applications.

The various users can be divided into three categories: small, medium, and large. Small-sized users include lighting, domestic and rural users, as long as the power does not exceed 100 kVA. Small and medium-sized industries, points of supply for collective needs (schools, hotels, hospitals, etc.) belong to medium-sized users: users with a power lower than 10,000 kVA are usually supplied in medium voltage. Large-sized users (e.g., heavy industries) are generally served by the HV network.

In this section, the public MV distribution network and the quality of its service are discussed in detail, as they are of greatest interest for the purposes of the thesis work.

As regards the layout of the networks, the current provision in Italy is to operate the MV public distribution network through a radial configuration, even in cases where, as in urban networks, the grid structure is generally meshed (Figure 1.1).

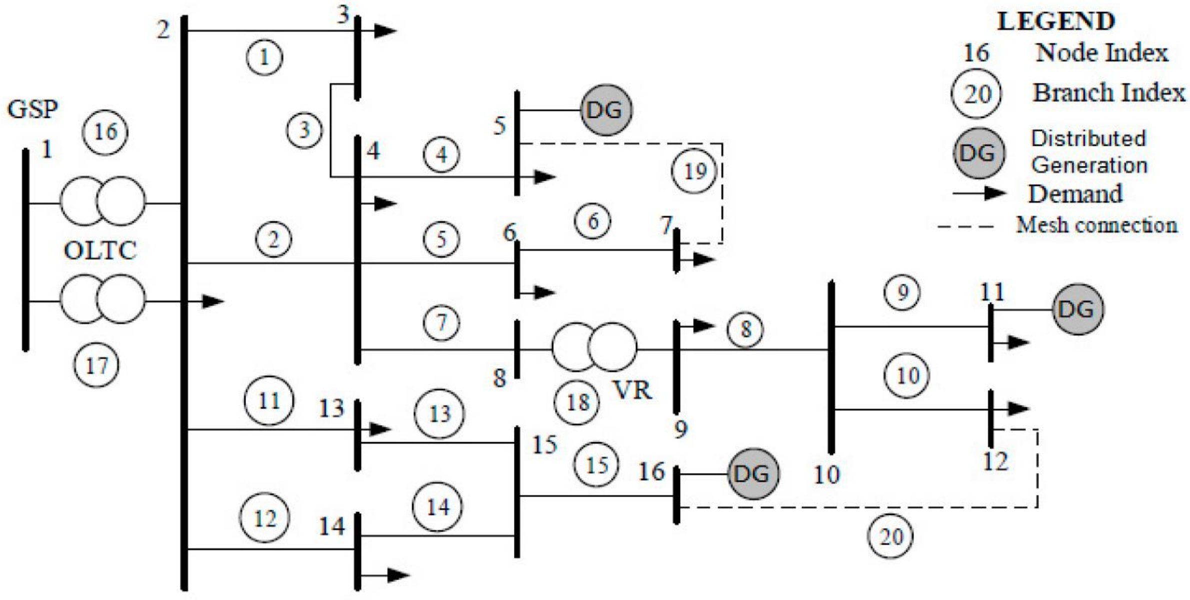

Figure 1.1: Weakly-meshed distribution system

In the radial configuration (Figure 1.2 on the left), several distribution lines exit radially from the HV/MV substations, supplying different loads. Instead, a meshed system (Figure 1.2 on the right) interconnects more than one busses, creating connection loops (rings) that pass through the different areas and return to the original point. The ring is usually linked to alternative energy sources. By placing switches in strategic positions, the DSO can supply power to the customers from several directions. If one energy source fails for some reason (e.g., faults), power can be supplied to customers from other sources. This system is more expensive than the radial because more switches and conductors are needed, but the increase in the quality of the electric service is worth the money.

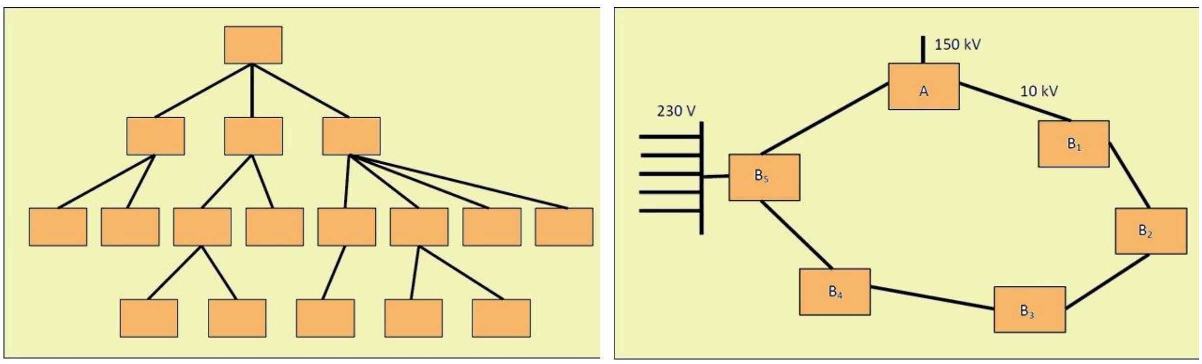

Figure 1.2: Radial configuration (on the left), meshed configuration (on the right)

The radial configuration is generally preferred because it facilitates the management and protection of the network and allows reducing the intensity of short-circuit currents compared to their value of mesh-type networks [3].

However, the pure radial arrangement has a major disadvantage: in case of a line failure, the underlying consumers are de-energized as there are no alternative paths to power the system [4]. In the nowadays context, maintaining high standards of service is one of the most important challenges that DSOs are called to face. The quality of the electricity distribution service is the ability to guarantee the continuity of the electricity supply and compliance with adequate power supply voltage and frequency standards over time. It is an aspect of increasing importance for the growing electrification of consumption (e.g., e-mobility, electric pumps). However, it is not always possible or convenient to mesh a grid: for example, in mountain areas, where the lines run along the valleys, this is often not feasible. Therefore, new solutions need to be found to increase the quality of the service also in radially arranged distribution networks and to mitigate the effects of unwanted events on the grid.

The quality of the service prescriptions are reported in the Annex of Resolution 567/2019/R/eel [5], which defines the technical quality of the electric service as a combination of two aspects:

- continuity of service;
- resilience of the system.

1.2. Continuity of service

Since 2000, ARERA, the institution that provides regulation and control activities in the electricity, natural gas, water services, and waste cycle sectors in Italy, has defined service continuity standards through the introduction of "target levels" to reduce interruptions. These target levels establish the levels of continuity of the service that each DSO is required to achieve in the various territorial areas. They are uniform throughout the country and differentiated only by the type (load density) of the network. Based on these targets, a reward-penalty mechanism has been set up in order to push the DSOs to reach the target levels for the number and duration of interruptions per user.

In particular, the number of interruptions per user is defined as:

$$Ni = \frac{\sum_i^n U_i}{U_{TOT}} \tag{1.1}$$

Where the sum is extended to all the n interruptions that occurred in the calendar year, and where:

- Ui is the number of users involved in the i-th interruption considered;
- Utot is the total number of users served by the DSO in the area.

As well, the overall duration of interruptions per user is defined as:

$$Di = \frac{\sum_i^n \sum_j^m (U_{i,j} * t_{i,j})}{U_{TOT}}$$

(1.2)

Where the external sum is referred to all the n occurred interruptions in the calendar year and, for each of them, to all the m groups (inner sum) of users affected by the same interruption; in addition:

- Ui, j is the number of users involved in the i-th interruption (with i = 1, …, n) and belonging to the j-th group of users affected by the same interruption duration (with j = 1, ..., m);
- ti,j is the corresponding duration of the interruption for the user group Ui,j;
- Utot is the total number of users served by the distribution company in the area considered.

Target levels have been defined related to Ni and Di; in particular, for the reference indicator Ni:

a) for high concentration territorial areas: 1.0 interruptions/user;
b) for territorial areas with medium concentration: 2.0 interruptions/user;
c) for low concentration territorial areas: 4.0 interruptions/user.

And for the reference indicator Di:

a) for high concentration territorial areas: 25 minutes/user;
b) for areas with medium concentration: 40 minutes/user;
c) for low concentration territorial areas: 60 minutes/user.

To fulfill the above-mentioned reference indicators Ni and Di, the DSO must make sure that the system is adequate and secure. Adequacy is the structural ability of the power system of suppling the load, considering any out-of-service situation that can be foreseen for lines and generators (e.g., involving statistics, failure rates). It is a requirement related to the planning of the power system capability, in the long-term framework, dealing with the design of the power system. Adequacy means that the system operator must guarantee:

- enough generation capacity;
- enough transmission capacity;
- a suitable margin to manage uncertainty.

Security, instead, is defined as the ability of the power system to survive low probability perturbations (faults, not expected operating conditions, abnormal load values, etc.) with a minimum (zero) load curtailment. A system is secure if, in case of a credible perturbation:

- there are not violations of technical constraints both on transmission devices and on generators (overloads, out-of-limit voltages, real and reactive generation within capability curves);
- a suitable operational plan (schedule) has been set up for generators and transmission devices, so that possible uncertain events can be managed by re-dispatching power.

In this context, DSOs who do not meet the annual targets must pay penalties calculated in proportion to both the difference between the level reached and the assigned target for the distributed energy. For DSOs that obtain better indicators than those established, economic rewards are provided, calculated in the same way as for penalties.

1.2.1. Penalties for the outage of the distribution system

According to the end users (MV or LV), and the kind of interruptions, quality standards for the maximum time to restore the supply are highlighted in Table 1.1.

Table 1.1: Standard for the maximum time to restore the supply

Type of interruption	Territorial concentration for MV and LV users	Standard for LV users [hours]	Standard for MV users [hours]
Interruption without notice	High concentration: Medium concentration: Low concentration:	8 8 12	4 4 6
Interruption with notice	For all concentrations	8	8

According to the past regulation, for unscheduled long-term outages that exceed standards in Table 1.1, the customer was entitled to automatic compensations from the DSO and/or Terna, the Italian Transmission System Operator (TSO); the compensation increased with the duration of the outage, up to a maximum of 300 € for domestic customers.

From 1st October 2017, the previous limit of 300 € is overcome and, in the event of interruptions caused by force majeure:

- before 72 hours of suspension: compensation is paid through the Exceptional Events Fund (FEE);
- after 72 hours of suspension and up to a maximum of 240 hours (10 days): the compensation is be paid directly by the DSO or by the TSO (Table 1.2).

72 hours is the time within which it is believed that the service can be restored even in the presence of force majeure events. The direct responsibility of the operators in the payment of indemnities beyond 72 hours ceases only in limited and documented cases of suspension and postponement of reactivation operations for safety reasons of the repairers [5]. Therefore, simple cases of mere inaccessibility of roads or falling trees are excluded, which the DSO can deal with by finding special means to remove the problem. If the outage is caused by force majeure events, such as natural disasters, compensation is paid through the FEE, funded by customers and operators, for the first 72 from the start of the interruption.

Table 1.2: Automatic refunds in the event of non-compliance with the quality standards [5]

	Domestic users/non-domestic users with available power ≤ 6,6 kW	**LV and MV users other than domestic ones with available power ≥ 6,6 kW**	**LV users other than domestic ones with available power ≥ 16,5 kW**	**MV users with available power ≥ 16,5 kW**	**LV and MV users, owners of production plants**
Exceeding standards of Table 1.1	30 €	150 €	2 €/kW	1,5 €/kW	0,15 €/kW
For each subsequent period	15 € every 4 hours	75 € every 4 hours	1 €/kW every 4 hours	0,75 €/kW every 2 hours	0,075 €/kW every 4 hours
Revenge period on FEE	first 72 hours from the start of the interruption	first 72 hours from the start of the interruption	first 72 hours from the start of the interruption	first 72 hours from the start of the interruption	first 72 hours from the start of the interruption
Maximum duration for calculation of reimbursements	240 hours	240 hours	240 hours	240 hours	240 hours
Maximum repayment ceiling	n.d.	n.d.	10000 €	40000 €	10000 €

Even if a system is reliable, faults and undesired events may occur; if those events provoke unwanted interruption in the supply of energy to the loads, penalties will be applied to DSOs. The higher the out-of-service period per user, the more expensive will be the fees for the DSO.

1.3. Resilience of the system

The resilience of a system is the ability to withstand stressful situations that have exceeded the limits of the system itself; it is the responsibility of DSOs to reduce recovery times in case of prolonged outages, even by exceptional weather conditions. In Italy, the risk factors related to exceptional weather conditions are:

a) snowfall of particular intensity capable of causing the formation of ice or snow sleeves (wet snow);
b) flooding due to particularly intense rainfalls;
c) landslides and floods caused by hydrogeological instability;
d) heat waves and prolonged periods of drought;
e) windstorms and the effects of saline pollution near the coast;
f) falls of trees on overhead lines.

In addition, a resilient system must be capable to return to the normal operating condition, even if with temporary interventions, through the use of temporary power supplies (such as the usage GSs).

In the nowadays context, DSOs prepare a plan with at least a three-year horizon, aimed at increasing the resilience of the electricity distribution system: the so-called Resilience Plan. The Resilience Plan includes the interventions identified by the distribution company and aimed at containing the risk of power outages against the main critical risk factors that may impact its distribution network. The Plan is assessed both based on the expected increase in terms of withstanding of the network to mechanical stresses and in relation to the expected increase in the effectiveness of the activities of restoration through prevention activities, including management alert, or mitigation.

To increase the resilience of the system, ARERA provides that it is possible to:

- increase the robustness of the network to external stresses;
- improve the effectiveness of the restoration.

The distribution companies develop a Resilience Plan in a coordinated way with the TSO to achieve the maximum effectiveness and efficiency of the reinforcement interventions. The plan must be sent to ARERA for approval.

1.4. Islanded operation - Generalities

A way to reduce times of outage in order to increase the continuity of service and resilience of the system is to create intentional islands powered by GSs.

The formation of an island can be due to a variety of causes (i.e., a failure on the HV/MV network, disturbances in the voltage waveform, or even intentional events, such as maintenance) that result in the opening of switches in the primary or secondary substation.

The recently released Italian standards CEI 0-16 [6] and CEI 0-21 [7] prescribe the technical connection rules for active users in medium voltage (MV) and low voltage (LV), respectively, and contain precautions to be applied to generating units to limit the risk of an unwanted island forming.

However, even if an unwanted island represents most of the formed electric islands, it is not the only typology. The other typology is the intentional island: it is designed to let a portion of the system properly works even if other parts remain de-energized.

1.4.1. Intentional Island

Innovative solutions need to be introduced to reduce the number and the duration of interruptions of the electric service, as well as to increase the resilience of the system. In this context, more than ever, GSs represent a valid solution; their introduction could solve or at least mitigate these problems both from the DSOs' and users' standpoints.

In a distribution system working in a radial arrangement, after the occurrence of a fault, the GS should be connected to the LV side of a secondary substation, feeding a portion of MV/LV network. Thanks to its connection, the portion of the system can work in an intentional islanding condition, regulating the grid's voltage and frequency.

The benefits related to the introduction of a GS to energize a portion of the MV/LV grid are extensive:

- for DSOs: the duration of the interruption would be reduced and the fees of the lack of service as well;
- for the end users: the duration of the interruption would be reduced; this aspect is of fundamental importance for the safety of things/people, especially in isolated contexts (such as mountains) where users would otherwise remain isolated for days [8].

An example of its applicability may be associated with faults caused by exceptional weather conditions in rural or mountain areas. In those areas, the distribution configuration is purely radial, and, in case of fault, there is no other path to feed a portion of the system; in addition, the restoration of service in these places usually requires more time than in urban areas due to the environmental constraints. For example, in 2018, Vaia's storm produced severe damage to the Italian grid: about 120 km of MV lines (20 kV), hundreds of LV lines, and 3 primary plants were damaged at that time. The restoration of energy requires more than two days, and intensive interventions in the following years [8]. A temporary intervention of GSs to restore the electric service and reduce the duration of the interruption would have been a partial relief for the grid: the GS would work counter-feeding the radial system, energizing it under intentional islanding conditions.

Maintaining the network parameters within the required standards is not trivial, but essential, considering that nowadays loads are increasingly sensitive to disturbances; if the governors of the GS are not able to maintain voltage and frequency inside the desired ranges, a black out may occur.

2 Gensets: state of the art

In order to increase the continuity of service and the resilience of the network, a portion of the grid is counterfed by means of a GS (intentional island operation). Thus, a general framework related to the components, operating conditions, capability curve of a GS is provided in this chapter. In addition, the reasons for the selected components of the GS are given.

A GS consists of an internal combustion engine (reciprocating or rotary), which moves an electric generator [9]. The thermal energy developed during the combustion process inside the engine is transformed into mechanical energy through a reciprocating movement (Otto or Diesel cycle) or a rotary movement (gas turbine). The systemic scheme of a GS unit is represented in the next figure:

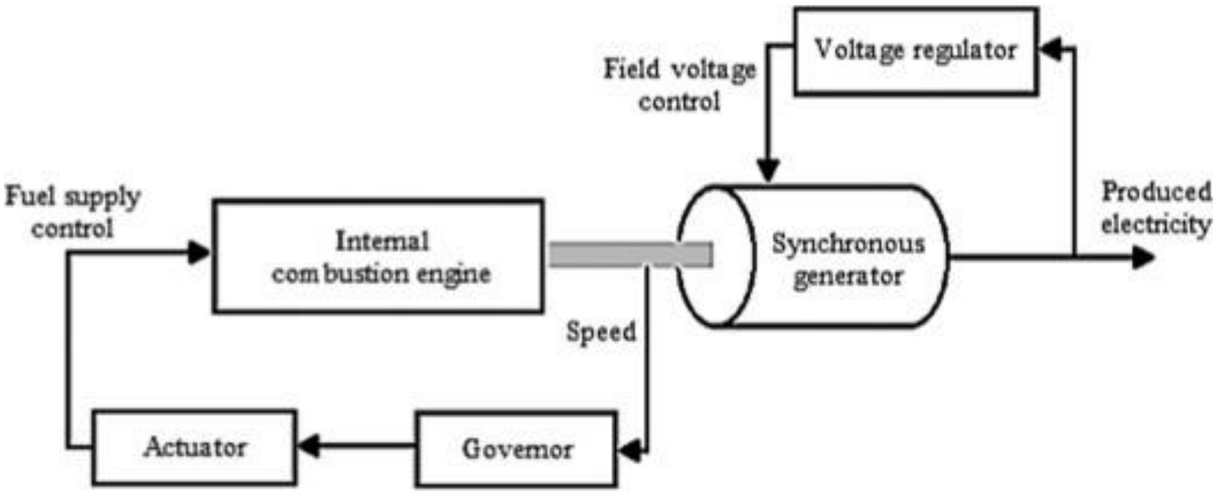

Figure 2.1: Block representation of a GS unit

For the thesis project, a transportable (wheeled) GS is selected; they are large power units mounted on a mobile vehicle, generally a trolley, to facilitate their transport where needed. Stationary GSs can be also used for the purpose, but their transport becomes more difficult.

2.1. Main components of a GS

The main components related to the GS are:

- the motor;

- the alternator;
- the circuit breaker;
- the electrical control switchboard;
- the excitation system;
- the speed governor.

All these components are addressed in the next sections, except for the voltage excitation system and the speed governor that are addressed in detail in chapter 4.

2.1.1. Motor

The choice of the type of engine depends on the power rating and intended application of the GS itself. GSs can be equipped with:

- Otto cycle reciprocating engines;
- Diesel cycle reciprocating engines;
- Gas turbines.

In the thesis, large wheeled GSs with diesel engines are used to counter-feed a portion of the public distribution network, when a portion of the MV/LV network goes out of service (due to faults or for maintenance services). The diesel engines are used on three-phase GSs, with stationary or wheeled installation; the power rating is 10kW ÷ 5MW or above. Diesel engines run at 1500 rpm, they are air or water cooled, and they are often used for emergency supplies.

Otto cycle engines are usually adopted on transportable vehicles, and their power rating (2 ÷ 6 kW) is not sufficient for the intended application. Also, gas turbines are not a feasible solution: even if often adopted for stationary applications in electric power plants (to work in parallel with the public grid), their power rating is usually too high (2 ÷ 100 MW) and their transport results impossible.

2.1.2. Alternator

The electric generators coupled with prime movers are:

- synchronous generators;
- asynchronous generators;
- dynamos.

The alternator chosen for the thesis is a three-phase synchronous generator. Depending on the conformation of the magnetic poles of the rotor, the synchronous alternator can be with salient poles, or with a wound rotor. The number of pole pairs p of the alternator is associated with the speed of the engine n [rpm] and to the frequency f [Hz] by the following relationship:

$$p = 60\frac{f}{n}$$

(2.1)

For example, an alternator working at 50 Hz, coupled with a diesel engine at 1500 rpm, has two pole pairs associated. Synchronous generators driven by diesel engines are equipped with salient pole rotors.

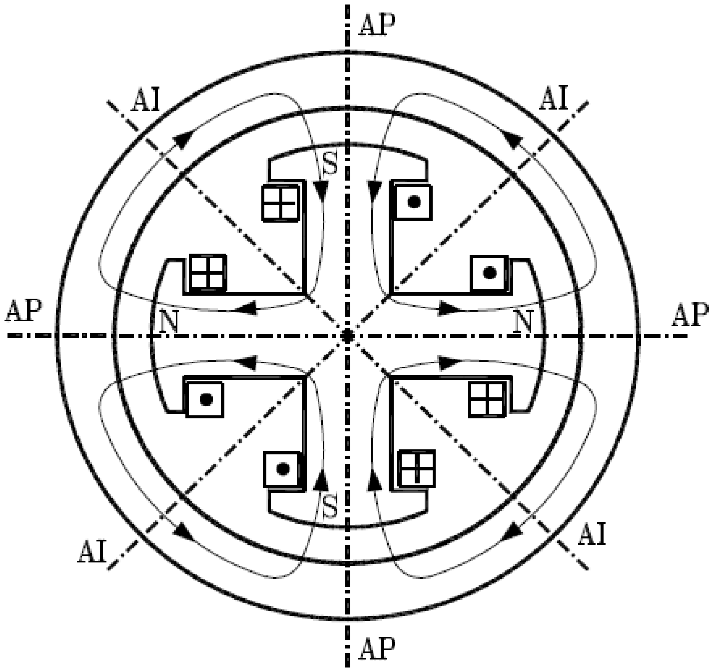

Figure 2.2: Salient pole rotor (two pole pairs) [10]

In reciprocating motions, the angular speed of the driving shaft is not constant but varies with the driven torque. A flywheel is placed between the engine and alternator to prevent this cyclical irregularity and to have repercussions on the output voltage on the alternator; for the same reason, short-circuited windings are added to the rotor poles (damper winding). Due to the changes in the rotor speed, the current induced in the damper winding by the magnetic field tends to oppose the cause that generated it (Lenz's law). These speed changes are related to the motor oscillations.

Asynchronous machines, as well as synchronous machines, can work both as a motor and as a generator. However, they usually operate in parallel to the external grid, from which they draw the reactive power necessary to generate the rotating magnetic field. Asynchronous generators must receive reactive energy from outside to work in islanded mode: capacitor banks of suitable capability are used to this purpose; however, they can give rise to resonance phenomena, with the consequent risk of over-voltages on the system. For these reasons, an asynchronous generator is not a feasible solution to be implemented in islanded systems. They are used for GSs for continuous service in cogeneration power plants, operating in parallel with the grid.

Dynamo-equipped GSs are intended for DC systems, for example for electric traction. Thus, also dynamos cannot be installed on GSs for the intended purpose.

2.1.3. Circuit breaker

The evaluation of the protection systems (for both the motor and the alternator) is of fundamental importance. The main protection of the GS is the automatic circuit breaker at the alternator terminals. The circuit breaker is equipped with opening and closing coils. The GS powers the closing coil so that it is possible to close it only when the group can provide power. Instead, the auxiliary equipment energizes the opening coil so that the circuit breaker can be opened even when the GS is not in operation.

The protection system performs two basic functions:

- engine protection;
- alternator protection.

Engine protections

Table 2.1 shows a wide range of protections for diesel engines. Each manufacturer chooses the most suitable ones, based on the power of the engine and the specific needs of the customer.

Table 2.1: Engine protections for GSs

Protections	Intervention mode	Calibration	Notes
Overspeed	Block	1,10 ÷ 1,15 the rated speed	speed governor and/or injection pump failure
Low oil pressure	Alarm/block	2 ÷ 3 bar	Ordinary pressure: 6 ÷ 8 bar
Low oil level	Alarm	Operational level	Consumed oil, or oil leaks
Excessive oil temperature	Alarm/block	> 105 °C	At elevated temperatures, the oil degrades
Lack of auxiliary power supply	Alarm	To be defined on the GS	Pumps, fans, dampers, etc.
Unavailability of auxiliaries	Block	to be defined for the specific system	Pumps, fans, dampers, etc.
Low voltage of the starter battery	Alarm	0,9 Vn	Battery defects
Low air pressure at start-up	Alarm	< pavv	pavv is the pressure sufficient to conduct the required number of starts
High differential pressure oil, air, or fuel filters	Alarm	On manufacturer data	Maintenance is needed
High water temperature	Alarm/block	> 85 °C	Instead of stopping the engine, the switch can be opened, and the unit works in no-load condition
Low water level in the radiator	Alarm	Operational level	Leaks in the radiator or in the water circuit
Insufficient water pre-heating	Alarm	< 35 °C	Water heater faulted, or not activated
Excessive water pre-heating	Alarm	> 55°C	Thermostat not working
Lack of pre-lubrication	Alarm	On manufacturer data (< 0,2 bar)	Electric pump faulted or broken pipes
Low water pressure in ordinary service	Alarm	On manufacturer data	Faulted water pump, or circuit problems
Excessive temperature in the cylinders	Alarm/block	On manufacturer data	Combustion problems
Low fuel level in the tank	Alarm/block	Operational level	Refill pump not working
Presence of water in the fuel	Alarm	On manufacturer data	Check the water filter at the engine inlet

The most important protection is the overspeed one, as the diesel engine is irreparably damaged if it exceeds 10÷15% of the rated speed; a fault in the injection pump-speed regulator system can cause this dangerous condition. The safest device for the overspeed protection consists of a system of rotating masses driven by the engine; those masses, displaced by the centrifugal force, act on the group stop logic, and mechanically on the fuel interception.

A tachometer relay is equally reliable and constitutes a valid alternative for small GSs. A coil with a permanent magnet, commonly referred to as a pick-up coil, is placed approximately one millimeter from the gear flywheel, perpendicular to the gear surface. The movement of the wheel (made of ferromagnetic material) induces a small voltage in the pick-up winding with a frequency equal to:

$$f = \frac{n * z}{60} \tag{2.2}$$

where n is the number of revolutions per minute and z the number of flywheel teeth. The relay intervenes instantaneously when the frequency of the induced voltage exceeds a preset threshold. The automatic circuit breaker installed at the alternator output trips when the current delivered by the alternator exceeds the calibration one and can be used to protect the engine from an excessive load.

Alternator protections

The GS circuit breaker protects the alternator against over-currents. According to the rating of the GS, or at the request of the customer, the manufacturer can install other alternator protections; Table 2.2 shows a list of them:

Table 2.2: Alternator protections for GSs

Protections	Notes	CEI 11-20 Prescriptions
Maximum current relay (50) (51)	Relay incorporated in the group switch or powered by a CT	Always required
Minimum (27) and maximum (59) voltage relay	Tripping for voltage values outside the range (0,8 ÷ 1,15) Vn	Always required
Minimum and maximum frequency relay (81< ad 81>)	Tripping for frequency values outside the range 48 ÷ 52 Hz	Always required
Stator earth fault relay (59N or 64G)	Calibrated according to the state of the alternator neutral	Only required for groups in continuous service with rating > 500 KVA
Rotor earth fault relay (64R)	If provided, it is connected by means of a brush on the rotor	Only required for groups in continuous service with rating > 1500 KVA
Differential relay of the generator (87G)	Calibrated at 15% of the alternator rated current	Required for groups with rating > 1500 KVA
Maximum temperature relay of the stator windings (49) and alarm and block	Calibrated according to the manufacturer's instructions, according to the insulation class (100 ÷ 165) °C	Only required for groups in continuous service with rating > 500 KVA
Directional relay of active power (32 or 67)	Motor power calibration with a delay of (5 ÷ 10) seconds	Always required for groups in parallel
Excitation loss relay (40)	Provided on request for groups in parallel condition	Only required for groups in continuous service with rating > 500 KVA in parallel
Synchronization failure relay (25)	Provided on request for groups in parallel condition	Not required
Failure to open the GS switch	Consisting of an undervoltage relay, mounted as an auxiliary to the circuit breaker of the group	Required for groups with rating > 1500 KVA

In addition, further requirements concern the overload and short-circuit protections.

Related to the overload protection, if the alternator has a rated apparent power S and can tolerate a 10% overload for one hour, the current Ih which determines the tripping of the group circuit breaker within one hour must satisfy the conditions:

$$I_h \leq \frac{1{,}1S}{\sqrt{3}V} \tag{2.3}$$

Related to short-circuit protection, the magnetic tripping threshold of the circuit-breaker Im must be lower than the minimum short-circuits current that the alternator can provide. If the circuit breaker is not delayed, in favor of safety, Im should be lower than three times the rated current of the alternator, as shown in the next equation:

$$I_m \leq 3I = \frac{3S}{\sqrt{3}V} = \sqrt{3}S \tag{2.4}$$

2.1.4. Electrical control switchboard

Each GS has its own electrical control switchboard (Figure 2.3). In small generators they are a unique switchboard, while in larger GSs the auxiliary equipment has its own. Each manufacturer builds the switchboard in a unique way, also according to the customer's needs and considering the economic constraints.

Figure 2.3: Electrical control switchboard

Reported below are the minimum indications that the GS should have on the switchboard:

- indicator tools;
- optical signals;
- control devices.

Indicator tools

A suitable instrumentation allows the operator to check the status of the GS to make targeted interventions. On the panel there should be:

- AC voltmeter and ammeter (with relative phase and neutral switches);
- frequency-meter;
- wattmeter;

- DC voltmeter and ammeter;
- air pressure gauge;
- engine cooling water thermometer;
- engine oil pressure gauge;
- synchronization column for parallel units.

Visual signals

The optical signals send messages to the operator, completing the indications provided by the indicator tools, and should concern:

- presence/absence of mains voltage and auxiliary voltages;
- engine ready to start;
- engine stopping;
- GS ready to deliver power;
- open/close group switch;
- network-group switch position;
- auxiliaries in operation;
- indication for each pre-alarm, alarm, or block.

Control devices

Based on the information received from the indicator tools and optical signals, the operator decides to intervene on the GS unit by the control devices:

- manual start/stop button;
- motor speed calibration selector or potentiometer;
- alternator voltage calibration selector or potentiometer;
- opening/closing group switch to connect the group to the network;
- opening/closing switch for each auxiliary group;
- test button for signaling lamps;
- operation reset button.

2.2. Types of power

Without any other specification, the nominal power of a GS unit is related to the active power in kW that the alternator, moved by the prime mover, can supply to the output terminals with a power factor of 0,8 (inductive load). Powers are defined according to the ISO standards for the motor and to the IEC (CENELEC and CEI) standards for the alternator. The electrical standards are not coordinated with the mechanical ones.

The ISO standards distinguish four types of power, depending on the working conditions [11]:

1. Continuous Power (COP): it is defined as the maximum power that a GS can supply in continuous service (unlimited number of hours per year) with a constant electrical load, under the environmental conditions established by the manufacturer, with proper maintenance and within the times indicated by the manufacturer;
2. Prime Power (PRP): it is defined as the maximum power that a GS can supply in continuous service (unlimited number of hours per year), with a variable electrical load according to a certain sequence (work cycle), at the environmental conditions proved by the manufacturer, with maintenance conducted according to the methods and times indicated by the manufacturer. The average power over 24 hours, must not exceed a percentage of the power previously established by the manufacturer;
3. Limited-Time Running Power (LTP): it is defined as the maximum power that a GS can provide to a constant electrical load, up to 500 hours per year, at environmental conditions established by the manufacturer, with proper maintenance and within the times indicated by the manufacturer;
4. Emergency Stand-By Power (ESP): it is defined as the power defined as peak value with variable load, with an operating time of 200 hours per year.

The GS is placed to supply a portion of the system for a limited time, until the restoration of the power supply is not completed. However, the GS will be connected to another portion of the grid whenever required. Thus, the operating time is reasonably long, and the COP is the suitable working condition (Figure 2.4).

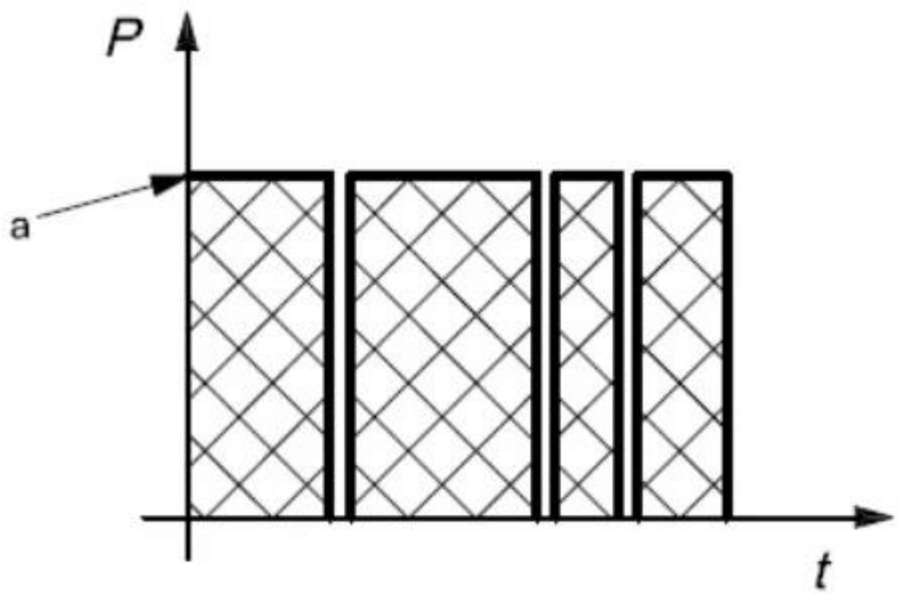

Figure 2.4: Continuous Power (COP)

In the last figure, the "a" parameter stands for the continuous power that the GS can deliver (100%Pmax). The white spaces between one bar and the others represent the period in which the GS is not working (e.g., maintenance)

According to the electrical standards [12] [13], two types of power for the alternators of the GSs are defined:

1. Basic continuous rated power (BR): for continuous service;
2. Peak continuous rated power (PR): for service characterized by a sequence of constant loads different from each other for the required active power from the alternator.

2.3. Capability curve

The capability curve of a synchronous generator defines a static boundary within which the GS can safely operate [14]. The curve is relevant for power-plant operators who are responsible for the proper loading and operation of synchronous generators.

It is constructed on the assumption that the generator has a fixed terminal voltage Vt (kept fixed through the voltage excitation system of the GS) and negligible stator resistance. Construction begins with the phasor diagram of the machine, considering Vt as the reference phasor, as it is shown in the next phasor diagram:

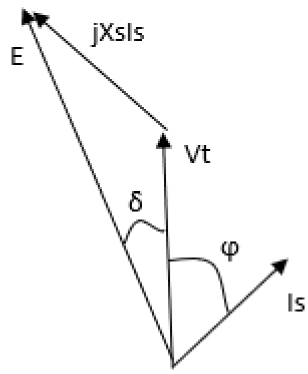

Figure 2.5: Phasor diagram of a synchronous machine

Is the current flowing inside the windings, E the no-load voltage, and Xs the synchronous impedance. δ is the load angle, while ϕ is the characteristic angle between the voltage and current phasor (the angle ϕ is defined positive for lagging power factors). By rotating the phasor diagram, the capability curve is obtained as shown in the next figure:

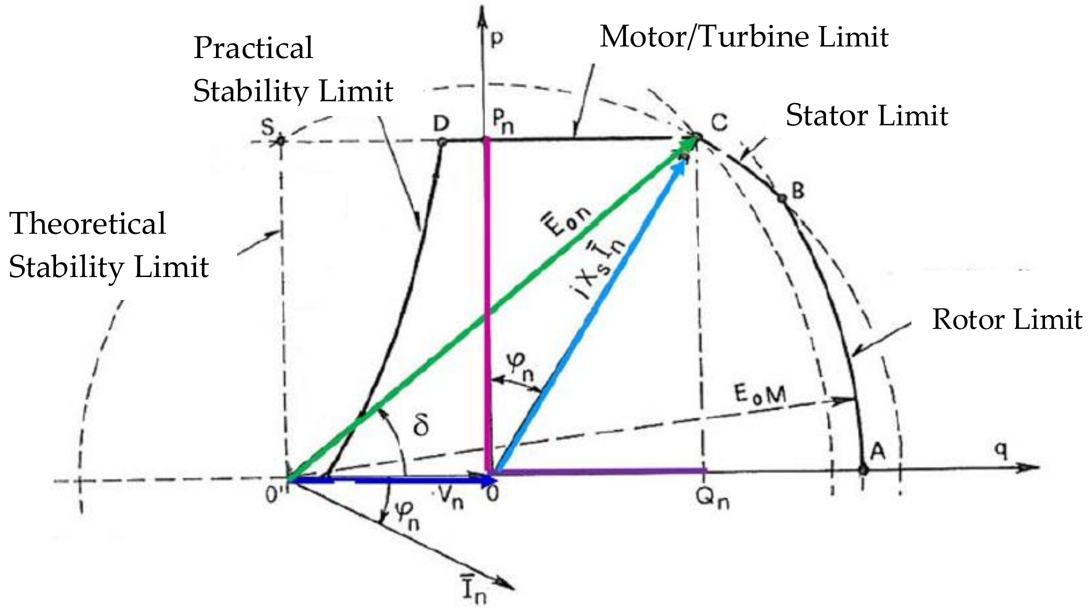

Figure 2.6: Capability curve of a synchronous machine working as a generator

The capability curve in Figure 2.6 is defined with different loci that correspond to five possible operating modes; in these operating modes, one parameter of the synchronous generator is kept constant, while the others vary.

Constant excitation

The constant excitation locus is a circle with point O' as a center, and a radius of length O'B equal to the internal voltage magnitude |E|. The no-load voltage |E| can be maintained constant by holding the field current Iecc (or the field voltage) constant.

Constant stator current

The circle for constant stator current has point O as a center and radius of length OB proportional to the constant value of |Is|. Because the terminal voltage is fixed, the operating points on this locus correspond to the constant apparent power (|Vt||Is|) output from the generator.

Constant active power

The active power output of the machine is given by:

$$P = |V_t||I_s|\cos(\varphi)$$

(2.5)

Since |Vt| is constant, horizontal line at the fixed distance Xd|Is|cos(ϕ) from the horizontal axis represents a locus of operating points at constant active power. Working as a generator, the active power output of a synchronous machine is always positive regardless of the power factor of the output itself.

Constant reactive power

The reactive power output of the machine is given by:

$$Q = |V_t||I_s|\sin(\varphi)$$
(2.6)

When the terminal voltage is constant, vertical line at the fixed distance $X_s|I_s||\sin(\phi)|$ from the vertical axis represents a locus of points for constant reactive power. For unity power factor operation, the reactive power output of the synchronous machine is zero, corresponding to an operating point on the vertical axis. For lagging (leading) power factor, the reactive power output is positive (negative), and the operating point is in the half-right (left) plane with respect to the vertical axis.

Constant power factor

The radial line that corresponds to a fixed power factor angle ϕ between the stator current and the terminal voltage.

Power-plant operators try to avoid operating conditions in the under-excited region of the capability curve for two distinct reasons. The first is related to steady-state stability of the system and the second relates to overheating of the machine. Theoretically, the so-called steady state stability limit occurs when the angle δ between E and Vt reaches 90°. In practice, however, system dynamics complicate the determination of the actual stability limit. For this reason, power-plant operators prefer to avoid under-excited machine operation whenever possible. As the machine enters the under-excited region of operation, eddy currents induced by the system in iron parts of the armature begin to increase. Also, RI^2 heating losses increase in the end region of the armature. To limit such heating, the machine manufacturers prepare capability curves specific to their own designs and recommend limits within which to operate.

3 Grid services of distributed generation

When the GS is connected to the MV/LV network, the intentional island is established. As already said in chapter 1, the frequency and voltage must be regulated not to let the island diverges into a blackout [15] [7].

In this chapter, the DG is considered. Indeed, during the islanded operation of the MV/LV system, DG units may reconnect to the passive network, creating interactions that need to be studied.

In accordance with CEI 0-21 and CEI 0-16, the reconnection process of the DG is investigated. In particular, if the service parameters are maintained inside specific ranges (default range for frequency: 50 ± 0,1 Hz, and default range for voltage: 90 ÷ 110%Vn) for a significant period of time (default time: 300 s), DG units automatically reconnect to the grid.

In addition, some active and reactive control logics are analysed to observe if their activation provide benefits to the islanded system.

3.1. The role of the Interface protection device

In order to enable the reconnection process of a DG unit to the system, an interface protection device (IPD) - is installed on the LV distribution network (Figure 3.1).

Figure 3.1: Commercial IPD

A brief evolution of the legislation on DG and re-connection of DG units to networks is considered.

3.1.1. Technical prescriptions prior to 2012

Before 2012 (up to CEI 0-16 II ed.) - no particular requirements were envisaged about the IPS of the DG.

The connection rules were defined by each DSO and specified on a case-by-case basis on the operating agreements signed with the users. The operating requirements for the generation plants connected to MV and LV were mainly thought for production plants based on rotating machinery. Consequently, no grid services were required from the MV/LV generation, nor capabilities useful to support the stability of the electricity system in the case of perturbations. An example of such connection rules was Enel's DK5600 [16] and DK5740 [17]; the conditions for which the generation plants connected to the MV distribution network had to remain connected were:

- for frequency 49,7 ≤ f ≤ 50,3 Hz (instantaneous protection);
- for voltage values 0,7/0,8 ≤ V ≤ 1,2 Vn (with delayed interventions of 100/150 ms).

In particular - given the relatively low incidence of static converters at that time - there were no specific requirements for DG units connected to the grid by such converters.

3.1.2. CEI 0-16, CEI 0-21 & Annex 70

Starting from 2012, CEI 0-16 (third edition), and Terna's Annex A70 require a series of performances and characteristics useful to support the grid's operational stability for all connected MV plants. These characteristics are useful to reduce the possibility of unwanted islanding phenomena. In particular, the installation of an IPS regulates frequency thresholds wider than those generally provided for in the previous connection rules defined by the individual DSOs. These thresholds must be controlled by a voltage unlock logic based on the zero-sequence components of the voltage measured at the connection point: in the absence of faults, the generator must remain permanently connected to the grid in the 51,5 ÷ 47,5 Hz frequency range; otherwise, the thresholds are restricted to 50,2 ÷ 49,8 Hz to avoid unwanted island operation of the DG in the event of re-closing by the DSO. Regarding voltage ranges, the Standard says that the generating plant remains permanently connected to the network for values at the delivery point between 85 ≤ V ≤ 110% Vn.

In Table 3.1, the protection system regulations for power plant > 800 W are reported:

Table 3.1: Protection system regulations for power plant > 800 W

Protection	Intervention threshold	Variable intervention time
Maximum voltage (59.S1)	1,10 Vn	≤ 603 s
Maximum voltage (59.S2)	1,15 Vn	0,2 s
Minimum voltage (27.S1)	0,85 Vn	0,15 s
Minimum voltage (27.S2)	0,15 Vn	0,2 s
Minimum frequency (81 < S2)	47,5 Hz	0,1 s ÷ 4 s
Maximum frequency (81 > S2)	51,5 Hz	0,1 s ÷ 1 s
Minimum frequency (81 < S1)	49,8 Hz	0,1 s
Minimum frequency (81 > S1)	50,2 Hz	0,1 s

The intervention time is the time that elapses between the start of the anomalous condition and the release of the trip command (in LV the interruption time of the IPD is conventionally equal to 100 ms); in case of disconnection, the DG is allowed to automatically reconnect to the network (by closing the related IPD), provided that:

- the voltage remains stable in the starting process (90 ÷ 110% Vn);
- the frequency remains stable in an adjustable range around the nominal value (default 50 ± 0,1 Hz) for a selectable time in the range 0 ÷ 900 s (default value 300 s);
- the active power delivery gradually with the same load take-off ramp required at the starting process.

The take-off ramp should not exceed the maximum positive gradient of 20% per minute of the maximum power provided by the generating unit itself.

Also, in 2012, through the CEI 0-21 Standard, the above requirements were extended, with the necessary simplifications, to LV systems as well.

3.1.3. Resolution 84/12/R/eel

For plants connected to the grid before March 31, 2012, a partial adaptation plan to the CEI 0-16 and CEI 0-21 standards has been envisaged, regulated by Resolution 84/12/R/eel and similar. This plan has required, for plants connected to the MV grid with a power exceeding 50 kW:

- the replacement of the IPD with a protection equipped with voltage release, with restrictive thresholds at 50,3 ÷ 49,7 Hz (time 0,1 s) and permissive thresholds at 51,5 (time 1,0 s) ÷ 47,5 Hz (time 4 s);
- that the system can operate permanently in the range 85 ≤ V ≤ 110% Vn in voltage and 47,5 ≤ f ≤ 51,5 Hz in frequency;
- it has not provided for any specific prescriptions regarding the reconnection of the generator after a trip of the IPD, when the parameters (voltage and frequency) return to the predetermined ranges.

Subsequently, the retrofit was progressively extended to smaller plants, providing performances equal to or lower than those applied on the MV, up to the LV generators with a power greater than 6 kW.

3.2. Control laws provided by DG units

In order to avoid any dangerous behavior when the DG is reconnected (in accordance with ramp required for the process), CEI 0-21 [6] and CEI 0-16 [7] provide services that DG units are needed to perform on the MV/LV network. When a DG unit is reconnected to the portion of the grid in islanding condition, it may occur that the electric parameters of the grid change, leading the island to instability problems. These services are related to the quality of the voltage and frequency of the grid at the connection points, through the regulation of active and reactive power provided by themselves. Two services are considered in the project: one for the regulation of reactive power as a function of the voltage profile (Q(V)), and the other one for the regulation of active power as a function of the frequency of the grid (P(f)).

3.2.1. Automatic exchange of reactive power according to a characteristic curve Q(V)

According to CEI 0-16 and CEI 0-21, all static converters in power plants with active power higher than 11,08 kW must be able to absorb or deliver reactive power automatically and autonomously (local control logic), according to the characteristic curve Q(V) shown in Figure 3.2. DG units must allow the supply/absorption of reactive power according to local logic regulations based on the value of the voltage at the output terminals, according to a characteristic curve Q(V). This type of control logic may require the plant to position itself in a work point outside the triangular capability and instead included in the rectangular capability.

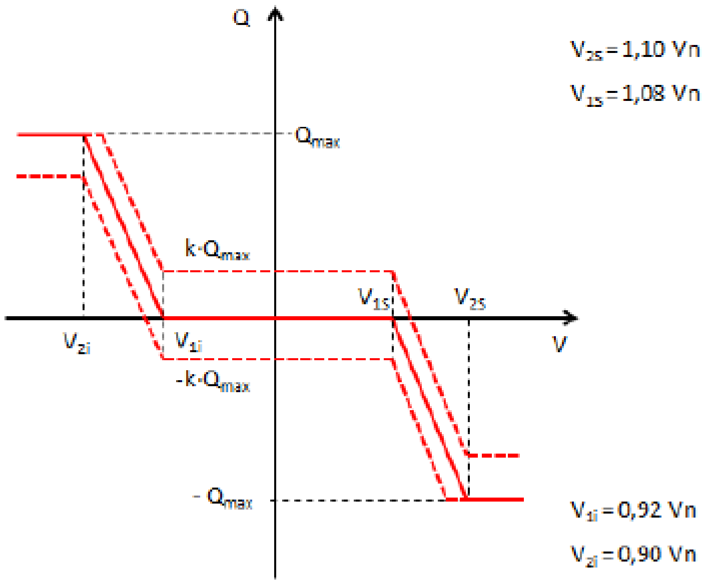

Figure 3.2: Characteristic curve Q(V)

The following voltage thresholds uniquely define Figure 3.2: V2s, V1s, V1i, V2i.

The maximum/minimum voltage protections implemented on the system defines V2s and V2i; ARERA provides default values for both: Vmin ≥ 27.S1 (V2i = 0,9 Vn) and Vmax ≤ 59.S1 (V2s = 1,1 Vn). V1s and V1i are adjustable thresholds inside the following ranges:

- V2i < V1i < Vn;
- Vn < V1s < V2s.

Activation must take place at the request of the DSO, and it must also specify the values of the parameters that uniquely characterize the curve (with step 0,01 Vn), as well as the lock-in value active power (default value P = 0,2 Pn). Conventional parameters values are:

- V2s = 1,1 Vn;
- V1s = 1,08 Vn;
- V1i = 0,92 Vn;
- V2i = 0,9 Vn.

The reactive power upper and lower limit has the same value, just changed in sign. In particular:

- +/-Qmax corresponds to the rectangular capability limits, and it is equal in modulus to 0,436 Pmax.

In Figure 3.2, the convention used for reactive power exchange is the generator one, which is:

- positive reactive power: the generator delivers reactive power by delivering a current that lags the voltage;
- negative reactive power: the generator absorbs reactive power by delivering a current that leads the voltage.

The exchange of reactive is enabled when a minimum active power level (Lock-in value) is exceeded. The power Lock-in value must be adjustable between 0,1 Pmax and Pmax in steps of 0,1 Pmax. If the regulation is activated according to a characteristic curve Q(V), each reactive power value is automatically adjusted by the system within the settling time Tr. Tr (10 seconds) describes the period from the instant in which the new regulation set-point command is sent; it is defined to ensure that the system has reached a new steady-state.

After the settling time Tr, the Q(V) regulation works correctly if the maximum reactive power error ΔQ between the reference reactive power value and the measured value is equal or lower to the 5%. This measured reactive power consists of the mean value of reactive power for 60 seconds; this mean value is compared to the reference value.

3.2.1.1. Operating Modes

There are three operating conditions of the Q(V) regulator:

1. If the threshold V1s or V1i are exceeded, the system checks whether the active power supplied is higher than the Lock-in value (default value equals to 0,2 Pmax).
2. If the check is positive, the reactive regulation is activated according to the profile in Figure 3.2; otherwise, the machine continues to deliver at the unitary power factor.
3. The activated regulation condition is removed only when:
    - the active power delivered steadily drops below 5% of Pmax - the power Lock-out value - regardless of the voltage detected at the terminals;
    - the measured voltage is within the range defined by V1s and V1i.

3.2.2. Automatic reduction of active power in the presence of over-frequency transients according to a characteristic curve P(f)

In the presence of an over-frequency transient on the network, the injection of active power provided by the DG unit should be regulated according to the control logic described in [7].

Definitions are provided:

- Pimax: active power delivered when the activation threshold is exceeded.
- Pimin: minimum power reached during the over-frequency transient; it is uniquely defined by Pimax, by the selected droop s and by the amount of over frequency.

- Pmax: nominal power of the static generator.
- Droop s: frequency variation, expressed as a percentage of the nominal frequency, which produces a power variation equal to 100% of the instantaneous power.

The droop s must be adjustable between 2 ÷ 5%, with a default value of 2,6%. The activation threshold must be adjustable between 50 Hz and 51,5 Hz, with a default value of 50,2 Hz.

In the frequency range between 47,5 Hz and 50,2 Hz, the static generator must deliver the maximum active power that it can produce. When the activation threshold is exceeded, the DG unit must reduce Pimax according to the droop s, as a function of the positive frequency difference. The active power delivered by the DG unit should be regulated according to a characteristic curve P(f) like the one shown next:

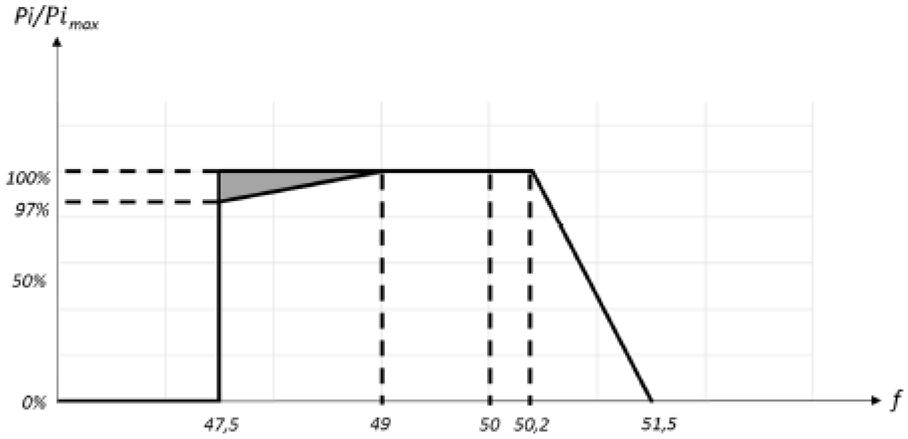

Figure 3.3: Characteristic curve P(f)

3.2.2.1. Operating Modes

The reduction of the power fed into the network is defined by the magnitude of the over-frequency. The reduction must occur linearly, in a period between 1 second and 2 seconds. Frequency measurement accuracy must be at least 10mHz.

In case of a later decrease of frequency, the power supplied must be limited to the minimum value reached during the over frequency transient. If the frequency settles stably in the 50 ± 0,1 Hz band for a minimum continuous time of 300 seconds, the limit of the deliverable power can be brought back to the previously stored Pimax value according to a linear ramp with a slope of 20% Pimax per minute, and not less than 5% Pmax per minute.

4 Theoretical framework of the modelled system

In this chapter, all the theoretical framework of the speed governor and voltage excitation system are introduced.

Proper control strategies of a speed governor and a voltage excitation system are of fundamental importance to maintain the voltage and frequency of the islanded grid inside the operating ranges. Hereafter the theoretical description of models, equations and block schemes are introduced; they represent a good starting point for an appropriate implementation in the DigSilent PowerFactory software, described in the next chapter 5.

4.1. Frequency and Voltage Regulation

In this paragraph, the aim is to understand which parameters affect the frequency and the voltage variation of a generic grid, and the time constant related to each regulation. A simple scheme of a generic grid (Figure 4.1) is introduced to develop the discussion.

In Figure 4.1, the phase voltage at the generator terminals is called Vt, the phase voltage across the load terminals is called Vu, and the parameters of the line between the two elements of the grid have a resistance value R and a reactance value X; I is the flowing current from the generator to the load.

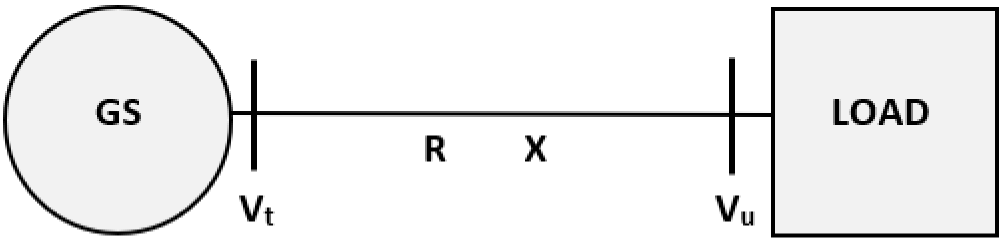

Figure 4.1: Representation of a grid

Vt can be expressed according to the KVL of the grid itself:

$$\bar{V}_t = \bar{V}_u + R\bar{I} + jX\bar{I} \tag{4.1}$$

Considering X>R, I can simplify the last expression as:

$$\overline{V_s} = \overline{V_u} + jX\overline{I}$$

(4.2)

Plotting the phasor diagram of the last expression and dividing all the phasors for the reactance X of the line, Figure 4.2 is obtained:

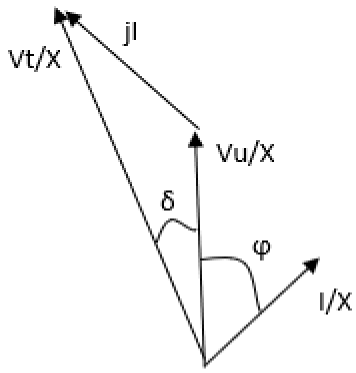

Figure 4.2: Phasor diagram of a generic grid

From trivial geometrical considerations, it can be stated that:

$$Icos(\varphi) = \frac{V_t}{X}\sin(\delta)$$

(4.3)

$$Isin(\varphi) = \frac{V_t}{X}\cos(\delta) - \frac{V_u}{X}$$

(4.4)

And recalling the active and reactive power formula on the load side:

$$P_u = V_u Icos(\varphi) = 3 * \frac{V_t V_u}{X}\sin(\delta)$$

(4.5)

$$Q_u = V_u Isin(\varphi) = 3 * \frac{V_u(V_t \cos(\delta) - V_u)}{X}$$

(4.6)

If the load has an inductive behavior, the load angle δ is small and, the last expressions can be simplified considering:

$$\begin{cases} \sin(\delta) \approx \delta \\ \cos(\delta) \approx 1 \end{cases}$$

(4.7)

Thus:

$$P_u \approx 3 * \frac{V_t V_u}{X} \delta$$

(4.8)

$$Q_u \approx 3 * \frac{V_u}{X} (V_t - V_u)$$

(4.9)

If the rotational speed of the generation unit varies, the phasor position of Vt varies, modifying the load angle. From the above formula, the variation also affects the active power supplied to the load. If the active power generated by the motor does not promptly change in accordance with the power balancing equation (4.10), the frequency of the grid changes. The power balance must be restored as fast as possible. In must be noticed that, due to the presence of Inertia J, the regulation of frequency is slow. Hereafter, the power balancing equation:

$$P_m - P_e = J \frac{d\Omega_m}{dt} \Omega$$

(4.10)

By varying the difference between the generator and load voltage, the reactive power varies; thus, by changing the load voltage, the reactive power flux would change. This is a fast regulation.

The difference between the two dynamics in equations (4.8) and (4.9) leads to a decoupling of the power fluxes. Thus, to control the frequency and the voltage of the grid (and, respectively, active, and reactive power fluxes), two separated regulators/governors can be implemented on the GS. Firstly, the selected speed governor is described in the next paragraph, while the voltage excitation system is explained in the following (Paragraph 4.3).

4.2. Speed Governor

Under the limitations imposed by the nature of the load, generators need to provide electrical energy at a constant frequency (50 Hz).

The frequency regulation, thus, consists of controlling the rotational speed of the motor. The motor changes the speed when, given the same traction torque, the resistive torque at the shaft changes (Equation (4.11)); to maintain the frequency constant, it is necessary to act on the fuel supply to the engine (on the throttle in particular), balancing the traction torque with the new resistive one, as the next equation suggests:

$$T_T - T_R = J \frac{d\Omega_m}{dt}$$

(4.11)

In a typical situation, a generator is started in no-load conditions, and then the electrical load is connected to it. After a transient, the motor reaches the regime speed n_C that can be equal or not to the no-load condition speed n_0, depending on the droop characteristic. Considering the no-load and steady-state speed, it is possible to define the droop D of the frequency control as the next equation suggests:

$$D = 100 * \frac{n_0 - n_C}{n_C} \tag{4.12}$$

As the load varies, the speed governor maintains the motor speed constant within the droop limits; however, during transient conditions, the speed (and so the frequency) inevitably changes (Figure 4.3):

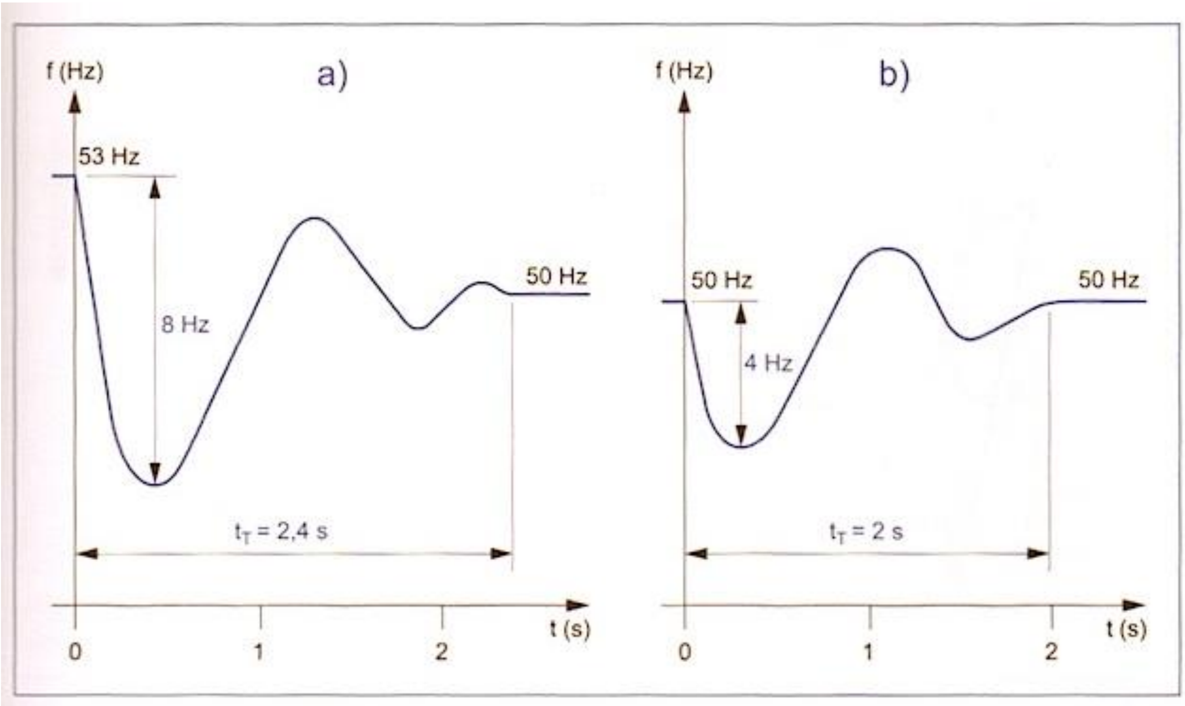

Figure 4.3: Transient of frequency with different droops

Figure 4.3 shows the changes of frequency during a transient condition considering two different droops. Depending on the selected droop, the transient conditions change, both in amplitude and in time:

a) the governor has a droop of 6%;
b) the governor has a droop of 0%.

Higher oscillation occurs when the droop is different from zero. The maximum oscillation in the droop condition is twice the oscillation without droop.

In particular, the speed governors of the individual GSs automatically and autonomously perform primary regulation. Sensing a decrease in frequency, each governor reacts by gradually increasing the power generated by the prime mover. The overall power introduced by the groups increases, compensating for the power lost; to let that happen, it is necessary for the groups to have an adequate "primary regulation reserve" at the time of the outage or failure. The autonomous action of the governors ceases when the power balance in the network is re-established, and the decrease in frequency has consequently stopped. Now the network is in a new steady state situation, in which the frequency has a lower value than the programmed one, and the overall primary regulation reserve has been partially consumed. If the primary regulation reserve in the GS is not present, an increase of required power is not compensated by an increase in the produced power, the system frequency reaches another steady state, and the alternator protections may trip.

4.2.1. DEGOV1: Model Description

The implemented speed governor DEGOV1. It is the Woodward diesel generator governor that works in a feedback control system. The controlled variables are the instantaneous speed and the generated power. This governor comprises a “setpoint” or reference input (a reference speed), a controller function (the electric control box), one control actuator and the droop feedback (Figure 4.4).

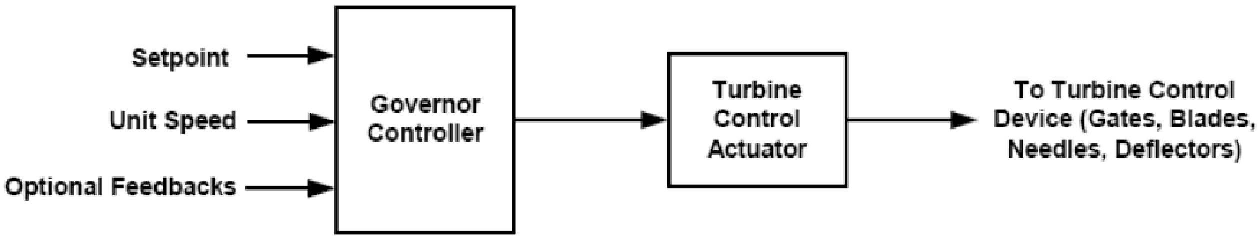

Figure 4.4: Schematic representation of a speed regulator

In particular, the feedback control signal of DEGOV1 is characterized by a permanent speed droop [18].

Permanent speed droop

The principle of operation of a GS with permanent speed droop is essentially the same for both small, isolated systems and large, interconnected systems. Permanent speed droop determines the amount of change in gate servomotor position in response to a change in the speed [18]. Permanent speed droop (in per-unit terms) is defined as the change in unit speed (as a percentage of rated speed) divided by the change in governor output (as a percentage of gate position). In Figure 4.5, a block diagram representation of a typical governor controller using the permanent speed droop:

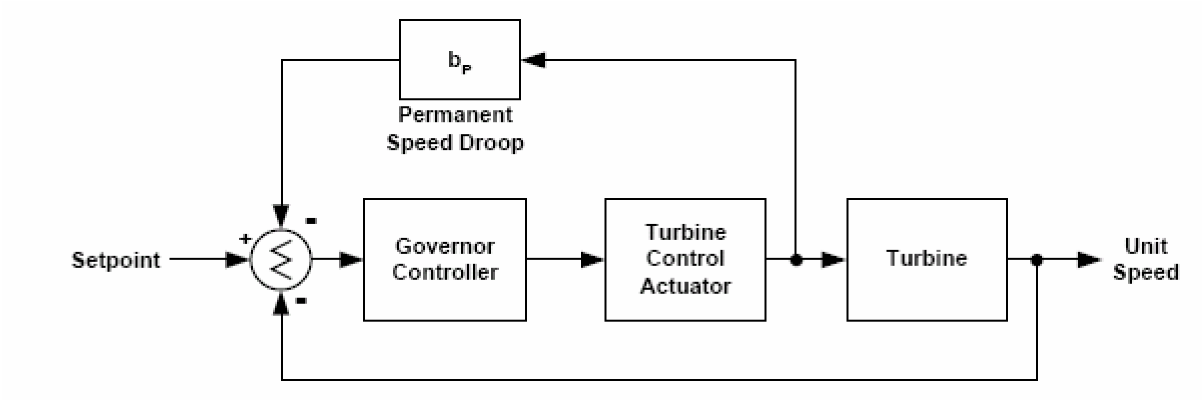

Figure 4.5: Block representation of a permanent speed droop regulator

The steady-state effect of adding the permanent speed droop feedback loop has the operating characteristic shown in Figure 4.6: the value of the permanent speed droop determines the slope of the characteristic curve. A typical permanent speed droop value is 5%, resulting in a unit that changes speed by 1% (0.5 Hz on a 50 Hz system) in response to approximately a 20% change in load when operating connected to an islanded load. Corresponding changes in turbine power output depend on the gate-to-power characteristics of the motor.

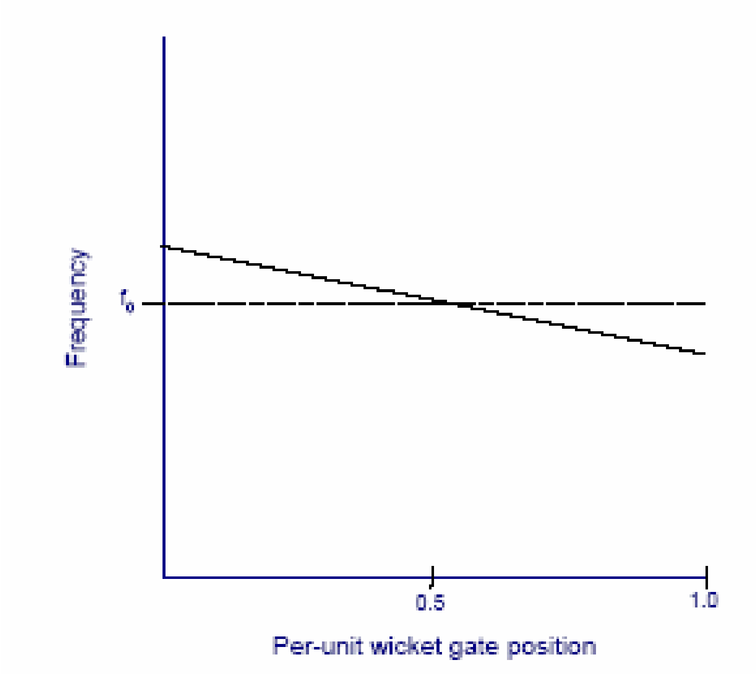

Figure 4.6: Droop characteristic on a f(P) graph

In addition to the primary frequency regulation, the presence of an astatic governor helps the frequency behavior. As it appears in the figure below (Figure 4.7), if the permanent speed droop is set to zero, for any change in the power (in a specific active power range) requested by the load, the frequency will always be restored (after a short transient period) to the reference value (50 Hz). This governor provides to the system a sort of secondary regulation: after a perturbation, the frequency returns to the reference value (50 Hz).

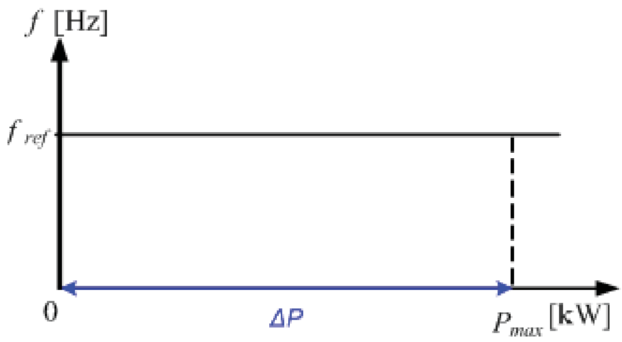

Figure 4.7: Isochronous condition in a f(P) graph

In the thesis, the implemented DEGOV1 can work with a null droop: this operating principle is called isochronous operation [9]. In the case study of the thesis, the droop is not usually necessary because the GS in islanded systems does not have to work in parallel to any other generation units or external grid; however, the effect of the droop (Figure 4.8) on the stability of the island has been evaluated.

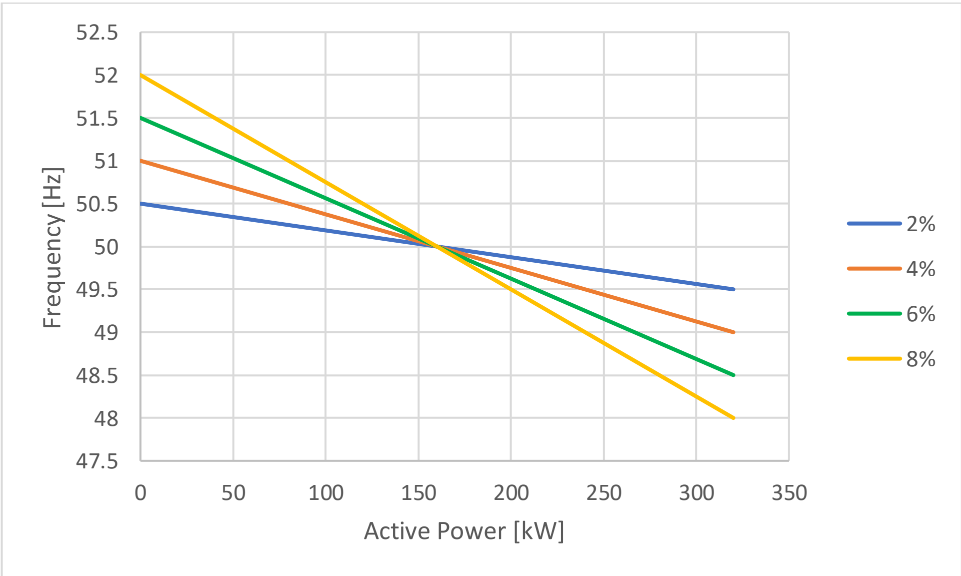

Figure 4.8: Different droop characteristics

4.2.2. Block scheme of DEGOV1

In Figure 4.9, DEGOV1 has three inputs:

- the instantaneous value of speed ω;
- the reference value of speed ωref;
- the electrical generated power pgt.

As an output, the turbine power pt.

The additional input signal pgt is included in the model to allow the active power sharing among different generating units; however, in the considered model, there is only one generation unit (the GS itself), and no-load sharing power is needed.

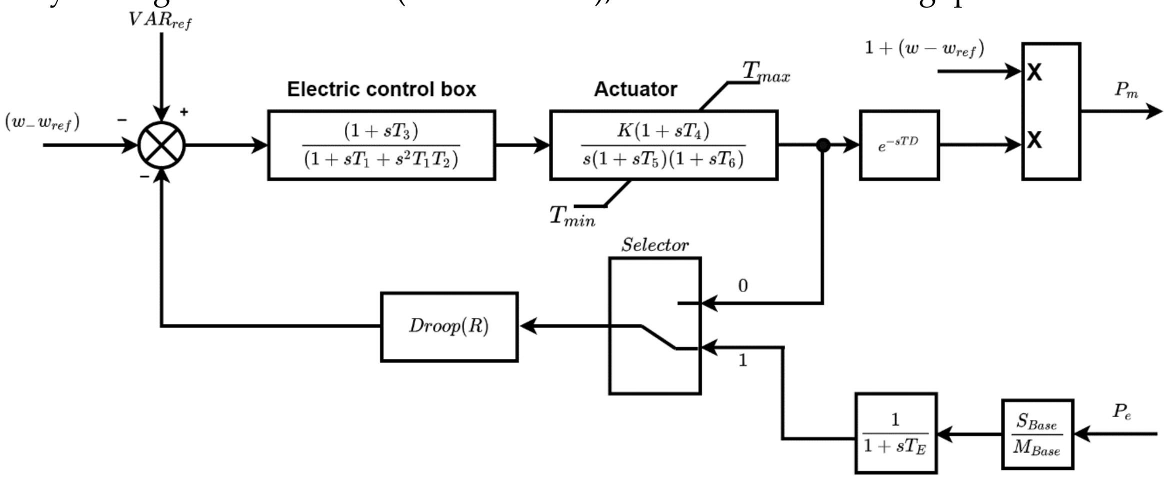

Figure 4.9: Woodward Diesel Governor DEGOV1

Working principle

If just one GS that supplies the network, the droop K is set to zero (isochronous condition). Thus, the effect of feedback signals, which multiply the droop block R, are not significant. In this condition, the block scheme of DEGOV1 is the same as DEGOV. The considered model consists of three main components:

- The Electric Control Box (ECB)

The ECB has as an input the speed error: in the previous summation point, the instantaneous value of speed is subtracted from the reference speed value; the result is the speed error. The ECB consists of the following transfer function:

$$ECB = \frac{1 + sT_3}{1 + sT_1 + s^2 T_1 T_2} \tag{4.13}$$

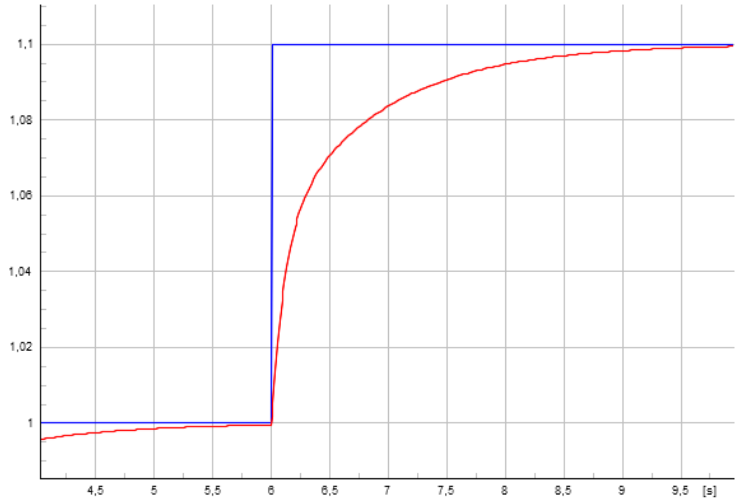

Figure 4.10: Step response of the electric control box

This is a bypass transfer function that transforms the input speed error signal into an output governor one; the governor signal is the fuel flow that needs to be controlled.

- The Actuator

The Actuator has the aim to transform the input fuel flow signal into the output throttle signal. The throttle signal represents the mechanical torque output; this operation is provided by the transfer function of the Actuator itself:

$$A = \frac{K(1 + sT_4)}{s(1 + sT_5)(1 + sT_6)} \tag{4.14}$$

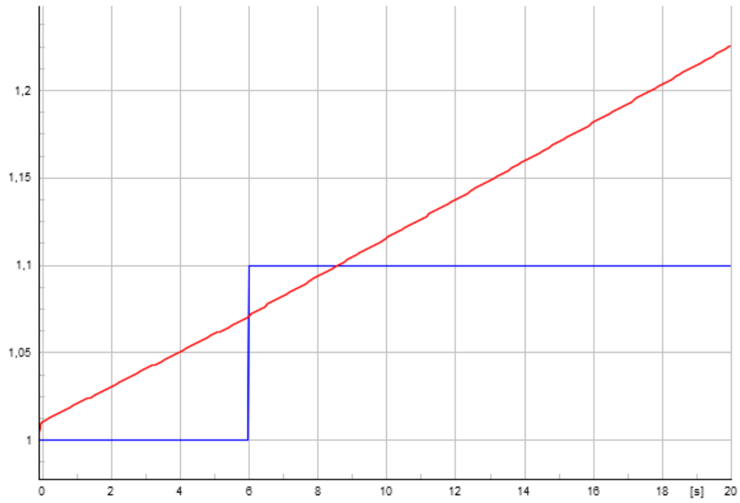

Figure 4.11: Step response of the Actuator block

The output mechanical torque is upper and lower saturated by the Actuator block itself. The saturation of the mechanical torque is needed to limit the maximum amount of power that the motor can bear as an input.

- The Time Delay (TD)

The TD simply introduces a delay in the frequency governor: the higher the delay, the later the motor power changes its value to regulate speed and frequency.

$$TD = e^{-sT_D} \tag{4.15}$$

The last block of DEGOV1 is a multiplication between the mechanical torque (delayed in time) and the instantaneous speed to provide the motor power.

4.3. Voltage Excitation System

Keeping all the other variables constant, the voltage at the terminals of the alternator Vt changes from no-load to load condition due to the internal impedance of the alternator, the synchronous reactance Xs. By means of the automatic voltage regulator, the excitation is controlled so that the voltage drop on the internal reactance of the alternator is compensated by an increase of the electromotive force (the so-called no-load voltage E).

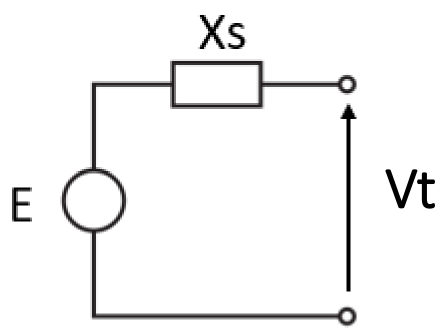

Figure 4.12: Equivalent circuit synchronous machine

The aim is to maintain the voltage at the terminals of the alternator constant. Voltage Vt is obtained thanks to the KVL:

$$V_t = E - X_S I_s \tag{4.16}$$

Changing the current, the no-load voltage E needs to be controlled to guarantee a constant Vt.

The voltage drop X_SIs increases with the supplied current, and the load voltage Vt changes with the power factor of the load, as it is shown in the phasor diagram of Figure 4.2.

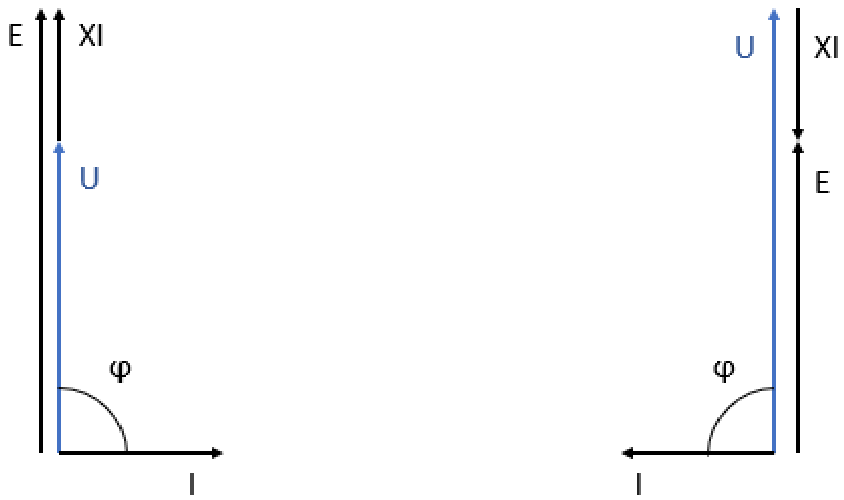

Figure 4.13: Pure inductive (on the left) and pure capacitive (on the right) phasor diagrams

If the load is purely inductive, considering the same output current I, the vectors E and XI are in phase, the vector difference becomes arithmetic and therefore the voltage drops from no-load to load condition is maximum (Figure 4.13 on the left). If the load is purely capacitive, the vectors E and XI are in opposition of phase, the difference becomes the arithmetic sum and the voltage at the alternator terminals increases (Figure 4.13 on the right). For this reason, a generation unit can power a capacitive load not exceeding 25 ÷ 30% of the alternator power.

Thus, to maintain constant the voltage supplied by the alternator Vt, it is necessary to act on the excitation current of the alternator Iecc, increasing or reducing it depending on the nature of the load. The next figure indicates the trend of the excitation current Iecc, necessary to keep the voltage Vt constant, as a function of the apparent power delivered:

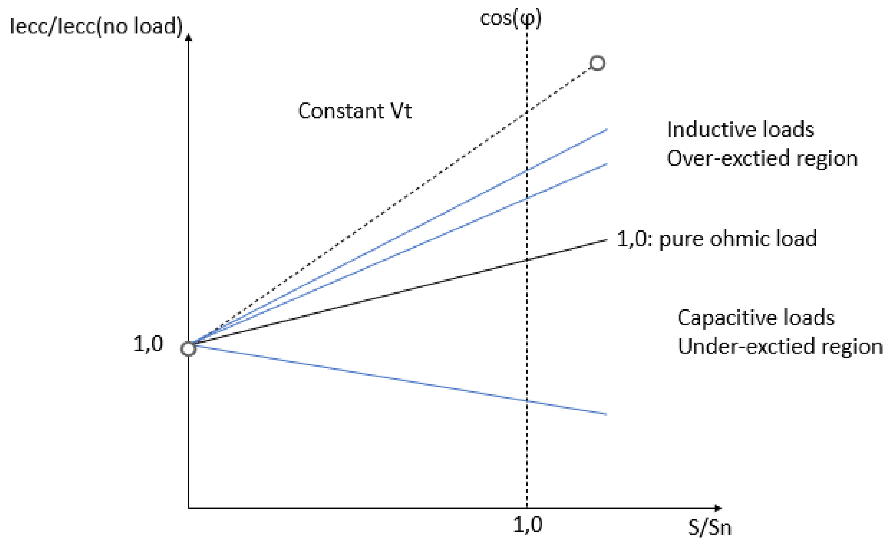

Figure 4.14: Excitation current trend with respect to complex power

From Figure 4.14, it emerges that, with the same power output,:

- the more capacitive the load, the more the excitation must be reduced;
- the more inductive the load, the more the excitation must be increased.

However, the excitation current cannot exceed the design limits since the temperature of the winding of the exciter on the rotor would unacceptably increase. Therefore, if the generator must supply inductive loads with a power factor lower than 0.8 (reference value), it is necessary to make prior agreements with the manufacturer of the group.

The considered grid is a temporary island caused by a fault; for this reason, the system lacks pivot nodes or any daily optimization process, and so secondary and tertiary voltage regulations are not implemented. Only the primary voltage regulation is implemented through the voltage excitation system of the GS. The primary regulation, also called local regulation, controls the voltage at the terminals of the generation units thanks to the excitation system of the group.

4.3.1. EXST2A: Model Description

A modern excitation control system includes several controls, limiting and protective functions that assist in fulfilling the performance requirements. Figure 4.15 illustrates the nature of these functions and the way they are interconnected to each other:

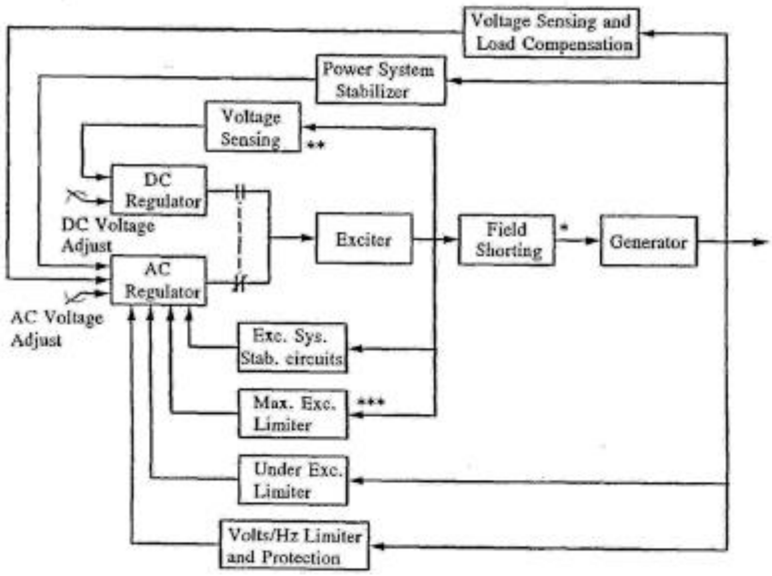

Figure 4.15: Functions implemented in modern excitation systems

For the proposed model, the excitation system is provided with:

- control functions that regulate specific quantities at the desired level;
- limiting functions that prevent certain quantities from exceeding set limits;
- if any of the limiters fail, then protective functions put the unit out of service.

There are three types of excitation systems:

- dynamo excitation (no longer in use);
- static excitation;
- brushless excitation.

The selected voltage excitation system is EXST2A. It is a static excitation system that consists of a static thyristor group, which converts the three-phase AC voltage of the alternator into a DC voltage. The static unit is housed in one or more cabinets placed in the immediate vicinity of the alternator. The terminals of the excitation windings are connected to two collector rings, isolated from each other and rigidly keyed to the shaft. The brushes (which are stationary) are used to connect the DC excitation system, as shown in the next figure:

Figure 4.16: Stationary brushes and ring collectors

This excitation system compared to the methods used in the past (consisting of a main dynamo excited by an auxiliary dynamo) offers several advantages:

- the axial dimensions of the machine are reduced;
- higher reliability;
- higher efficiency;
- better regulation of excitation current (faster response times).

Nevertheless, it requires periodic replacement of the brushes (ring excitation system, with sliding contacts (Figure 4.16)).

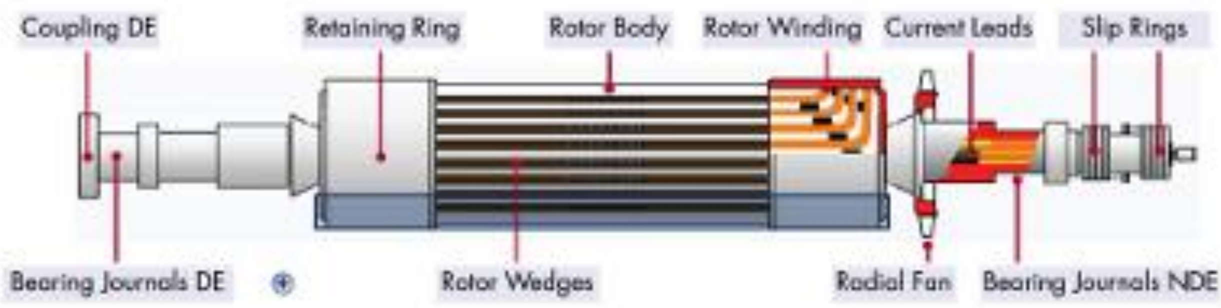

Figure 4.17: Components of a static excitation system

The periodic replacement of the brushes can be overcome: in the scenario considered in this thesis, the GS should work just for a specific amount of time (e.g., until the fault on the external grid is solved), and the replacement procedure could be performed when GS is not in service (Paragraph 2.2).

4.3.2. Block scheme of EXST2A

The voltage excitation system implemented is the EXST2A. Type ST2A excitation system is a compound-source rectifier system. This system is achieved through a power potential transformer (PPT) and a saturable current transformer (SCT):

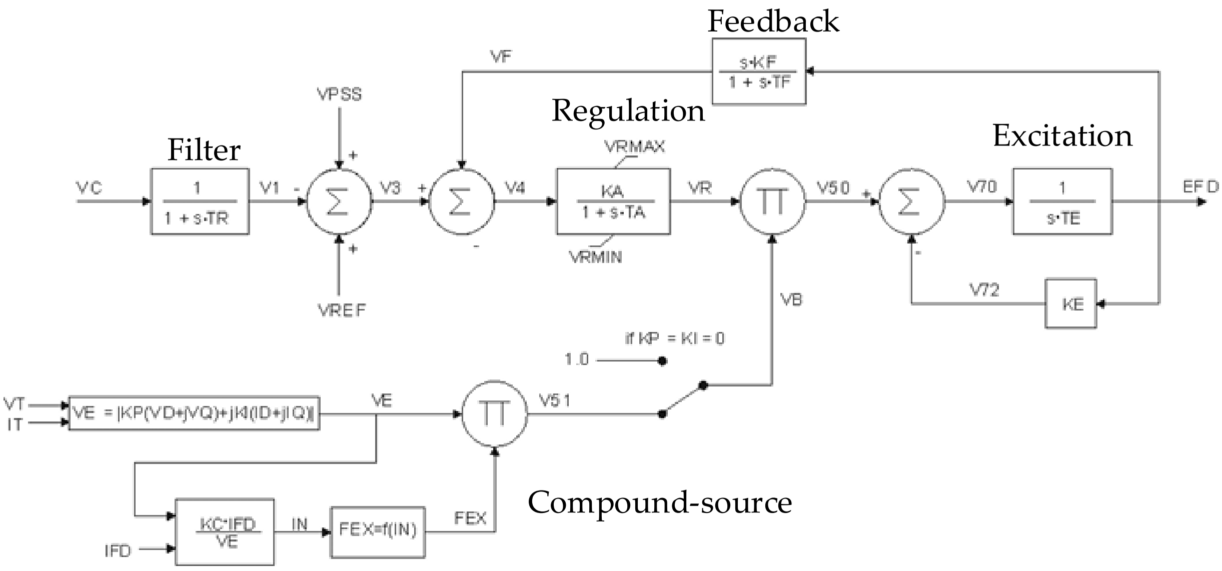

Figure 4.18: ST2A Excitation system

From the original configuration, the compound-source rectifier part was removed because unnecessary: just the voltage control signal (without the contribution of the current and voltage control signals) is enough to perform a proper voltage regulation. The compound scheme is substituted with a constant value (equals to one) as an input of the multiplication block.

Working Principle

The following block diagram represents the actual implemented EXST2A for the proposed model:

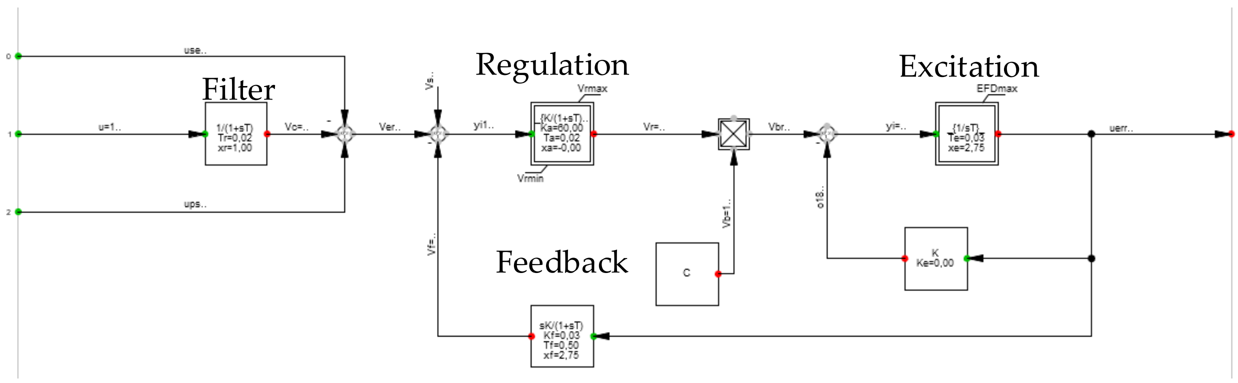

Figure 4.19: Implemented EXST2A

The inputs of the system are:

- the voltage at the terminals of the generator uerrs;
- the voltage signal provided by the PSS upss;
- the reference voltage value usetp.

In particular, the voltage signal provided by the PSS is null since GSs have not implemented the PSS. The output of the excitation system is the excitation voltage for the alternator.

In this configuration, the main blocks of the EXST2A excitation system are:

- The Input Filter (IF)

The input filter has as an input the instantaneous voltage at the generator terminals and as an output, the voltage Vc. The IF block works as a first order lag, in which the signal reaches the steady state value after a small transient, avoiding any step change.

$$IF = \frac{1}{1 + sT_R}$$

(4.17)

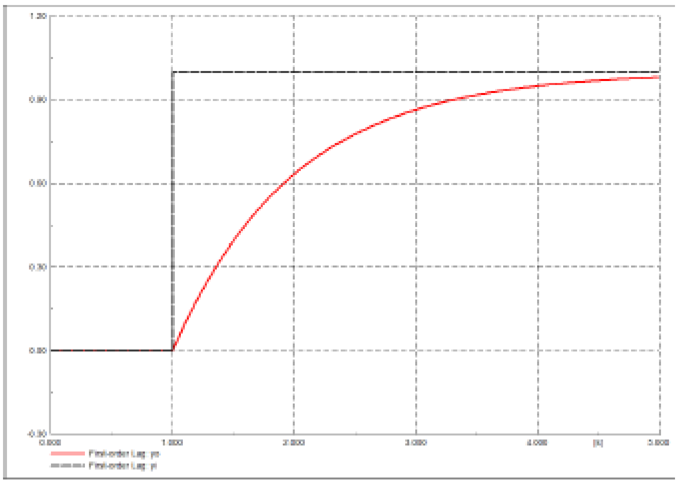

Figure 4.20: Step response of first-order lag

- The Regulation (R)

The regulation block has as input the error in voltage and as an output the regulated voltage Vr. This block behaves as a first-order lag (as well as the previous one) with a multiplication constant. Thus, it works as an amplifier, amplifying the input signal, and damping any abrupt change. Furthermore, this block is saturated in order not to reach too high or low regulation voltage values. The regulation block controls the exciter output through the controlled saturation of this component.

$$R = \frac{K_A}{1 + sT_A}$$

(4.18)

- The Excitation (E)

Then, the excitation block works as a pure integrator: the input regulation voltage Vr is converted into the excitation voltage uerss.

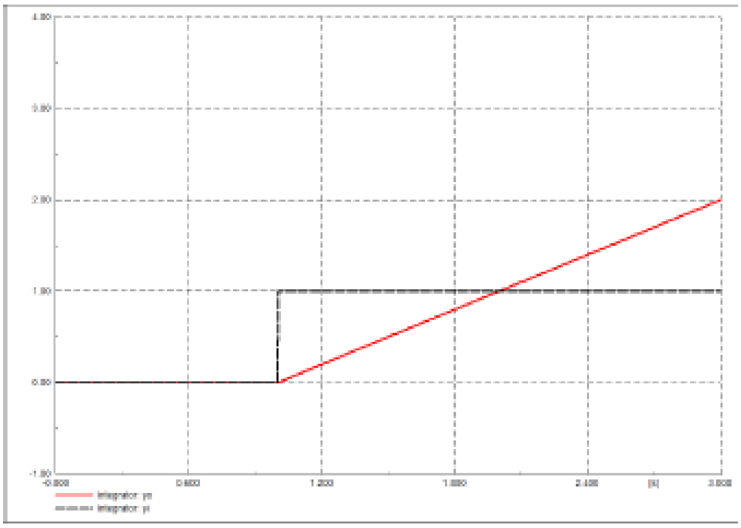

Figure 4.21: Step response of integrator

Even this block has a saturation parameter *EFD*max: the saturation in this case works to limit the maximum excitation voltage. The parameter *EFD*max represents the limit on the exciter voltage due to the saturation of the magnetic components. The time constant *TE* is associated with the inductance of the control windings.

$$E = \frac{1}{sT_E} \tag{4.19}$$

- The Stabilization Feedback (SF)

The SF block works as a First-order Lag Differentiator: the output voltage signal Vf is the first derivative with respect to the time of the input voltage signal. This first derivative feedback is used to improve the dynamic response of the system. It works as a compensation feedback signal.

$$R = \frac{sK_F}{1 + sT_F} \tag{4.20}$$

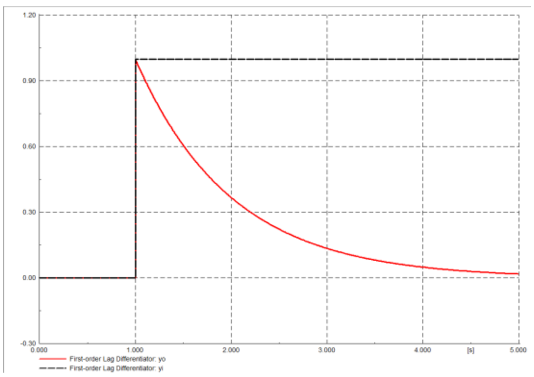

Figure 4.22: Step response of first lag differentiator

5 Intentional islanded operation: modelling and numerical simulations

In this chapter, all the previous introduced elements (GS and capability curve, speed governor, voltage excitation system) are modelled in DigSilent PowerFactory software The simulated case study follows the operational practices of the DSOs and it consists in a GS connected to the LV busbars of a secondary substation; the GS is used to power a MV feeder. This grid is called Passive Network (PN).

Then, numerical simulations have been conducted to deeply study the dynamic stability of the islanded system; different parameters (lines, loads, and motors) are changed to analyse the system under different configurations.

An index of the conducted numerical simulations is reported below:

Table 5.1: Index of the numerical simulations conducted

GS	No-Load	Partial Load	Full Load
Isochronous	• Overhead line: 5.2.1 • Cable: 5.2.2	• Overhead line: 5.3.1 • Cable: 5.3.2	• Overhead line: 0 • Cable: 5.4.2
Droop	-	-	• Cable: 5.4.3

5.1. Model of the grid

The case study is implemented according to the operational practices of DSOs. In particular:

- it is supposed to have a fault inside the system (not simulated);
- the DSO opens the switch in the primary station, deenergizing the entire system below-connected;
- the DSO selects a portion of the deenergized grid to be energized by means of an emergency power supply;
- the GS is connected to the LV side of a secondary station to power up the MV/LV selected portion of the system.

The operational practices of DSOs are properly implemented inside the software through the following events:

- for t <0 s: the system is in steady-state condition;
- at t=0 s: the fault occurs (not simulated). The grid remains deenergized no power supplies are connected to the system;
- for 0<t<5 s: the system remains deenergized. This interval of time between zero and five seconds represents a generic interval between the occurrence of the fault, and the connection of the GS; in real-existing grids, the connection of the GS occurs after several hours, and the grid remains deenergized for a long period; according to the type of fault, and geographical position (for example, urban or mountain context), this interval of time varies.
- at t=5 s: The GS is connected, and it starts to re-energize the entire grid.

The selected portion of network for the study cases is modelled in DigSilent Power Factory software, as shown in Figure 5.1.

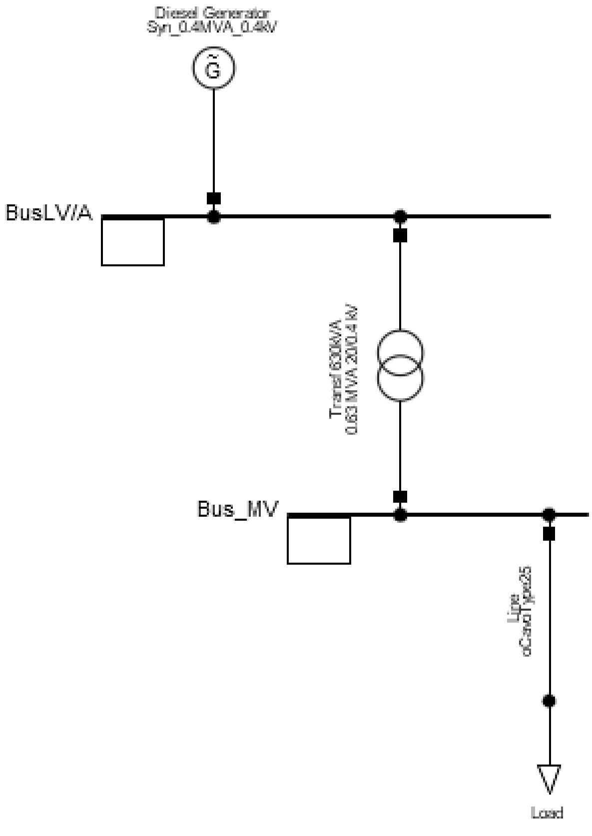

Figure 5.1: Network configuration considered

All the elements are connected to two busbars: BusLV/A (nominal line-to-line voltage: 400 V) and Bus_MV (nominal line-to-line voltage: 20 kV). The first one represents a secondary substation at with the GS is connected to counterfeed the entire MV feeder. The second one represents a MV bus at which a load is connected through a line.

Significant variables of the system are analysed through dynamics simulations made possible by the Simulation RMS tool of the software. Starting from these plots, results, and conclusions will be conducted for each study case. The simulation period (40 s) is set to observe all the electric parameters reaching a new steady-state condition after the connection of the GS to the PN.

The four main components of the PN and their implementation are presented in the next paragraphs (5.1.1, 5.1.2, 5.1.3, 5.1.4).

5.1.1. Alternator of GS

The synchronous generator has been modelled according to the data of a commercial product (produced by the Marelli Generators company). The electrical parameters are reported in Table 5.2. These parameters refer to a salient-pole synchronous generator. All parameters have been faithfully inserted into the software to obtain a simulation that reflects the real behaviour of the GS under examination as much as possible.

Table 5.2: Electrical parameters of the alternator of the GS

Parameters	Implemented values
Nominal Complex Power [kVA]	400
Nominal Voltage [V]	400
Frequency [Hz]	50
Power Factor	0,8
Poles	4
Direct axis synchronous reactance Xd [%]	330
Quadrature axis synchronous reactance Xq [%]	175
Direct axis transient reactance X'd [%]	29,5
Direct axis sub-transient reactance X''d [%]	13,2
Quadrature axis sub-transient reactance X''q [%]	15,6
Negative sequence reactance X2 [%]	14,4
Zero sequence reactance X0 [%]	3,3
Open circuit time constant (T'do) [s]	1,6
Transient time constant (T'd) [s]	0,145
Sub-transient time constant (T''d) [s]	0,014
Armature time constant (Ta) [s]	0,018
Moment of Inertia (J) [kgm^2]	4,8

The different impedance values are expressed as a percentage of the internal impedance of the GS unit; the actual value of the internal impedance is calculated as:

$$Z_{ref} = \frac{\sqrt{3}V_{fn}^2}{A_n} = 0{,}4\ p.u. \tag{5.1}$$

Where Vfn is the nominal line-to-line voltage (400 V).

The size of the GS (400 kVA) is selected because represents a good trade-off between ease of transport and adequate power to feed the loads underlying the MV feeder.

From Table 5.2, the capability curve of the GS can be retrieved, as shown in Figure 5.2:

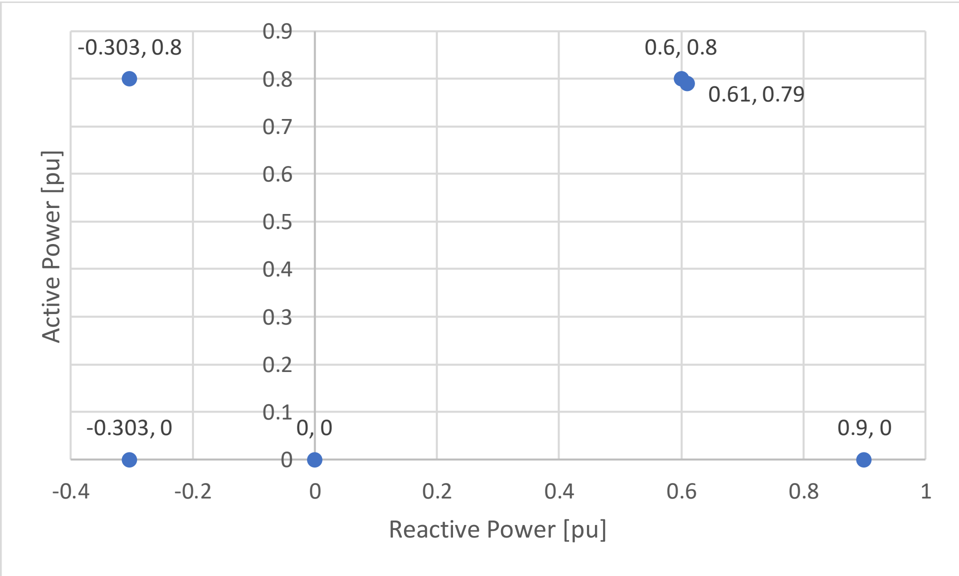

Figure 5.2: Capability curve of the selected GS

Regarding the speed governor model (DEGOV1, see paragraph 4.2.2), the following parameters are implemented:

Table 5.3: DEGOV1 parameters

Parameters	Implemented values
Actuator Gain K [p.u./p.u.]	8
T4 [s]	0,15
T5 [s]	0,1
T6 [s]	0,12
Combustion Delay [s]	0,01
Droop [p.u.]	0
Time constant Power Feedback [s]	0,01
T1 [s]	0,1
T2 [s]	0,008
T3 [s]	0,05
Droop Control	0
Minimum Throttle TMIN [p.u.]	0
Maximum Throttle TMAX [p.u.]	1,25

Regarding the voltage regulator (EXST2A, see paragraph 4.3.2), the following parameters are adopted:

Table 5.4: EXST2A parameters

Parameters	Implemented values
Measurement Delay Tr [s]	0,02
Controller Gain Ka [p.u.]	60
Controller Time Constant Ta [s]	0,02
Excitor Time Constant Te [s]	0,03
Excitor Constant Ke [p.u.]	0
Stabilization Path Gain [p.u.]	0,03
Stabilization Path Time Constant Tf [s]	0,5
Controller Output Minimum Vrmin [p.u.]	-10
Controller Output Maximum Vrmax [p.u.]	10
Excitor Maximum Output EFDmax [p.u.]	4

For both the speed governor and voltage excitation system, all the implemented parameters have been checked in Neplan guidebook [19] and [20]. Appendix A reports the typical ranges for each parameter of DEGOV1 and EXST2A.

In each study case, a null droop (isochronous condition) is implemented; in paragraph 5.4, a droop condition is implemented in order to highlight the differences in the dynamic stability of the islanded system under different droop conditions.

5.1.2. Transformer

The transformer has been implemented in order to reflects the behaviour of a real-existing MV/LV transformer as much as possible [21]. In particular, the characteristics of the considered transformer are reported below:

Table 5.5: Characteristic of a 630 kVA transformer

Nominal Power [kVA]	HV [kV]	LV [kV]	Vcc [%]
630	20	0,4	6

The transformer needs to be coordinated with the size of the GS. In the case study, the GS has a nominal power of 400 kVA, while the MV/LV transformer of 630 kVA.

5.1.3. Lines

Only one MV line is present in the model of the PN: the line that connects the MV busbar to the load.

In order to exploit a wide range of scenarios, the line typology is varied [22]. In particular, two typologies are implemented:

- overhead lines;
- cable lines.

Overhead lines

The conductors of the overhead lines are usually made up of a set of elementary wires that are helically wound around themselves to form a rope (rope conductors). Compared to single-wire conductors, this type of conductor presents greater flexibility and ease of installation.

The implemented materials must have:

- low electrical resistivity;
- low specific weight.

The implemented overhead lines are simple copper-stranded conductors because this is the most used in the real life. The use of copper is due to its great mechanical resistance and low tensile elongation [23].

Cable lines

The implemented cable lines are copper-based cables.

The main drawback related to cable lines is related to the parasitic effect: the parasitic effect is represented as an unwanted capacitance that exists between the parts of an electric components or circuits because of their proximity to each other (Figure 5.3).

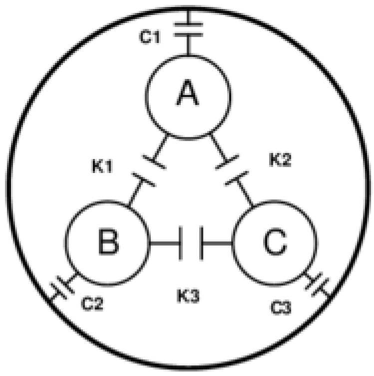

Figure 5.3: Parasitic capacitance in a cable

The effect on the electrical behaviour of parasitic capacitances is to increase the transversal parameters. In particular, cable lines present higher susceptance values than overhead lines.

Both typologies are implemented in the software with a lumped parameter representation. For broad considerations, three different sections for overhead lines and three different sections for cable lines are implemented. In Table 5.6, the parameters of overhead and cable lines are reported:

Table 5.6: Parameters of overhead lines

	Material	Cross Section [mm^2]	Resistance R [Ω/km]	Reactance X [Ω/km]	Susceptance S [µS/km]	Capability [A]	Working Temperature [°C]
Overhead Line	Cu	25	0,7271	0,4213	2,7799	125	80
	Cu	50	0,4102	0,4001	2,8594	197	80
	Cu	70	0,2683	0,3892	3,0265	248	80
Cable	Cu	25	0,9290	0,1500	56,548	135	90
	Cu	50	0,4950	0,1300	59,690	191	90
	Cu	70	0,3420	0,1300	65,597	265	90

In addition to the typology of the line, also the length is varied: its value ranges from 0 km up to 15 km. The maximum length (15 km) is selected because it represents an average length value for MV line.

5.1.4. Load

The main classifications of loads are static and dynamic models. As a static load model is not dependent on time, it describes the relationship of the active and reactive power at all times to the voltage and/or frequency [24]. On the other hand, a dynamic load model expresses this active/reactive power relationship at any instant of time as a function of voltage and/or frequency.

However, the modelling of a MV real-existing load is complicated: a typical load is composed of a large number of devices, such as fluorescent and incandescent lamps, refrigerators, heaters, compressors, motors, etc [25]. Also, its composition changes depending on many factors, including time, weather conditions, and the state of the economy. In distribution networks, most nodes are not voltage controlled and so, voltages vary widely along system feeders; therefore, load characteristics are extremely important in distribution system analysis [26] [27]. In reality, the distribution network presents composite loads.

Thus, in the PN configuration, static, dynamic, and composite typologies of loads are modelled in DigSilent PowerFactory. In particular:

- constant impedance load model (constant Z): A static load model where the power varies with the square of the voltage magnitude. It is also referred to as constant admittance load model;
- constant power load model (constant PQ): A static load model where the power does not vary with changes in voltage magnitude. It is also known as constant MVA load model;
- a composite load: 50% static, 50% dynamic.

Dynamic simulations and results are conducted with these three types of loads. In the software, the implementation of the typology of the load is provided by the following parameter selection window:

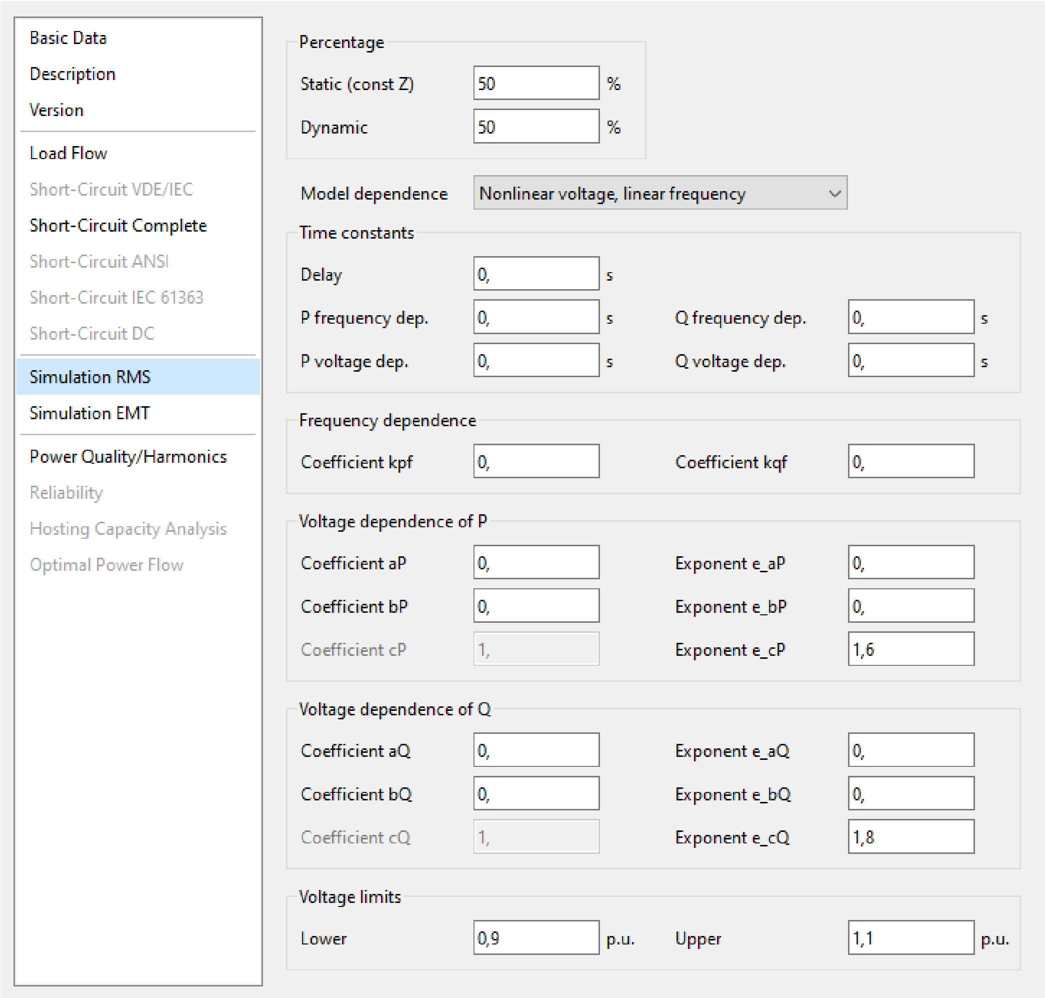

Figure 5.4: Parameter selection window for load type

5.2. Dynamic stability in no-load conditions

This case study aims to determine practical limits in the length of the lines (overhead and cable ones) and to observe the network's re-powering, keeping the GS inside its capability curve, avowing instability issues. The implemented code in DigSilent PowerFactory to study the dynamical stability of the PN in no load condition is explained in detail in Appendix B.

For this case study, a no-load condition is implemented; in particular:

$$\begin{cases} P_{load} = 0\ MW \\ Q_{load} = 0\ Mvar \\ \quad PQ\ type \end{cases} \tag{5.2}$$

Looking at the capability curve of the GS unit (Figure 5.2), the no-load condition should be located at the origin of the capability curve where both active and reactive power injected into PN by the GS are null. Nevertheless, the connection between the load and the MV busbar should be investigated. Indeed, depending on the type of line considered (overhead line or cable line) and the length of the line itself, the operating point moves inside the capability curve because both active and reactive power injected by the GS changes. The operating point changes its position for two main reasons:

- even if the load requires null active power, the losses of the system are present. The losses of the line are represented with a lumped resistive contribution, the losses of the MV/LV transformer with the transformer impedance (resulting from Vcc% and resistive losses); the GS produces a small but positive active power to compensate these losses.
- the transversal susceptance of the line. It introduces a negative (capacitive) reactive contribution that moves towards the under-excited region of the capability curve the operating point of the GS.

In particular, from the capability curve of the GS, the minimum stable value of reactive power in the under-excited region is:

$$Q_{min} = -0{,}303\ pu = -0{,}121\ Mvar$$

If the value of the reactive power exceeds this limit, the GS is no longer able to work under stable conditions, the load angle exceeds the 90° limit, and the system diverges. In Figure 5.5, it is supposed to connect a GS to a deenergized system. The length of the line is high enough to exceed the Qmin limits. The voltage and frequency of the system are represented in the next figure. In real-existing grids, the voltage/frequency protections mounted on the alternator of the GS would immediately trip, deenergizing the entire grid.

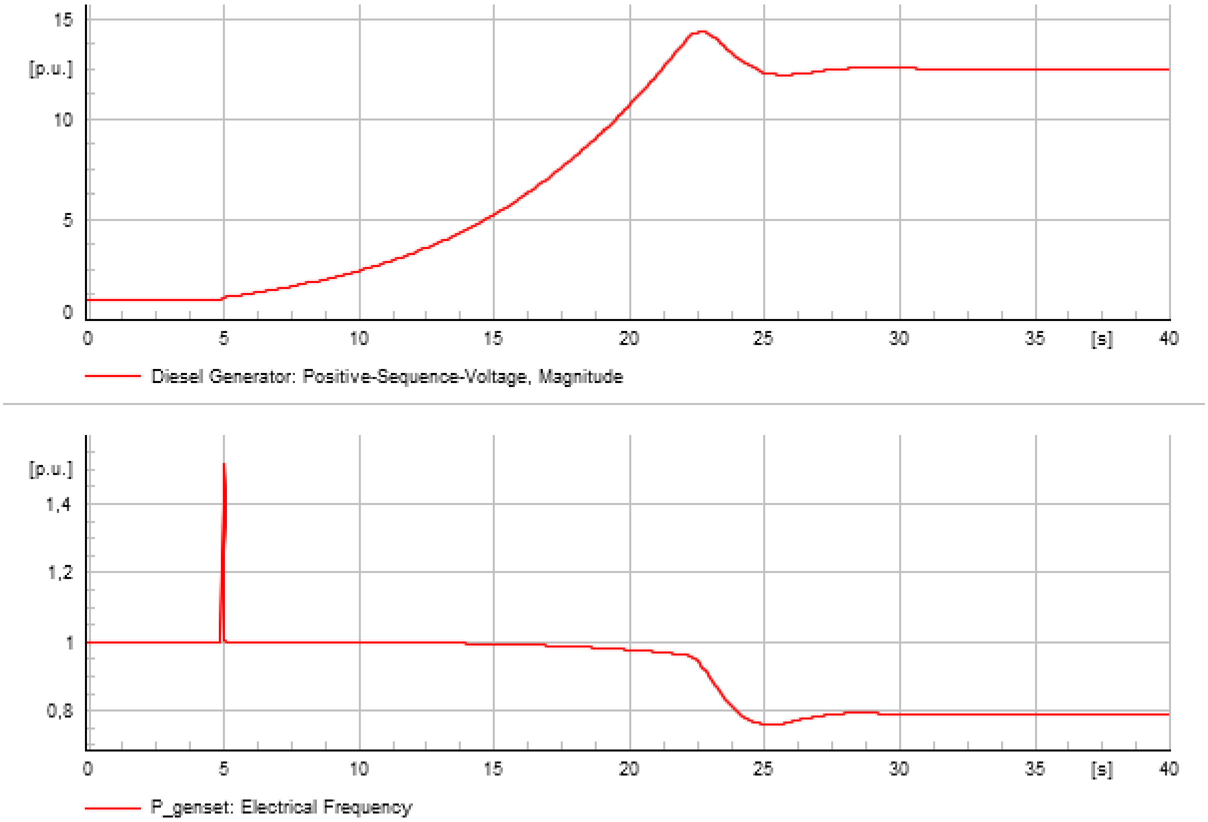

Figure 5.5: Voltage and frequency: blackout condition

5.2.1. Overhead lines

The susceptance of overhead lines is responsible for introducing negative reactive power in the grid. The value of negative reactive power increases, increasing the line length; for the computations, a parametric configuration with per unit of length parameters is considered. However, the transversal parameters of overhead lines are small, twenty times lower than the cable ones (Table 5.6); thus, no criticalities are expected in the entire range of length (0 km ÷ 15 km). If the value of negative reactive power overcomes the stability limit imposed by the capability curve, the GS unit stops working.

In particular, the following plots are related to a copper overhead line of 25 mm^2 section; this section is selected because represents a trade-off between overheat negative effects (for minor sections) and oversizing costs(for major sections). However, larger sections are also considered for the increased transversal parameter (Table 5.6). To distinguish the effect of an increase of length on the dynamic stability, different lengths in the interval 0 ÷ 15 km are reported in the next figures.

Firstly, the capability curve for different lengths of line is reported in Figure 5.6. In the capability curve, series of point are plotted. This issue is related to the small initial transient of active and reactive power when the GS is connected to the passive system.

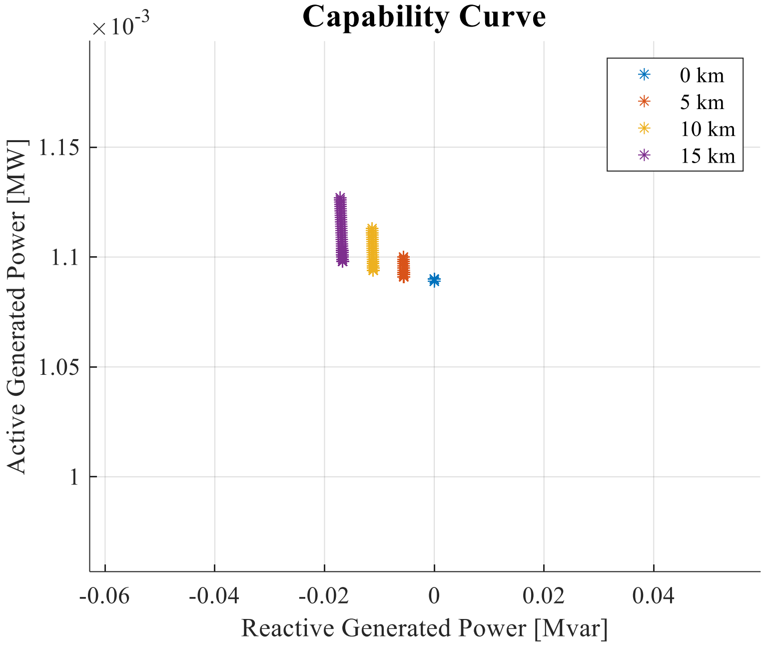

Figure 5.6: Capability curve – no load- 25 mm^2 overhead line

In particular, active power is negligible (1 kW), while the transversal parameters of the overhead lines bring the system on the under-excited region of the GS, without overcoming the stability limit. The limit Qmin (-0,12 Mvar) is far for each considered length. By increasing the length, the susceptance increases, and the operating point moves to the left of the PQ characteristic. Active and reactive powers exchanged by the GS are plotted separately in the next figure:

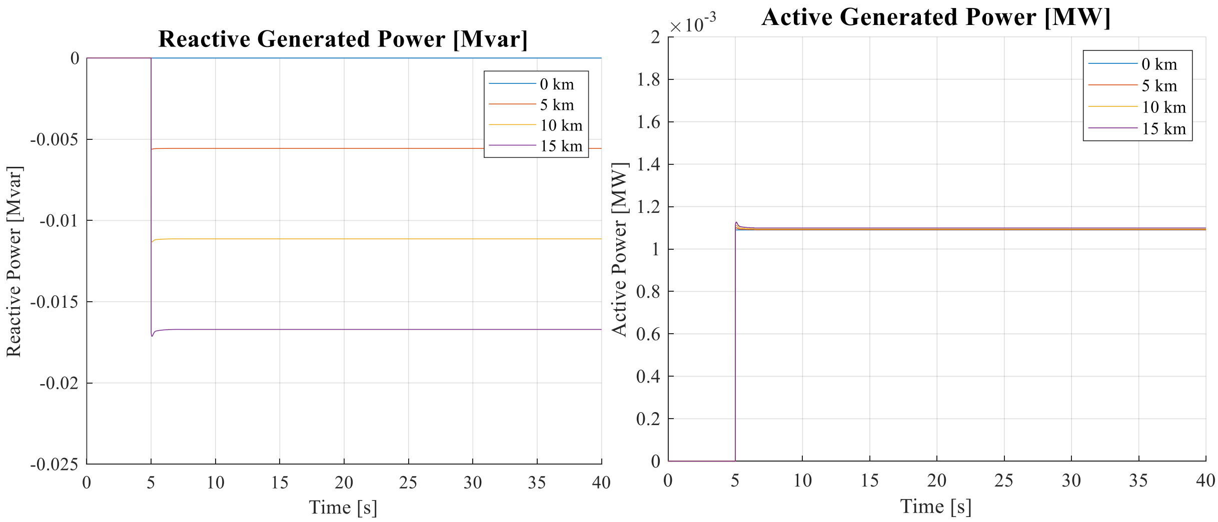

Figure 5.7: Generated active (on the left) and reactive power (on the right) – no load- 25 mm^2 overhead line

As observed from the capability curve of the GS, the active power is just enough to cover the losses on the overhead line and transformer impedance. Instead, the reactive power increases (in absolute value) when the length of the line increases due to the parasitic capacitance on the line itself. With a 15 km-length, the overhead line does not overcome Qmin, and the stability of the island is still maintained.

An additional parameter for the stability of the grid is the voltage at load terminals (Figure 5.8).

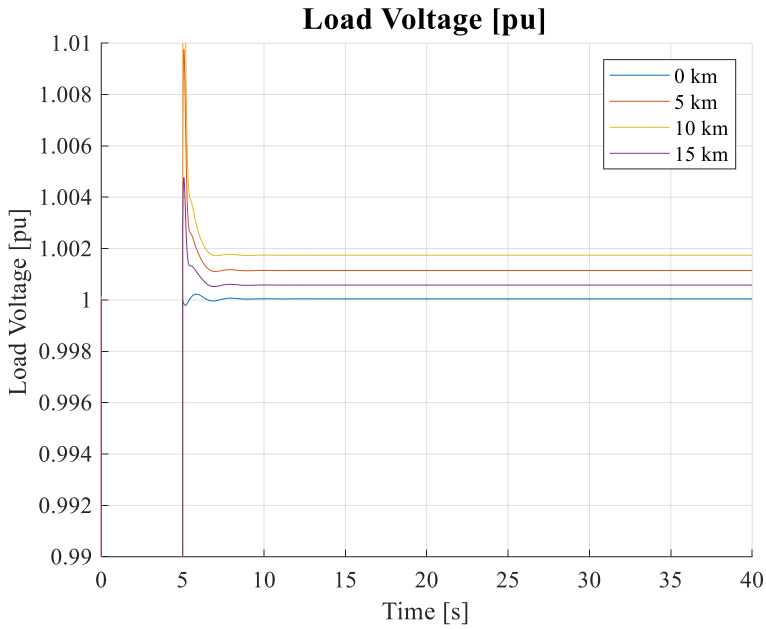

Figure 5.8: Load voltage profile – no load- 25 mm^2 overhead line

The effects of transversal parameters of the line can be observed on load voltage profile. A negative reactive contribution tends to increase the voltage at the load terminals, reaching values higher than 1 p.u. From a theoretical standpoint, this behaviour is validated through the equation (4.9).

Summarizing, different considerations can be made considering these plots:

- the active power is negligible (1 kW); from a theoretical point of view, it slightly increases when the length of the line increases. This is due to the fact that the overhead line has a resistive value per unit of length that represents the dissipation of the line. When the line has a length of 0 km, the losses are still present due to the internal impedance of the transformer (and so the active power delivered from the GS is not zero also in that case). For these reasons, the current generated by the GS is not zero when the overhead line has a null length;
- the generated reactive power decreases when the line's length increases. This behaviour is the foreseen one. Due to the increase of the line, the transversal susceptance increases, and the negative reactive request increases. However, the line is not long enough to overcome the stability limit of the system (Qmin), and PN remains stable.

In conclusion, in the no-load condition, considering an overhead line of 25 mm^2, the system can be re-energized for every length in the range 0 ÷15 km.

Same results can be achieved considering different sections of the overhead line: also considering an overhead line with 50/70 mm^2 of section, the system can be re-energized for every length in the range 0 ÷15 km.

5.2.2. Cable Lines

Cable lines are more often used in urban contexts and their susceptance is about twenty times the susceptance of overhead lines; hence criticalities are expected by increasing the length of the line: transversal parameters strongly increase, creating stability problems for the GS and the entire system.

The range of length considered is reduced with respect to overhead lines because – as it appears from the capability curve (Figure 5.9)– the amount of reactive power is higher than before (the GS unit works in the under-excited region) and the stability limit Qmin may be overcome:

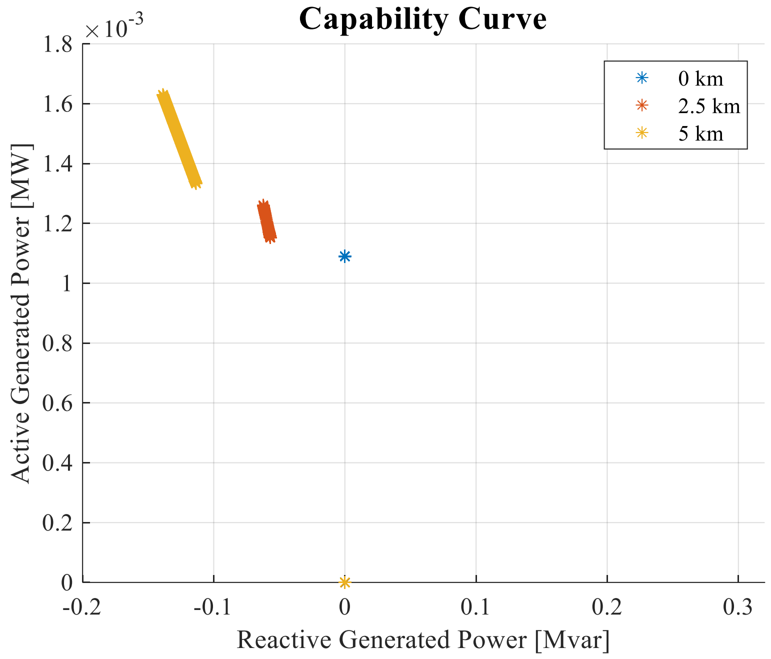

Figure 5.9: Capability curve – no load- 25 mm^2 cable line

For each considered length, more than one operating point is plotted. As for the overhead scenario, the reason is related to the initial transient of both active and reactive generated power.

As Figure 5.9 shows, the yellow curve (related to a cable line of length 5 km and section 25 mm^2) varies in the proximity of the stability limit of the GS. Further confirmation is provided by the voltage at the load terminals (Figure 5.10):

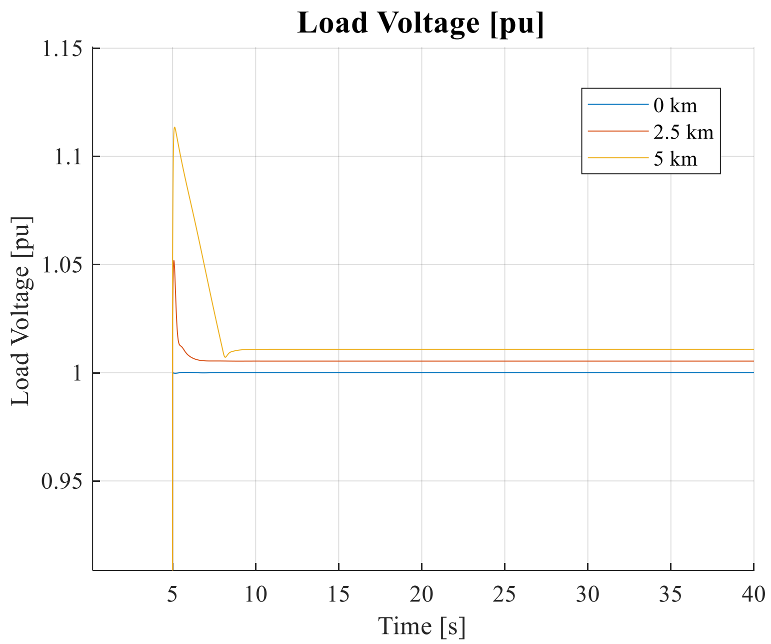

Figure 5.10: Load voltage – no load- 25 mm^2 overhead line

In this condition, the transversal parameters of the cable lines bring the voltage at 1,01 p.u. The active ad reactive powers delivered by the GS are shown in Figure 5.11:

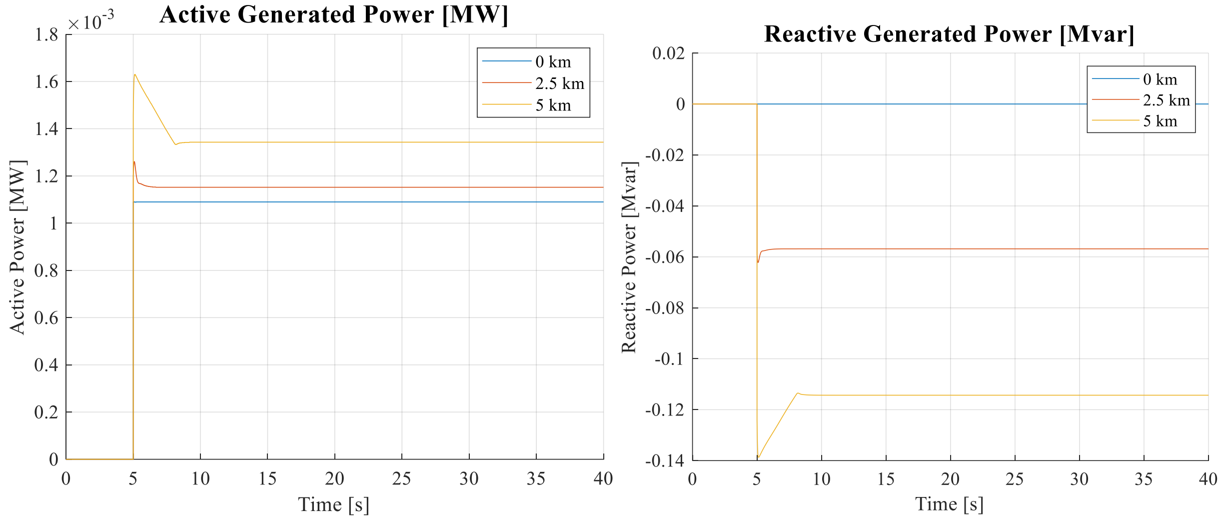

Figure 5.11: Generated active (on the left) and reactive power (on the right) – no load- 25 mm^2 cable line

As seen in the overhead case (Figure 5.7), the active power has a negligible value (Figure 5.11 on the left) just enough to fulfil the losses of the cable line and the transformer impedance. Instead, the reactive power increases (in absolute value) when the length of the line increases due to the parasitic line's capacitance (Figure 5.11 on the right).

If the length of the MV cable line is increased (e.g., 5,5 km), the stability of the entire system is compromised (Figure 5.12).

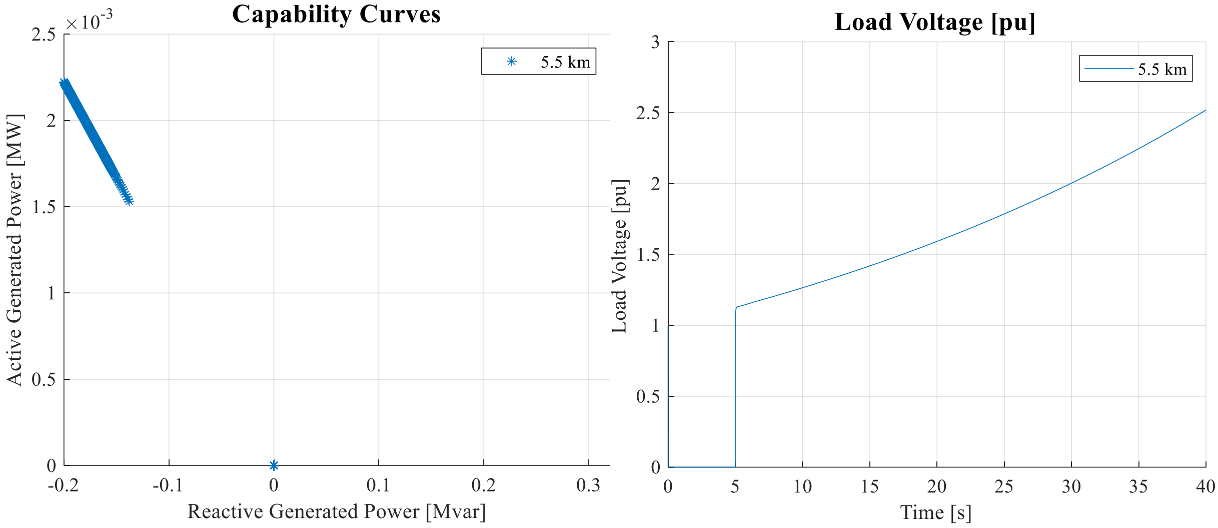

Figure 5.12: Capability curve (on the left) and load voltage (on the right) – no load- 25 mm^2 cable line

The voltage excitation system cannot control the voltage level at the generator/load terminals, and the voltage exceeds the protection limits. The maximum voltage relay (59) (Table 2.2) trips, and the entire system is de-energized.

Different considerations arise:

- if the length of the cable line (25 mm^2) is lower or equal to 5 km, the repowered grid is stable. It means that the reactive power has not reached the practical limit of stability;
- from 5 km, increasing the length, the negative reactive power reaches the minimum of the under-excited region, and the system tends to become unstable; after the 5 km length, the system becomes unstable, and the generated voltage, the active and reactive powers diverge.

The stability limits for three different sections (25, 50, 70 mm^2) are reported in the next tables (Table 5.7, Table 5.8, Table 5.9):

Table 5.7: No-load, cable line dynamic stability (25 mm^2)

	Copper Cable Sez. 25 mm^2																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
No-Load	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No

Table 5.8: No-load, overhead line dynamic stability (50 mm^2)

	Copper Cable Sez. 50 mm^2																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
No-Load	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No

Table 5.9: No-load, overhead line dynamic stability (70 mm^2)

	Copper Cable Sez. 70 mm^2																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
No-Load	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No

5.3. Dynamic stability in partial load conditions

This case study aims to determine practical limits in the length of the lines (overhead and cable ones) to observe the dynamic stability limits of the grid, keeping the GS inside its capability curve. The system in islanded condition is stable if remains properly energized and never experiences blackouts related to the tripping of protections.

For this case study, the implemented load has the following characteristics:

$$\begin{cases} P_{load} = 0{,}6\,P_{max} = 0{,}192\ MW \\ \cos(\varphi) = 0{,}9\ inductive \\ PQ\ type \end{cases} \tag{5.3}$$

Where:

$$P_{max} = 0{,}8A_n = 0{,}32\ MW \tag{5.4}$$

These load characteristics are provided to study the dynamic stability of the system when the GS unit is partially loaded (60% Pmax).

Starting the considerations from a static point of view, and looking at the capability curve of the GS, the operating point should be located in the over-excited region, far away from the stability limit of the GS itself. Nevertheless, depending on the type of line considered (overhead line or cable line), the operating point moves inside the capability curve.

5.3.1. Overhead Lines

The transversal parameters of overhead lines are relatively small; thus, no criticalities are expected in the entire range of length considered (0 ÷ 15 km).

The system is always stable because the operating condition is inside the capability curve per each considered length (Figure 5.13 on the left). In particular, the system is working in the over-excited region of the capability curve (both active and reactive power are positive). The parameters of the overhead line tend to move the operating point towards the left part of the graph, but the reactive power required by the load is higher than the negative contribution related to the line itself. From a dynamic point of view, the load angle (Figure 5.13 on the right) reaches 32° for the system with 15 km of overhead line, far away from the stability limit (≈ 70°).

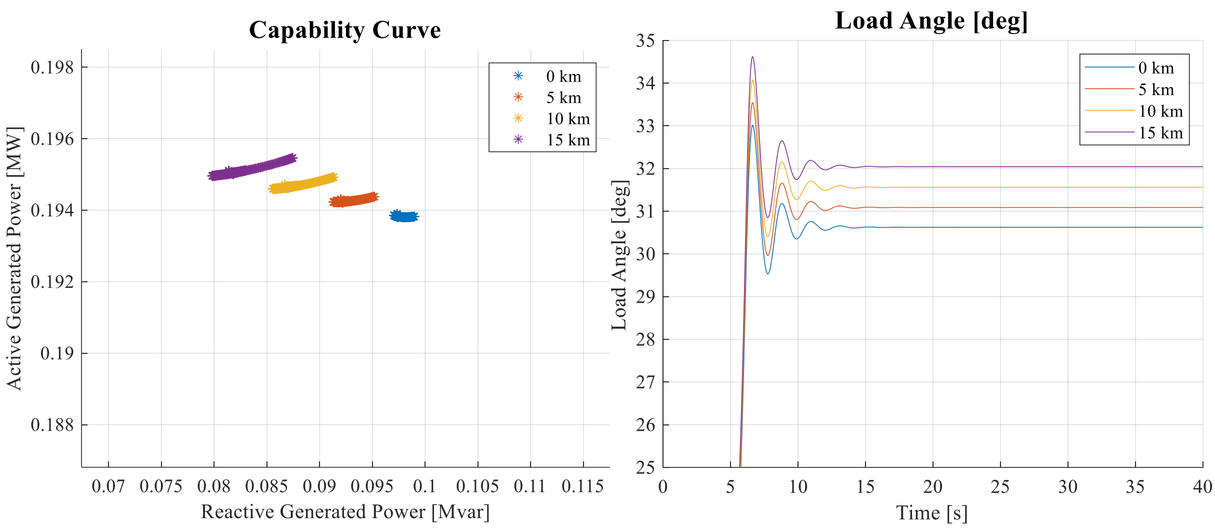

Figure 5.13: Capability curve (on the left) and load angle (on the right) – partial load-25mm^2 overhead line

A clear look at what happen to the system and to the operating condition is given by Figure 5.14. The active power remains constant (from a theoretical point of view, it slightly increases when the length of MV line increases). Instead, the reactive power decreases (moving the operating point towards the under-excited region) when the length of the line increases due to the parasitic capacitance on the line itself.

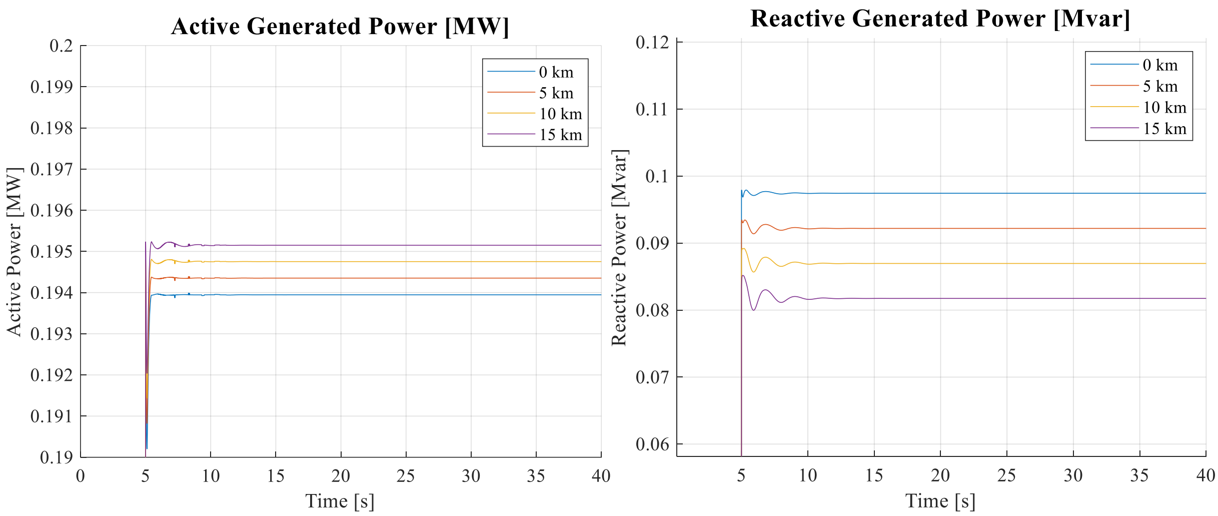

Figure 5.14: Generated active (on the left) and reactive power (on the right) – partial load-25mm^2 overhead line

In Figure 5.15, the effect of an increase in the length of the line results in a higher voltage drop; higher the length, lower the voltage at the load terminals. However, in all the range of lengths considered, the minimum voltage protection (Table 2.2) never trips because the voltage values remain inside the allowed range. Regarding the voltage at the GS terminals, the EXST2A always brings the system at the reference voltage value.

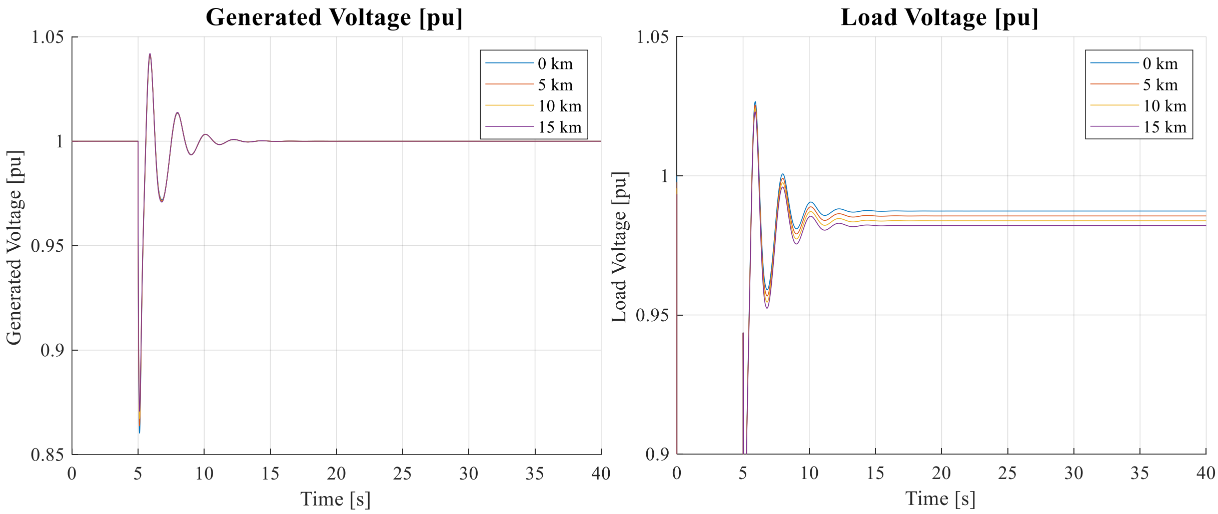

Figure 5.15: Load voltage – partial load- 25mm^2 overhead line

Summarizing, different considerations arise considering the partially load condition:

- load is a PQ type, so, in order to provide the same amount of power to it, the active generated power increases when the length of the line increases;
- the generated reactive power decreases when the length of the line increases: the capacitive contribution increases;
- the operating point is in the over-excited region because the inductive demand of the load is greater than the capacitive contribution of the overhead lines;
- the load angle presents a low value for each considered scenario.

In conclusion, the system is stable for every length in the considered range (0 ÷ 15 km).

Same results can be achieved considering different sections of the overhead line: also considering an overhead line with 50/70 mm^2 of section, the system can be re-energized for every length in the range 0 ÷15 km.

5.3.2. Cable Lines

As for the no-load case, criticalities are expected by analysing cabled systems since the susceptance of cable lines is twenty times the susceptance of overhead lines. Stability problems arise when the length of the cable line is increased over a given threshold.

Also in this study case, a 25 mm^2 cable copper line is considered as a trade-off between overheating problems and oversizing costs.

The stability is evaluated looking at Figure 5.16. The yellow curve represents a working condition close to the limit of stability. From the capability curve is difficult to describe the behaviour and the final operating condition of a 10 km cable system because more than one operating point is plotted (due to the active and reactive transient). From a dynamic point of view, the load angle reaches high values, reaching the stability limit (≈ 70°).

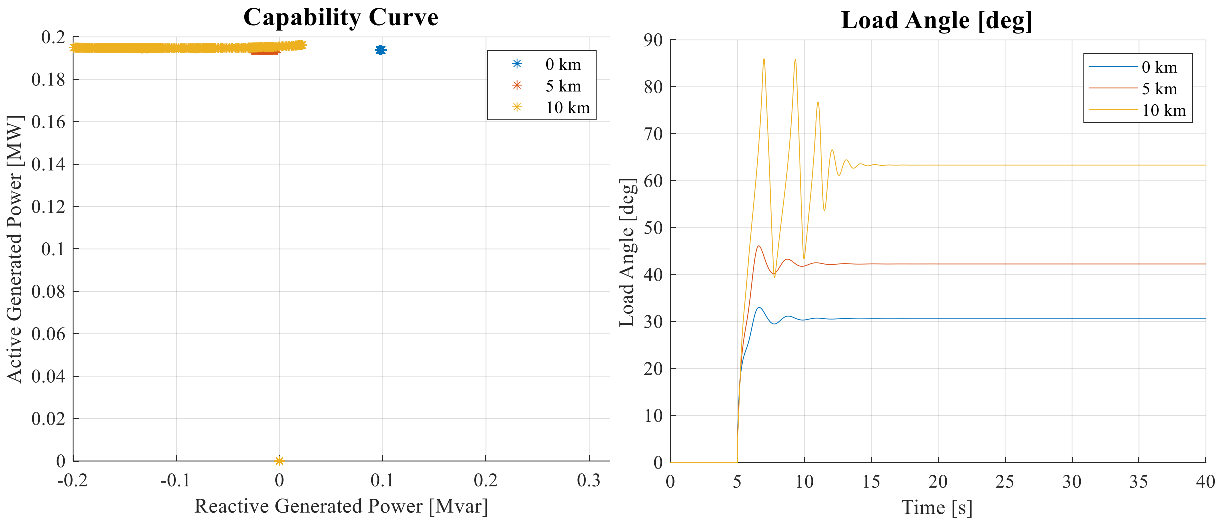

Figure 5.16: Capability curve (on the left) and load angle (on the right) – partial load- 25mm^2 cable line

If the length is further increased (i.e., 11,5 km), the stability of the system is compromised (Figure 5.17):

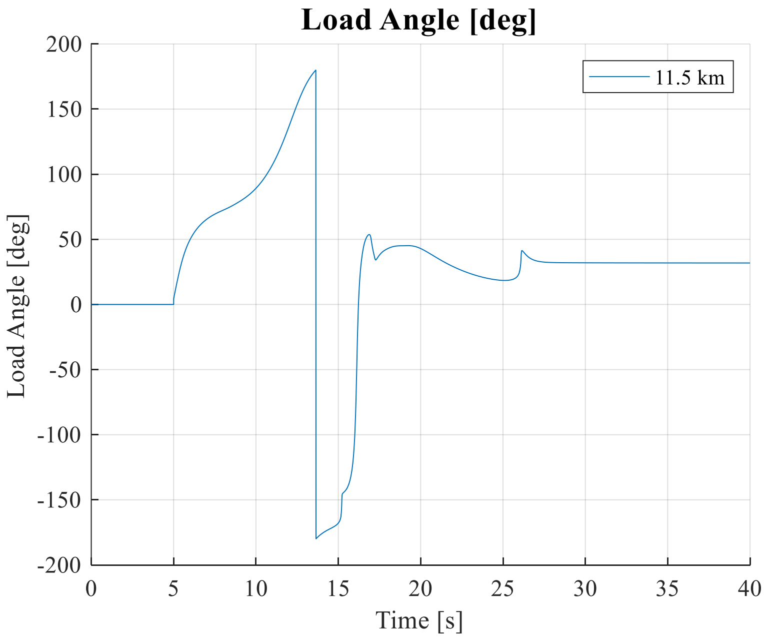

Figure 5.17: Unstable load angle – partial load- 25mm^2 cable line

Summarizing, different considerations arise considering the partially load condition:

- if the length of the cable line is lower or equal to 10 km, the load angle is lower than the stability limit and the reactive power has not reached Qmin;
- increasing the length, the negative reactive power reaches the minimum of the under-excited region, and the system tends to become unstable; from 11 km length, the system becomes unstable, and the load angle diverges.

In conclusion, given the high value of transversal susceptance, the operating point moves towards the under-excited region, overcoming the practical stability limit (Table 5.10). A similar study is conducted reducing the value of active power required by the load (40% Pmax).

Table 5.10: Partial load, cable line dynamic stability (25 mm^2)

	Copper Cable Sez. 25 mm^2																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
60%Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	No	No	No	No	No
40%Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	No	No	No	No	No	No	No	No

In the last table, static (blue font) means that that particular amount of cable line can be reenergized only if the load is a static one; it means, if the load is treated as a constant impedance for the grid.

Reducing the value of active power required by the load (keeping constant the power factor at 0,9), the system is stable with a lower amount of line. This phenomenon is due to the fact that, considering the same length of the cable, the active and reactive power generated by the GS are lower. The inductive contribution of the load is lower, and this causes a lower reactive compensation.

Comparable results are obtained by changing the section of the cable line (Table 5.11, and Table 5.12):

Table 5.11: Partial load, cable line dynamic stability (50 mm^2)

	Copper Cable Sez. 50 mm^2																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
60%Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	No	No	No	No	No
40%Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No

Table 5.12: Partial load, cable line dynamic stability (70 mm^2)

	Copper Cable Sez. 70 mm^2																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
60%Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No
40%Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No

Increasing the section of the cable, the stability of the system is reduced due to the increase of the susceptance. The load angle moves towards the instability limit.

5.4. Dynamic stability in full load conditions

This case study aims to determine practical limits in the length of the lines (overhead and cable ones) to observe the network's re-powering, keeping the GS inside its capability curve. The system in islanded condition is stable if remains properly energized and never experiences blackouts related to the tripping of protections.

For this case study, I implemented a variable load with the following characteristics:

$$\begin{cases} P_{load}: 0{,}28\ MW \div 0{,}32\ MW \\ \cos(\varphi) = 0{,}9\ inductive \\ PQ\ type \end{cases} \tag{5.5}$$

Set the length and the type of the line, the aim is to study the maximum load that the GS unit is able to withstand maintaining frequency, powers, and voltages inside their own limits. In addition, referring to the capability curve of the GS, the value of the maximum active power that the GS itself can reach (under steady-state considerations) is set to:

$$P_{max} = 0{,}8A_n = 0{,}32\ MW$$

Hence, the active power generated by the GS should not overcome this limit.

Starting the considerations from a statical point of view, looking at the capability curve of the GS, the operating point should be located in the over-excited region, far away from the stability limit of the GS itself. Nevertheless, depending on the type of connection of the load to the busbar (overhead line or cable line), the operating point moves inside the capability curve.

5.4.1. Overhead Lines

No criticalities occur when the connection between the load and the grid is an overhead line. Independent from the section and the requested power, the system is always dynamical stable.

An example of the behaviour of the PN is reported in the figures below; in particular, the overhead lines has a 25 mm^2 section, a length of 15 km, and power values that varies between 0,28 ÷ 0,32 MW (87% ÷ 100%Pmax).

As it appears from Figure 5.18, the capability curve and the load angle are plotted, as shown:

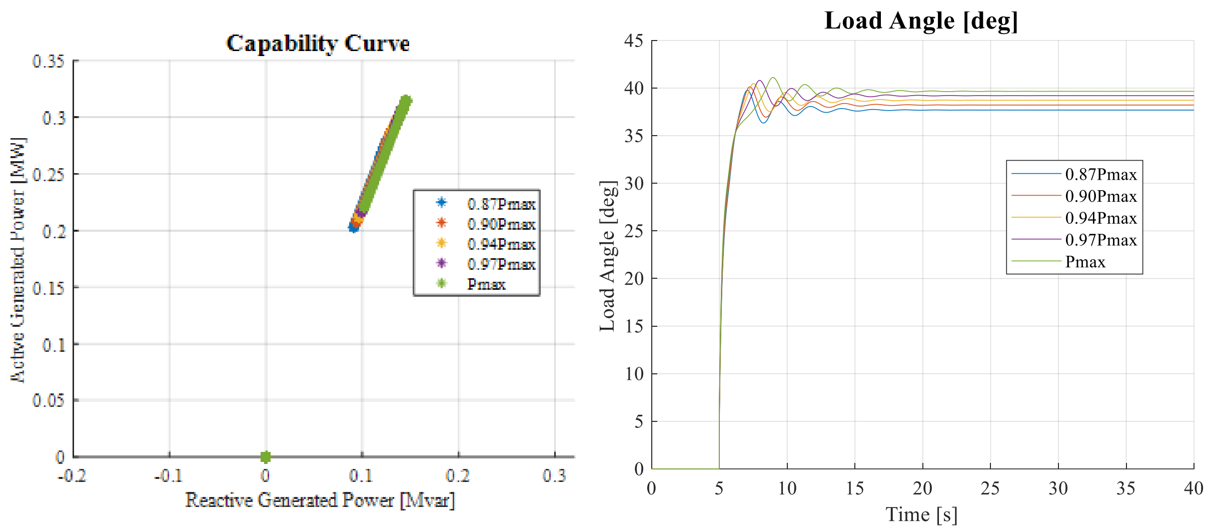

Figure 5.18: Capability curve (on the left) and load angle (on the right) – full load- 25mm^2 overhead line

As expected from a statical point, the operating point is in the over-excited region; the presence of the overhead line tends to move the operating point towards the left part of the graph (Figure 5.18 on the left), but the inductive contribution of the load is higher than the negative contribution of the overhead line. A better look can be obtained by studying the load angle of the GS (Figure 5.18 on the right): higher the length, more the load angle increases. For all the considered powers (0,28 ÷ 0,32 MW), the load angle is below the stability limit.

Even if at the GS terminals the voltage excitation system brings the voltage at 1 p.u, greater the length of the MV line, higher would be the voltage drop at the load terminals. However, in all the range of length considered, the minimum voltage protection (Table 2.2) never trips because the voltage values remain inside the allowed range (Figure 5.19).

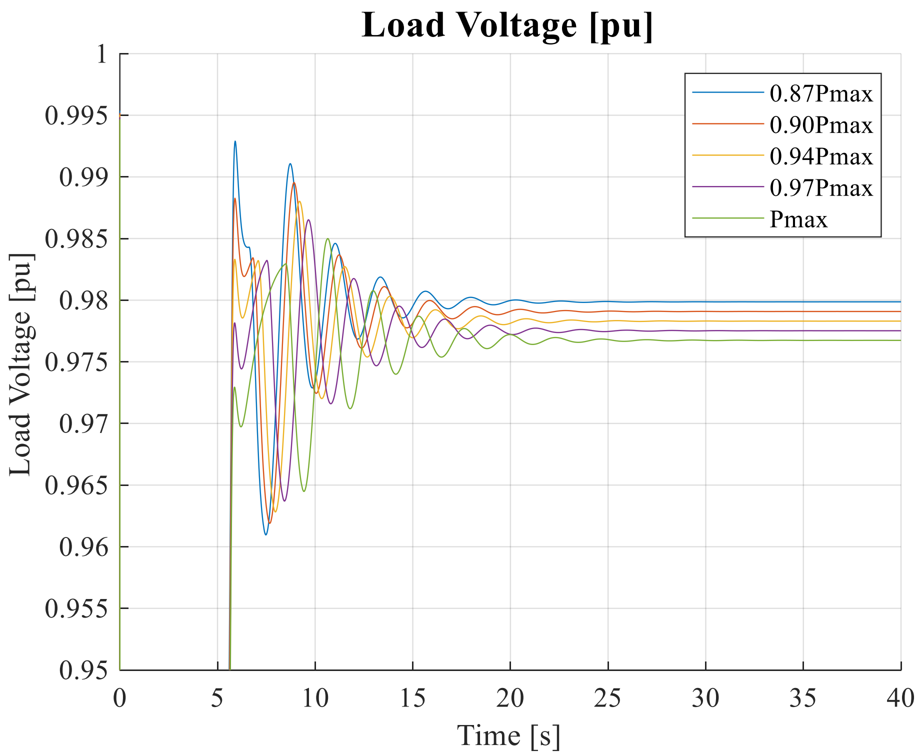

Figure 5.19: Load voltage – full load- 25mm^2 overhead line

Summarizing, all the lengths and sections of an overhead line do not present stability issues and, for all the considered powers, the islanded system remains stable.

5.4.2. Cable Lines

For cable lines, the numerical simulations are reported for two different cases, according to the behaviour of the electric island:

1. loads with active power lower than 90% Pmax;
2. loads with active power higher or equal to the 90% Pmax.

5.4.2.1. Loads with active power lower than 90% Pmax

In this study case, the length of cable line that can be repowered (maintain the system stable) using the previously described GS is extensive, comparable to the partial load scenario. If the load angle reaches the practical stability limit (≈70°), the stability of the system is compromised.

Hereafter the capability curve and the load angle of the 87% Pmax (0,28 MW) case are presented (Figure 5.20):

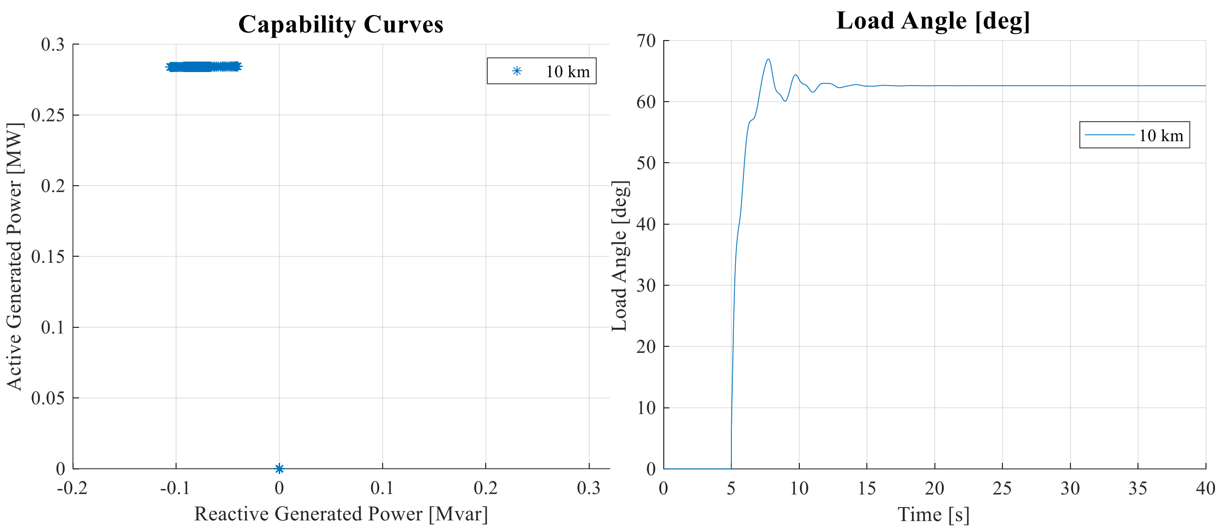

Figure 5.20: Capability curve (on the left) and load angle (on the right) – full load- 25mm^2 cable line

The negative contribution of reactive power introduced by the cable line increases the load angles to 60/70°.

5.4.2.2. Loads with active power higher or equal to the 90% Pmax

In the second case, for loads with active power higher or equal 90% of Pmax, the range of lengths in order to maintain the system stable is significantly reduced.

In the second case, the limit is not imposed by the stability of the load angle, but by the speed governor of the GS. In the paragraph related to the speed regulator (Paragraph 5.1.1), the upper limit of the throttle equals to 1,25 p.u. The limitation imposed on the throttle is a constrain for the mechanical power. The limit, thus, is imposed on the mechanical power related to the diesel engine of the GS; i.e., it can produce power that cannot exceeds 1,25 the maximum power. Otherwise, if this value is overcome, the protections of the diesel engine (Table 2.1) trip. In particular, if a mechanical power equals to 1,25 time the maximum electric power is not able to fulfil the requested power by the load, the frequency drops according to the power balancing equation (4.11) and the entire system collapses.

Hereafter, the length of the cable that can be safely energized without affecting the dynamic stability of the GS are reported:

Table 5.13: Full load, cable line dynamic stability (25 mm^2)

	Cable Line (section 25 mm^2)																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,875Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	No	No
P=0,9Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	No	No	No
P=0,94Pn	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No
P=0,97Pn	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
P=Pn	Yes	Yes	Yes	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No

In particular, the green font represents the length of the cable line that can be energized considering all types of loads, the blue font the length of the cable line that can be energized considering a static load type, the red one the part of the line that cannot be energized in every load condition. If the load is a static one (seen as a constant impedance), the amount of line that can be energized increases considerably; this fact is explained by the nature of the load itself. A PQ type requires the same amount of active and reactive power under every condition; a static load behaves as an impedance of known value and the power required changes depending on the configuration of the grid. However, even if the static type of load is more flexible than the PQ type, and the PQ load type is the most stringent condition, inside distribution systems the most common representation of loads is provided by the combination of the two types. This means that the actual range of cable lines that can be energized in stable conditions is between the ranges of the PQ and static load type.

Similar results can be obtained by chancing the size of the cable line, as shown in the next tables:

Table 5.14: Full load, cable line dynamic stability (50 mm^2)

	Cable Line (section 50 mm^2)																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,875Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	No	No	No	No
P=0,9Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	No	No	No	No	No
P=0,94Pn	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No
P=0,97Pn	Yes	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
P=Pn	Yes	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No

Table 5.15: Full load, cable line dynamic stability (70 mm^2)

	Cable Line (section 70 mm^2)																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,875Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	Static	No	No	No	No
P=0,9Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	No	No	No	No	No
P=0,94Pn	Yes	Yes	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No
P=0,97Pn	Yes	Static	Static	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
P=Pn	Yes	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No

Additional graphs for each numerical simulations and considered power levels can be found in Appendix C.

5.4.3. Droop Condition

Some differences arise between the isochronous condition and the droop one. Both for overhead lines and cable lines, the length that can be stably energized is reduced with respect to the isochronous condition. Table 5.16, Table 5.17, Table 5.18, Table 5.19, Table 5.20, and Table 5.21 describes the stability of the system for different loads, length and sizes. As for the isochronous condition, the stability of the system is studied with both PQ load and static load types.

In particular, a droop equals to 4% is selected in order to maintain the frequency inside the range of 49 ÷ 51 Hz for every active power considered. As mentioned in paragraph 3.1.2, this particular frequency range is the maximum range to let a DG unit reconnect to the islanded grid according to CEI 0-21.

Table 5.16: Full load, droop, overhead line dynamic stability (25 mm^2)

	Overhead Lines (25 mm^2)																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,875Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,9Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,94Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,97Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=Pn	Yes	Yes	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static

Table 5.17: Full load, droop, overhead line dynamic stability (50 mm^2)

	Overhead Lines (50 mm^2)																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,875Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,9Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,94Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,97Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=Pn	Yes	Yes	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static

Table 5.18: Full load, droop, overhead line dynamic stability (70 mm^2)

	Overhead Lines (70 mm^2)																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,875Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,9Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,94Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,97Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=Pn	Yes	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static

Table 5.19: Full load, droop, cable line dynamic stability (25 mm^2)

	Cable Line (section 25 mm^2)																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,875Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	Static	Static
P=0,9Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	No	No
P=0,94Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No
P=0,97Pn	Static	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
P=Pn	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No

Table 5.20: Full load, droop, cable line dynamic stability (50 mm^2)

	Cable Line (section 50 mm^2)																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,875Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	Static	Static	Static
P=0,9Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No
P=0,94Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No
P=0,97Pn	Static	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
P=Pn	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No

Table 5.21: Full load, droop, cable line dynamic stability (70 mm^2)

	Cable Line (section 70 mm^2)																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,875Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	Static	Static	Static	No	No
P=0,9Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No
P=0,94Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
P=0,97Pn	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
P=Pn	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No

A severe reduction in the stable length of the system is observed in cable lines compared to the isochronous condition; the reason behind this reduction is related to the frequency of the system. In full load condition, loads requesting powers similar to the maximum one of the GS, and the value of frequency is far below the nominal value. In particular, for the considered droop characteristic of 4%, the frequency of the system in this study case reaches values around 49 Hz (0,98 p.u.) (Figure 5.21).

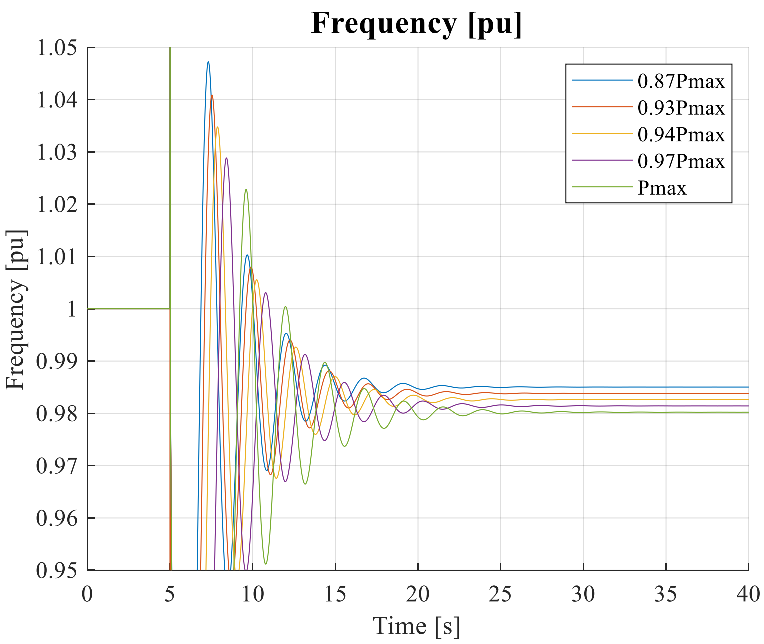

Figure 5.21: Frequency in a droop condition

Looking back at the block scheme of the speed regulator of the GS unit (Figure 4.9), the only limit is related to the maximum value of the throttle. The throttle is multiplied by the instantaneous value of speed to provide the actual turbine power. Thus, keeping unchanged the load demand and line configurations (in terms of active power delivered, load type, and length of the line), to maintain the same turbine power, if the frequency is below the reference value, the throttle is higher. For this reason, under droop conditions, the stable amount of length is lower than in the isochronous case study. In Figure 5.22, the change in the throttle is represented (blue curve):

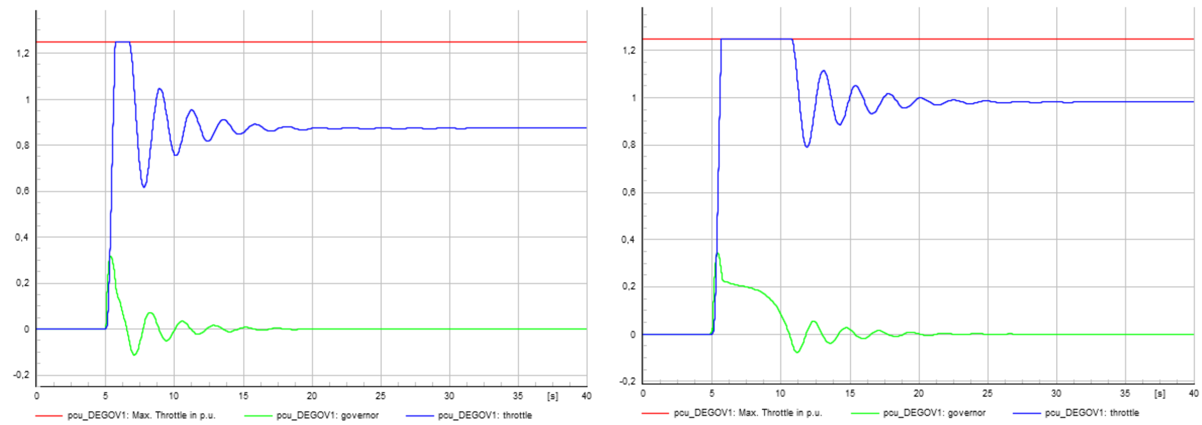

Figure 5.22: Differences in throttle between isochronous (on the left) and droop (on the right) conditions.

The throttle difference between the two cases is more than 0,10 p.u. In addition, another drawback in implementing a droop solution is related to the period of time in which the throttle is saturated: if in the isochronous case this period of time is 1 second, in the droop one is more than 5 seconds.

The throttle signal is provided by the governor signal (green curve). The governor signal is given by the error in frequency between the actual value and the reference value (50 Hz). Thus, lower the reached frequency, higher the error in frequency, higher the governor and the throttle signal. In conclusion, the droop case reduces the stability of the grid.

Just mentioned results are taken considering:

$$\begin{cases} s = \ 70\ mm\hat{}2 \\ l = 4\ km \\ Static\ Load \\ P_{Load} = 0{,}31\ MW \\ PF = 0{,}9 \end{cases}$$

In Appendix D, all the introduced numerical simulations (as well as results and tables) have been performed on the same PN configuration, equipped with a different GS. The rating of this newly implemented GS is 250 kVA, lower than the already implemented 400 kVA.

5.5. Starting of an induction motor: dynamic stability

In this case study, the MV load is substituted with a LV industrial Asynchronous Motor (AM), and the dynamic stability of the system is evaluated. As for the last study case, this one is implemented according to the operational practices of DSOs that provides to reduce the outage for a portion of the MV network by temporally supplying it by a GS. The AM represents the only element on the grid that requires a certain amount of active and reactive power. It is connected to the LV bus through a cable line. All the other parts of the system remain unchanged from the PN configuration.

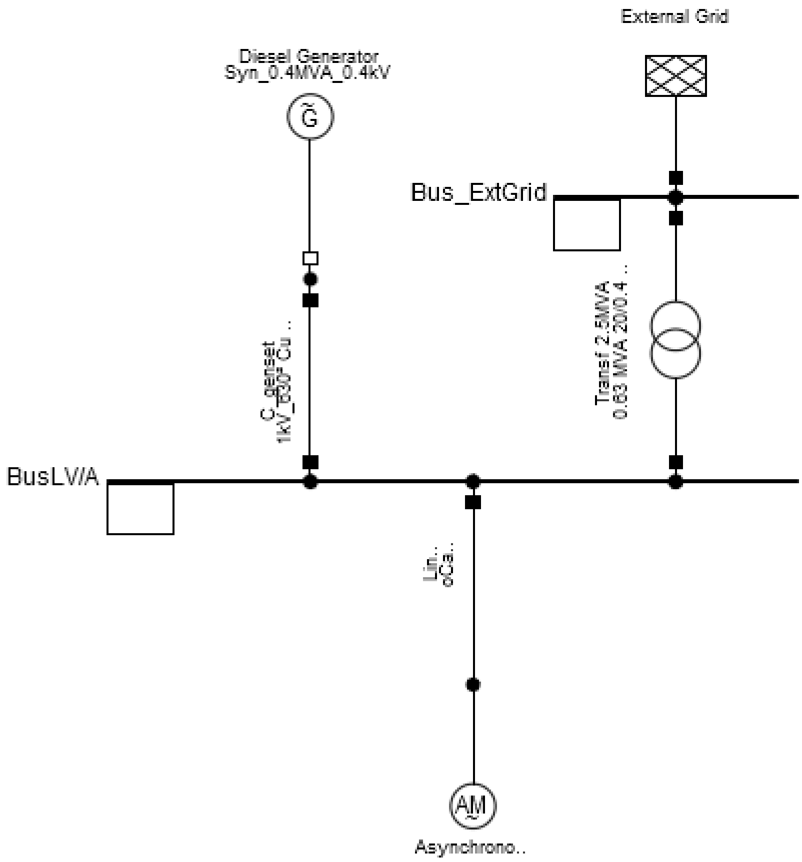

Figure 5.23: Passive grid configuration for motor analysis

As for the last case study, the portion of grid remains deenergized for several hours. In this blackout time, the AM has lost pace and its rotational speed is null. Thus, in the implemented system, the motor starts from a null speed and its starting process is evaluated.

To represent this behaviour, the GS is connected to the passive system at 40 seconds.

5.5.1. Asynchronous three-phase motor

The implemented motor is a three-phase AM; the choice of the motor is related to the fact that this type of motor is a widely used in industrial and household applications thanks to its many advantages [28], such as:

- robustness;
- easy maintenance;
- easy control;
- a wide range of power/voltage;
- low cost.

The mechanical characteristic (Figure 5.24) of the motor represents a key element for the proper implementation of the AM on DigSilent PowerFactory. In particular, the torque profile is represented according to three points:

- starting torque;
- pullout/stalling torque;
- full-load torque.

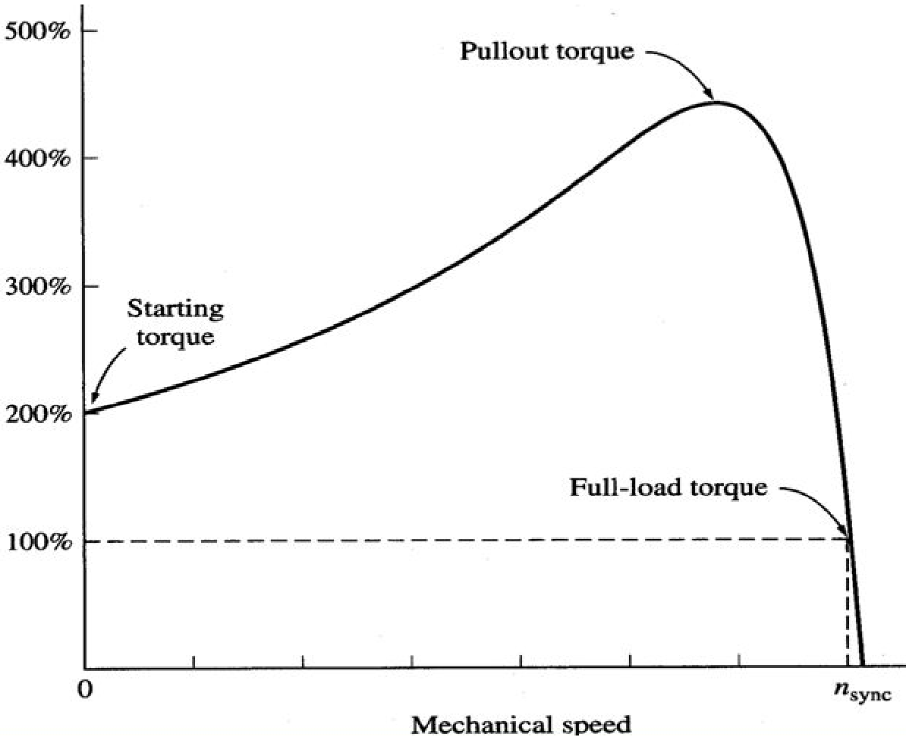

Figure 5.24: Mechanical characteristic of an AM (single cage)

In this study case, both single cage and double cage AMs are analyzed. Double cage AMs have the rotor equipped with two coaxial cages, with different sections: the external/upper cage has a much smaller section than the internal/lower one. The starting torque is given by the sum of the initial torque of both cages as shown in Figure 5.25:

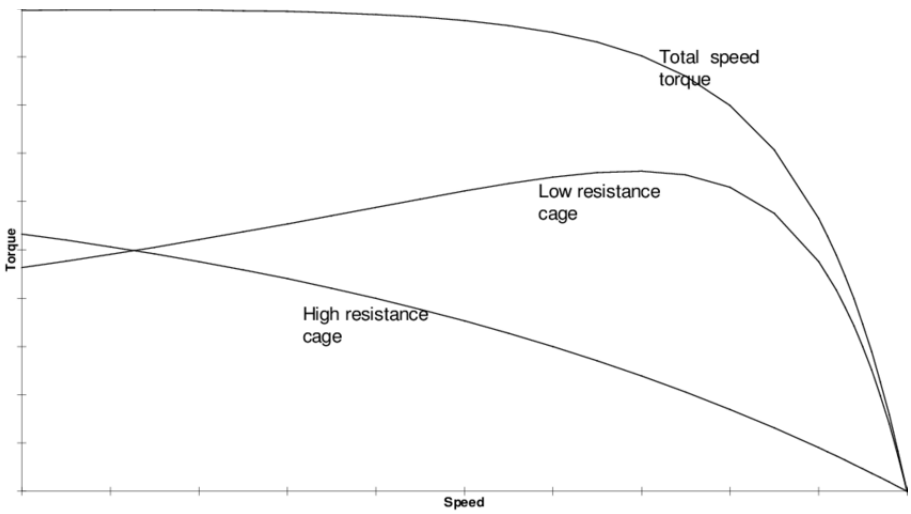

Figure 5.25: Mechanical characteristic of an AM (double cage)

The advantage for users of double cage AMs is that the value of the initial torque is increased, and the value of current is reduced, as well as the period in which the current has higher values than the nominal one.

This thesis deals with AM direct start-up. During the AM direct start-up, the machine current can be 6÷7 times higher than the rated phase current, which can cause the activation of machine relays. For that reason, the AM starting process duration is very important for proper machine protection-relay settings (for example, the setting of the over-current protective devices). Furthermore, the high value of the phase current and machine starting process duration can cause machine overheating.

The aim is to observe what happens to the stability of the grid if the starting of a three-phase AM is considered.

In Table 5.22, the parameters of AM1 and AM2 are reported:

Table 5.22: AM1 & AM2 implemented parameters

	AM1 Single Cage	AM2 Double Cage
Nominal Complex Power [kVA]	132	132
Nominal Voltage [kV]	400	400
Rated Current [A]	224	220
Frequency [Hz]	50	50
Power Factor cos(ϕ)	0,89	0,84
Poles	2	4
Rated Speed [RMS]	2980	1495
Rated Torque [Nm]	423	410
Starting Torque [p.u.]	2,15	2,9
Stalling Torque [p.u.]	3,1	3,1
Moment of Inertia [kgm^2]	1,96	1,96
Efficiency η [%]	95,6	97,5

The choice of the power rating of the AMs (132 kVA) is related to the complex power required by the motor for the direct start-up. During the starting process, the complex power required by the AM is:

$$S_{starting} = k\sqrt{3}VI \tag{5.6}$$

Where kI is the starting current, k times (6÷7) higher than the nominal value.

Recalling that:

$$\frac{P}{\cos(\varphi)\,\eta} = \sqrt{3}VI$$

(5.7)

It results that:

$$S_{starting} = k\frac{P}{\cos(\varphi)\,\eta}$$

(5.8)

Thus, for all the starting process (2÷20 s) the GS must provide the complex power Sstarting to the AM. If the starting current is 6÷7 times the rated value, it means that the nominal power of the GS should be at least three times the nominal power of the motor. It means that the nominal power rating of the AM is the maximum one for the GS considered (400 kVA) [9].

Dynamic stability limits are evaluated according to RMS simulations. For both configurations, the single cage and double cage conditions are evaluated.

5.5.2. Results

Numerical simulations have been performed considering the same length of the LV line (0,3 km).

The active power required by the AMs is varied in order to observe the main differences between the two motors. From Table 5.23, it results that AM2 (double cage configuration) may require more power than AM1 (single cage configuration). The reason behind is related to the direct start-up of these two motors, and to the mechanical characteristic of them.

Table 5.23: AMs dynamic stability

	Percentage of active power required [%]										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
AM1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No
AM2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No

For all the implemented AMs, the presented graphs are obtained considering an AM with the following characteristics:

$$P = 70\%Pmax = 0{,}09\ MW$$

(5.9)

Where Pmax equals the rating power of the motor (132 kW). The effect of the single/double cage AM on the system can be seen in Figure 5.26:

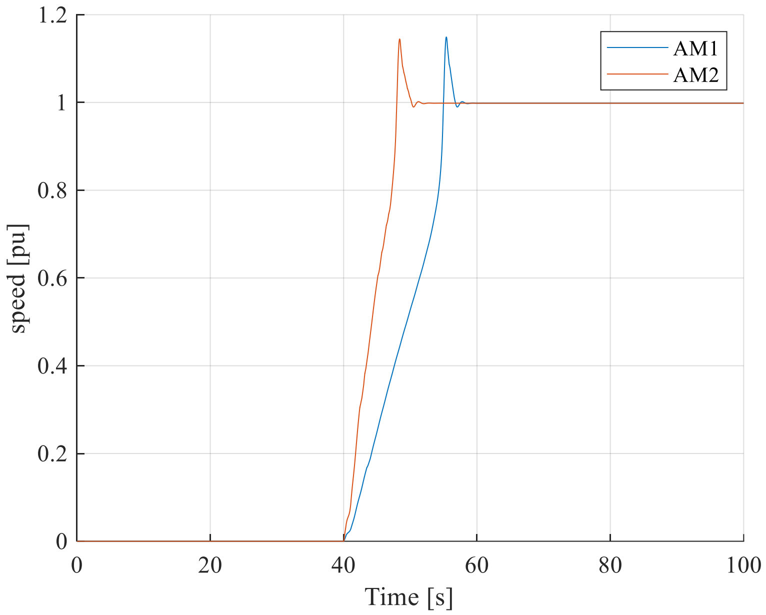

Figure 5.26: Speed comparison between AM1 and AM2

A single cage AM takes more time to reach the nominal speed of rotation (except for a small slip value). In the same figure, considering the same required power by AM1 and AM2 (0,09 MW), AM2 takes 10 seconds less to reach the nominal speed, except for a small slip value.

If the current, as well as the reactive power, exceed the limits for a significant period, the voltage excitation system is not able to bring the voltage back to the nominal value and the island becomes unstable (Figure 5.27).

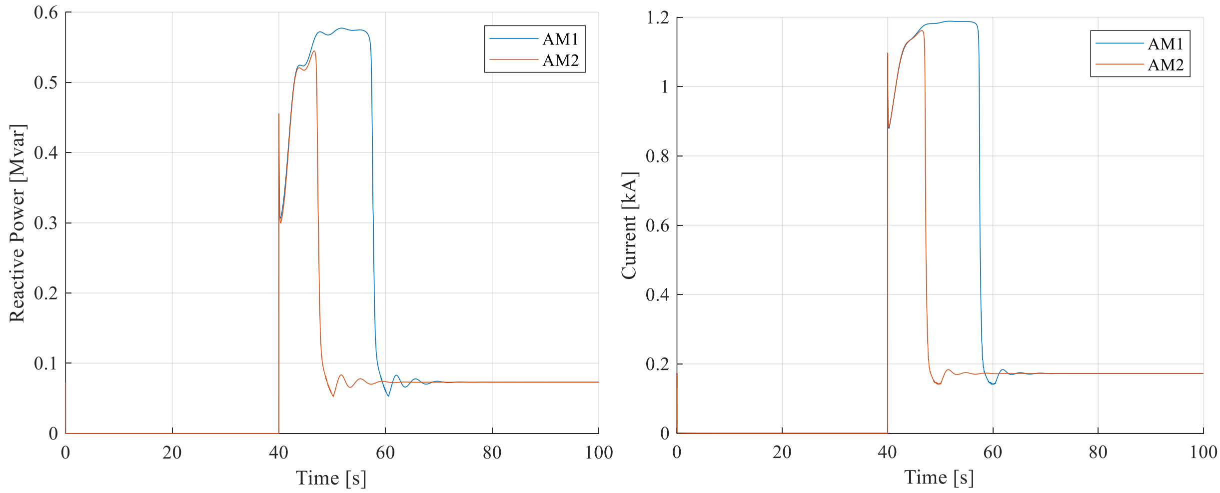

Figure 5.27: Reactive power (on the left) and current (on the right) of AM1 (single and double cage)

In Figure 5.28, the voltage of AM2 remains at 0,9 p.u. for 10 second more than AM1; voltage protections would be carefully considered in order to avoid tripping in the starting process of the motor; otherwise, GS protections trip, and the system will be deenergized.

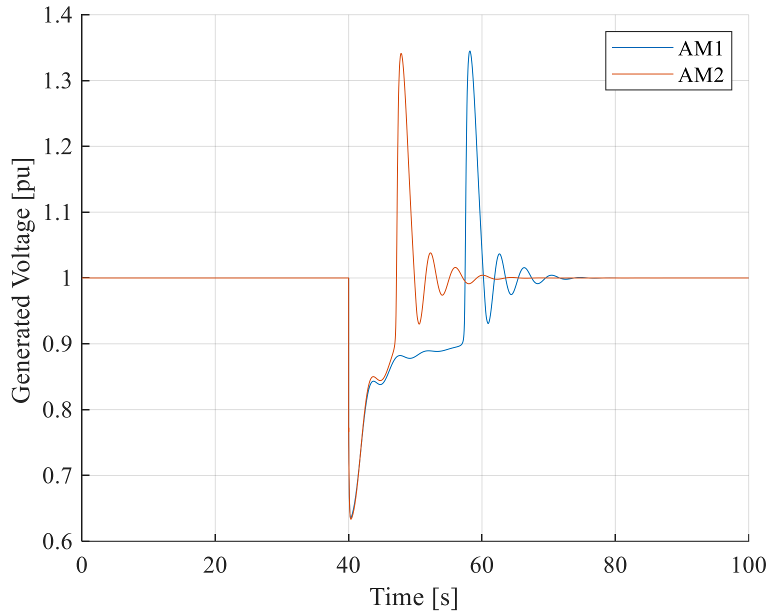

Figure 5.28: Voltage profile for AM1 and AM2

Regarding the frequency of the grid and the active power required by AMs, the profiles are reported in the next figure:

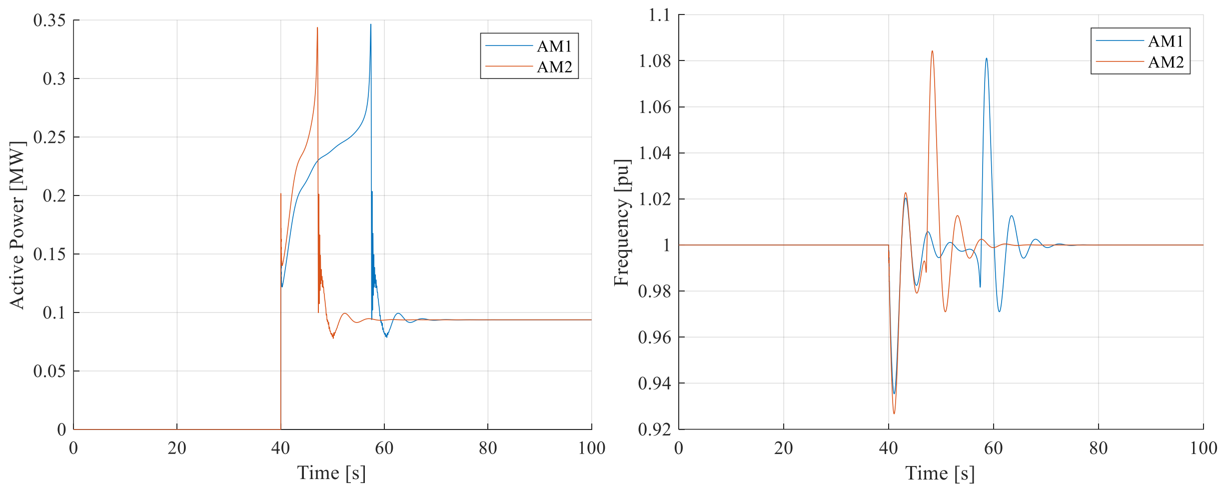

Figure 5.29: Active power (on the left) and frequency (on the right) of AM1 and AM2

The frequency profile is divided into two different transients:

1. the first one is related to the energization of the entire grid when the GS is connected;
2. the second one occurs when the speed reaches the nominal (except for the small slip contribution) speed of the AM.

The peak on the active power is reached at the same time the reactive power reaches its own peak; then, both the active and reactive power evolves to the new steady-state value. The frequency trend follows the active power profile, regulated by the speed governor. Also in this case, AM1 presents the same behaviour, but delayed in time.

In conclusion, the starting of LV AMs has been studied in islanded conditions. The double cage AM creates less problem to the stability of the islanded grid than the single cage one and can be started for wider active power rangers. A higher starting torque, a lower starting current, as well as a faster transient period, help the stability of the island supplied by the GS.

6 Active Network study case: modelling and numerical simulations

According to CEI 0-21 prescriptions, after the formation of the electric island, the DG is allowed to automatically reconnect to the network (by closing the related IPD), provided that:

- the voltage remains inside the thresholds established for the starting process (90 ÷ 110% Vn);
- the frequency has remained stable in an adjustable range around the nominal value (default 50 ± 0,1 Hz) for a selectable time in the range 0 ÷ 900 s (default value 300 s);
- the active power delivery gradually with the same load take-off ramp required at the starting process.

The take-off ramp should not exceed the maximum positive gradient of 20% per minute of the maximum power provided by the DG itself.

In this chapter, the aim is to model a DG unit in the most realistic way possible in order to simulate what would happen in a real-existing network. The DG unit is reconnected to a LV busbar (400 V), and its rating power is 200 kW. If the reconnection process is successful, the network passes contains more than one generator (the GS, and DG units) that feed the intentional island.

Two different control laws are implemented on the DG as grid services:

- the reactive power follows the characteristic imposed by the Q(V) control law (see paragraph 3.2.1);
- the active power follows the characteristic imposed by the P(f) control law (see paragraph 3.2.2).

6.1. DG unit: construction of the model

In this paragraph, the aim is to build inside the PowerFactory environment a DG unit that resemble the behavior of a real-existing one. The models of the Q(V) and P(f) control logics are presented according to CEI 0-21.

Firstly, the composite model of the DG unit is studied in the next section.

6.1.1. DG unit: composite model

The composite model of the DG unit implemented in DigSilent PowerFactory is shown in the next figure:

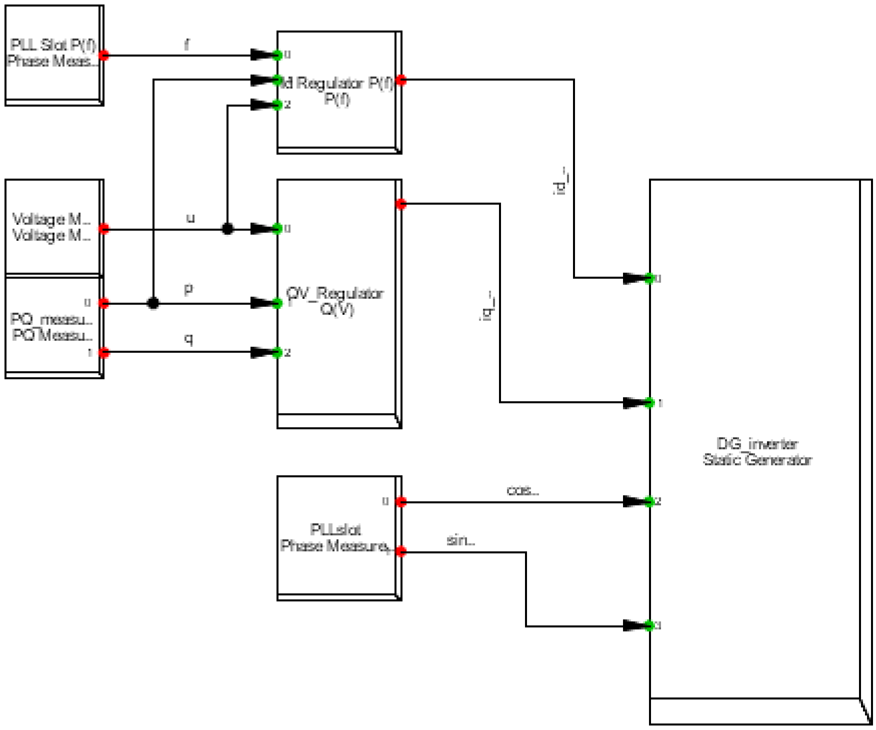

Figure 6.1: Composite model of the DG unit

In LV applications, most DG units are composed by static generators (photovoltaic panels, small wind turbines, etc..). Thus, in DigSilent PowerFactory the composite model of the DG unit is equipped with a static generator. For the project, it works as a current source inverter model as shown in Figure 6.2:

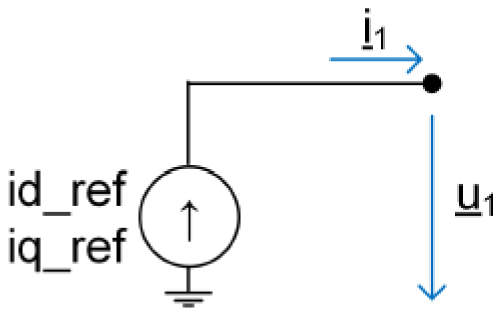

Figure 6.2: Current source model

It presents four input signals:

- d-axis current reference in p.u: id_ref;
- q-axis current reference in p.u: iq_ref;
- cosine (dq-reference angle): cosref;

- sine (dq-reference angle): sinref.

The first two inputs control respectively the active and reactive power exchanged by the static generator itself. The cosine and sine, instead, provide the reference value of cosine and sine to perform a correct Park's transformation between the phasor domain and the time domain. If the input signals cosref and sinref are taken from a Phase-Locked Loop (PLL), then the following transformation for the current is used:

$$\overline{\iota_1} = (id_{ref} * cosref - iq_{ref} * sinref) + j(id_{ref} * sinref + iq_{ref} * cosref) \tag{6.1}$$

The d-axis current reference and the q-axis current reference are obtained respectively by the "P(f) Regulator" block and by the "Q(V) Regulator" block described in the following paragraphs (see paragraphs 6.1.3 and 6.1.4). The reference angle signals, instead, are obtained by using the PLL.

The measurement block for the active and reactive power, voltage, and PLL are the standard models found in the technical references of DigSilent PowerFactory [29].

6.1.2. Active Power Supply and Loading

The static generator supplies an amount of active power to the grid depending on the input d-axis current reference. The d-axis current reference signal is controlled inside the "P(f) Regulator" block as shown in the next figure:

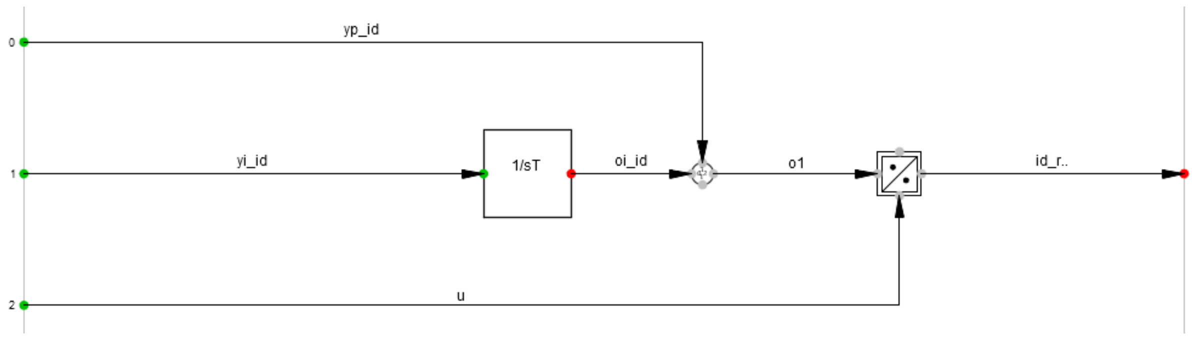

Figure 6.3: Common model of the reference d-axis current

The aim of this common model is to let the DG unit reconnect to the system following the reconnection ramp in CEI 0-21. The output signal id_ref is responsible for the active power provided by the DG unit; by varying yi_id, the output signal (and the active power) varies following a ramp.

The reconnection process is supposed to follow the most recent version of the CEI 0-21. The loading of the DG unit, thus, must be gradual: the transient from the initial no-load condition (at the instant of connection) to the nominal power value should not exceed a maximum positive gradient of 20% per minute of the maximum power of the static generator.

6.1.3. Reactive Power Supply and Absorption

The exchange of reactive power must be supplied automatically, according to the voltage measured at the static generator terminals, as shown in the next figure:

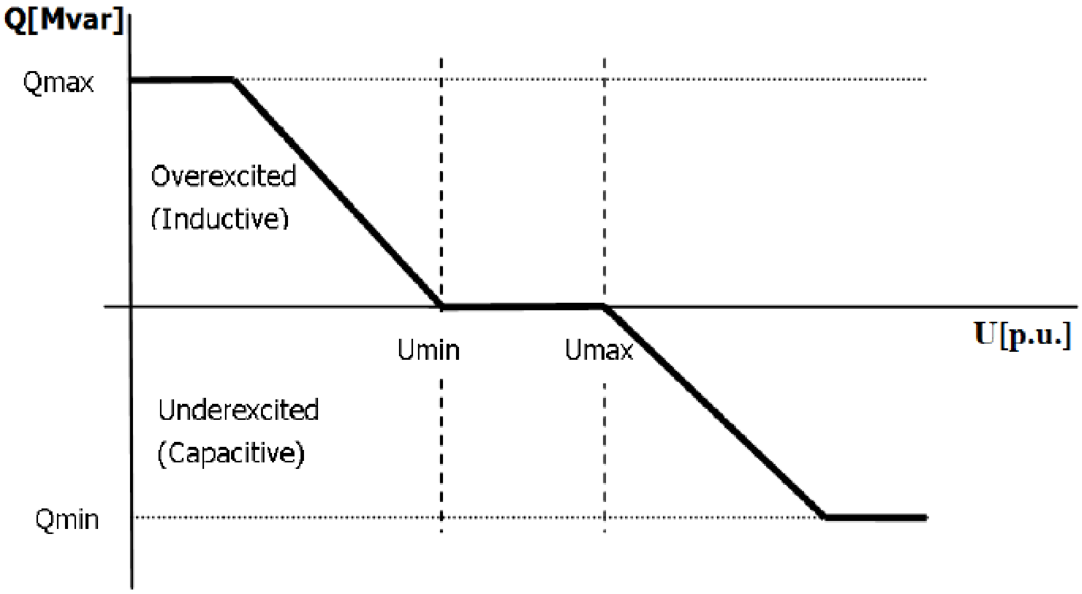

Figure 6.4: Characteristic curve Q(V)

This graph is univocally defined by the following voltage thresholds: V2s, V1s, V1i, V2i. For the thesis, the selected values are reported in Table 6.1:

Table 6.1: Q(V) control law thresholds

Q(V) control law	V2i	V1i	V1s	V2s
[p.u.]	0,90	0,95	1,05	1,10

6.1.3.1. Implementation of the Q(V) Regulator

In Figure 6.5, the block diagram of the Q(V) control law is reported:

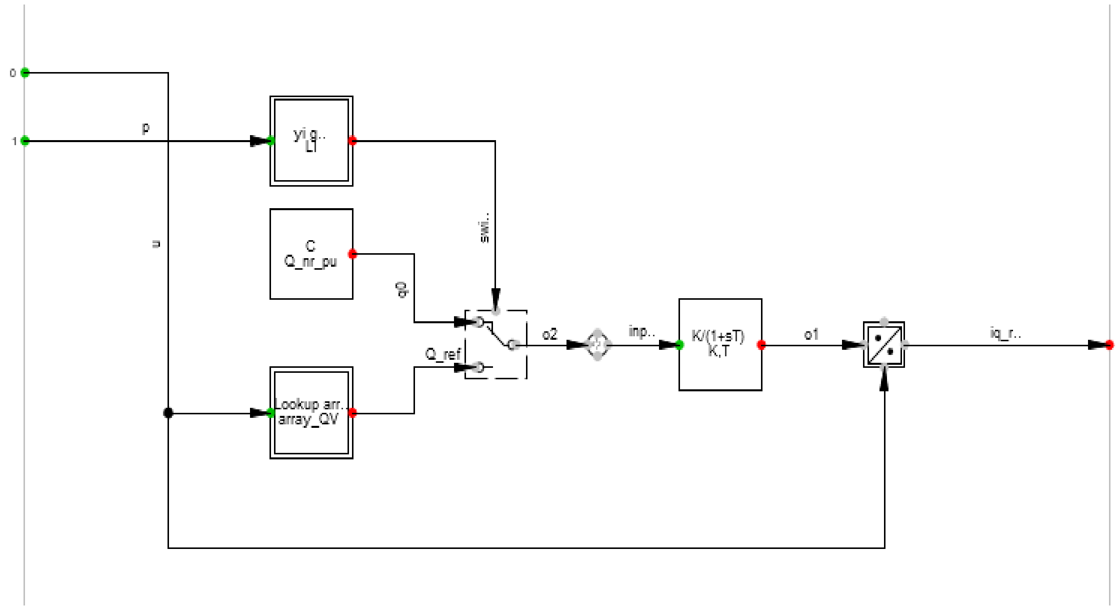

Figure 6.5: Block representation of Q(V) control laws

In Table 6.2 the inputs and output of the model are reported:

Table 6.2: Q(V) input and output variables

Q(V) control law	
Input	• 0: DG active power acquired [p.u.] • 1: voltage at the DG bus [p.u.]
Output	• iq_ref [p.u.]

The Q(V) control law is activated by performing different checks on the voltage and active power provided by the DG unit. The first check is computed on the active power: it must be greater than the lock-in value (in this case 0,2 Pmax). CEI 0-21 also requires a lock-out value (usually 0,05 Pmax) related to the active power: if this threshold is reached, the regulator must stop working.

If the delivered active power is higher than the lock-in value, the regulation is enabled. The switch block has as inputs a zero constant value related to the lack of regulation Q_nr_pu (the static generator works at unitary power factor), and the output of a look-up table when the regulation is activated. The look-up table takes as input the value of the instantaneous voltage (in p.u.) and as output the corresponding value of reactive power according to the above-reported characteristic of the Q(V) control law (Table 6.3).

Table 6.3: Characteristic of the look-up table of the Q(V) control law

Look-up table of Q(V)	
Input voltage [p.u.]	**Output reactive power [p.u.]**
0	+0.436
0.90	+0.436
0.95	0
1.05	0
1.10	-0.436
2	-0.436

Below the parameter window of the common model of the regulator:

Table 6.4: Q(V) common model parameters

Q(V)	**Parameters**
Q_nr_pu	0
K	1
T	1
LI	0.2 p.u.

Q_nr_pu stands for reactive power that the DG unit exchanges with the grid when Q(V) regulation is not activated; as previously said, this amount is zero because the static generator works with a unitary power factor. K and T are respectively the amplification factor and the time constant related to the low pass filter with output o1. LI is the lock-in value in p.u.

6.1.3.2. Test of the Q(V) regulator

The next figures (Figure 6.6 and Figure 6.7) report the voltage and powers of the DG unit after a step change in the voltage profile. The step change brings the grid voltage at 1,1 p.u, activating the Q(V) when the active power overcomes the lock-in value of 0,2 Pmax.

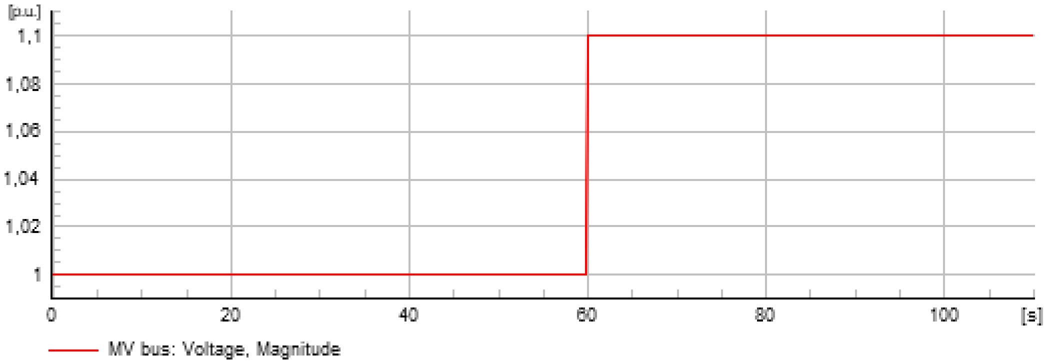

Figure 6.6: Step change in the voltage profile

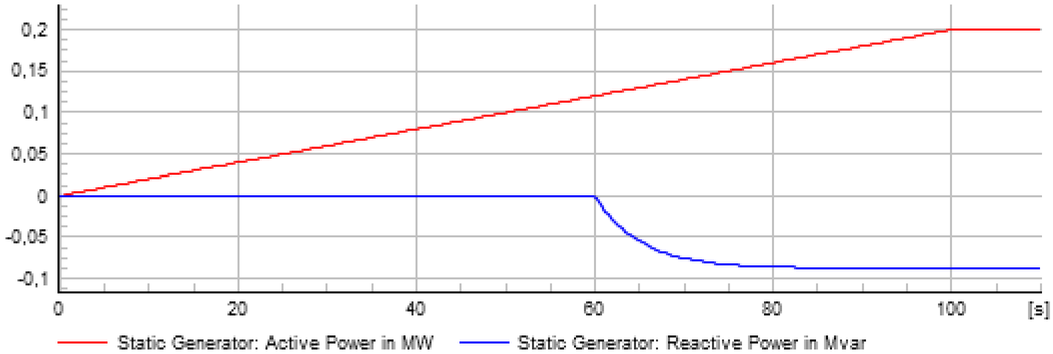

Figure 6.7: Trends of active and reactive power according to Q(V)

As expected, the active power provided by the DG unit increases as a ramp up to the nominal value (0,2 MW) and the reactive power reaches the value of -0,436 p.u. (-0,0872 Mvar). In this example, the reactive power is negative following the Q(V) characteristic: it means that the DG unit is absorbing reactive power, working in the under-excited region.

6.1.4. Limitation of the Active Power of the DG unit

In the presence of an over-frequency transient on the islanded grid, the injection of active power provided by the DG unit should be regulated according to the control logic described in paragraph 3.2.2.

In the frequency range between 47,5 Hz and 50,2 Hz, the static generator must deliver the maximum active power that it can produce. Instead, when the activation threshold is exceeded, the DG unit must reduce the exchanged active power according to the droop s, as a function of the over-frequency event. The active power delivered by the DG unit should be regulated according to a characteristic curve P(f) like the one shown next:

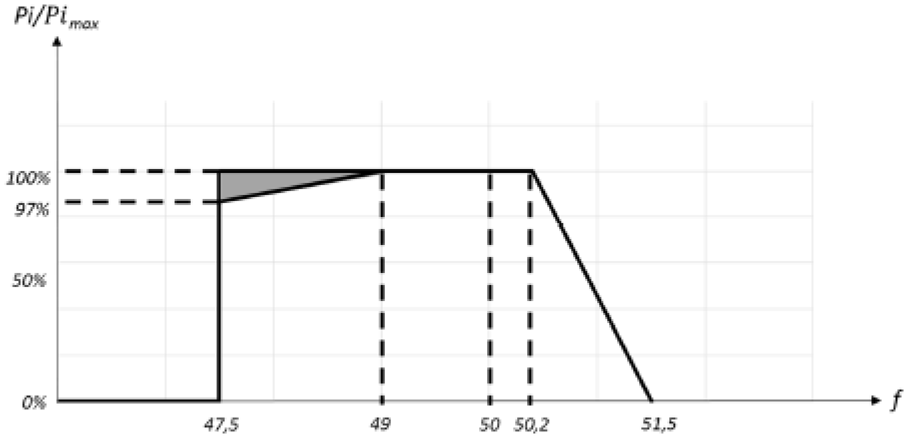

Figure 6.8: Characteristic curve P(f)

The droop s must be adjustable between 2% and 5%, with a default value of 2,6%. The activation threshold must be adjustable between 50 Hz and 52 Hz, with a default value of 50,2 Hz. In the project, the selected thresholds in frequency are reported in Table 6.5:

Table 6.5: P(f) implemented parameters

P(f) regulation	Frequency threshold	Maximum frequency value
[Hz]	50,2	51,5

The power reduction occurs linearly, in a period between 1÷2 s. Frequency measurement accuracy must be at least 10 mHz.

6.1.4.1. Implementation of the P(f) Regulator

In Figure 6.9, the block diagram of the P(f) control law is reported:

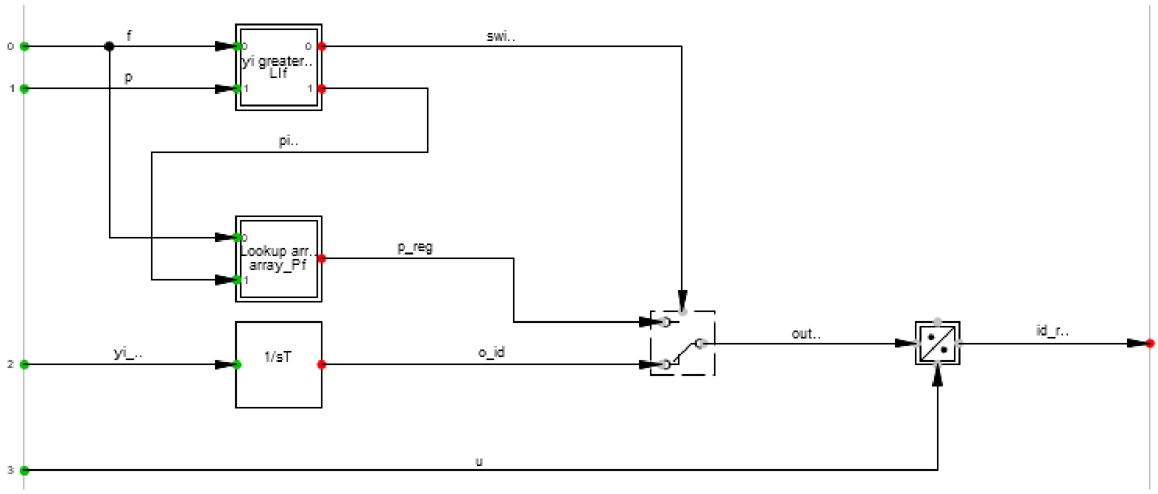

Figure 6.9: Block representation of P(f) regulator

The inputs and outputs of the common model of the P(f) regulator are described in the next table:

Table 6.6: P(f) input and output variables

P(f) control law	
Input	• 0: DG bus frequency acquired by the PLL block [Hz] • 1: DG active power acquired by the measurement power block [p.u.] • 2: yi_id [dimensionless] • 3: voltage at the DG bus [p.u.]
Output	• id_ref [p.u.]

The first two inputs are processed in the comparator block: if the activation threshold (50,2 Hz) is never reached, the switch block remains to the original position and the active power follows the ramp of connection previously described (Paragraph 6.1.2). In the other case, the upper output signal of the comparator block changes the position of the switch, and the regulation is enabled.

The input power signal p is used to track and save the active power delivered by the DG unit before the frequency activation threshold (50,2 Hz), and to verify if the DG unit is delivering a volume of power such as to justify any intervention of the regulation. The same signal is an input of the look-up table (Table 6.7): as output, it provides the value of active power that the static converter must deliver in the over-frequency condition according to the droop s of the characteristic, and the amount of over-frequency.

Table 6.7: Characteristic of the look-up table of the P(f) control law

Look-up table of P(f)	
Input frequency [p.u.]	**Output active power [p.u.]**
47.5	1
50.2	1
51.5	0
60	0

And the parameter selection window of the common model of the P(f) regulator is reported in the next table:

Table 6.8: P(f) common model parameters

P(f)	Parameters
LIf	50,2

LIf stands for the activation threshold of the P(f) control law.

6.1.4.2. Test of the P(f) regulator

Figure 6.10 and Figure 6.11 report the significant variables (frequency and active power) during a ramp change in the frequency profile. The ramp brings the grid frequency to 51,5 Hz.

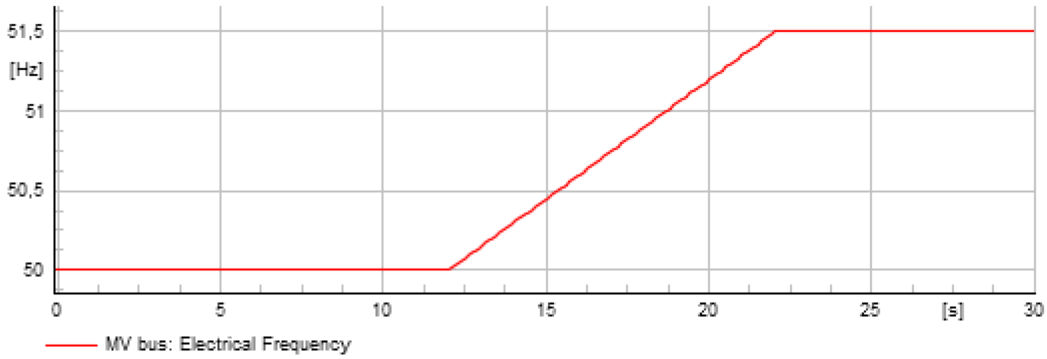

Figure 6.10: Ramp change of the frequency profile

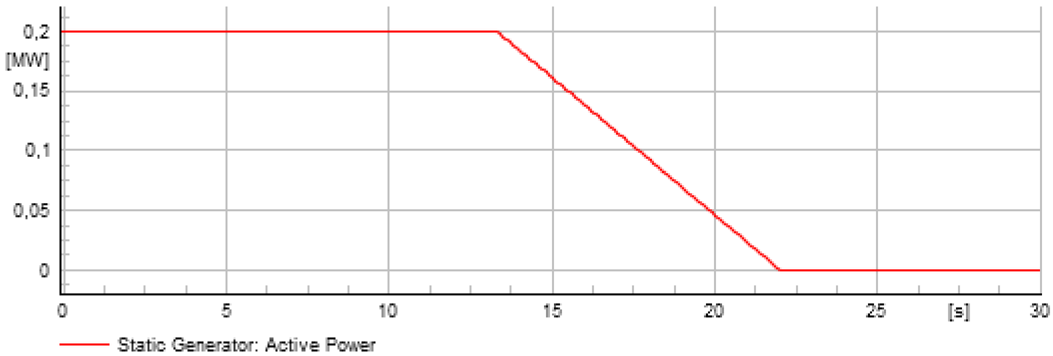

Figure 6.11: Trend of the active power of the DG unit according to P(f)

As expected, when the frequency overcomes the activation limit of 50,2 Hz, the active power decreases. When the frequency reaches the upper limit (51,5 Hz), the DG unit does not exchange any power with the grid (Pimin = 0 MW).

6.2. Active Network: model description

After a certain period of time (100 ÷ 900 s), it may occur that some DG units try to reconnect to the islanded system according to CEI 0-21/0-16. The events modeled in the present case study aim to replicate the reconnection process and its effects on the stability of the island: at the beginning of the numerical simulation, the GS alone feeds the grid. Then, the automatic reconnection of a DG unit is analyzed.

If the reconnection process does not cause instability issues, the benefits of the Q(V) and P(f) control laws are evaluated. The new configuration of the grid is reported in Figure 6.12. This model wants to represent a real-existing islanded grid in which the reconnection of the DG starts from the LV part of the network. The DG unit is trying to reconnect to the islanded system (the same one of the PN configuration presented in chapter 5).

The aim of the numerical simulations conducted on the AN is to trigger:

- the voltage upper or lower threshold (V1s, V1i) of the Q(V) regulation;
- the frequency threshold (50,2 Hz) of the P(f) regulation.

A model of the entire grid in presented (Figure 6.12).

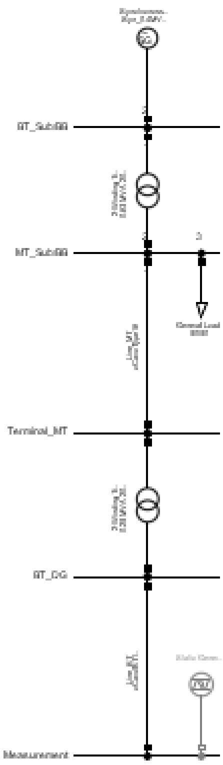

Figure 6.12: Configuration of the AN grid considered

The GS unit, as well as the entire network model on the MV side, are the same presented in paragraph 5.1. The DG unit is supposed to be connected on the LV side of the 250 kVA transformer through a LV cable line.

Table 6.9 and Table 6.10 report the parameters of the new implemented 250 kVA transformer and the MV and LV cable lines [21] [30]:

Table 6.9: Characteristics of a 250 kVA transformer

Nominal Power [kVA]	HV [kV]	LV [kV]	Vcc [%]
250	20	0,4	4

Table 6.10: Characteristics of the MV and LV cable

	Material	Cross Section [mm^2]	Resistance R [Ω/km]	Reactance X [Ω/km]	Susceptance S [μS/km]	Capability [A]	Working Temperature [°C]
LV Cable	Cu	185	0,0991	0,110	0,600	516	90

6.3. Numerical simulations

The model of the AN is the one reported in section 6.2 (Figure 6.12).

In order to prevent disturbances to the network, the reconnection of DG units occurs only when the frequency and voltage detected at the connection bus remain within the following ranges for at consistent period of time (default value: 300 s):

- 85%Vn < V < 110%Vn;
- 49,90 Hz < f < 50,10 Hz (default setting in a setting range between 49 Hz and 51 Hz).

In the next figure, the voltage and frequency profiles at the DG bus are shown, just before the reconnection of the DG itself (100 s):

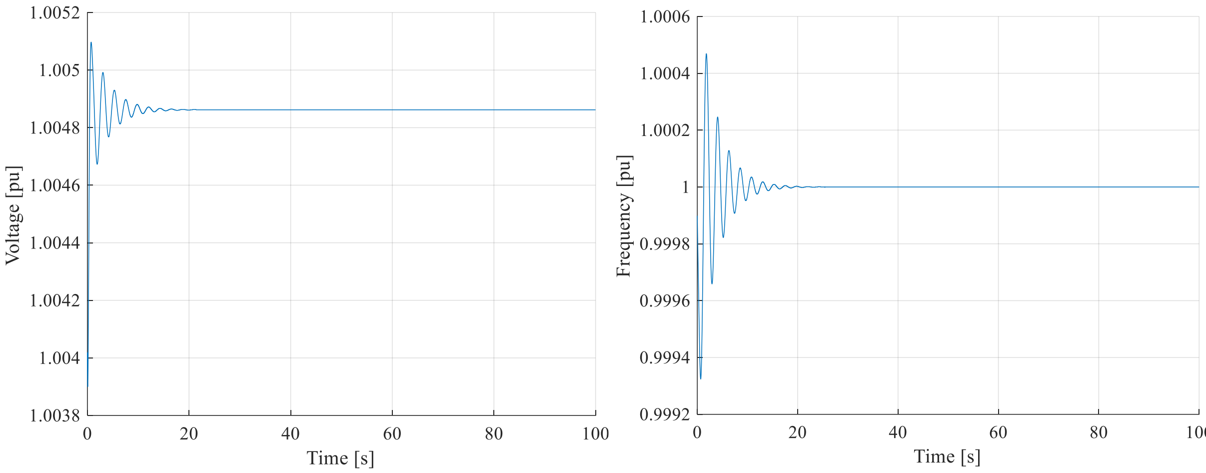

Figure 6.13: Voltage and frequency before the connection of the DG at the measurement bus

As it appears in Figure 6.13 (on the left), the voltage measured is inside the range 0,85Vn < V < 1,1Vn. Also, the frequency remains inside the frequency range (paragraph 6.1.2). Figure 6.13 (on the right) shows that the frequency value returns at the nominal value (50 Hz). The oscillations at 0 s are related to the connection of the GS to the passive network; at time 100 s the reconnection the DG unit occur.

In addition, the active power should follow a reconnection ramp to avoid unbalancing between generated and requested power (and so frequency oscillations).

In the study, the ramp profile of the active power lasts 5 minutes, with a variation of 20%Pmax per minute; from the beginning of the RMS simulation, the ramp occurs at 100 seconds and ends at 400 seconds.

Numerical simulations to study the islanded grid powered by both GS and DG units together have been conducted and possible benefits of the Q(V) and P(f) control laws (Table 6.11 reports the indexes of the conducted numerical simulations) on the islanded system have been analysed.

Table 6.11: Index of numerical simulations conducted

GS & DG	Q(V)	P(f)	Q(V) & P(f)	Motorization & P(f)
Isochronous	0	-	-	6.7
Droop	-	6.5	6.6	-

The characteristics of the load are:

$$\begin{cases} P_{load} = 0{,}8\, P_{max} = 0{,}25\ MW \\ \cos(\varphi) = 0{,}9\ inductive \\ 50\%\ static, 50\%\ dynamic\ load \end{cases} \tag{6.2}$$

Where Pmax is given by:

$$P_{max} = 0{,}8\, A_n = 0{,}32\ MW$$

(6.3)

6.4. The effect of the Q(V) regulation on the system

Once the DG is reconnected to the grid, and the reconnection process starts, the voltage at the DG bus starts increasing. This behavior is related to the nature of the orientation of the power flux along the line; before the reconnection of the DG unit, power was flowing from the GS to the LV bus: active and reactive powers were drawn from the grid. With the connection of the DG unit, the power flow reverses, and power starts to flow in the opposite direction along the same line.

6.4.1. Q(V) regulator: OFF

To highlight the benefits of the Q(V) control laws, a first simulation without regulation in place is performed: therefore, in this scenario, the DG unit supplies only active power to the system. Working at a unitary power factor, the reactive power supplied is null. At the end of the reconnection ramp, the active power delivered from the DG reaches the nominal value (0,2 MW) and the voltage profile is shown in the next figure:

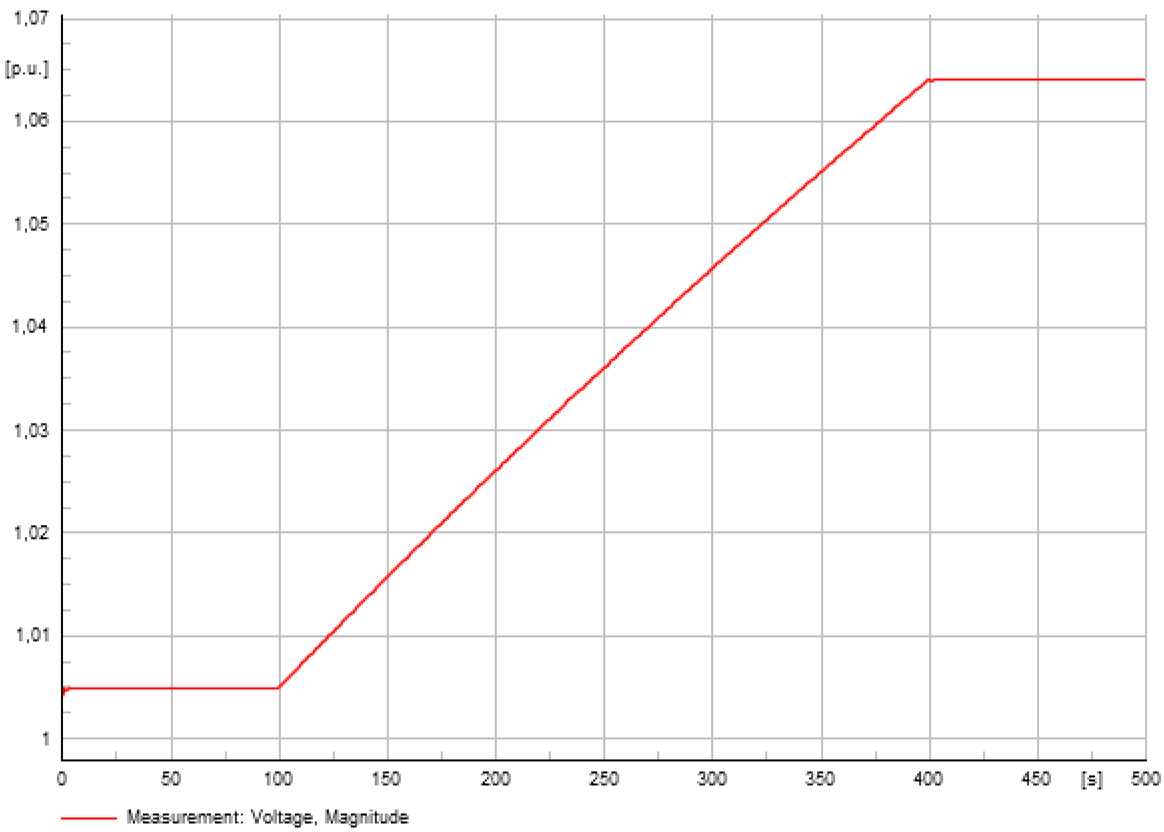

Figure 6.14: Voltage at the Measurement bus without Q(V)

In Figure 6.14, the effect of the active power ramp can be observed in the interval 100-400 s as the ramp increases by 20%Pmax per minute. At that point, the voltage reaches another steady-state value equal to 1,064 p.u.

In Figure 6.15 and Figure 6.16, the exact representation of the active and reactive powers exchanged from the DG unit and the GS are reported. Even when the Q(V) regulation is not activated, the presence of the DG unit provides a benefit to the GS: the power required by the load is now shared between the GS and the DG unit.

Figure 6.15: Active and reactive power of the GD without Q(V)

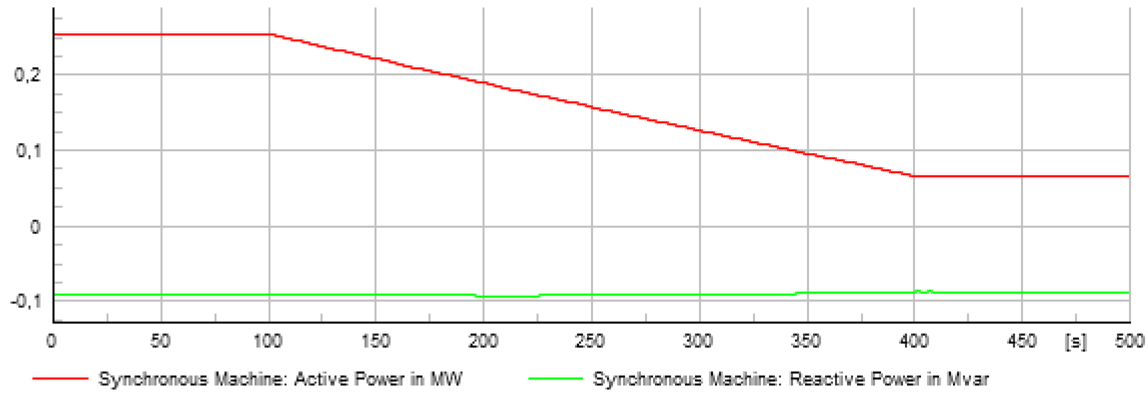

Figure 6.16: Active and reactive power of the GS without Q(V)

In Figure 6.17, both voltage and frequency at the terminals of the GS are represented. Excepting for the connection transient at the beginning of the simulation, two small transients are shown: both are related to the reconnection ramp of the DG unit: at the beginning of the simulation when the power starts to increase and at 400 s when it reaches the maximum value. Both voltage and frequency transients are not significant and do not compromise the stability of the AN or the tripping of protections. Both voltage and frequency protections of the GS (reported in Table 2.2) are regulated to trip for higher variations from the nominal values.

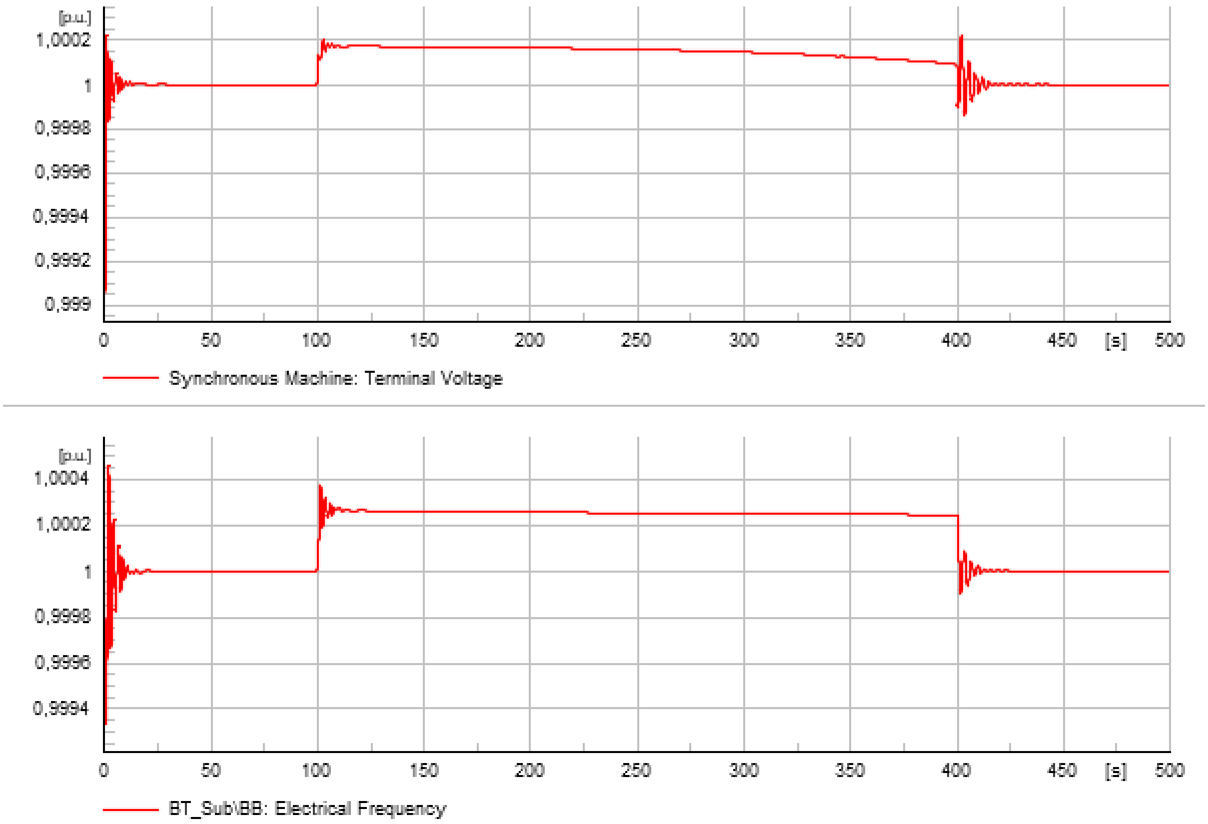

Figure 6.17: Voltage and frequency at the GS terminals without Q(V)

6.4.2. Q(V) regulator: ON

In the second scenario, the regulation Q(V) is activated: the aim is to regulate the voltage at the measurement point for values higher than V2i (1,05 p.u.) when the delivered active power reaches the lock-in value (0,2 Pmax).

In Figure 6.18, the voltage at the measurement bus is reduced with respect to the case in which the control law was not activated.

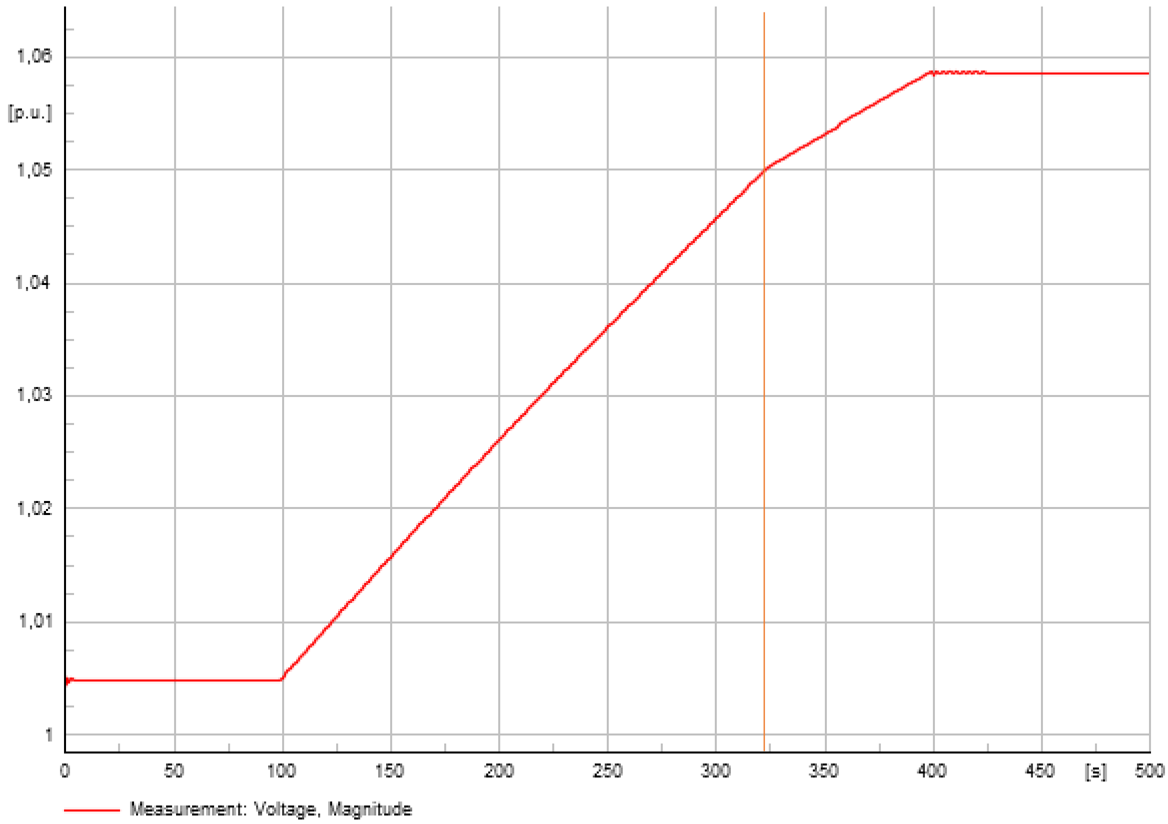

Figure 6.18: Voltage at the Measurement bus with Q(V)

The regulator works on the reactive power reducing the value of steady-state voltage: with the Q(V) regulation, the final value of voltage is 1,058 p.u, reducing the steady state value of voltage by 0,06 p.u. From the same figure, it is possible to determine when the regulation starts; at 320 s (orange vertical line), the voltage value reaches V2i, and the slope of the voltage is reduced.

In Figure 6.19 and Figure 6.20, the representation of the active and reactive powers exchanged from the DG unit and the GS are reported. With respect to the previous case without the Q(V) regulation, when the V2i (1,05 p.u.) threshold is reached, the power delivered by the DG unit is not at a unitary power factor and an exchange of reactive power occurs. From Figure 3.2, if the voltage increases, the reactive power becomes negative; the steady-state value of reactive power delivered by the DG unit is -0,015 Mvar. The reactive power provided by the GS increases by the same amount. The same behavior is seen on the active power profile: with the reconnection ramp, the DG unit active power reaches its nominal value (0,2 MW), reducing by the same amount the active power produced by the GS.

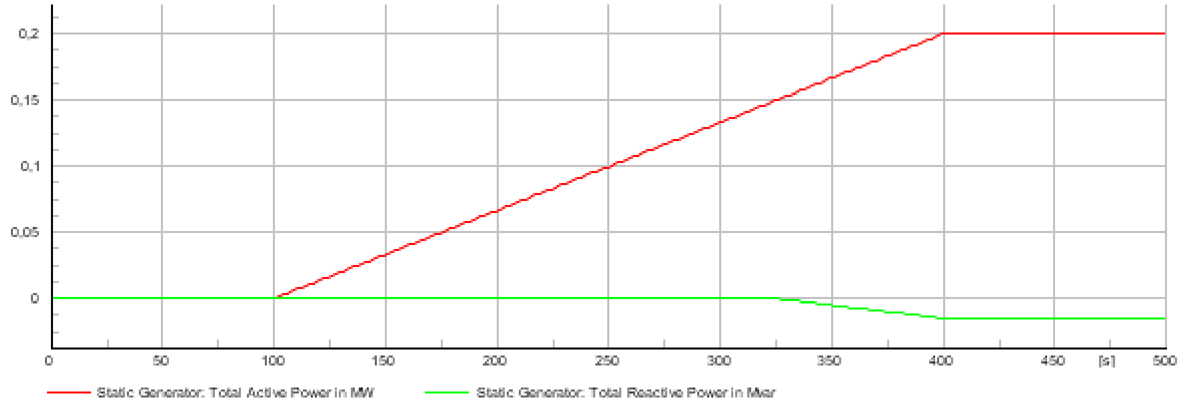

Figure 6.19: Active and reactive power of the DG with Q(V)

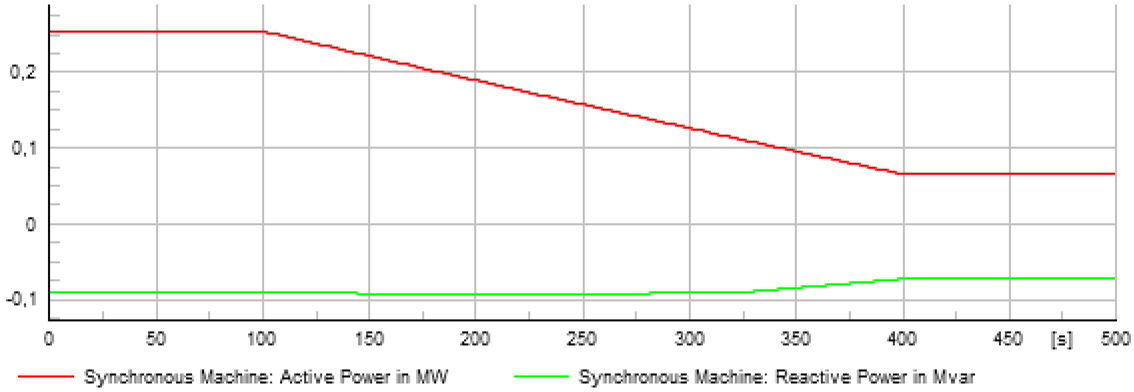

Figure 6.20: Active and reactive power of the GS with Q(V)

In Figure 6.21, voltage and frequency of the GS have small transients related to the reconnection ramp of the DG unit; both voltage and frequency transient are not significant and do not compromise the stability of the AN or the tripping of protections.

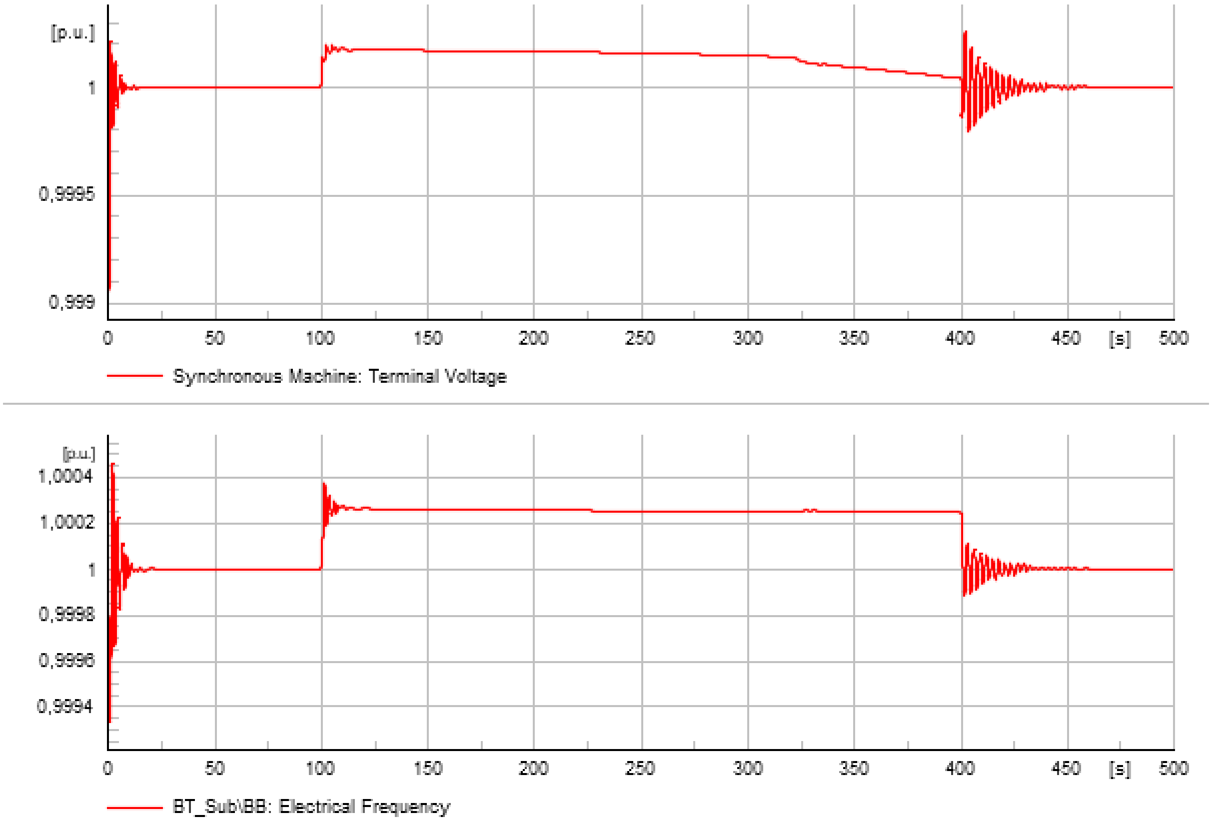

Figure 6.21: Voltage and frequency at the GS terminals with Q(V)

In conclusion, no criticalities occur when a DG unit equipped with the Q(V) control logic is reconnected to the islanded system. The transient phenomena do not compromise the stability of the system or the tripping of protections. In addition, the Q(V) control logic provides a benefit to the voltage profile at the connection point: the new steady-state value is reduced with respect to the case when the Q(V) regulation was off. Related to the GS, the reconnection process moves its operating point away from the instability region; the new steady-state value of reactive power of the GS is farther from Qmin (-0,12 Mvar).

6.5. The effects of the P(f) regulation on the system

In this study case, the isochronous condition is not considered because the frequency would remain at the nominal value (50 Hz), and activation threshold of the P(f) would never be triggered. Thus, the speed governor of the GS is implemented with a droop different from zero (equals to 4%). Before the DG unit reconnection, the frequency reaches values lower than the nominal one (50 Hz) because a MV load is connected to the grid; then, when the reconnection of a DG unit, the frequency increases. The increase of frequency is due to the load sharing between the GS and the DG unit. The load must receive the active and reactive power shown in Equation (6.2), thus, when the active power of the DG unit increases as a ramp, the active power of the GS decreases. Consequently, the resistive torque seen from the GS is reduced (Equation (4.11) and the frequency increases. In this condition, it might be possible that the frequency reaches high values (over-frequency event), and the frequency protections will trip.

In the study case, the implemented droop is equal to 4% (Figure 6.22); this specific droop is selected because, regardless the MV load and its required power, the frequency will always range between 49 ÷ 51 Hz; it means that the reconnection process is allowed for every condition of the island.

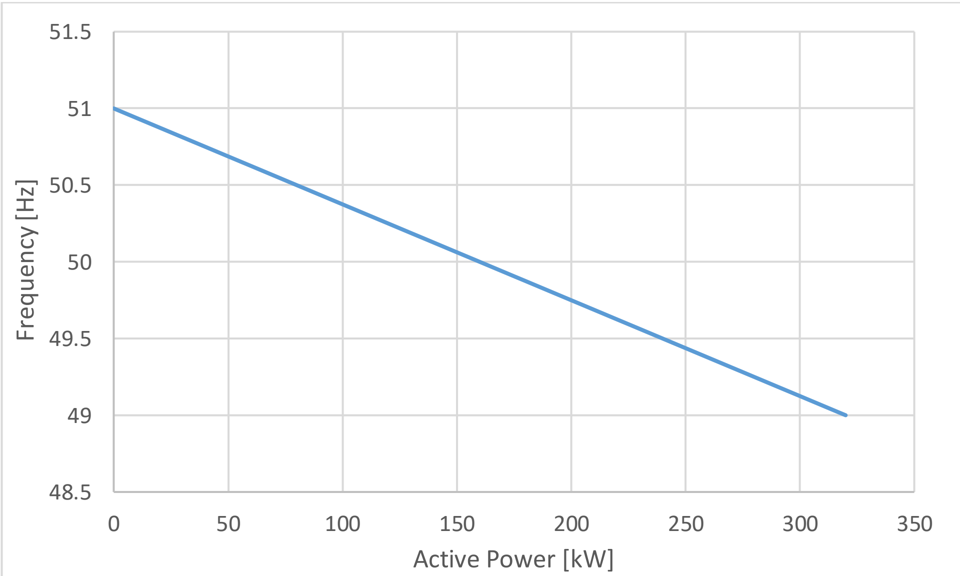

Figure 6.22: Implemented 4% droop of the speed regulator

Thus, if the frequency of the grid exceeds the activation threshold of the P(f), the regulation is activated, and the over-frequency condition stopped.

As already said, the reconnection of the static generator to the grid occurs according to a ramp. In this case, however, the ramp does not reach the maximum value (0,2 MW) due to the P(f) regulation (Figure 6.23). The stop of the reconnection ramp can be studied according to the behavior of the frequency over the period of the simulation (500 s) (Figure 6.24):

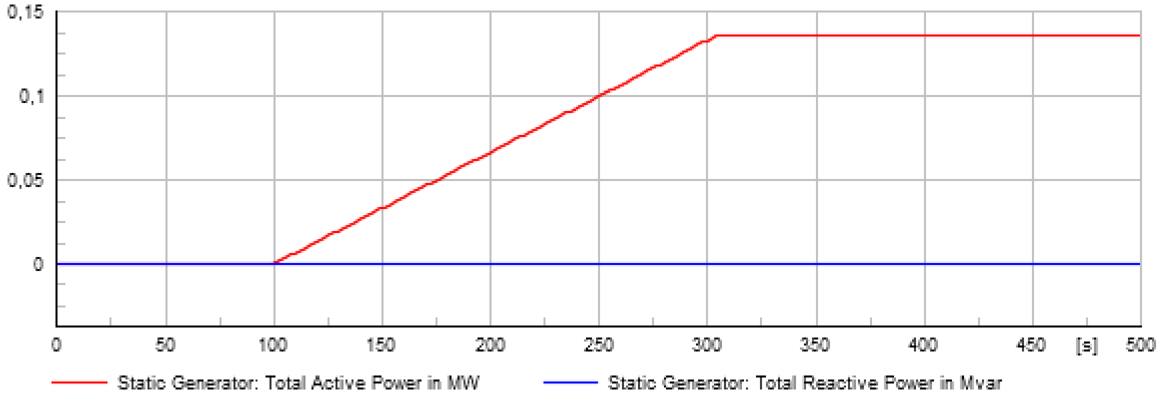

Figure 6.23: DG unit active and reactive power with P(f) regulation

In Figure 6.24, after the connection transient of the GS, the frequency reaches a steady-state value that is different from the nominal one (49,36 Hz); this behavior is imposed by the droop of the speed regulator, and by the load characteristics. Then, when the DG unit is reconnected to the grid and the reconnection ramp occurs, the frequency increases until it reaches the activation threshold of the P(f). This threshold is set to 50,2 Hz. In that instant (300 s), the active power of the DG unit remains constant. The active power provided by the DG unit equals 0,135 MW.

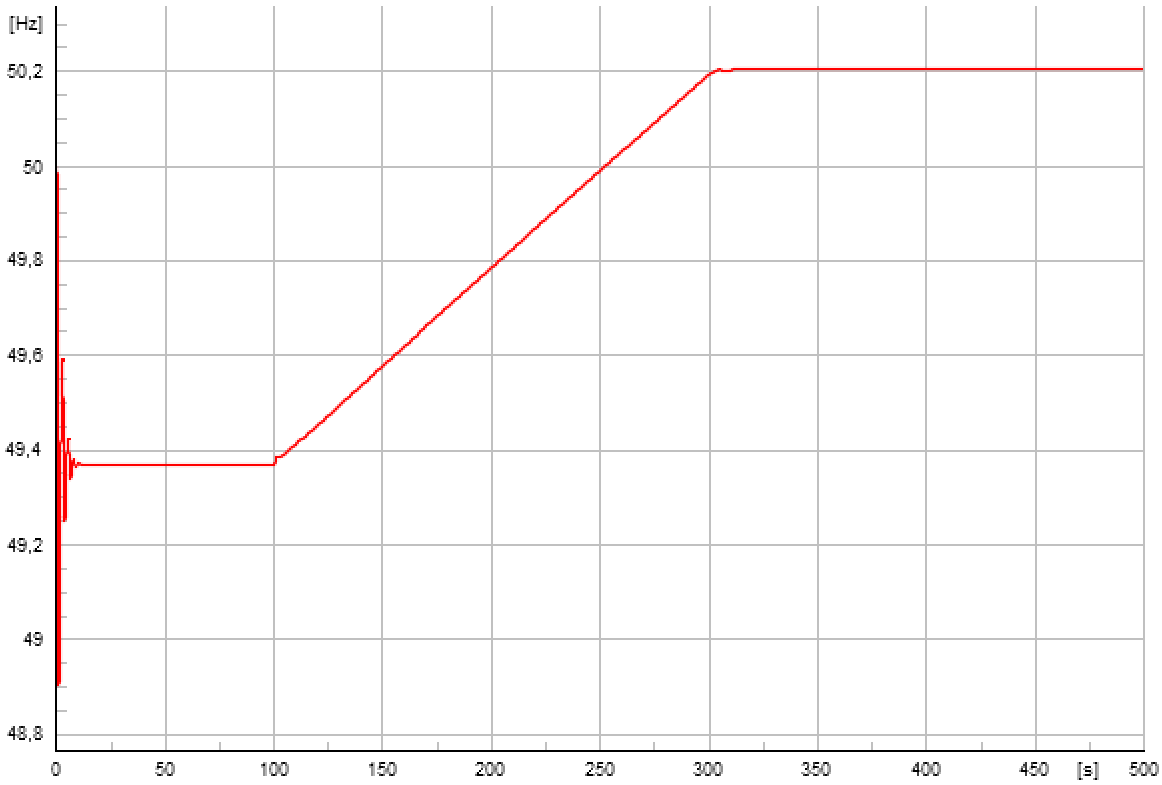

Figure 6.24: Frequency of AN with P(f) regulation

In Figure 6.25, the active and reactive powers of the GS are plotted. The active power follows a descending ramp, and the steady-state value is equal to 0,124 MW. The reactive power remains constant for the whole simulation.

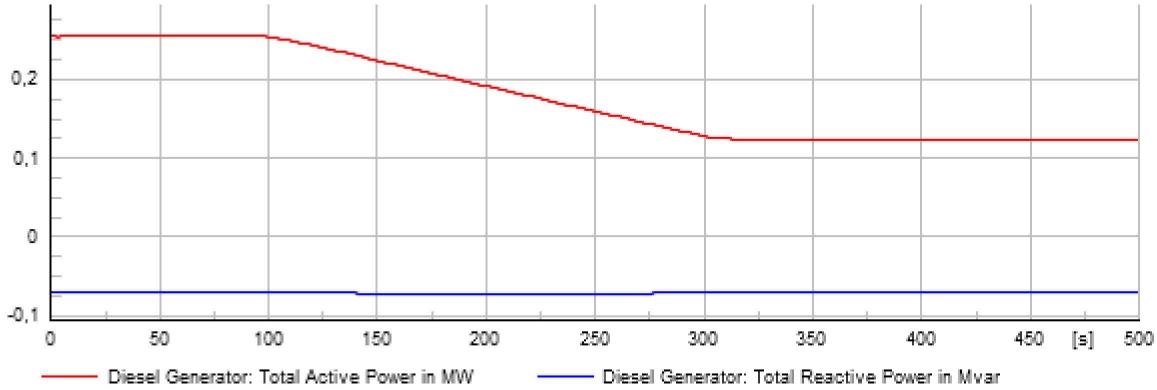

Figure 6.25: GS active and reactive power with P(f) regulation

Another positive aspect of the P(f) regulation is related to the voltage profile at the DG bus: if the active power does not reach the maximum value, the voltage does not reach the maximum value itself. The voltage increases because an amount of active power flows from the DG unit to the grid, but if this amount is lower than the maximum (0,2 MW), even the voltage increase is lower than the expected one. In Figure 6.26, when the frequency reaches the threshold of activation, the voltage profile decreases at 1,067 p.u.

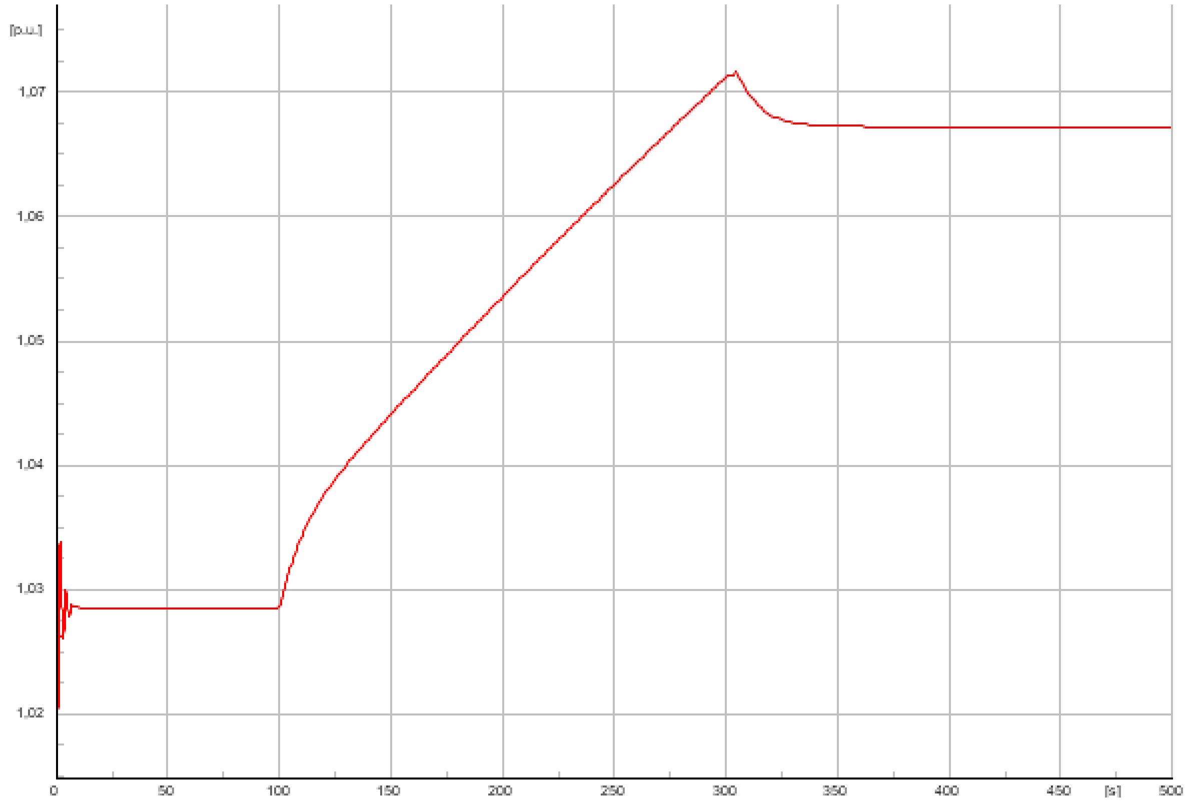

Figure 6.26: Voltage measurement with P(f) regulation

In Figure 6.27, the voltage profile at the GS terminals presents a small transient related to the reconnection ramp of the DG unit: it does not compromise the stability of the AN or cause the protections' tripping. The frequency profile – being the grid small – is the same of Figure 6.24.

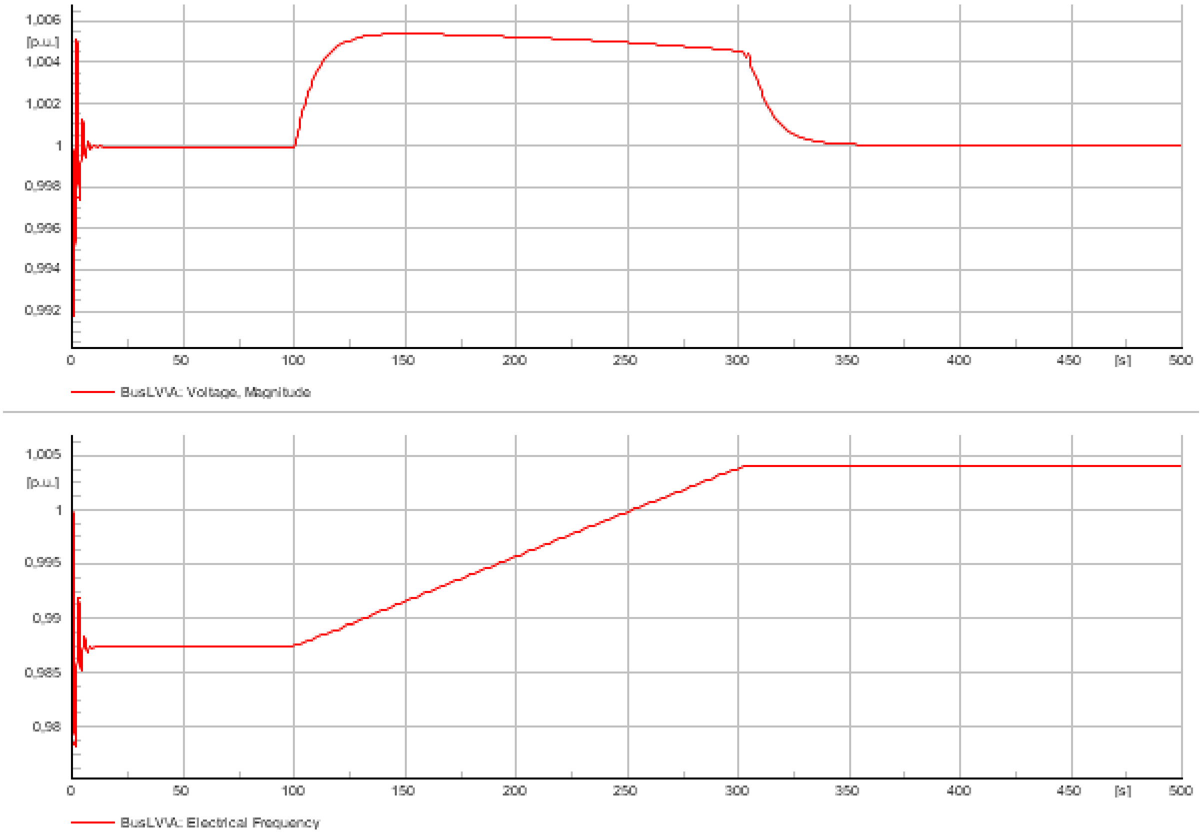

Figure 6.27: Voltage and frequency at the GS terminals with P(f)

No criticalities occur when a DG unit equipped with the P(f) control logic is reconnected to the islanded system. The transient phenomena do not compromise the stability of the system or the tripping of protections. In addition, this control logic provides a benefit to the frequency profile of the entire grid: over-frequency events are regulated by the active power provided by the DG unit. However, this regulation has a drawback for generator users: when an over-frequency condition is observed, the active power provided by the DG unit limited even if the grid is stable.

Related to the GS, the reconnection process moves its operating point away from the instability region; the new steady-state value of reactive power of the GS is farther from Qmin (-0,12 Mvar).

Considering the widest range of frequency for the reconnection of DG units in CEI 0-21 (49 ÷ 51 Hz), the 4% droop is selected because it allows the reconnection of the DG for every load conditions. An additional analysis has been performed on other droops; the amount of active power that the load required, as well as the active power range to start the reconnection process, have been studied. The droops considered are reported in Figure 4.8. If the frequency is higher than 51 Hz or lower than 49 Hz, the reconnection process is not enabled. The active power variations for different droop conditions are reported in the next table:

Table 6.12: Active power ranges for different droops and frequency ranges

	49,90 ÷ 50,10 Hz	49,50 ÷ 50,50 Hz	49,00 ÷ 51,00 Hz
2% droop, ΔP [p.u.]:	0,22 (0,41 ÷ 0,63)	1 (0 ÷ 1)	1 (0 ÷ 1)
4% droop, ΔP [p.u.]:	0,11 (0,44 ÷ 0,55)	0,52 (0,23 ÷ 0,75)	1 (0 ÷ 1)
6% droop, ΔP [p.u.]:	0,08 (0,47 ÷ 0,55)	0,34 (0,33 ÷ 0,67)	0,67 (0,17 ÷ 0,84)
8% droop, ΔP [p.u.]:	0,05 (0,48 ÷ 0,53)	0,26 (0,38 ÷ 0,64)	0,42 (0,25 ÷ 0,67)

From this table:

- higher the droop, lower the range of active power for the reconnection of the DG unit;
- wider the frequency range, higher the range of active power for the reconnection of the DG unit.

6.6. Q(V) & P(f)

In this study case, the reconnection of a DG unit equipped with both control laws is studied.

The aim is to evaluate the benefits related to a DG unit with both control laws working together. In particular, the implemented model of DEGOV1 is the one with droop equal to 4% as for the P(f) regulation.

Regarding the frequency of system (Figure 6.28), the behaviour is the same as the previous study case (Paragraph 6.5): after an initial transient, the frequency reaches a steady-state value that depends on the size of the load, and the considered droop. At 100 s, the frequency starts to increase due to the reconnection ramp of the DG unit to the system. A portion of the power required by the load is provided by the DG unit (no more by the GS one). The frequency increases until the activation threshold of P(f) (50,2 Hz) is reached.

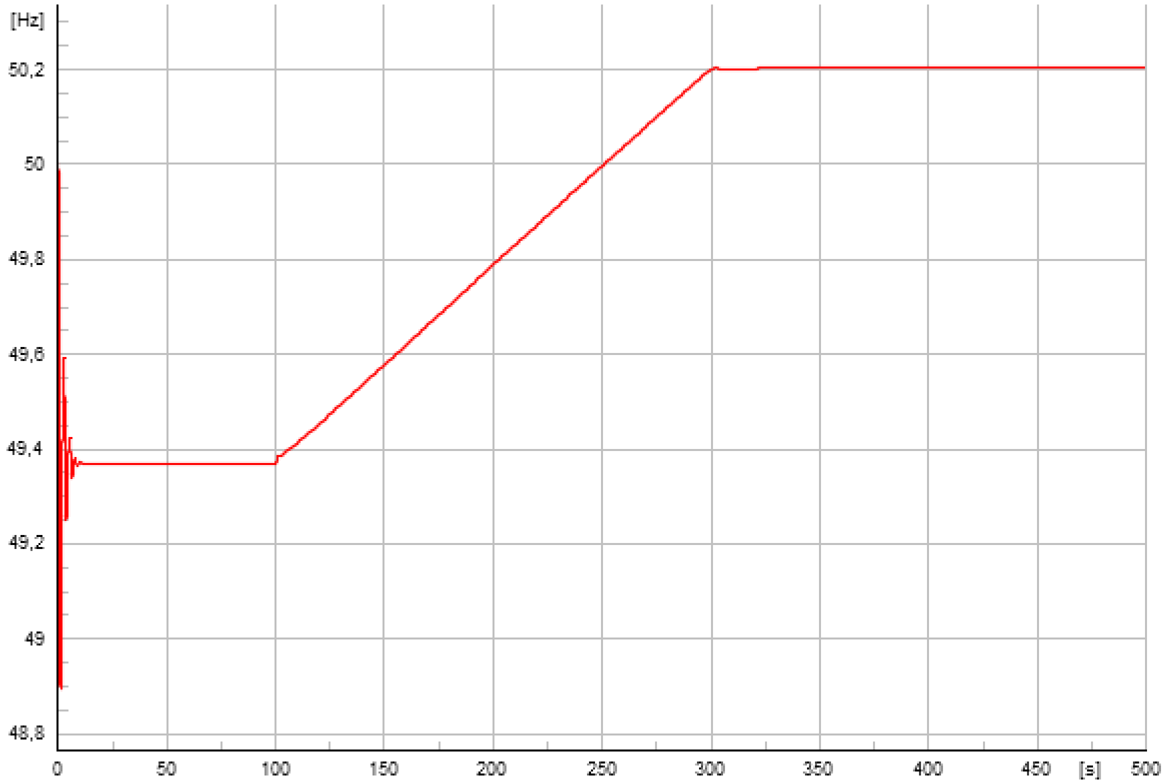

Figure 6.28: Frequency of the grid (GS + DG) with Q(V) and P(f)

When the activation threshold is reached, the ramp ends, and the active power injected by the DG unit remains constant at 0,14 MW. Being activated the Q(V) control logic, the reactive power exchanged by the DG is different from zero. Following the characteristic in Figure 6.4, the DG absorbs reactive power, providing a positive effect for the GS (Figure 6.30). The reactive power produced by the GS is reduced and the operating point is more stable than before, according to the capability curve of the GS (Figure 6.29). The load sharing effect reduces the active and reactive (in absolute value) power produced by the GS.

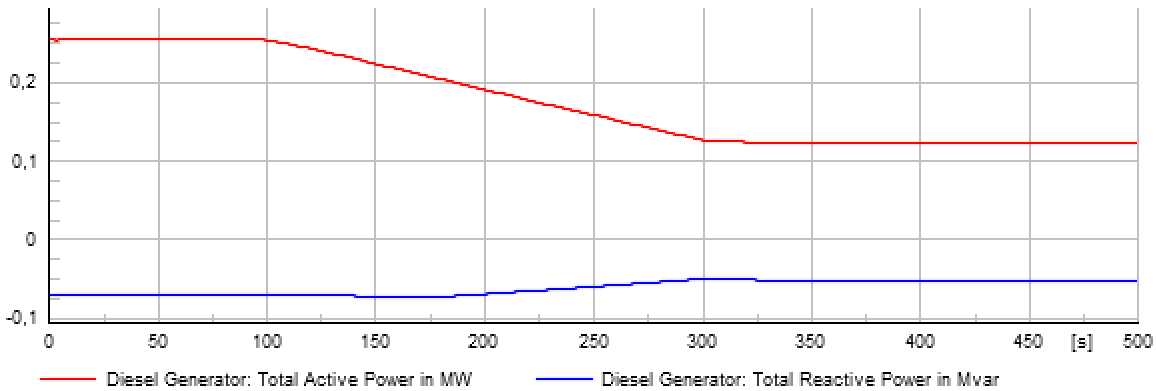

Figure 6.29: GS active and reactive power with Q(V) and P(f)

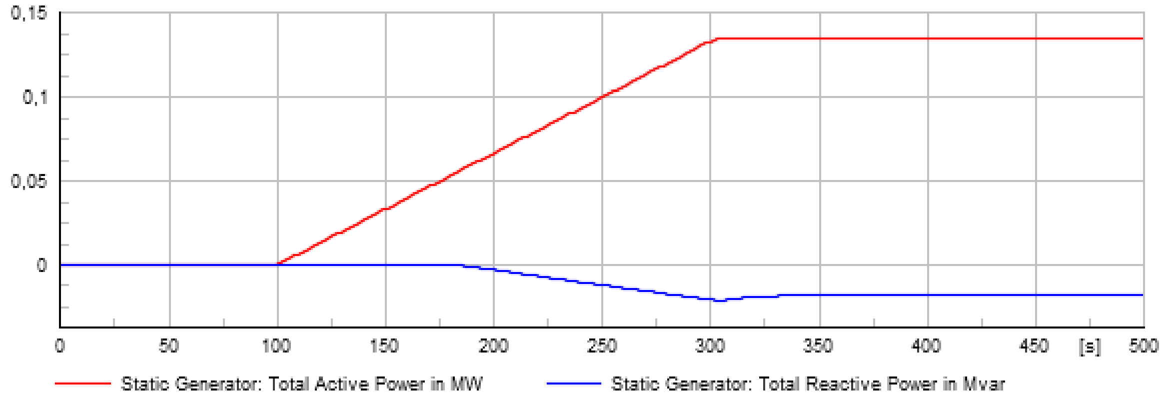

Figure 6.30: DG active and reactive power with Q(V) and P(f)

Regarding the voltage profile at the connection point (Figure 6.31), a dual contribution of both regulations can be seen. The Q(V) regulation acts when the voltage reaches the 1,05 p.u by absorbing reactive power from the grid; instead, the P(f) – acting on the active power provided by the DG unit, reduces even more the voltage because the active power does not reach the maximum power that it can provide to the grid. Thus, when only the P(f) regulation was activated the steady-state value of voltage was 1,067 p.u, now – with both regulations activated – the final steady-state value is equal to 1,061 p.u.

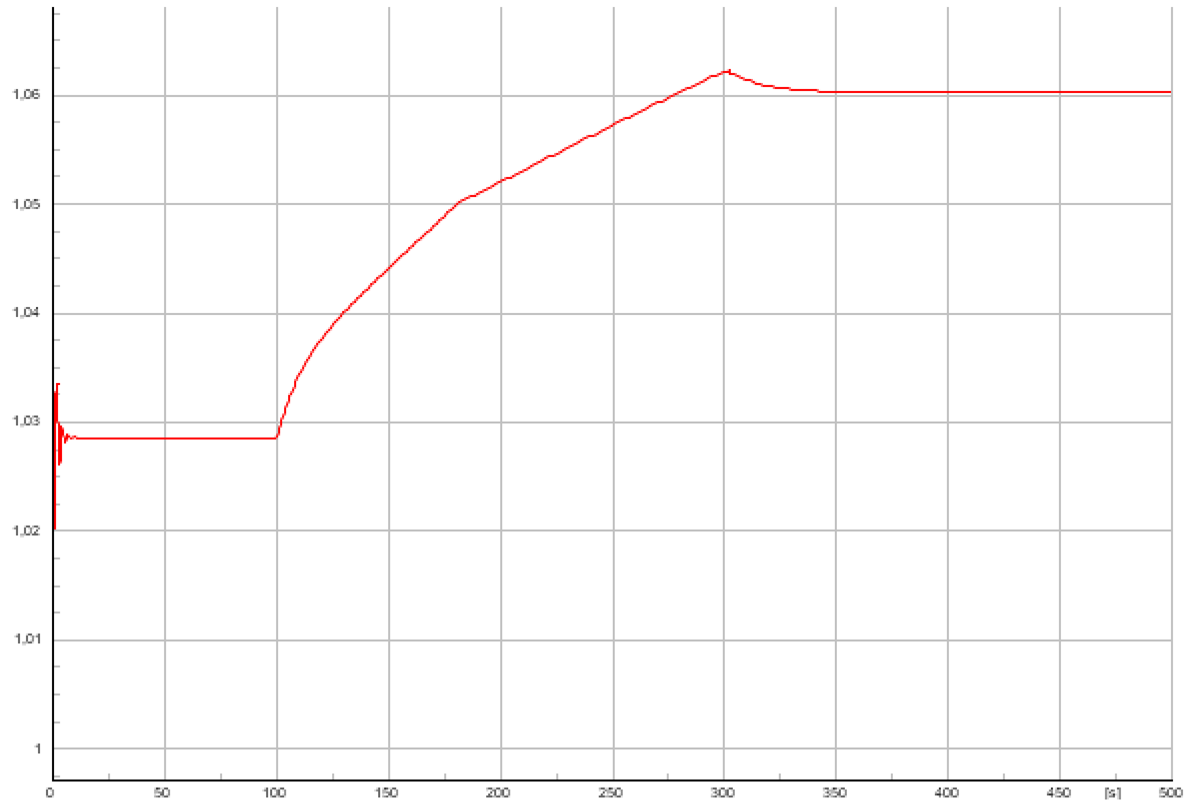

Figure 6.31: Voltage measurement with Q(V) and P(f)

In Figure 6.32, the behavior of frequency follows the same trend of Figure 6.28; regarding the voltage profile, no significant transients are present, and the protections do not trip.

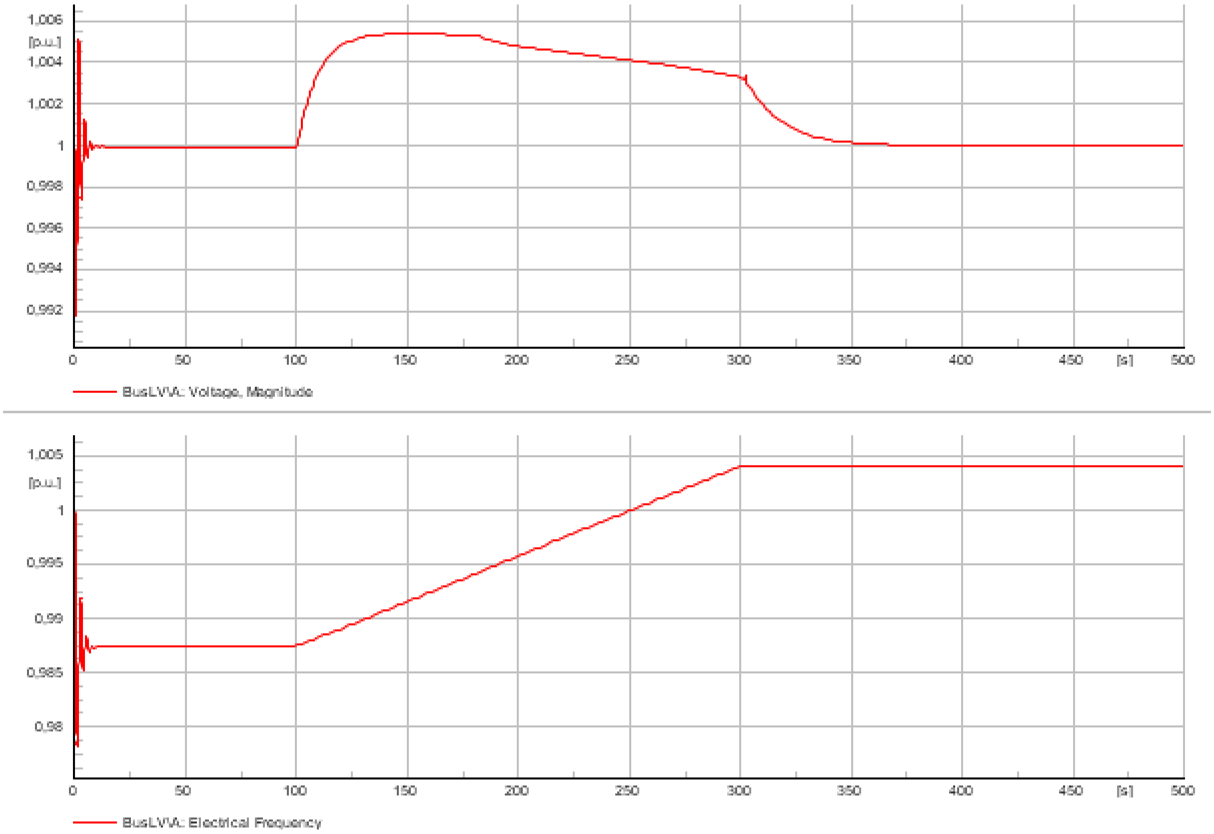

Figure 6.32: Voltage and frequency at the GS terminals with Q(V) & P(f)

In conclusion, no criticalities occur when a DG unit equipped with both control logics is reconnected to the islanded system. The transient phenomena do not compromise the stability of the system or the tripping of protections. In addition, the Q(V) control logic provides a benefit to the voltage profile at the connection point: the new steady-state value is reduced with respect to the case when the Q(V) regulation was off. The P(f) control logic provides a benefit to the frequency profile at the connection point: the new steady-state value cannot reach frequencies higher than the activation threshold of the P(f) regulation (50,2 Hz). However, the P(f) regulation has a drawback for generator users: when an over-frequency condition is observed, the active power provided by the DG unit limited even if the grid is stable.

Related to the GS, the reconnection process moves its operating point away from the instability region; the new steady-state value of reactive power of the GS is farther from Qmin (-0,12 Mvar).

6.7. Motorization process

In the last simulations, the MV load requests an active power that is higher than the nominal active power delivered by the DG unit; this means that the GS continues to work as a generator even when the ramp of active power of the DG is completed, supplying the remaining active power to the load. The aim is now to understand if the intentional island is still stable even if the GS starts working as a motor (i.e., reverse power flow condition: motorization) and the active power is provided to the MV load just by the DG unit. By recalling the alternator protections of Table 2.2, if two or more GS fed the grid, each GS is equipped with a directional relay protection (Table 6.13): if the GS starts working as a motor, the protection trips and the group is disconnected from the grid.

Table 6.13: Directional relay protection for active power fluxes

Directional relay of active power (32 or 67)	Motor power calibration with a delay of (5 ÷ 10) seconds	Always required for groups in parallel

Therefore, in this study case, the power required by the load is reduced to make the phenomenon of motorization happen; the characteristics of the MV load become:

$$\begin{cases} P_{load} = 0{,}3\ P_{max} = 0{,}1\ MW \\ \cos(\varphi) = 0{,}9\ inductive \\ 50\%\ static, 50\%\ dynamic\ load \end{cases}$$

In this study case, before the reconnection of the DG unit, the amount of active power produced by the GS equals the one required by the load; then, when the connection and loading ramp of the DG unit occur, both the GS and DG units feed the system, supplying the load. After some time (225 s), the amount of power produced by the DG unit reaches the power required by the load (0,1 MW in this case study).

6.7.1. Modified speed governor

If the GS starts working as a motor, it is not able to control and regulate the frequency of the grid. Thus, some adjustments should be made on the speed governor (Figure 6.33). The output of the actuator block of the speed governor is the throttle signal, a signal that controls the position of the fuel gate. For the last numerical simulations (thus, for all the applications in which the GS injects active power into the grid), this signal was lower-saturated at zero. As a result, the torque as well as the active power of the GS were not able to reach negative values. In this study case, the lower-saturation is set at -1 p.u. Thus, the torque and the active power could be negative. However, another adjustment is implemented: when the active power reaches zero, an additional path is enabled; a positive signal comes at the switch that changes its position: the input signal of the switch is no more the output of the actuator block, but t2.

With these changes, if the active power is lower than zero, the frequency of the system is no more regulated by the speed governor (due to the fact that GS is working as a motor), and the output pt of the speed governor is controlled by t2.

Of primary importance is the value of the signal t2. This value it is difficult to quantify because it depends on the diesel motor of the GS; it has been estimated between the 0,2 ÷ 0,3 p.u. of the maximum active power. For this study case, t2 is set to 0,2Pmax, and this value is maintained constant despite the trend of the active power of the DG unit [31].

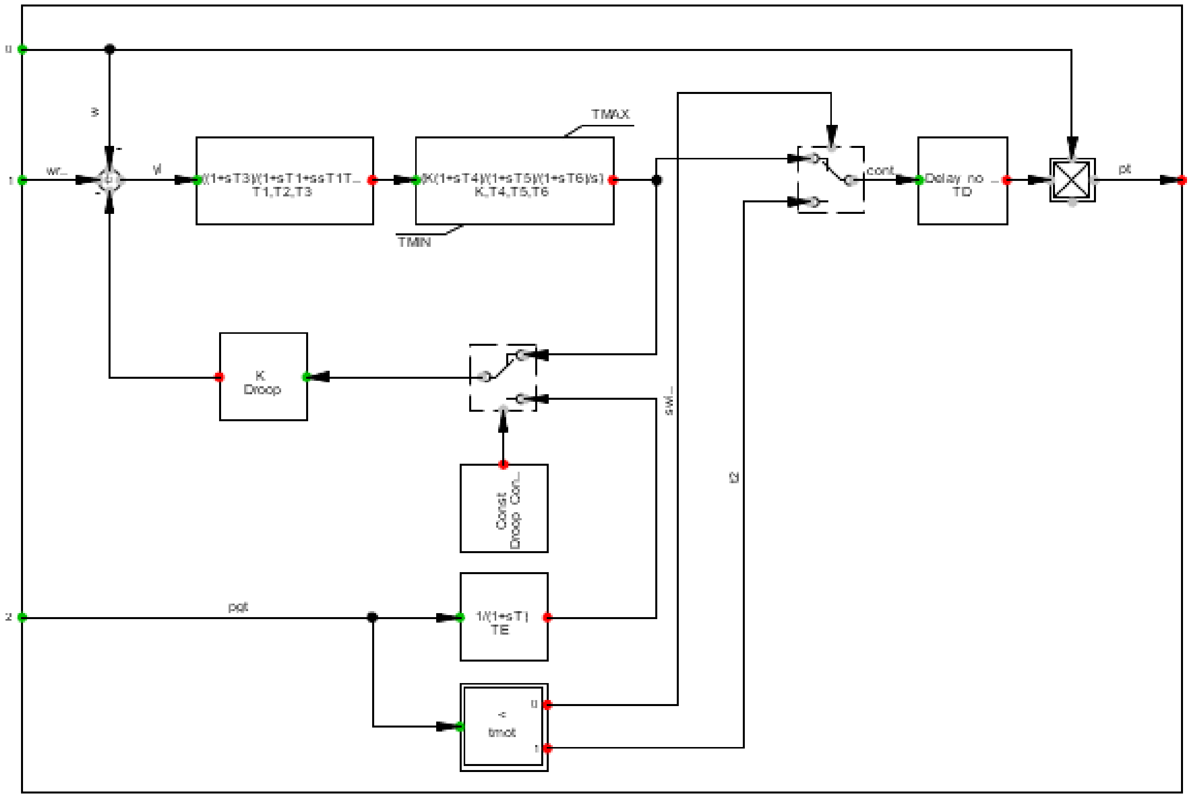

Figure 6.33: Modified block scheme of DEGOV1

6.7.2. Numerical simulation & results

A dynamic simulation is conducted through DigSilent PowerFactory software to understand if the stability of the system is maintained or not, even if the GS is not equipped with a directional active power protection (Table 6.13).

In Figure 6.34, the frequency is kept constant at the nominal value (50 Hz) until the GS active power is delivered to the grid. The active power of the GS starts to decrease and reaches zero at 225 s (orange vertical line). Then, the frequency is no more regulated by DEGOV1 (the switch changes the input signal to t2), and it reaches 40 Hz. Frequency protection would immediately trip, and the GS is disconnected from the grid.

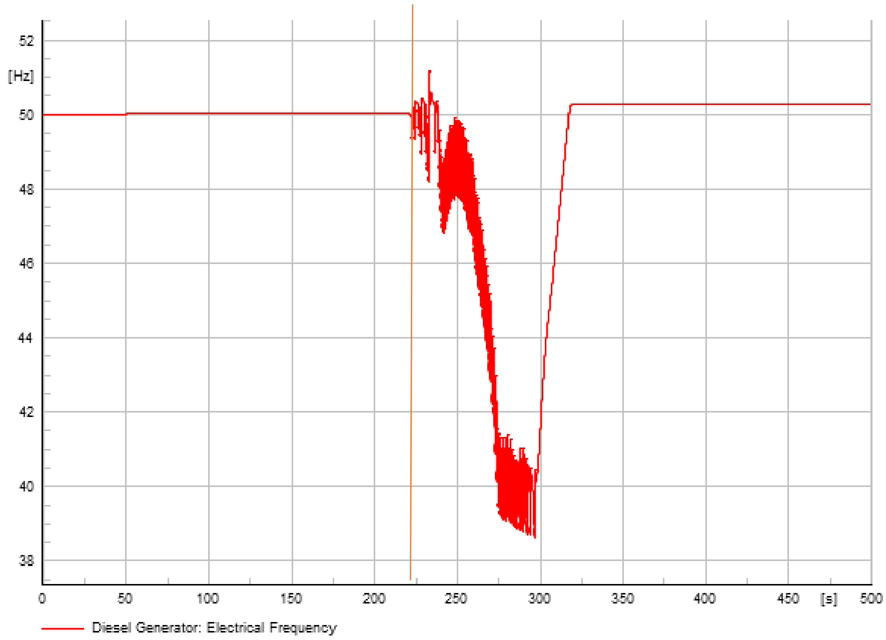

Figure 6.34: Frequency variation in motorization process

In addition, in Figure 6.35, the active and reactive power of the GS are shown. When the active power becomes negative, a huge transient occurs for both powers; the capability limits are overcome, and the island will degenerate.

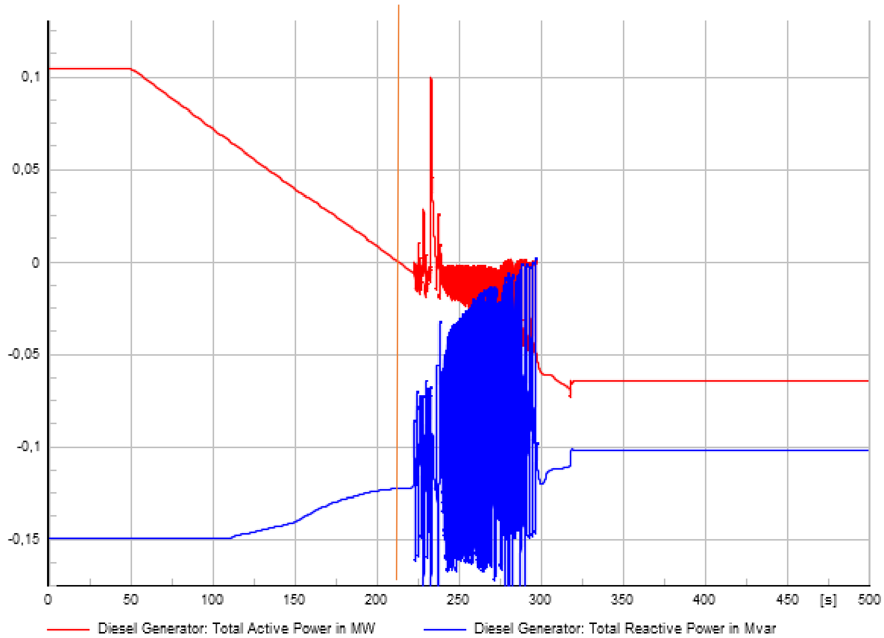

Figure 6.35: Active and reactive power during the motorization process

In conclusion, if the active power required by the load is lower than the power provided by the DG unit, the stability of the island is compromised. The island runs out anyway, even without protection of directional power flux on the GS, but the presence of the protection is still desirable to avoid damage to the machine, as it will reasonably open in a shorter time than frequency or voltage protections.

7 Conclusions

The analysis of technical aspects related to intentional islanded operation on distributed network by GSs and DG units have been conducted. To this end, a deep analysis was conducted through models of the grid, used to highlight the static and dynamic limits on the stability of the intentional island. In particular, elements such as significant voltage drops due to the extension of the lines, different loading conditions, have been introduced. The behaviour of the island has been analysed when different types of generators (rotating and static ones) are forced to interact with each other: particular attention was related to the introduction of static converters, which today represent the majority of distributed generation plants.

Regarding the PN study case, the study suggests that the GS counterfeeding process is practically feasible in islanded portions of the grid. In particular:

- under any load conditions, overhead line-systems can be energized through GS without stability issues for the island for a maximum of 15 km of length. The environments in which most of the lines are overhead are rural or mountain areas. In these contexts, the resolution of faults may require days, and the introduction of a GS should significantly improve the quality of the service for end users;
- cable line-systems could present stability issues when the length of the line increases over a certain level(i.e., in full load condition, the maximum length is 10 km for 25 mm^2 of section). This threshold depends on the size of the GS and power required by the load, as well as if the speed governor is working with a droop different from zero or not. Thus, in urban environments (or in mountain contexts where long cable lines have been laid), the GS counterfeeding method should be carefully evaluated.

Thus, GS counterfeeding process reduces the period of outages for the final users.

In addition, the direct starting process of a LV three-phase AM has been studied. It results that the direct starting is possible for motors with active power lower than one third the complex power of the GS. Better starting performances are related to double cage AMs because of the higher starting torque, reduced starting current/reactive power, and faster transients.

In conclusion, LV AMs can be powered by the GS without creating instability issues to the islanded PN system. However, an extensive analysis should be conducted for the implemented protections and their own tripping thresholds and time of interventions. Depending on the implemented protections, the voltage ones may trip at the starting process, when the current reaches abnormal values.

Regarding the AN study case, the reconnection process have been investigated. Control logics of active and reactive power have been modelled according to the standards.

When reconnected, the regulations Q(V) and P(f) of the DG provide some benefits to the system:

- the voltage at the connection point is reduced, according to the Q(V) characteristic. This regulation helps the system remains inside stabile conditions.
- the frequency could not reach abnormal values due to the P(f) control logic: whenever the activation threshold is reached, the active power provided by the DG becomes constant.

However, the reconnection process may also create instability to the system. The active power injected inside the system by the DG units should not exceed the effective active power delivered by the GS. Otherwise, the remaining active power contribution flows inside the GS, inverting the power flux. Directional active power flux protections will trip immediately.

7.1. Future developments

This work lends itself to future improvements in the direction of further extending the knowledge of the limits of GS. The implementation of the GS in a real-existing grid (both in a rural and urban context) should be developed.

Lastly, the difficulty in promptly deploying GS, related to the fact that they need to be physically carried and placed nearby the portion of the grid to be re-energized (time-consuming procedure, which increases the out-of-service time) could be avoided in the future thanks to DERs. Great interest exists in using DERs power plants in place of GSs to manage the electric island, enabling their black start and grid forming capabilities. Different coordination logics between these suppliers should be investigated, as well as their protection systems and operating regulations.

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A Appendix A

A.1. DEGOV1

DEGOV1 parameters	Ranges
Actuator Gain K [p.u./p.u.]	5 ÷ 25
T4 [s]	0 ÷ 25
T5 [s]	0 ÷ 10
T6 [s]	0 ÷ 0,5
Combustion Delay [s]	0 ÷ 0,125
Droop [p.u.]	0 ÷ 0,1
Time constant Power Feedback [s]	0 ÷ 1
T1 [s]	0 ÷ 25
T2 [s]	0 ÷ 0,5
T3 [s]	0 ÷ 10
Droop Control	0/1
Minimum Throttle TMIN [p.u.]	-0,05 ÷ 0,5
Maximum Throttle TMAX [p.u.]	0 ÷ 1,5

A.2. EXST2A

EXST2A parameters	Ranges
Measurement Delay Tr [s]	0 ÷ 0,5
Controller Gain Ka [p.u.]	10 ÷ 1000
Controller Time Constant Ta [s]	0 ÷ 1
Excitor Time Constant Te [s]	0,03 ÷ 2
Excitor Constant Ke [p.u.]	0 ÷ 1
Stabilization Path Gain Kf [p.u.]	0 ÷ 0,3
Stabilization Path Time Constant Tf [s]	0,04 ÷1,5

B Appendix B

This appendix includes the code used for the implementation of the various numerical simulations of the PN configuration. The code consists in several nested loops in which the characteristics of elements inside the grid (power absorbed and type of the load, dimension, and type of line) vary; the RMS simulation is executed, and the results saved in a csv file. This procedure is repeated for all the values inside the ranges of each component.

```
object oLMTL, oTypeLineMT, oLMT, case, oINC, oRMS, oRES, oLine, oLoad;

int m, intLMTTypeRows, intLMTLRows, SezLineMT;

double k, l;
double p, step, Pmax, Pmin, PF;

string Address, Test, chTypeLineMT, Name;

set sAllObjs, sObjs, scontents;

intLMTTypeRows = 6;

intLMTLRows = 10;

sAllObjs = GetCalcRelevantObjects();

oLMT = sAllObjs.FirstFilt('Line.ElmLne');

sObjs = GetCalcRelevantObjects();

oLoad = sObjs.FirstFilt('Load.ElmLod');

Address = 'C:\Users\Edoardo\OneDrive - Politecnico di Milano\Tesi Magistrale E

ClearOutput();
EchoOff();

step = 0.01; ![MW]
Pmin = 0.05; ![MW]
Pmax = 0.32; ![MW]

PF = 0.8;

```

```
oLoad:plini = Pmin;
oLoad:qlini = Pmin*sin(acos(0.9));

oINC = GetFromStudyCase('*.ComInc');
oRMS = GetFromStudyCase('*.ComSim');
case = GetActiveStudyCase();

oLMTL = this.CreateObject('IntVec','Lenght');

oLMTL.Resize(intLMTLRows);

oLMTL.Set(1, 0.5);

oLMTL.Set(2, 1.0);

oLMTL.Set(3, 1.5);

oLMTL.Set(4, 2.0);

oLMTL.Set(5, 2.5);

oLMTL.Set(6, 3.0);

oLMTL.Set(7, 3.5);

oLMTL.Set(8, 4.0);

oLMTL.Set(9, 4.5);

oLMTL.Set(10, 5.0);

oTypeLineMT=GetLocalLibrary('TypLne');

```

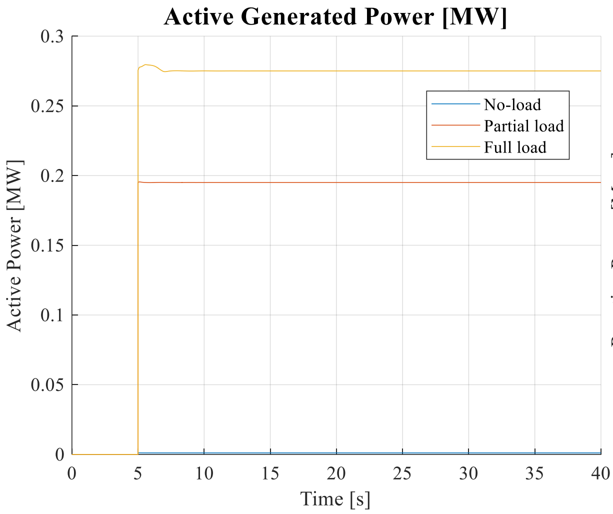
```
scontents = oTypeLineMT.GetContents('*.TypLne',1);
oLine = scontents.First();

oINC.Execute();

while (oLine) {

oLMT:typ_id=oLine;

chTypeLineMT=oLine:e:loc_name;


for(k = 1; k<=intLMTLRows; k=k+1){

oLMT:e:dline=oLMTL.Get(k);

l = oLMT:e:dline;

for (oLoad:plini = Pmin; oLoad:plini<=Pmax; oLoad:plini+=step) {

oLoad:qlini = oLoad:plini*sin(acos(0.9));

oINC.Execute();

!Niente da fare tra le due simulazioni

oRMS.Execute();

oRES=GetCaseObject('*.ComRes');

Test = sprintf('%sdati_%5.2f_%s_%5.2f.csv',Address,k/2,chTypeLineMT,oLoad:plin

oRES:e:f_name= Test;

oRES.Execute();

}

}

oLine = scontents.Next();

}

EchoOn();
Delete(oLMTL);
```

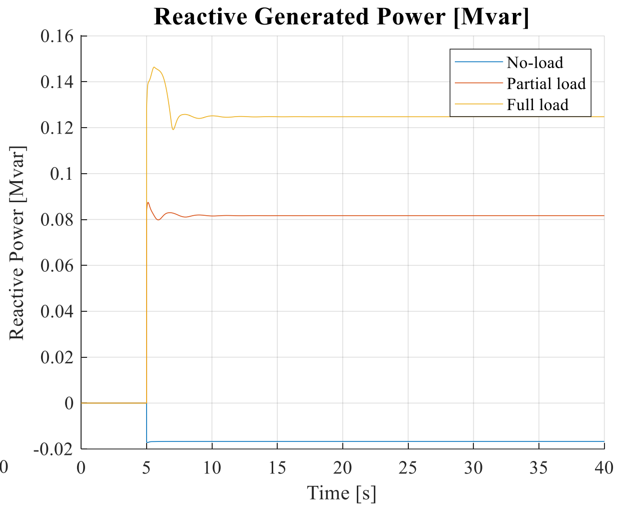
C Appendix C

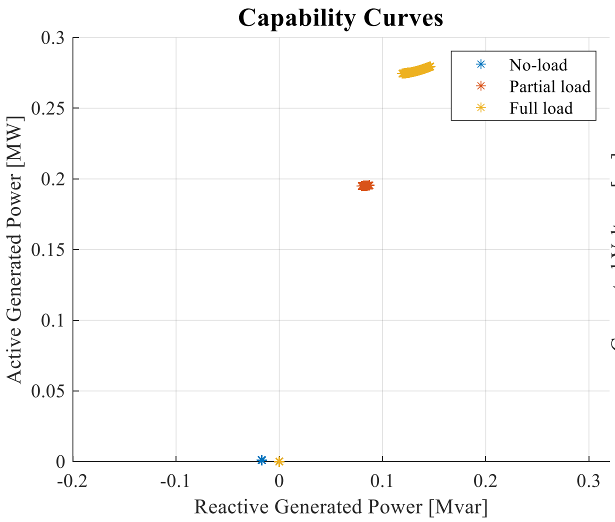
For the overhead line, the maximum considered length for each study case is 15 km. For the cable lines, the maximum length of the MV line to maintain the system stable is reported.

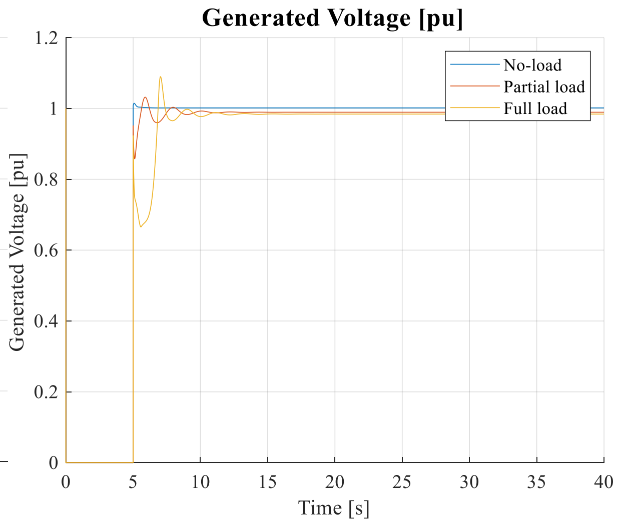
No-load, partial load and full load conditions are plotted on the same graph.

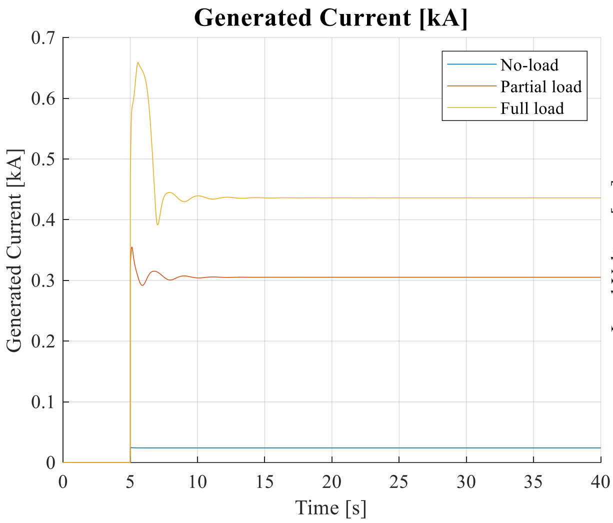
C.1. 25 mm^2 overhead line:

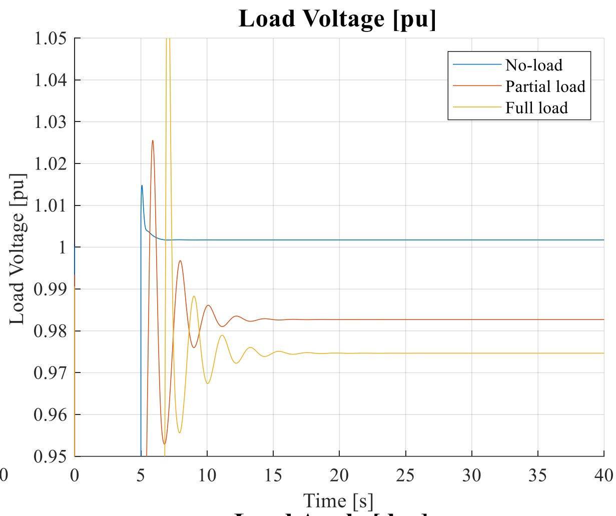


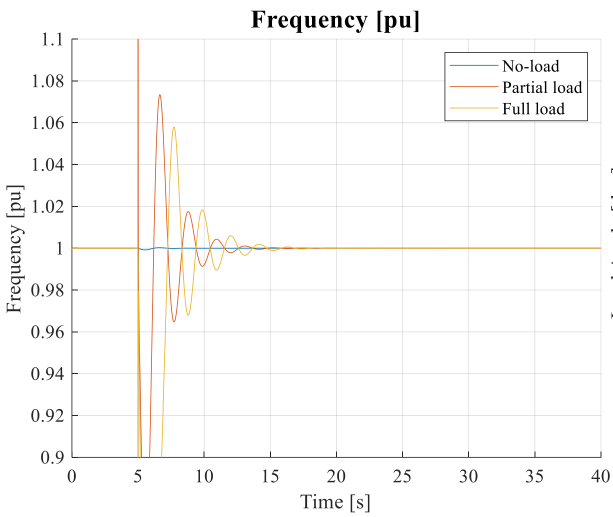


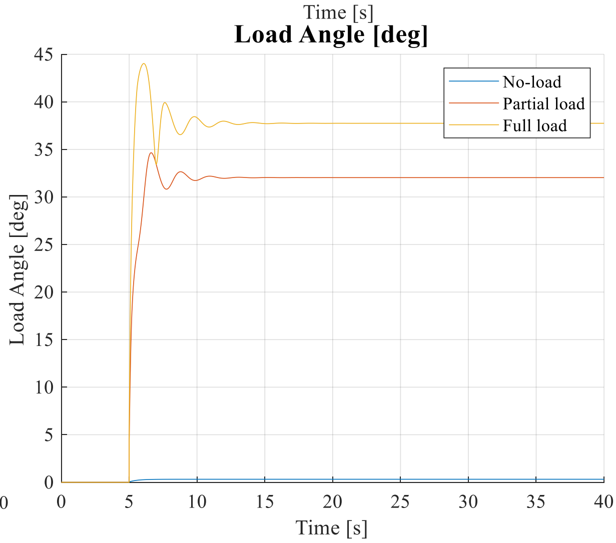


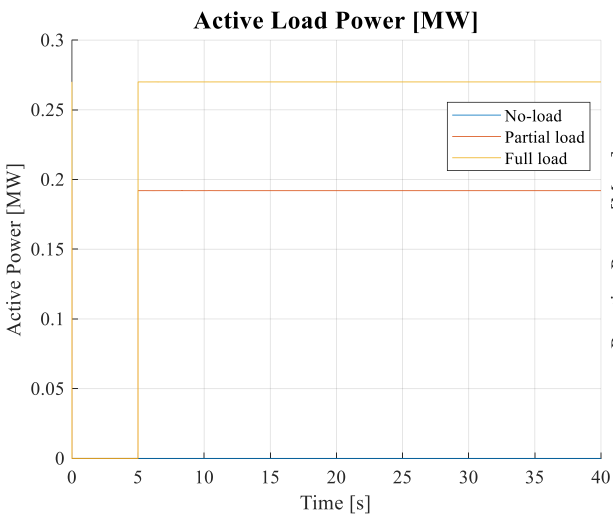


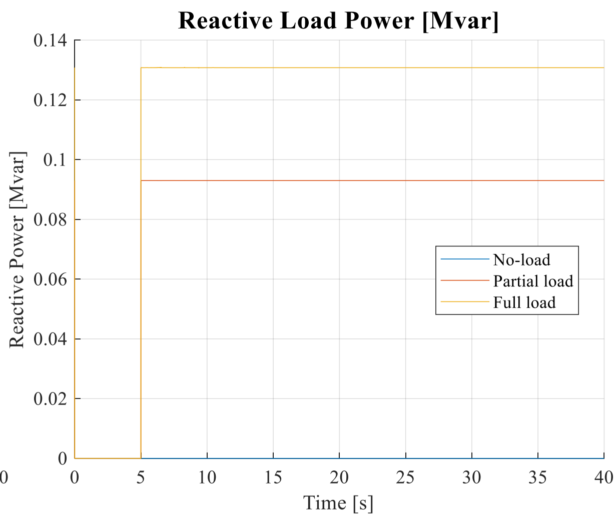

Generated Current [kA]
Generated Current [kA]
Time [s]
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
0 5 10 15 20 25 30 35 40
No-load
Partial load
Full load


Load Voltage [pu]
Load Voltage [pu]
Time [s]
0.95 0.96 0.97 0.98 0.99 1 1.01 1.02 1.03 1.04 1.05
0 5 10 15 20 25 30 35 40
No-load
Partial load
Full load

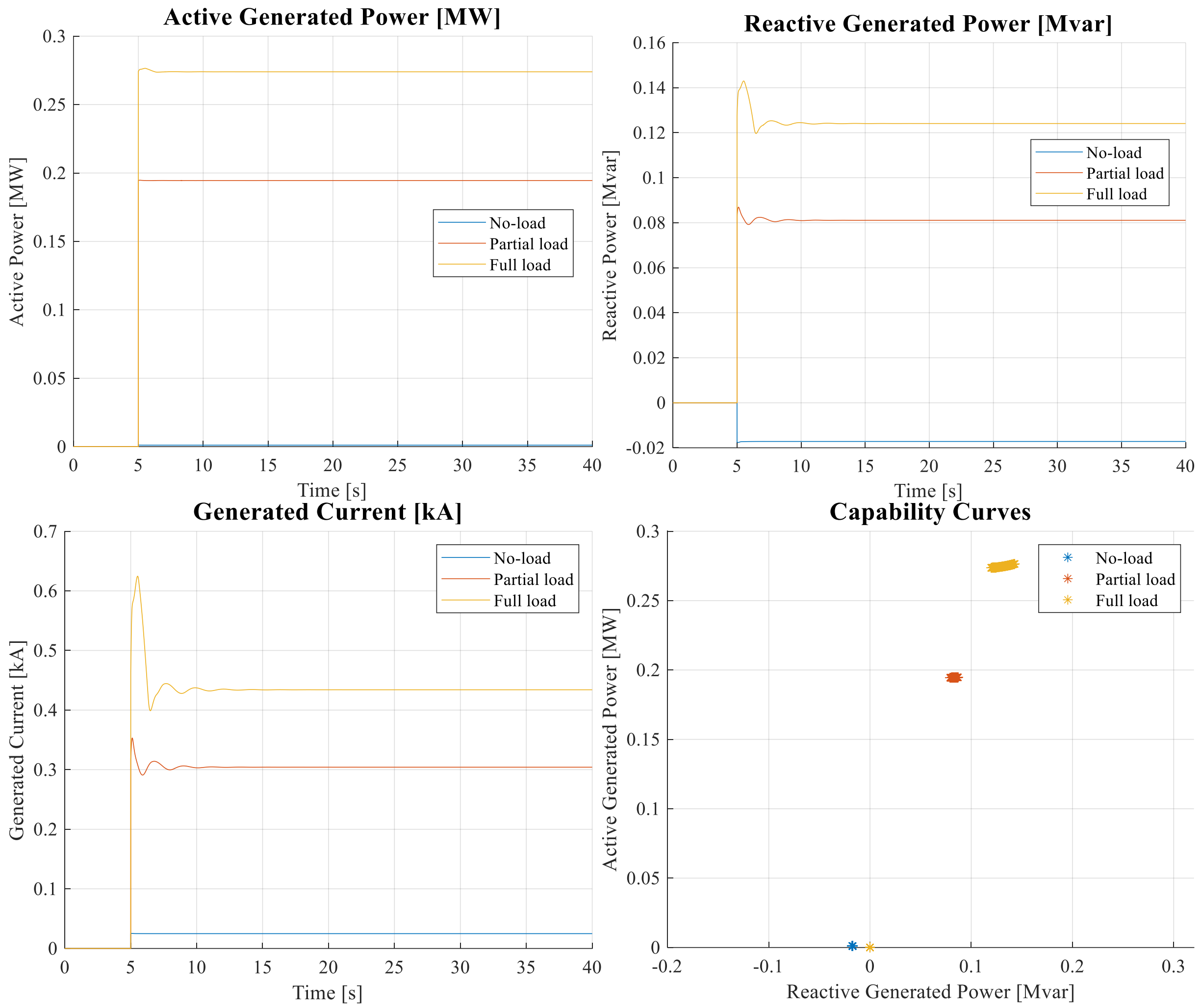

Frequency [pu]
Frequency [pu]
Time [s]
0.9 0.92 0.94 0.96 0.98 1 1.02 1.04 1.06 1.08 1.1
0 5 10 15 20 25 30 35 40
No-load
Partial load
Full load

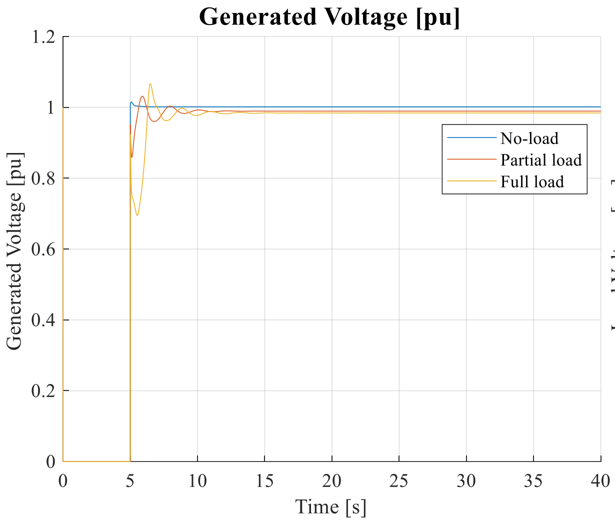

Load Angle [deg]
Load Angle [deg]
Time [s]
0 5 10 15 20 25 30 35 40 45
0 5 10 15 20 25 30 35 40
No-load
Partial load
Full load

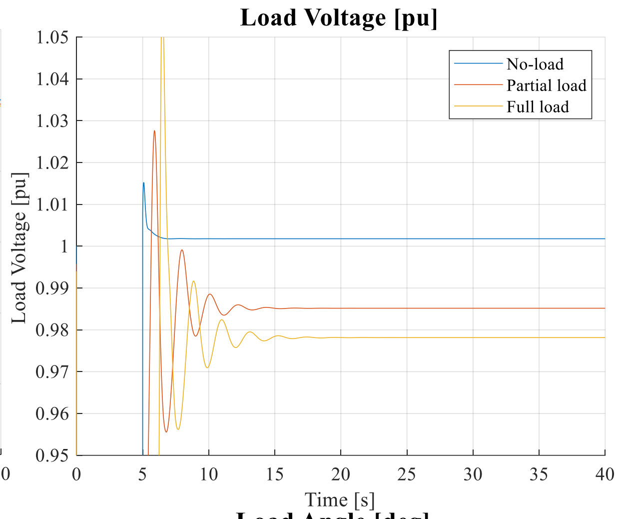

Active Load Power [MW]
Active Power [MW]
Time [s]
0 0.05 0.1 0.15 0.2 0.25 0.3
0 5 10 15 20 25 30 35 40
No-load
Partial load
Full load

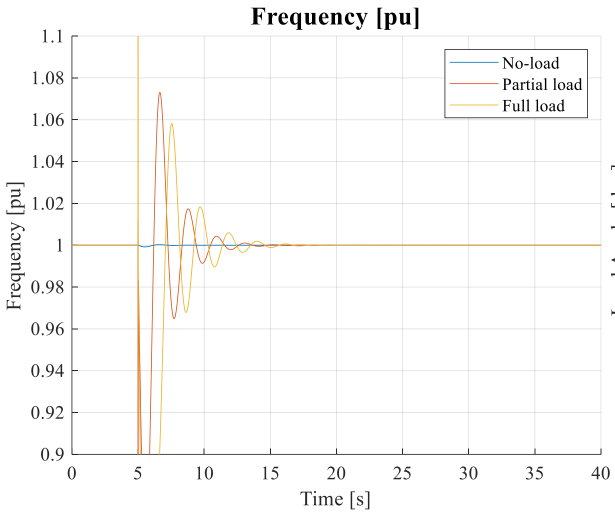

Reactive Load Power [Mvar]
Reactive Power [Mvar]
Time [s]
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14
0 5 10 15 20 25 30 35 40
No-load
Partial load
Full load

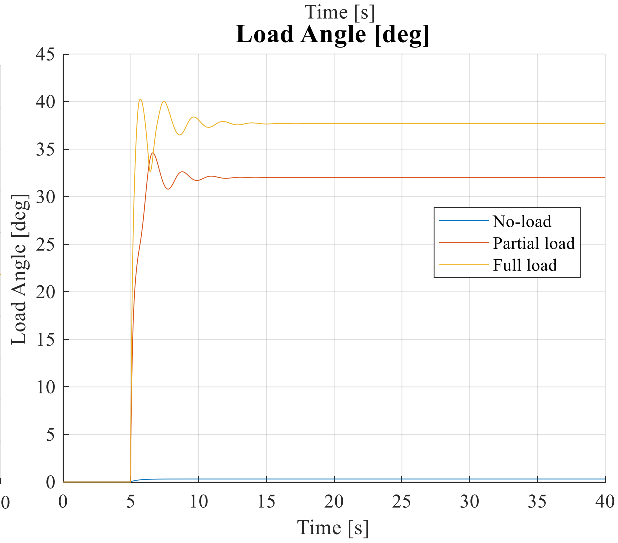
C.2. 50 mm^2 overhead line

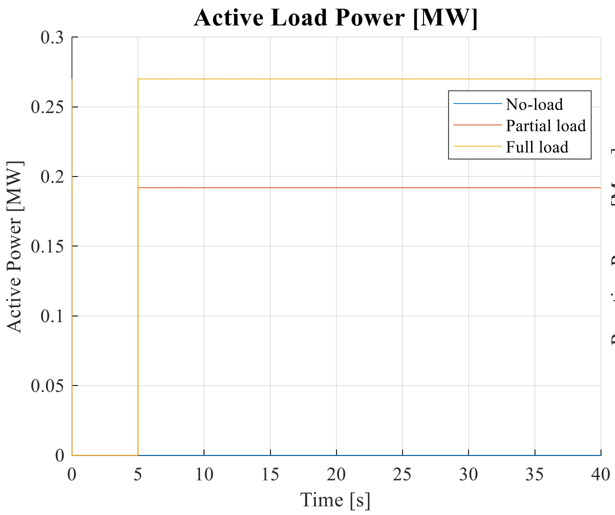


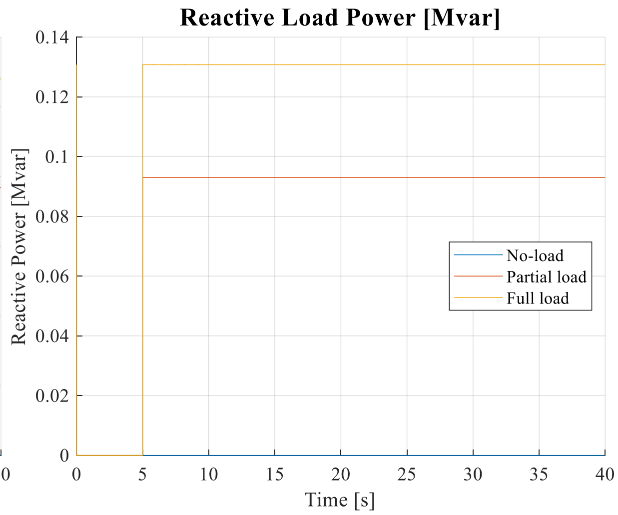

Generated Voltage [pu]
Generated Voltage [pu]
Time [s]
No-load
Partial load
Full load


Load Voltage [pu]
Load Voltage [pu]
Time [s]
No-load
Partial load
Full load

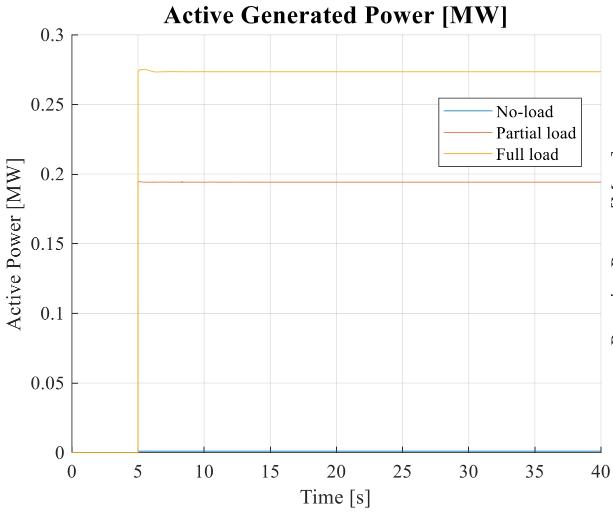

Frequency [pu]
Frequency [pu]
Time [s]
No-load
Partial load
Full load

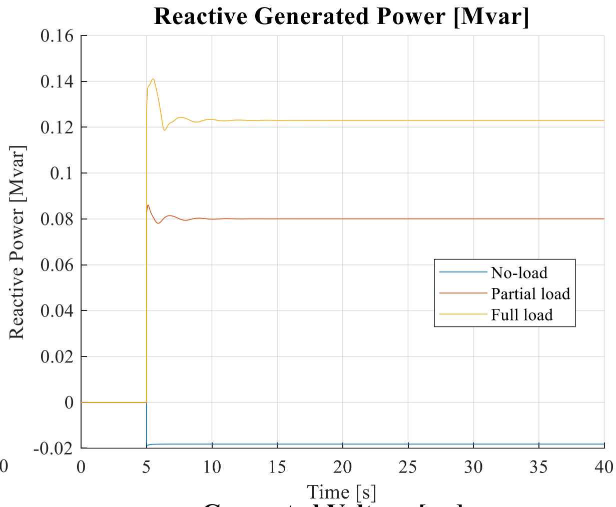

Load Angle [deg]
Load Angle [deg]
Time [s]
No-load
Partial load
Full load

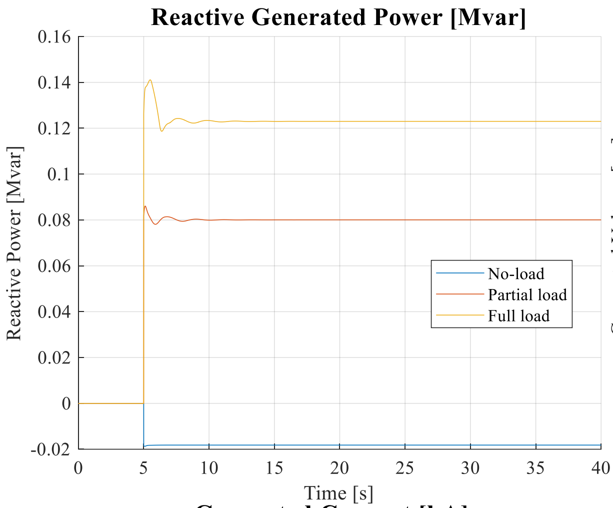

Active Load Power [MW]
Active Power [MW]
Time [s]
No-load
Partial load
Full load

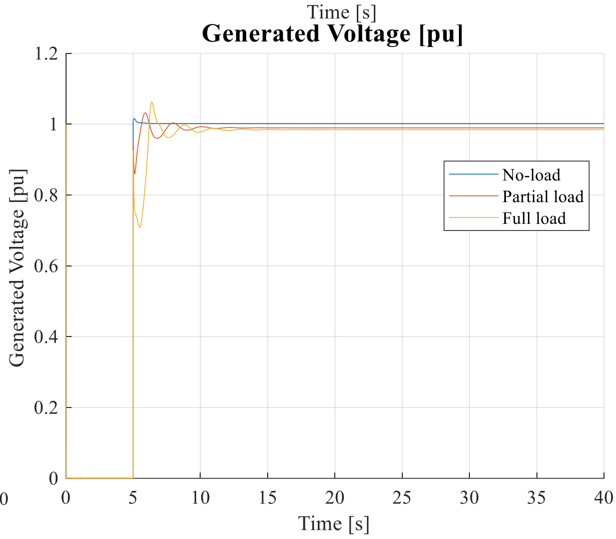

Reactive Load Power [Mvar]
Reactive Power [Mvar]
Time [s]
No-load
Partial load
Full load

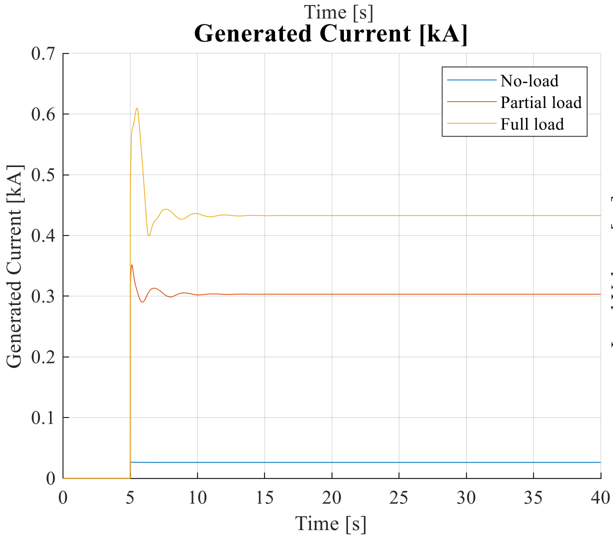
C.3. 70 mm^2 overhead line

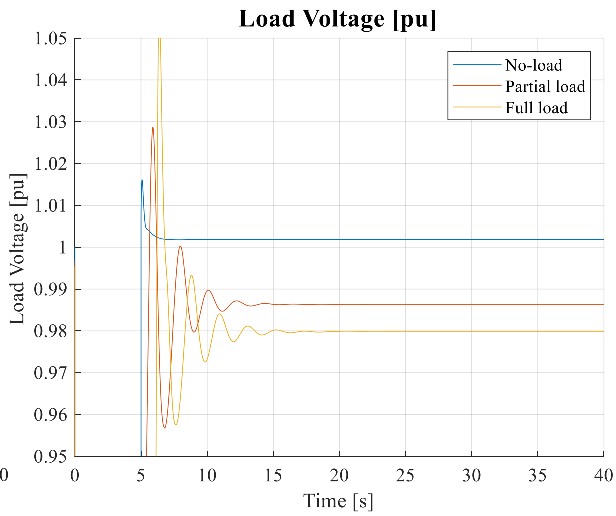


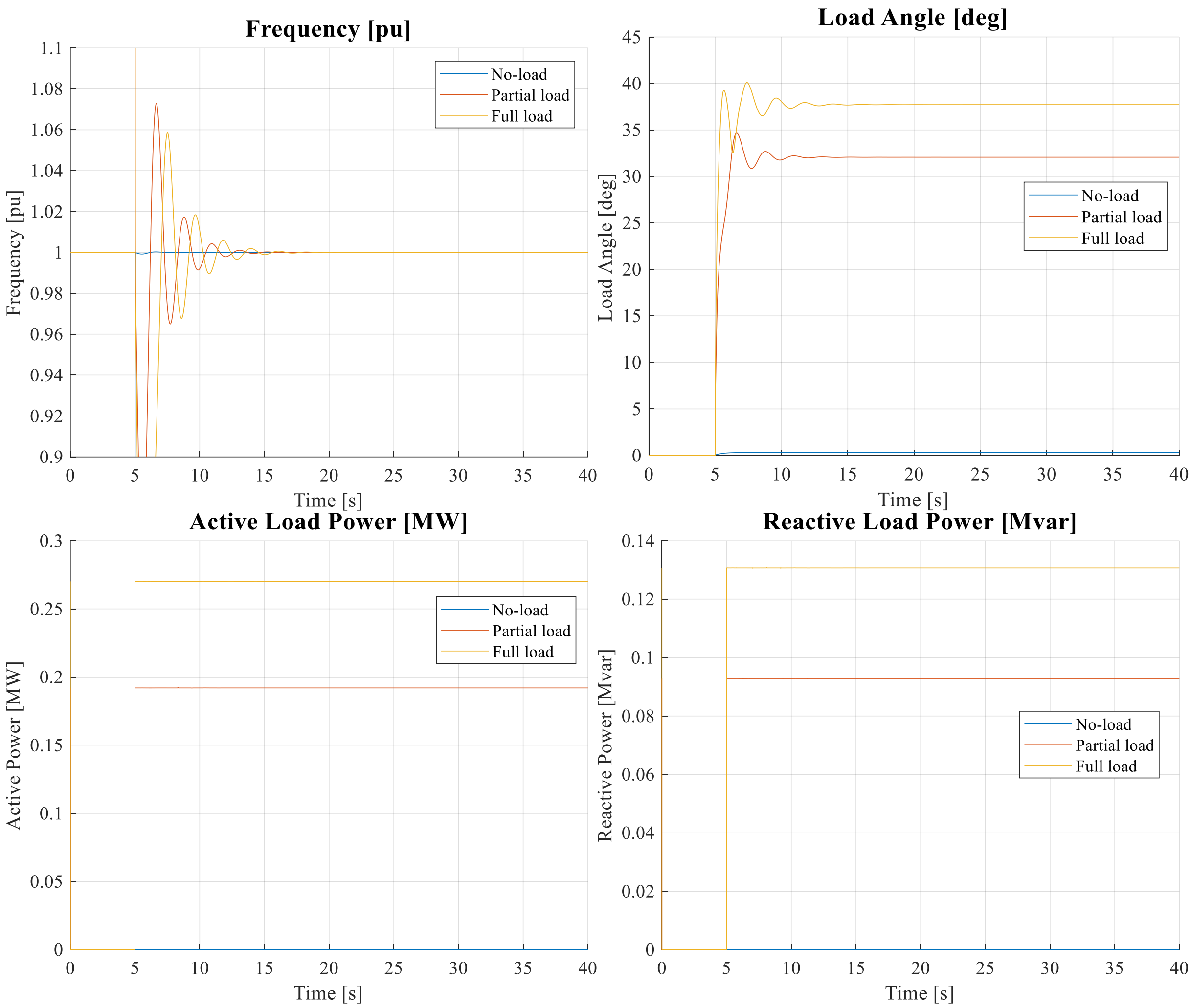




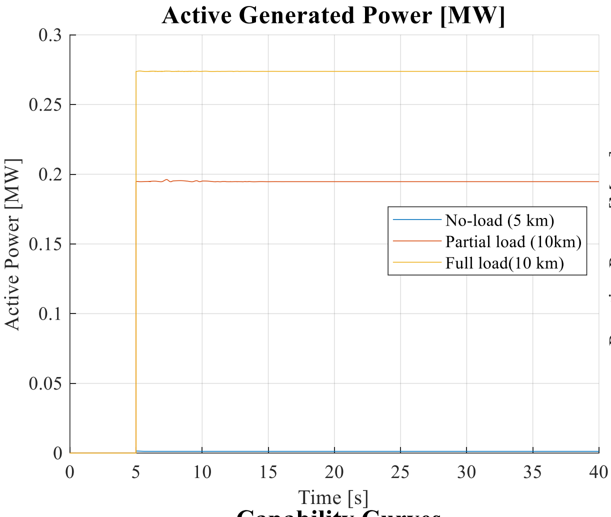


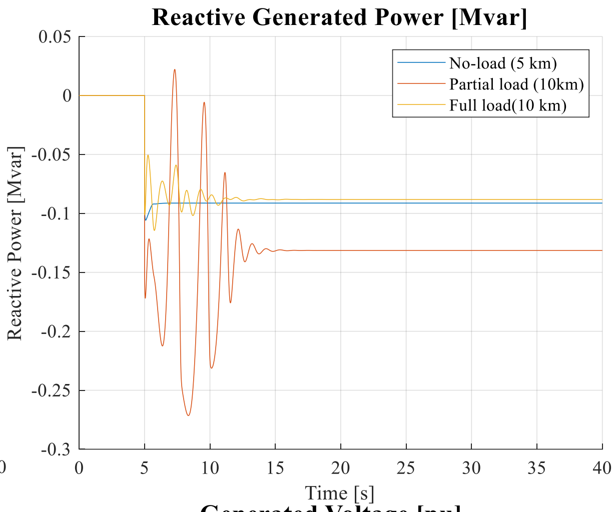


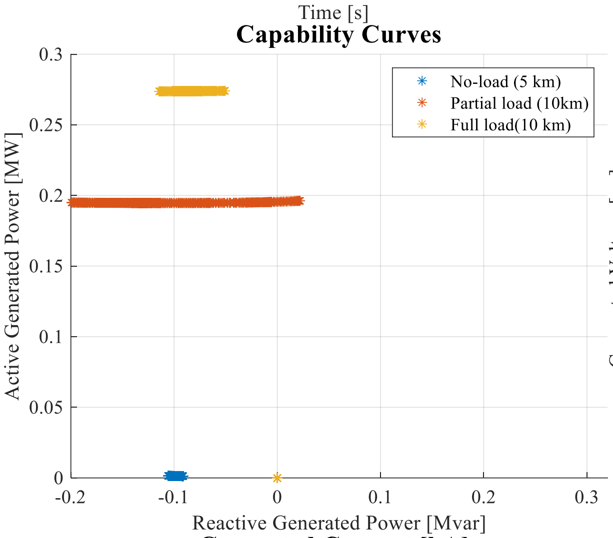


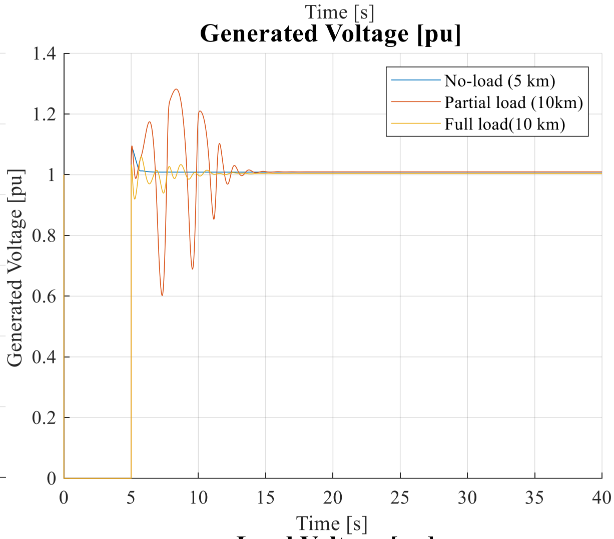

Frequency [pu]
Frequency [pu]
Time [s]
No-load
Partial load
Full load
Load Angle [deg]
Load Angle [deg]
Time [s]
No-load
Partial load
Full load
Active Load Power [MW]
Active Power [MW]
Time [s]
No-load
Partial load
Full load
Reactive Load Power [Mvar]
Reactive Power [Mvar]
Time [s]
No-load
Partial load
Full load

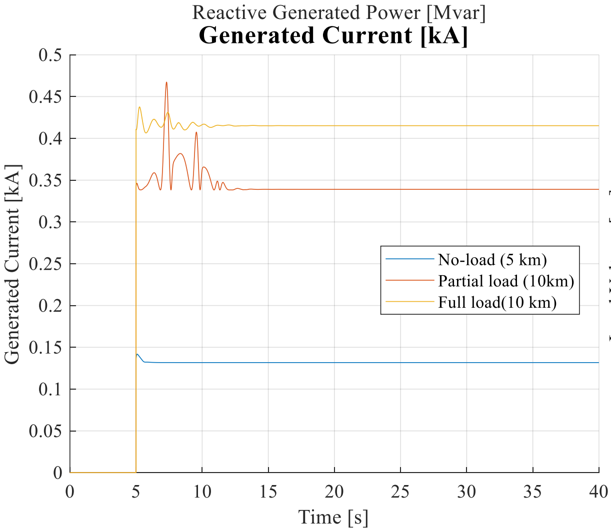
C.4. 25 mm^2 cable line

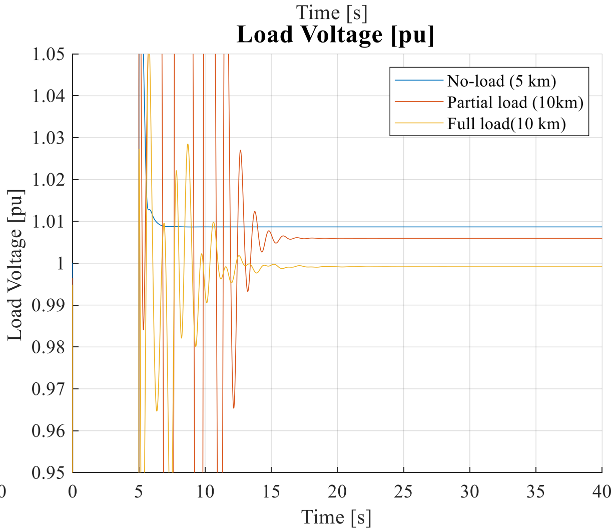


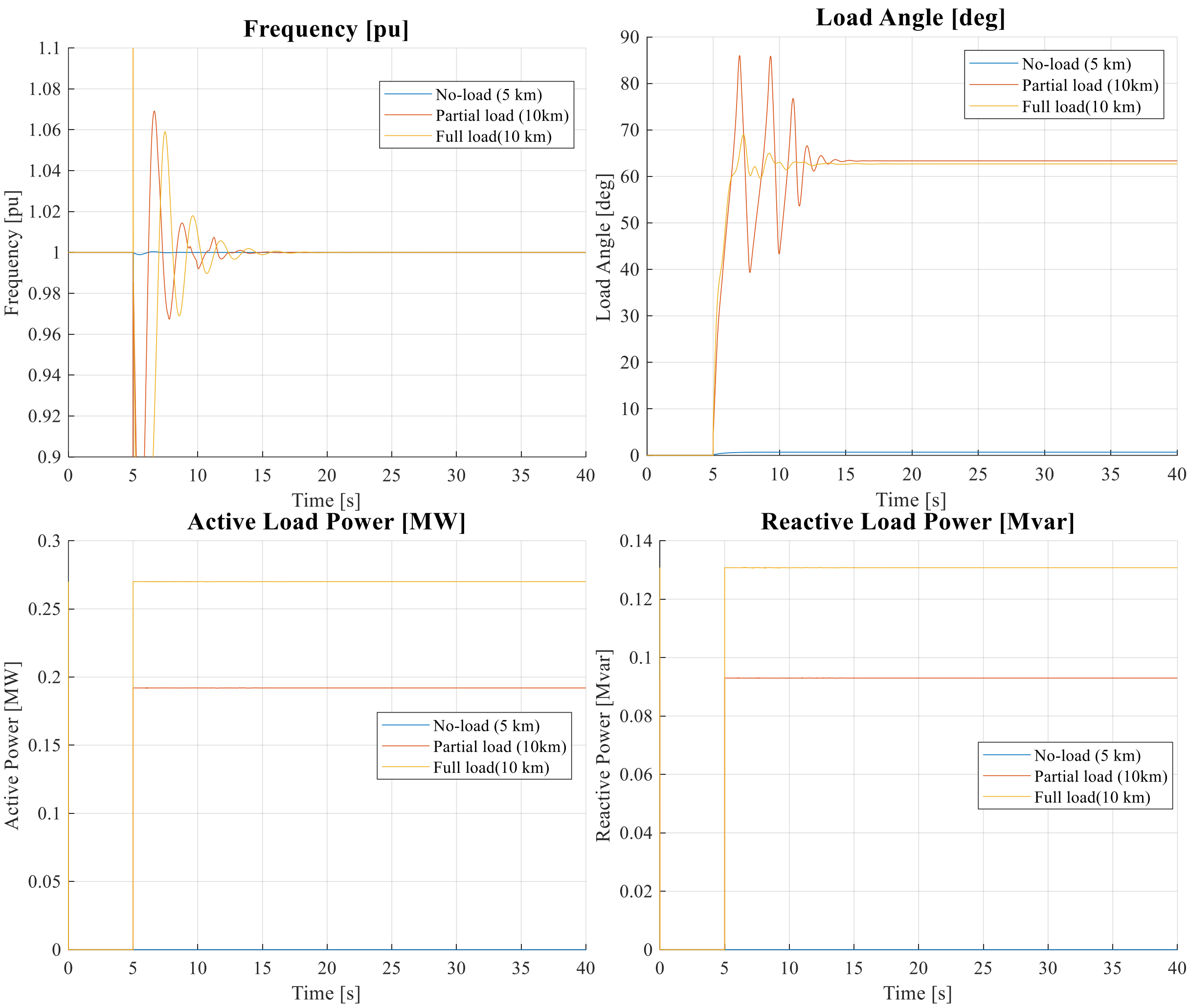




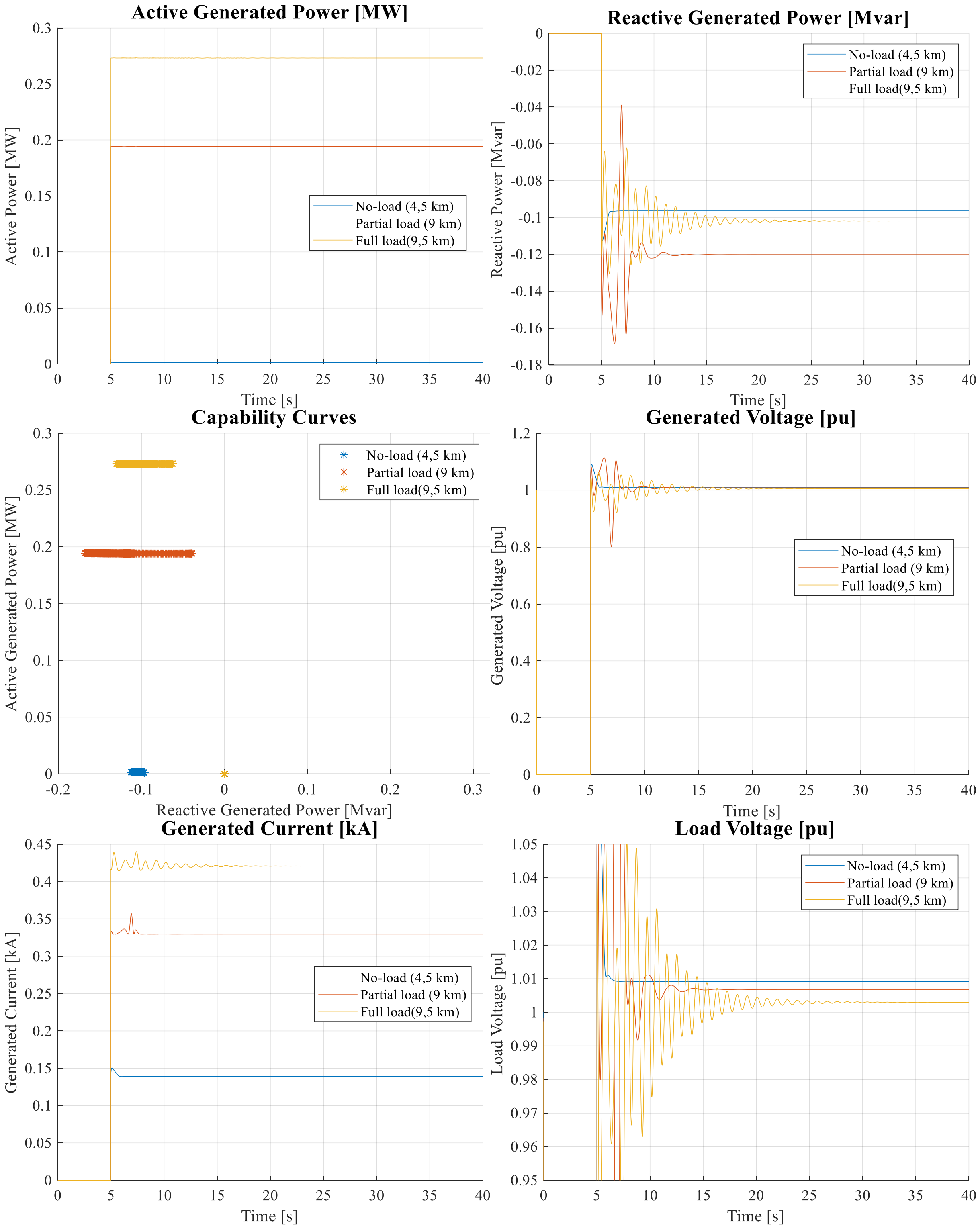


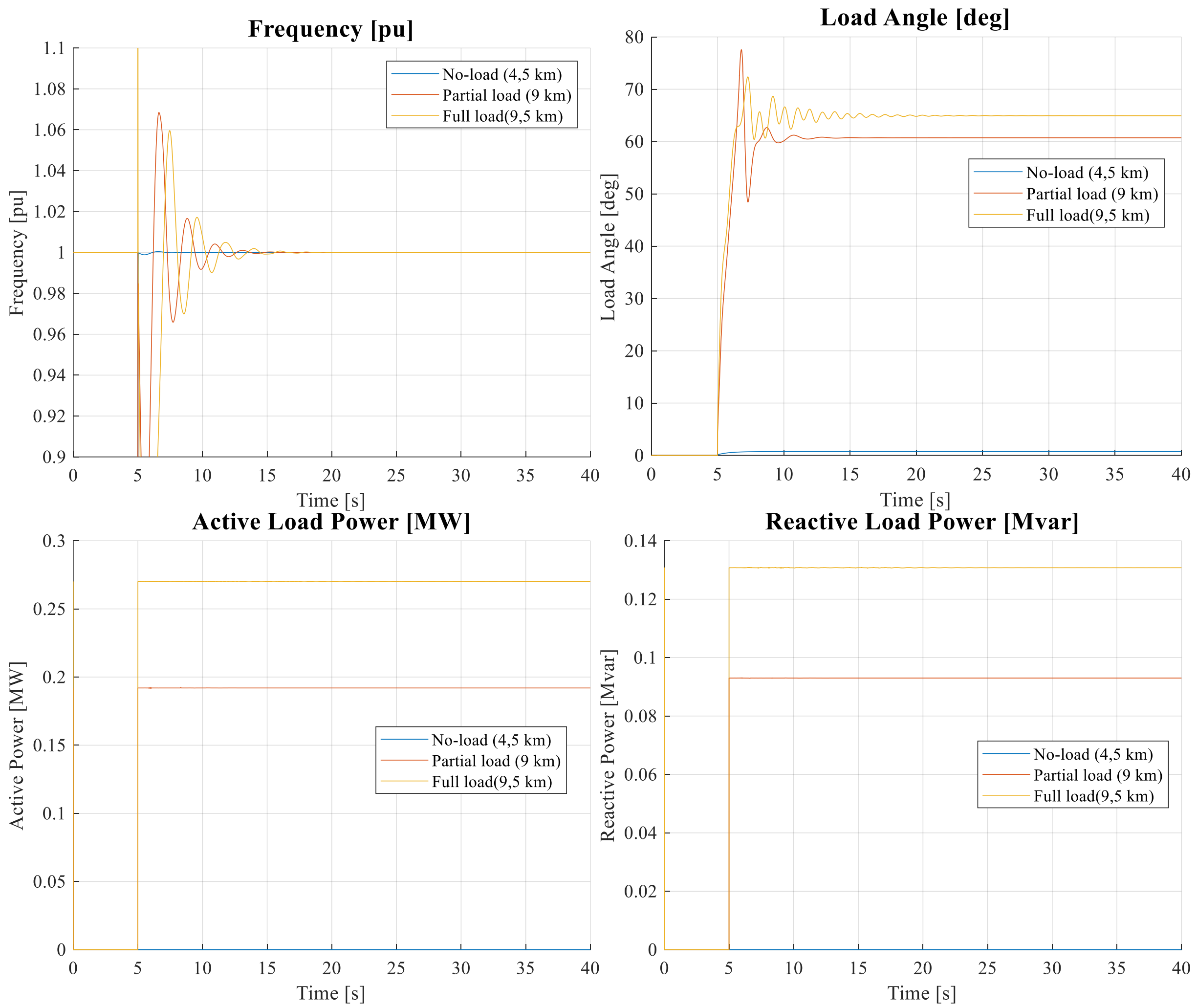




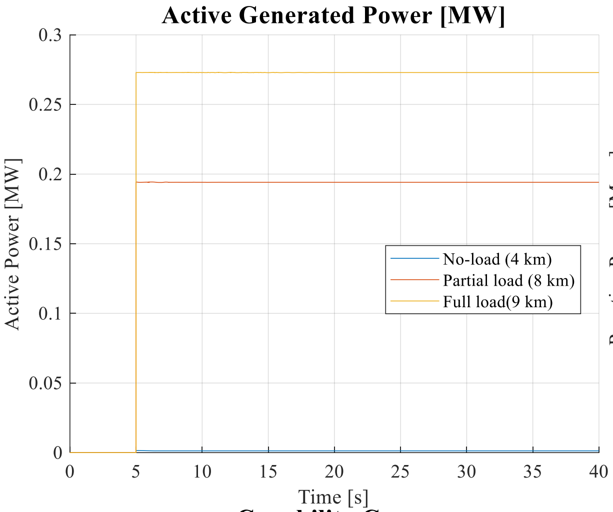

Frequency [pu]
Frequency [pu]
Time [s]
No-load (5 km)
Partial load (10km)
Full load(10 km)
Load Angle [deg]
Load Angle [deg]
Time [s]
No-load (5 km)
Partial load (10km)
Full load(10 km)
Active Load Power [MW]
Active Power [MW]
Time [s]
No-load (5 km)
Partial load (10km)
Full load(10 km)
Reactive Load Power [Mvar]
Reactive Power [Mvar]
Time [s]
No-load (5 km)
Partial load (10km)
Full load(10 km)

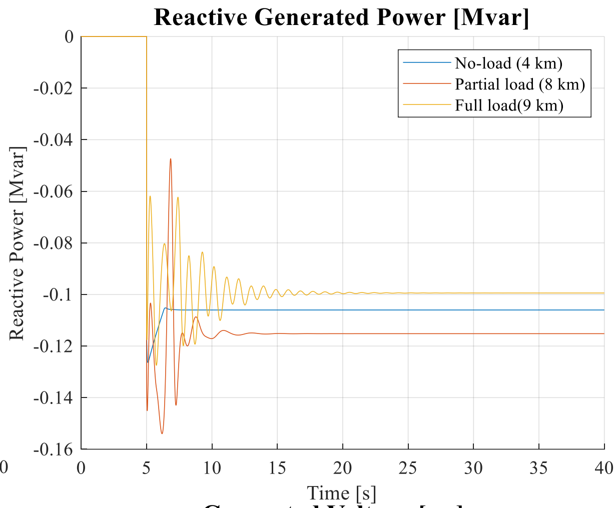
C.5. 50 mm^2 cable line

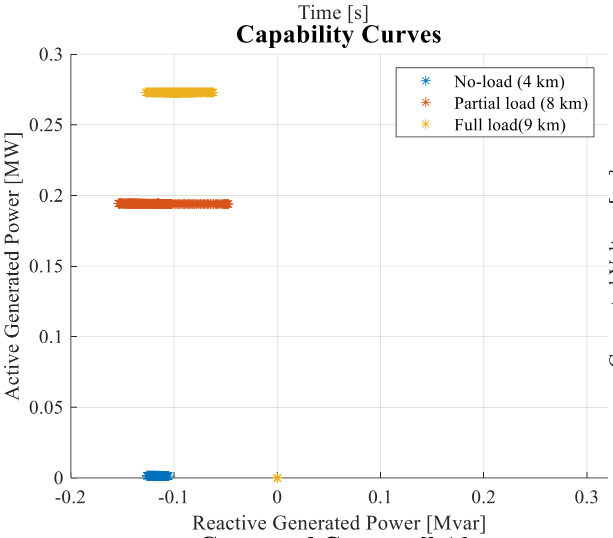


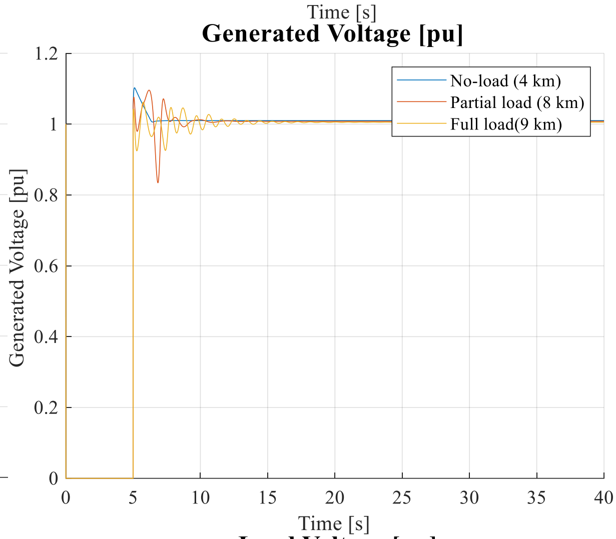

Frequency [pu]
Frequency [pu]
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
0
5
10
15
20
25
30
35
40
Time [s]
No-load (4,5 km)
Partial load (9 km)
Full load(9,5 km)
Load Angle [deg]
Load Angle [deg]
80
70
60
50
40
30
20
10
0
Active Load Power [MW]
Active Power [MW]
0.3
0.25
0.2
0.15
0.1
0.05
Reactive Load Power [Mvar]
Reactive Power [Mvar]
0.14
0.12
0.1
0.08
0.06
0.04
0.02

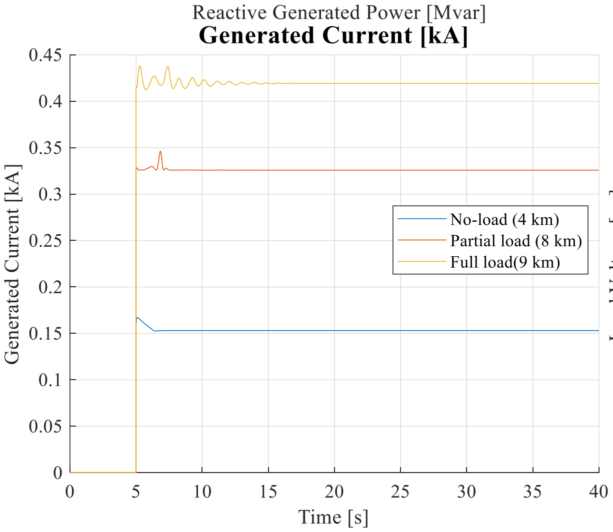
C.6. 70 mm^2 cable line

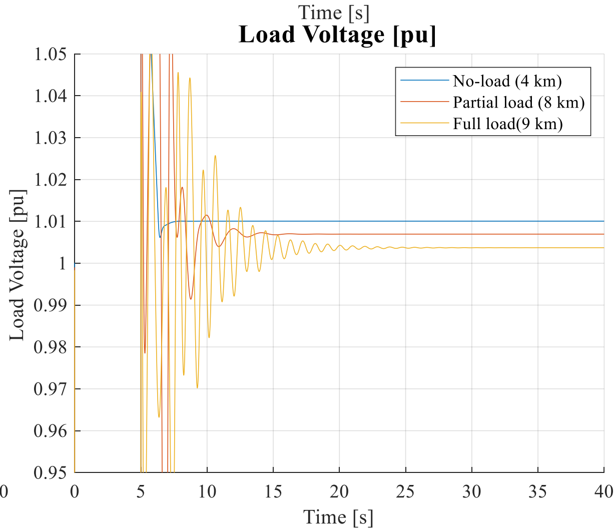


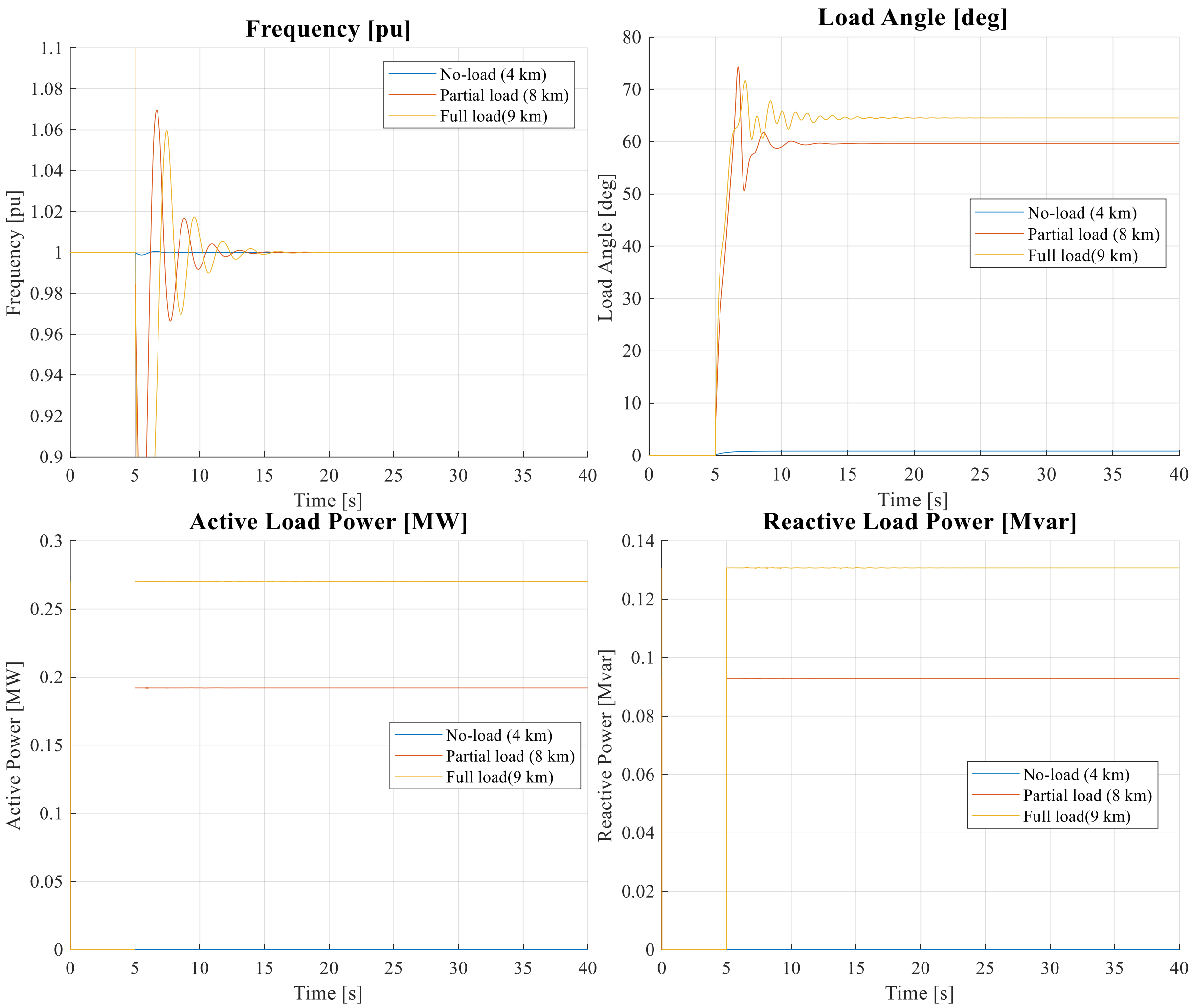











Frequency [pu]
Frequency [pu]
Time [s]
No-load (4 km)
Partial load (8 km)
Full load(9 km)
Load Angle [deg]
Load Angle [deg]
Time [s]
No-load (4 km)
Partial load (8 km)
Full load(9 km)
Active Load Power [MW]
Active Power [MW]
Time [s]
No-load (4 km)
Partial load (8 km)
Full load(9 km)
Reactive Load Power [Mvar]
Reactive Power [Mvar]
Time [s]
No-load (4 km)
Partial load (8 km)
Full load(9 km)

D Appendix D

D.1. 250 kVA GS model description

The electrical and mechanical parameters are reported in the next table:

Parameters	Implemented values
Nominal Complex Power [kVA]	250
Nominal Voltage [V]	400
Frequency [Hz]	50
Power Factor	0,8
Poles	Wound Rotor
Direct axis synchronous reactance Xd [%]	284
Quadrature axis synchronous reactance Xq [%]	244
Direct axis transient reactance X'd [%]	18
Direct axis sub-transient reactance X''d [%]	13
Quadrature axis sub-transient reactance X''q [%]	36
Negative sequence reactance X2 [%]	25
Zero sequence reactance X0 [%]	9
Open circuit time constant (T'do) [s]	1,7
Transient time constant (T'd) [s]	0,08
Sub-transient time constant (T''d) [s]	0,019
Armature time constant (Ta) [s]	0,018
Moment of Inertia (J) [kgm^2]	3,55

Regarding the speed governor and voltage excitation system, the already introduced models (respectively DEGOV1 and EXST2A) are equipped also to this GS. The parameters of the regulators are reported in Table 5.3 and Table 5.4.

D.2. Numerical simulations and results

The same numerical simulations have been performed with the new GS:

- dynamic stability under no-load condition;
- dynamic stability under partial load condition;
- dynamic stability under full load condition (isochronous and droop variant).

The resulting tables are reported next:

No-load condition:

	Copper Overhead Line Sez. 25 mm^2																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
No-Load	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

	Copper Overhead Line Sez. 50 mm^2																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
No-Load	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

	Copper Overhead Line Sez. 70 mm^2																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
No-Load	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

	Copper Cable Sez. 25 mm^2																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
No-Load	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No

	Copper Cable Sez. 50 mm^2																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
No-Load	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No

	Copper Cable Sez. 70 mm^2																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
No-Load	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No

Partial load condition:

	Copper Overhead Line Sez. 25 mm^2																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,5Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

	Copper Overhead Line Sez. 50 mm^2																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,5Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

	Copper Overhead Line Sez. 70 mm^2																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,5Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

	Copper Cable Sez. 25 mm^2																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,5Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No

	Copper Cable Sez. 50 mm^2																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,5Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No

	Copper Cable Sez. 70 mm^2																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,5Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No

Full load condition, astatic case:

	Overhead Lines (25 mm^2)																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,8Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,85Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,9Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,95Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static
P=Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static

	Overhead Lines (50 mm^2)																												
	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,8Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,85Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,9Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,95Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static
P=Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static

Overhead Lines (70 mm^2)

	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,8Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,85Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,9Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,95Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static
P=Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static

Cable Line (section 25 mm^2)

	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,8Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No
P=0,85Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No
P=0,9Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No
P=0,95Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No
P=Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No

Cable Line (section 50 mm^2)

	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,8Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No
P=0,85Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No
P=0,9Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No
P=0,95Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No
P=Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No

Cable Line (section 70 mm^2)

	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,8Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
P=0,85Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
P=0,9Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
P=0,95Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
P=Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No

Full load condition, droop case:

Overhead Lines (25 mm^2)

	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,8Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,85Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,9Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,95Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static
P=Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static

Overhead Lines (50 mm^2)

	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,8Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,85Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,9Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,95Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static
P=Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static

Overhead Lines (70 mm^2)

	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,8Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,85Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,9Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
P=0,95Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static
P=Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static

Cable Line (section 25 mm^2)

	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,8Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No
P=0,85Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No
P=0,9Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No
P=0,95Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No
P=Pn	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No

Cable Line (section 50 mm^2)

	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,8Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No
P=0,85Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No
P=0,9Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No
P=0,95Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
P=Pn	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No

Cable Line (section 70 mm^2)

	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	9,5	10	10,5	11	11,5	12	12,5	13	13,5	14	14,5	15
P=0,8Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No
P=0,85Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No
P=0,9Pn	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No
P=0,95Pn	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
P=Pn	Static	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No

The results are aligned with the ones of the 400 kVA GS. In particular, for the 250 kVA, the amount of line that can be reenergized is decreased. The positive amount of reactive power that the GS is able to provide is reduced with respect to the previous case, and so, less length can be reenergised under each load condition.

If the re-powered length of the line is comparable for overhead line due to the relatively small transversal parameters, for cable lines, the re-powered length is significantly reduced. The situation is even worse if a droop different from zero is applied to DEGOV1; in this case, under full load condition, the re-powered length is the lowest.

In conclusion, higher the rating of the GS, higher the positive reactive power it can provide to the system, lower the load angle, greater the re-powered lengths.

List of Figures

List of Tables

Acknowledgments

Here you might want to acknowledge someone.