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Photovoltaic generation impact on the distribution grid of Malta: voltage profile control by means of storage apparatus

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Un Grazie particolare ai miei genitori che mi hanno sempre sostenuto e spinto anche quando io non ne volevo sapere.

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Abstract

The penetration of distributed generation resources in distribution grids increasing worldwide is both a challenge and an opportunity for a variety of technologies and operating scenarios. The need to provide acceptable power quality and reliability will create a favorable climate for the entry of distributed resources, including distributed generation and distributed energy storage, and innovative operating practices. The integration of DG into an existing utility can result in several benefits: line energy loss reduction, overvoltage problems control, green and renewable energy exploitation, peak shaving etc. but imply also some disadvantages that must be carefully considered.
The impact of distributed photovoltaic plants is here analyzed for various possible configuration of the DG and the hosting capacity (HC the maximum power that can be installed in the grid) in each case determined. The results show that the HC is influenced by the position of the plants in the line and by the configuration: distributed generation or concentrated plants in one node of the low voltage (LV) portion of the grid. DG also affects positively the energy losses and negatively,if excessive power is installed, the steady state voltage of the grid. This requires new policies to control the overvoltage; the method implemented now that presuppose the detaching of the plants from the grid, sure, solve the problem but decreases also the exploitation of the available resources.
The introduction of storage systems to mitigate this problem is presented in this thesis. Storage systems are modelled and introduced in the simulation, and their effect on the hosting capacity and the grid voltage is analised.
The storage systems allow the accumulation of part of the energy produced by the solar panels, energy that doesn't influence the grid voltage. The installed power can therefore be increased, in relation to the nominal power and total capacity of the battery. The economical aspect has to be taken into account at this point because the actual cost of the storage systems can make their usage economically not convenient.
On this aspect is focused the last part of this work that evaluate the costs and benefits brought by the use of batteries. Results show that with the actual costs of the lead acid technology, the batteries are not convenient but this result can change considering the disconnection of the PV plant when the voltage reaches the upper limit in the case without storage and assuming

a decrease of the costs in the next years

Keywords : distributed generation, voltage control, storage system.

Sommario

La crescita della penetrazione di impianti di generazione distribuita (GD) nella rete di distribuzione in bassa tensione è una sfida e un'opportunita per lo sviluppo di nuove tecnologie e scenari operativi. La necessità di garantire un livello accettabile di qualità del servizio di fornitura dell'energia e di affidabilità del sistema porta alla necessità di analizzare nuovi apparati e nuove modalità di gestione delle reti elettriche quali i sistemi di accumulo e innovative procedure operative. L'introduzione di GD nella rete esistente comporta infatti lo sfruttamento di benefici diretti, tra cui la diminuzione delle perdite energetiche sulla linea, il possibile sfruttamento della generazione per il controllo dei problemi di sovratensione, il livellamento dei picchi di carico, lo sfruttamento di fonti energetiche rinnovabili e non inquinanti, ma anche degli svantaggi che vanno attentamente considerati.
La tesi qui presentata consegue da uno stage presso l'università di Malta (UoM University of Malta) ed è indirizzata proprio allo studio dell'impatto della GD, prevalentemente fotovoltaica, sulla rete BT di tale isola.
Sono stati costruiti modelli per la rete elettrica, i carichi connessi ad essa, i pannelli fotovoltaici e le batterie tramite l'utilizzo dell'ambiente *Simpowersystem* del programma *SIMULINK*.
L'impatto di impianti fotovoltaici distribuiti sulla rete è stato analizzato studiando varie configurazioni possibili per la GD e vari livelli di potenza installata.
I risultati mostrano che la potenza massima installabile è influenzata distanza elettrica degli impianti di generazione rispetto alla cabina secondaria e dalla configurazione della rete stessa. In particolare, se gli impianti di produzione sono connessi alla fine della linea, la potenza installabile risulta sensibilmente minore rispetto al caso in cui siano connessi all'inizio. La GD influenza positivamente le perdite di energia sulla rete riducendole sensibilmente rispetto al caso di rete passiva in quanto diminuisce la corrente che transita nella linea. Questo beneficio ha però un limite: se la potenza installata è più grande del carico il flusso di energia si inverte andando dalla rete verso la cabina secondaria di trasformazione e questo fa di nuovo aumentare le perdite di energia. L'iniezione di potenza in rete da parte delle GD influenza anche la tensione sulla linea. Per una forte penetrazione di fotovoltaico, infatti, la tensione può raggiungere livelli che vanno oltre il limite massimo fissato a +10% della tensione nominale della rete. Questo richiede l'introduzione di nuove politiche

di controllo delle sovratensioni; il metodo attualmente implementato nella rete di Malta che prevede il distacco degli impianti di generazione quando la tensione diviene troppo alta riduce, certo, il problema ma implica la diminuzione dello sfruttamento delle risorse disponibili.
In sistemi elettrici più strutturati ed evoluti, quali l'Italia, la Germania e la Spagna, opportune normative tecniche sono già state sviluppate con l'obiettivo di mitigare il problema per tramite delle iniezioni reattive della DG stessa. In questo lavoro di tesi si è invece avviato uno studio atto a valutare l'efficacia dell'uso di sistemi di accumulo dell'energia per mitigare questo problema. Sistemi di accumulo sono quindi modellati e introdotti nella simulazione, analizzando il loro impatto sulla massima potenza installabile e sulla tensione. I sistemi di accumulo consentono appunto l'accumulo di parte dell'energia prodotta dai pannelli solari, energia che dunque non influenza la tensione di rete. La potenza installata può quindi essere aumentata in quanto l'energia prodotta in più non viene vettoriata dalla rete in relazione alla potenza della batteria e alla sua totale capacità. In seconda analisi, il sistema di accumulo consente la massimizzazione dell'autoconsumo, ossia dello sfruttamento, da parte dell'utente stesso, dell'energia generata dal proprio pannello fotovoltaico.
L'aspetto economico deve essere preso in considerazione in quanto l'attuale costo dei sistemi di accumulo può rendere sconveniente il loro utilizzo.
Su questo aspetto si concentra l'ultima parte di questo lavoro valutando i costi e i ricavi derivanti dall'uso di sistemi di accumulo. I costi comprendono la batteria e il sistema di connessione alla rete (inverter e ausiliari), mentre i ricavi derivano dal mancato acquisto di energia dalla rete in quanto autoprodotta tramite impianti fotovoltaici e utilizzata quando necessaria grazie alle batterie. I risultati mostrano che gli alti costi degli impianti di accumulo non rendono economicamente conveniente l'uso di batterie che però potrebbero essere utilizzabili in un prossimo futuro prevedendo un calo dei costi.

Parole chiave : generazione distribuita, controllo di tensione, sistemi di accumulo di energia.

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Chapter 1

Introduction

The work presented in this thesis is the result of a six-months stage experience in collaboration with the UoM University of Malta. The internship was attended in the Faculty of Engineering, Department of Industrial Electrical Power Conversion (IEPC), under the supervision of Prof. Ing. Cyril Spiteri Staines and Dr. John Licari.
This thesis work focuses in particular on the integration in the Low Voltage portion of the grid of domestic photovoltaic power plants, their effect on the grid voltage and a possible solution to overvoltage problems by introduction of an energy storage system.
Considering the high number of possible solutions and different configurations that a LV grid can assume in an actual case, the study of a real grid would be unlikely and not corresponding to the real measurements. A model for the low voltage grid has therefore been built and simulated with the program *SIMULINK*, a data flow graphical programming language tool for modeling, simulating and analyzing multidomain dynamic systems integrated with the *MATLAB* environment from which it can be scripted. In particular the Simpowersystem ambient was used. It provides component libraries, that offer models of electrical power components, and analysis tools for modeling and simulating electrical power systems.
It is therefore possible to simulate a big number of different low voltage grid configurations with the same model used in this thesis simply changing the parameters of the line.
Afterwards,with the same Simpowersystem libraries and tools, models for the PV panels, domestic loads and batteries have been built and inserted in the grid model to simulate the effect of each system on the voltage profile.

These components can also be adapted to the actual situation that might be found in a real case of study: the load profile can be varied depending on the real data available for the region of interest; the solar panels output can change depending on the time of the year and on the location of the plant; the battery storage capacity is also dependent on the solar output, the load consumption and on the autonomy needed by the served apparatus. A big number of different situations can be therefore simulated with this model.
The analysis of the voltage trend has been then carried out for different levels of installed photovoltaic panels to evaluate, for every penetration degree, the gravity of the overvoltages caused by the PV installations and the efficiency of the storage system to moderate the problem.

The collaboration with the University of Malta and with Prof. Ing. Cyril Spiteri Staines and Dr. John Licari has allowed the access to the necessary context informations regarding the grid configuration, the typical maltese load profile, the typical winter production curve of a solar panel installed in the island and moreover has allowed the access to the databases of the local society of energy distribution Enemalta. Informations about the structure and operation of the grid have been collected in addition to the informations about the incentives systems applied in Malta for renewable energy sources powered power plants.

The thesis structure is as follows: the first chapter introduces in general the issue of distributed generation. Its definition, development, advantages and disadvantages will be discussed as well as the economic measure for its promotion and diffusion and the technical adjustement necessary for its connection. Finally the actual maltese energy production asset will be presented.
The second chapter present the structure of the maltese electric system with particular focus on the low voltage grid characteristics and operation, and the MV/LV substation properties.
In the third chapter the models of the various components of the grid and the devices connected to it used in the simulation will be presented.
In the fourth chapter the simulation results will be presented and discussed. Particular enphasis will be put on the overvoltage problem caused by the solar photovoltaic plants and its mitigation due to the use of batteries to store part of the energy produced.
Finally, a chapter of conclusions will summarize the obtained results and will report the final considerations about the future work that can be done.

Chapter 2

Distributed Generation

2.1 Definition and development of distributed generation

In the literature and in official international documents, different definitions of the term distributed generation (DG) can be found, each refering to various characteristics for the classification: the size of the power plant, its location, the energy source that is converted into electricity, the voltage level of the grid to which is connected, the dispatchment methodology etc. But a consistent and unified definition is not existent yet.
In general a definition of distributed generation can be assumed to be as follows: the production of electric energy through plants connected directly to the distribution network or connected to the network on the customer site of the meter. Usually these kinds of plants have small sizes and therefore another common definition for DG is a small scale electricity generation [1].
The maltese authority, which has regulatory responsibilities relating to water, energy and mineral resources in the Maltese Islands (MRA, Malta Resources Authority) [2], doesn't give his own definition for distributed generation, therefore another one has to be adopted. Among the european denotations, the italian one can be choosed: the Autoritá per l'Energia Elettrica e il Gas (AEEG) [3], the italian energy authority, defines the distributed generation as the set of all the generation plants with a nominal power less than 10 MVA. A subset of the distributed generation is the Small Generation (SG) defined as the set of the plants for the production of electric energy, also with combined production of heat and power asset, with a nominal electric power

less than 1 MW. The third and last subset is the Micro Generation (MG) that is the set of the plants for the production of electric energy, also with combined production of heat and power asset, with a nominal electric power less than 50 kW.
This defintion doesn't take into accout the voltage level at which the power plant is connected, but it is known that they usually are connected at the distribution grid and therefore at the low voltage network. The kind of plant and the energy source are also not defined by the AEEG, except the underlinement of the possibility of a combined production of heat and power.
In this thesis work it was choosen to adopt the term distributed generation with reference to the power plants connected in the low voltage portion of the grid that use as primany energy source a renewable and aleatory one.
A general overview on the different generation technologies available for the distributed generation, showing both renewable and traditional energy sources, is shown in Figure 2.1 [4]. The technologies considered from this point forward are therefore the ones on the right branch of the scheme, in particular photovoltaic (PV) panels and batteries will be discussed and modelled.

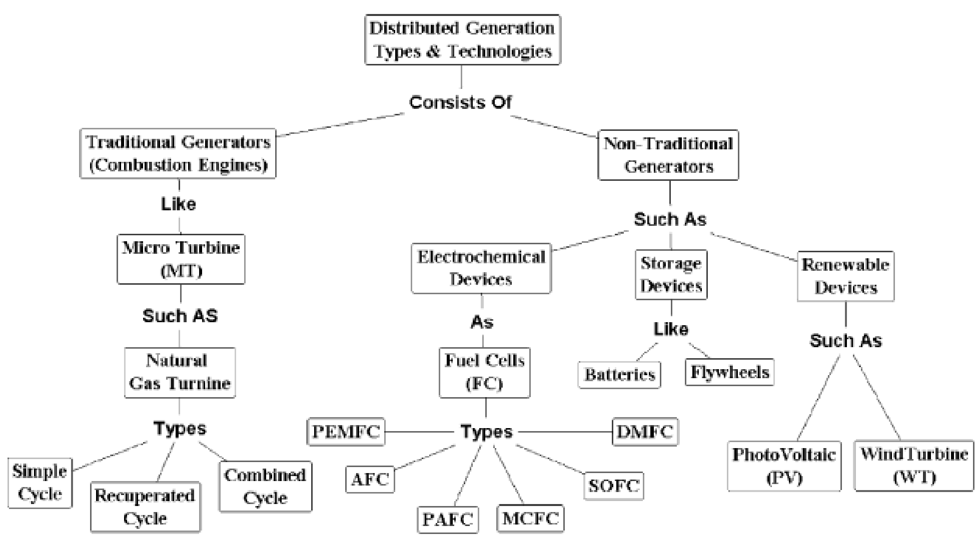


Figure 2.1: DG technologies

The need of a general and official definition of distributed generation, and

subsequently of a normative plan for its installation and operation, comes from the increasing level of its penetration in the territory but also the will of promoting its diffusion. As a matter of fact, the current energy production scenario seems to be unsuitable in a long term prospective to substain the actual energy demand that is continuously expanding.
The current production asset, widely based on traditional energy sources (as will be explained more extensively in a following section), having Malta no indigenous primary energy sources, is strongly dependent on the importation of non renewable fossil fuels and mainly relies on heavy fuel oil and light distillate. This situation is non-desirable for two principal reasons: the availability of fossil fuels and their derivates is not infinite though the previsions about their depletion are not uniquely defined and continually discussed. Furthermore the price of the fossil fuels is storically very much variable and affected by the political situation of the exporting countries. A few examples can be given: in 1980 when there was the Iranian revolution the price of crude oil rose till the maximum of the previous 100 years; when Iraq invaded Kuwait ten years later in 1990 and again with the invasion of Iraq in 2003 again the price of oil rose to the historical maximum.

In addition to these reasons, the increasing concern about the environmental impact of industrial processes, in particular those related to the comustion of fuels such as the ones needed for the traditional energy production, contributes to the expansion and the incentive of renewable distributed power plants. Various agreement have been taken at european and international level to reduce the emission of green house gases and other pollutants typical of the combustion processes, to increase the production of both electric energy and heat from renewable sources and to promote the energy efficiency. The European Union Directive 2009/28/EC set Malta's target share of renewable energy at 10% by the year 2020. The National Renewable Energy Action Plan for Malta is given in July 2010 [5]. According to the plan in 2020:

- renewable transport will be 37 ktoe (Tonne of oil equivalent);
- the wind energy production will be 0.3 TWh or 22 ktoe;
- Bio electricity will be 0.1 TWh or 12 ktoe;
- Wind power 15 MW and 38 GWh onshore wind and 95 MW and 216 GWh offshore wind;

- Solar photovoltaic 28 MW (43 GWh) and solar thermal 3 ktoe;
- The renewable electricity from solid biomass 86 GWh (7 ktoe) and biogas 50 GWh (4 ktoe);
- Renewable heat 0 ktoe for solid biomass and 2 ktoe for biogas.

To obtain these goals, distributed generation, intended as said as generation connected at the low voltage distribution grid and using renewable sources, is particularly indicated. Renewable sources are for their nature dispersed on the territory and therefore require several small plants for their conversion.
In addition to the exploitation of renewable resources and therefore the use of clean energy and the reduced environmental impact, the dispersed generation has other advantages (widely studied in literature [6] [7] [8]) that can be listed as follows:

- peak shaving: the distributed generation can help meeting the demand of energy in the part of the day when there is the peak consumption. The traditional power plants that normally meet this part of the demand, that are usually the less efficient, can therefore be switched off;
- voltage trend improvement: in a passive grid with no DG installed the voltage trend is decreasing from the substation to the end of the line. The dispersed generation causes a rise of the voltage level at the point of connection of the plant and the low voltage at the end of the line can be mitigated.
- deferred investments for the expansion of the distribution grid: when the physical capacity of the lines is insufficient to support the increase of the loads demand, building the distributed generation system could satisfy the partial increase of loads and reduce the investment of electricity generation and distribution facilities;
- increased reliability of energy supply: in case of fault along the line, the distributed generation can still supply energy to the loads;
- line loss reduction: line losses are always present in the grid because they are caused by the current flow in the cables and depend on the amount of current flowing and the line resistance. The presence of

distributed generation located near the loads reduces the current flowing from the substation transformer to the end of the line because the demand of energy is less.

On the other hand, dispersed generation has also some disadvantages that must be valued when installing power plants:

- technical point of view: the injection of energy in the grid causes the voltage to grow at the point of connection. When the level of penetration of the distributed generation reaches high levels this problem can get to an intolerable level violating the overvoltage limit of +10% of the rated voltage of the grid. Operating an electrical device above the specified voltage level range can lead to problems schu as malfunction, shut down, overheating, premature failure etc. so this condition is to be avoided. This is the problem this thesis is focused on.

- economical point of view: many technologies for the conversion of renewable energy are not yet economically mature to be sustainable without incentives. The costs are still too high and research must be carried on to reduce the plant investments that is the big part of the cost to be sustained since the fuel costs are null and the maintenance costs are low expecially for photovoltaic installations and fuel cells because of the absence of moving parts.

- dispatch point of view: the renewable sources are for their nature uncontrollable and not predictable except in short term and anyway with a low level of certanty. The energy produced is not precisely calculable and therefore traditional power plants must guaratee a bigger part of their capacity to be ready to cover the part of the load demand formerly covered by the renewable plant. The continuous switching on and off of the plants and the change of power supplied reduces the efficiency of the traditional power plants;

- operation point of view: when there is a fault on the line the distributed generation is obliged to disconnect from the grid. This causes a loss of efficiency because the renewable source is no longer exploited and moreover the grid looses a system that could help supporting the voltage. This operation mode is being changed: when a fault occurs the GD has to remain connected to the grid and support the voltage with its power injection.

2.2 Economic considerations about the integration of distributed generation

As said before, most technologies exploiting renewable energy sources are not economically mature to be sustainable without incentives. The Malta Resources Authority (MRA) has set during the last ten years various schemes to promote energy efficiency and energy production from renewable sources, some of which are today inactive. Incentives are partly funded under the European Regional Development Fund - Cohesion Policy 2007-2013 and from national funds.

2.2.1 Feed-in Tariffs

Solar photovoltaic plants (the only renewable source considered in this thesis) are now incentivated with the mechanism of the Feed-in Tariffs (FIT) that is regulated by the the Subsidiary Legislation 423.46 [9]. The FIT regulations were introduced for the first time on 10th September 2010. Before this date the net metering scheme was used: any units of energy produced by the solar power plant and exported to Enemalta was deducted from the units imported. Additional units consumed above those exported were charged at the published current tariffs. In the case where the units generated exceeded the units imported, the consumer was credited at 0.0699 Euro per unit. Energy balance was calculated on a yearly basis. The net metering arrangement is no longer an option for new PV systems.
The Subsidiary Legislation 423.46 now provides different feed-in tariff scheme options which a consumer can subscribe for the electricity produced by his PV system as follows:
For solar PV installation commissioned and connected before the entry into force of the new regulation in 2010 the installation operator may chose to:

- retain the net metering arrangements with Enemalta and be paid the spill-off tariff;

- request the Authority to:

    a) sell all the electricity produced by the solar power plant (Full Export option);

b) generate energy primarily for self consumption and be paid the feed-in tariff for the excess generated electricity (Partial Export option).

For solar PV installation commissioned after the entry into force of the new regulation and satisfying the eligibility criteria established in the legislation the operator may:

- sell all the electricity produced by the solar power plant (Full Export option);
- generate energy primarily for self consumption and be paid the feed-in tariff for the excess generated electricity (Partial Export option).

The metering configuration and equipment installed by Enemalta to measure energy flows is the same for every Feed-in Tariff option. It includes a meter on the PV plant that measure the energy produced by the panels and another one (import/export meter) that measure the electricity taken from the grid and the electricity that goes out from the building to the grid. In Figure 2.2 the scheme of the metering equipment is shown.

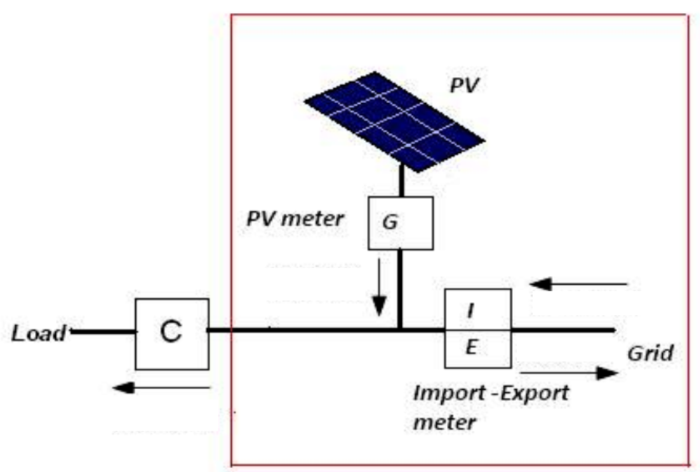


Figure 2.2: metering equipment installed with the solar plant

For the two options described before, the readings used to calculate what is due to the operator for the energy produced or what is due to Enemalta for the energy purchased are different:

- Full export option: Enemalta pays the producer for all the electricity generated by the PV panel as measured at point G on condition that this does not exceed the cap for the payment of the feed-in tariff, while the consumer has to pay for the electricity consumed at point C calculated as $C = I + G - E$.

- Partial export option: Enemalta pays the consumer for the electricity exported from the PV (as measured at point E) on condition that this does not exceed the cap for the payment of the feed-in tariff and the consumer pays Enemalta for the electricity imported from the grid (as measured at point I)

For all the PV systems approved in any of the feed-in tariff schemes, the cap for the payment of the feed-in tariff (the amount of units that may be sold to Enemalta each year at the applicable feed-in tariff and for the duration of the guaranted period) is calculated as the kWp installed multiplied by 1600. Any units generated and sold to Enemalta above the cap are paid at the marginal cost.
The tariffs and guarantee period are different according to the year in which the plant has been approved (only residential sector information are reported):

- FIT schemes from 2010 to 2012:

  a) for a PV plant installed in Malta benefitting from a grant not more than 50% on the purchase price and for which the FIT scheme was approved between the 10th September 2010 and the 31st December 2012 the feed-in tariff applicable is 25c/kWh for 8 years;

  b) for a PV plant installed in Gozo benefitting from a grant not more than 50% on the purchase price and for which the FIT scheme was approved between the 10th September 2010 and the 31st December 2012 the feed-in tariff applicable is 28c/kWh for 8 years;

- FIT schemes for 2013:

  a) For PV systems that benefit from a grant not exceeding 50% of the purchase price of the PV system and approved a FIT between the 1st January 2013 and the 31st December 2013 the feed-in tariff applicable is 22c/kWh for 6 years;

b) For PV systems that do not benefit from any grant and are approved a feed-in tariff between the 1st January 2013 and the 30th June 2013:
- For a PV system installed on a roof with a capacity of less than 1MWp the applicable feed-in tariff is 18c/kWh for 20 years;
- For a PV system installed on ground with a capacity of less than 1MWp the applicable feed-in tariff is 17c/kWh for 20 years;
- For a PV system installed on roof with a capacity of 1MWp or more the applicable feed-in tariff is 17c/kWh for 20 years;
- For a PV system installed on ground with a capacity of 1MWp or more the applicable feed-in tariff is 16c/kWh for 20 years;

c) for PV systems that do not benefit from any grant and are approved a feed-in tariff between the 1st July 2013 and the 30th September 2013:
- For a PV system installed on a roof with a capacity of less than 1MWp the applicable feed-in tariff is 17c/kWh for 20 years. The cap is 6,400,000 kWh/year;
- For a PV system installed on ground with a capacity of less than 1MWp the applicable feed-in tariff is 16c/kWh for 20 years. The cap is 6,400,000 kWh/year;
- For a PV system installed on a roof with a capacity of 1MWp or more the applicable feed-in tariff is 16c/kWh for 20 years. The cap is 6,400,000 kWh/year;
- For a PV system installed on ground with a capacity of 1MWp or more the applicable feed-in tariff is 15.5c/kWh for 20 years. The cap is 6,400,000 kWh/year.

2.3 Technical considerations

From the technical point of view, the integration of distributed generation in the national grid imply the existence of barriers arising from the assumption that the distribution grid is originally built as a passive system. The problems caused by the installed plants are proportional to the level of penetration of the DG itself. This means that when the installed capacity is low, the critical situations may not occur and that the technical solutions and the

eventually necessary renovation of the energy facilities can follow the gradual growth of the penetration of DG.
The first issue to be considered when connecting a generation plant to the distribution grid is the dispatching procedure, the active and reactive power flow and the consequent voltage and frequency regulation procedures. A high level of penetration of distributed generation would have to match with the present voltage adjustment mechanism that is necessary for the stability of the whole electric system. It is indeed important to mantain the balance between generated and consumed active power and the presence of non controllable generators, since we are considering renewable, non-predictable sources that until now don't have any obligation to support the grid, could conflict with the effort to obtain stability.
Regarding this problem the European Union has long term projects that aim to build a *smart grid* with high penetration of distributed generation from renewable sources equipped with advanced control and communication infrastructure between the various users of the grid (generators and consumers). The control of voltage and frequency will be then centralized and not left to each single generator: the level of efficiency of this type of system would be much higher than the decentralized.

The reactive power flow also has a significant role because it could be used in the voltage control. Generating the reactive power needed by the domestic loads near the loads themselves allows to decrease the amount of current flowing along the distribution lines and therefore to lower the voltage. This particular aspect of the DG integration,however, will not be considered more in this thesis.
The presence of distributed generation cause an alteration of the voltage trend along the lines proportional to the quantity of power injected and the reactance of the line (and therefore the position of the DG in the grid). The voltage drop can be in fact be written in a simplified for as:

$$\Delta V = R \cdot P + X \cdot Q \tag{2.1}$$

In this case too, with high level of penetration of distributed generation, the presence of active regulation would be necessary: the communication between the substation and the various generators would rise the overall efficiency of the control.

Regarding the energy losses along the line, the DG can help reduce them but only under precise limits. As long as the energy produced by the DG is less or equal to the energy absorbed by the loads, a reduction of line loss can be observed, but when the distributed plants produce more than required a situation of counterflow is established in the grid or in part of it meaning that the power is flowing toward the higher level of voltage. In such a case, expecially when the load demand is low, the line losses might be greater. In literature various studies have been carried out on this argument ([10], [11]).

2.4 Maltese actual energy production asset

The maltese islands don't have any indigenous traditional energy source and therefore are strongly dependent on the importation of fossil fuels from other countries. In Figure 2.3 are reported the data of the energy balance for Malta for the year 2011 in thousand tonnes of oil equivalent (ktoe) on a net calorific value basis [12].

	Coal and peat	Crude oil	Oil products	Natural gas	Nuclear	Hydro	Geothermal, solar, etc.	Biofuels and waste	Electricity	Heat	Total*
Production	0	0	0	0	0	0	1	47	0	0	48
Imports	0	0	2215	0	0	0	0	0	0	0	2215
Exports	0	0	-60	0	0	0	0	0	0	0	-60
International marine bunkers**	0	0	-1223	0	0	0	0	0	0	0	-1223
International aviation bunkers**	0	0	-94	0	0	0	0	0	0	0	-94
Stock changes	0	0	-28	0	0	0	0	-1	0	0	-29
TPES	**0**	**0**	**810**	**0**	**0**	**0**	**1**	**46**	**0**	**0**	**857**

Figure 2.3: Energy balances for Malta, year 2011

It can be easily seen that the maltese energy asset is mainly based on oil products: their share on the total of the Total Primary Energy Supply (TPES) is 94.5%. Big part of the 810 ktoe of oil used in the maltese economy is used in the two power plants for the production of electric energy (592 ktoe corresponding to 73% of the total TPES) while the rest is used in the transport sector (173 ktoe corresponding to 21.3%) in industry (1 ktoe corresponding to 0.1%) and the remaining part for other uses (54 ktoe corresponding to 5.6%). The value of the oil products imports is as said very high due to the lack of local production. The last important item present in the maltese energy balances is the international marine bunkers that move an amount of energy almost equal to half of the total imports.

This strong dependence on oil is also due to the lack of two important categories of energy production: the nuclear and the hydro. The maltese general opinion is strongly anti-nuclear so the first option has been rejected, while the second one is tecnically infeasible because there are no permanent lakes or rivers in Malta though in the two bigger islands of the archipelago a few rural watercourses flow all year round. It is however impossible to exploit this source in a cost effective manner and is therefore to be excluded from the maltese generation park.

Another absent source in the maltese generation asset is the natural gas that could be used in more efficient plants than the oil products and would therefore help Malta to achieve the goals of emission reduction required by the European Union. In this case, since there are no pipelines taking gas to Malta from any neighbouring country, its absence can be attributed to the higher cost of transport of gas than oil. Gas need in fact to be cooled to a temperature sufficient to mantain it liquid for transport and therefore appropriate facilities at the final destination to reconvert it in the gaseous state.

In Figure 2.4 is shown the amount of the various sources used for the production of electric energy or alternatively of heat.
Again the relevant role of oil in the production of electric energy can be easily noted with a small contribution of waste (part municipal and part industrial as shown in Figure 2.5) and solar photovoltaic, an energy sector still small but in great expansion in the last years thanks to the incentives provided by MRA. As for the production of heat, on the other hand, the waste sector is the most important and provides all the energy needed through CHP plants (Combined Heat and Power).

Regarding the production of energy from renewable resources, data are shown in Figure 2.5.
The big part of gross electric energy production from renewable sources is represented by solar photovoltaic plants with more than 50% of the total, with the contribution of municipal and industrial waste. The absence of

	Electricity	Heat
Production from:	*Unit: GWh*	*Unit: TJ*
- coal and peat	0	0
- oil	2181	0
- gas	0	0
- biofuels	0	0
- waste	5	1390
- nuclear	0	0
- hydro*	0	0
- geothermal	0	0
- solar PV	8	0
- solar thermal	0	0
- wind	0	0
- tide	0	0
- other sources	0	0
Total production	**2194**	**1390**
Imports	0	0
Exports	0	0
Domestic supply	**2194**	**1390**

Figure 2.4: production of electricity or heat for each energy source, year 2011

other important energy sources, such as hydroelectric, wind, geothermal and biogases has to be noted. From 2011, year to which the data refers, photovoltaic plant has increased in number thanks to the national incentives and some project for wind farms, both onshore and offshore, are under study for a future development.
Regarding the heat generation as said before, the big part is produced from municipal waste through CHP plants (Combined Heat and Power). Part of the production is also imputed to primary solid biofuels (primary solid biomass) and solar thermal. The former is entirely used for final consumption in the residential sector, and the latter is also used for final consumption but is not specified the particular sector. In the heat sector can be noted too the reduced diversification of the energy source because of the absence

	Municipal waste*	Industrial waste	Primary solid biofuels**	Biogases	Liquid biofuels	Geothermal	Solar thermal	Hydro	Solar photovoltaics	Tide, wave, ocean	Wind
Unit	GWh	GWh	GWh	GWh	GWh	GWh	GWh	GWh	GWh	GWh	GWh
Gross elec. generation	**3**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**8**	**0**	**0**
Unit	TJ	TJ	TJ	TJ	TJ	TJ	TJ				
Gross heat production	**1390**	**0**	**0**	**0**	**0**	**0**	**0**				
Unit	TJ	TJ	TJ	TJ	1000 tonnes	TJ	TJ				
Production	1868	19	24	0	1	0	30				
Imports	0	0	0	0	0	0	0				
Exports	0	0	0	0	0	0	0				
Stock changes	0	0	0	0	-1	0	0				
Domestic supply	**1868**	**19**	**24**	**0**	**0**	**0**	**30**				

Figure 2.5: energy from renewable sources and waste, year 2011

of biogases and geothermal plants.

Regarding in particular photovoltaic plants, in Table 2.1 the quantity of PV installation in all sectors (household, industrial, commercial, public, institutional household) is shown [13].

Year	Qty in Malta	Qty in Gozo	Total kWp
2006	17	3	42
2007	15	1	53.4
2008	12	6	130.9
2009	161	31	1168.8
2010	1162	232	3917.8
2011	575	103	3674
Q1 2012	1844	311	4424.4

Table 2.1: number of PV installation in all sectors

It can be seen that in the last years, in particular from the year 2009, the increase of plants is relevant due to the incentives set by the malta resources authority. It can be seen from these data and from Table 2.2, that shows the growth of the number of PV plants installed in the two bigger islands of the archipelago in the residential sector and the respective installation capacity, that the big part of the new installations after 2009 are in the residential sector, sign that the incentive methods have a great effect.

Year	Qty in Malta	Qty in Gozo	kWp in Malta	kWp in Gozo
2006	8	2	13.9	2
2007	5	0	8	0
2008	3	1	6.5	2.1
2009	149	6	197.3	6.8
2010	1141	175	2070	327
2011	550	32	1152.2	79.4
Q1 2012	1826	303	3737.8	588.4

Table 2.2: number of PV installation in the residential sector

Figure 2.6 and 2.7 show respectively the progress of the PV installation in the residential and in all sectors, with the installed capacities for the two island of Malta and Gozo.
Considering all possible sectors the cumulative installed plants in Malta is, in the first part of 2012, 3786 units and 687 units in Gozo with a total installed capacity of 13411.3 kWp. In the residential sector there are 3682 unities in Malta with a cumulated capacity of 7185.7 kWp and 510 in Gozo with a capacity of 1005.6 kWp.

At present time, the level of penetration of photovoltaic plants in the maltese

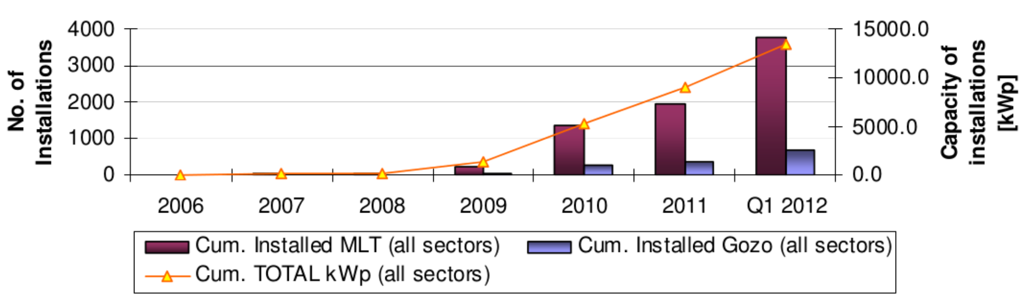


Figure 2.6: cumulative PV installations authorised in all sectors

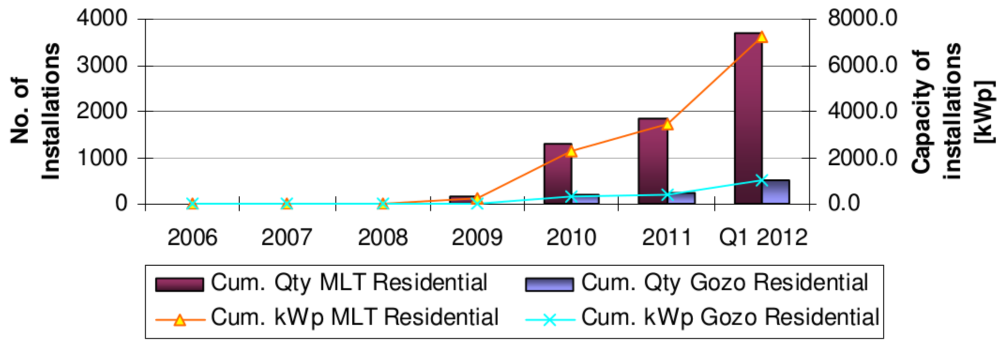


Figure 2.7: cumulative PV installations authorised in the residential sector

grid is not enough to cause overvoltage problems but its growth is constant and fast due to the incentives introduced by the Malta Resources Authority; this "stato de facto" makes near the reaching of intolerable levels of power connected to the low voltage lines. The particular need of Malta to reduce its dependance from the imports of energy sources from other countries induce the scientific community to look for solutions to the problem of excessive installation of renewable plants before it becomes a real problem.
This is the purpose of this work: analyze the amount of power installable without reaching the voltage limits and evaluate its increase if storage apparatus ace used to mitigate the problem of overvoltage.

Chapter 3

Maltese electric system

3.1 General overview

The Maltese national electricity grid is an isolated one and is not connected to any other electrical network. All the electrical energy that is required in the islands that form the maltese archipelago is therefore generated locally, in particular in the island of Malta. All the activities of energy generation and distribution are carried out by Enemalta Corporation (EMC) [14] that is also designed to be the Distribution System Operator (DSO) in Malta. At present EMC operates two power stations, which supply all the electrical power needs of the islands of Malta, Gozo and Comino. These stations, with a total combined nominal installed capacity of 571 MW, are interconnected together by means of the existing grid.

The distribution of electricity to the whole territory of Malta is achieved on four a total of voltage levels here described:

- 132 kV: at present there are two distribution systems, 8 km long 132 kV circuits in service and these are installed between Delimara Power Station locadet at the south-east of the island of Malta and the only 132 kV Distribution Centre in operation in Malta which is located close to Marsa Power Station at Marsa. The second distribution system is situated between Marsa and Mosta, an important and central city. Enemalta is investing heavily in a system of tunnels for future 132 kV circuits.

- 33 kV: consists of both overhead lines and underground cables whose lengths are 154 km and 60 km respectively. In order to safeguard the environment and to enhance system reliability, Enemalta's policy is that future 33 kV circuits shall be installed underground. Three submarine cable circuits also supply electricity from Malta to Gozo and Comino where there aren't power stations.

- 11 kV: the 11 KV system, which spreads throughout the Maltese Islands, is predominantly underground and future circuits will also be installed underground. So far, Enemalta has 1041 km of 11 kV underground cables and 159 km of 11 kV overhead lines in service. Some industrial and commercial customers are supplied directly with electricity at this voltage level. The 11kV system includes 1075 indoor type substations and 132 pole mounted transformers where the voltage level is stepped down from 11 kV to 400/230 V.

- 400/230 V: the low voltage system in the maltese islands is a three phase, 4 wire, 400/230 V system. Except in Valletta and Floriana, where the system is mainly underground, the low voltage system consists of overhead lines.

Figure 3.1 shows the high voltage electric grid on the maltese archipelago: the purple lines represent the 132 kV underground cables, the green ones the 33 kV grid that is divided as said in underground cables and overhead lines. The red spots show the location of the two power station that provide electricity to the whole territory.

3.1.1 Low voltage distribution grids

In this thesis only the low voltage grid and the transformers where the voltage level is stepped down from 11kV to 400/230V to final supply are considered; the behavior of the grid located upstream of the transformer is partially represented in the transformer's parameters and the semplification of not considering it is supposed to give an error in the calculation which is less than a few percentage points.

General characteristics

The maltese network code [15] approved by MRA presents the characteristics required for the operation of the grid The secondary distribution grid in

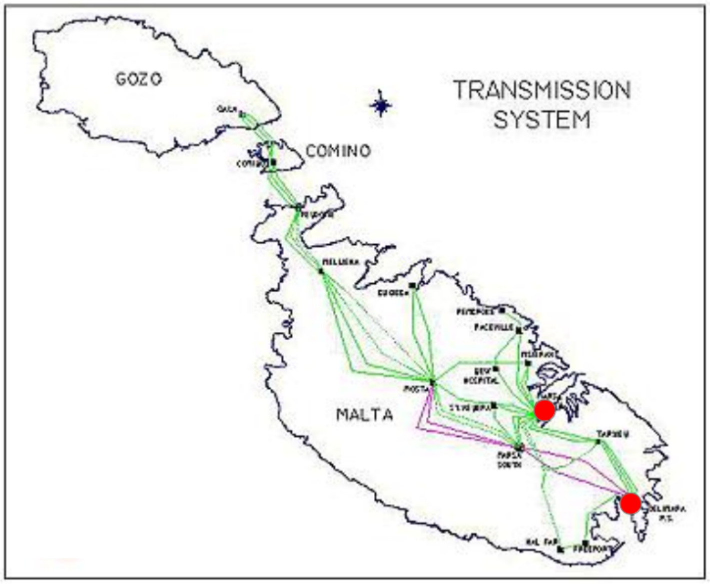


Figure 3.1: maltese electic grid map

Low Voltage (LV) is constituted by the most extent and periferical part of the entire system of production and distribution of electric energy. It has the task of providing energy to the big part of final domestic and industrial consumers except the limited ones connected directly to the Medium Voltage (MV) grid. The voltage level is set at 230/400 V (phase to neutral/phase to phase voltage) and the nominal frequency is the european standard: 50 Hz.

Earthing

As said before, the LV system is a three phase, 4 wire system: the neutral conductor is therefore used and has different treatment for the various supply voltages: in the LV system it is earthed at the LV winding of MV/LV transformer. Moreover the electrical installation of all consumers connected at low voltage have to be protected by a TT system: the privat electrical system is earthed with a dedicated installation.

Grid structure

The low voltage distribution grid structure is radial: from the second winding of the transformer one or more feeders depart (five or six ways are commonly used in practice). Through subsequent ramifications the energy is then taken to the final consumers . In Figure 3.2 is given an example of an urban area covered by a substation. The red lines represent the feeders departing from the substation, the green ones the cables of the overhead lines reaching the final consumers, and the area delimited by the blue line is the total area served by the substation considered.

(a) feeders departing from the substation (b) area covered by aerial lines

Figure 3.2: substation served area

Differences can be observed in the structure and size of the grid depending on the geographical context: in urban areas the density of power installed is high and the grid has a smaller extention; on the contrary, in the rural areas the density of power is low and therefore the feeders are less but longer.
Two different cable types with different properties are used for the two categories of connections: the feeders outgoing the substation and the aerial lines

departing from these and taking the electric energy to the final consumers. The characteristics of the two types are summarized in Table 3.1.

	diameter	material	Z [Ω/km]	length
feeders	$185mm^2$	Al	0.164+j0.0753	usually less than 150m
aerial lines	$70mm^2$	Cu	0.26+j0.23	depends on density of consumers

Table 3.1: cable characteristics

Connection conditions and operation for generation plants:

Where a generation unit is to be installed, Enemalta has to be informed and have the right to inspect the plant and ensure that all the requirements for security, safety and good working of the system are met. Generator operators have to provide Enemalta with informations on the generating unit and the proposed interface arrangements with the distribution system. These informations include rated power, type of generation plant (synchronous , asynchronous), operating regime of generation (continuous, intermittent, peak lopping), method of voltage control, means of synchronisation between Enemalta and the user, details of arrangements for connecting with earth that part of the generating plant directly connected to the distribution system etc.
The network configuration at the connection point can have different configurations depending on the nature of the installation and network arrangements.

Technical requirements

All generators have to comply with the relevant sections of the Network code, and the electrical parameteres to be achieved at the point of connection shall be specified by Enemalta with the offer for connection. Normal interface protection is required and can include all or some of the following facilities:
- Overcurrent protection;
- Earth fault protection;
- Intertripping.

Protection associated with the generating plant is required to coordinate with the distribution system protection regarding:
- Clearance times for fault ccurrents;
- protection settings of the controlling circuit breaker.
The total harmonic voltage distortion limit for generators connected at 400 V voltage system is 2.5%.

Metering

Metering equipment is supplied, owned and installed by Enemalta as close as possible to the user's incoming/outgoing switchgear terminals. It has to take measurements of energy and power flowingfrom the network to the generator's installation or vice versa or in both directions separately. The producer may have to provide space in his switchgear to eable Enemalta to install equipment to obtain such measurements.

Islanding

It is possible during emergency conditions that a part of the distribution system where the producers are connected become detached from the rest of the grid (Islanding). The common example of islanding is a grid that has solar panels connected to it. In case of a blackout, the solar panels will continue to deliver power as long as irradiance is sufficient. In this case, the supply line becomes an"island" with power surrounded by unpowered lines. Islanding should be avoided for different reasons:

- Safety concerns: if an island forms, repair crews may be faced with unexpected live wires.

- End user equipment damage: customer equipment can be damaged if the operationg parameters differ greatly from the norm.

- Ending of the failure: reclosing the circuit onto an active island may cause problems with the utility's equipment, or cause automatic reclosing systems to fail to notice the problem.

- Inverter confusion: Reclosing onto an active island may cause confusion among the inverters.

In such cases the maltese network code forces the generator to immediately disconnect itself from the system and remain detached unless authorised by Enemalta.

3.2 Substations and Transformers

As said before, in Malta the 11 kV system includes 1075 indoor type substations, usually used in urban context to reduce the noise and to protect the switchgear from extreme climate or pollution, and 132 pole mounted transformers where the voltage level is stepped down from 11 kV to 400/230 V. A typical domestic substation has the following characteristics:

- Step down: 11 kV to 400 V;
- Power range: 500 kVA, 1 MVA, 1.6 MVA;
- Tap changer: not automatic, not on-load;
- Feeders from substation: 5-6 ways are commonly used in practice;
- Number of consumers: on a substation the number of consumers can range between a few handreds up to 1000 customers on older systems; a reasonable assumption is to consider 500 customers on the substation.

The neutral cable of the LV winding of the transformer is earthed at the substation.

Chapter 4

Models

In this chapter the models of the various components of the grid and the devices connected to it are described and detailed. The part of the grid upstream of the low voltage system is not modelled; its behaviour is, as said before, partly represented in the transformer parameters, and the assumption of not considering it is supposed to give an error in the calculations less than a few percentage points.

4.1 Line model

As said in the previous chapters, in this thesis only the low voltage portion of the grid was considered and simulated. It is difficult to have effectively representative models of the LV system because of the big variety of possible configurations that this part of the line can assume: it has to reach the totality of the consumers, in rural or urban context, with different density of population etc. It was choosen therefore a model that is simple but that can be easily changed and adapted to different situations.
In Figure 4.1 the structure of the model of the grid is shown.
From the substation transformer a few feeders depart, five or six are commonly used in practice, with a bigger section ($185mm^2$) than the more peripheral part of the grid. In the simulation only one of the five feeders departing from the substation was considered. The feeders are further divided in smaller cables ($70mm^2$) that take the energy to the final consumers. Utilities can be connected to both of them but in this thesis it is assumed that the consumers are connected only to the thinner cables responsable for

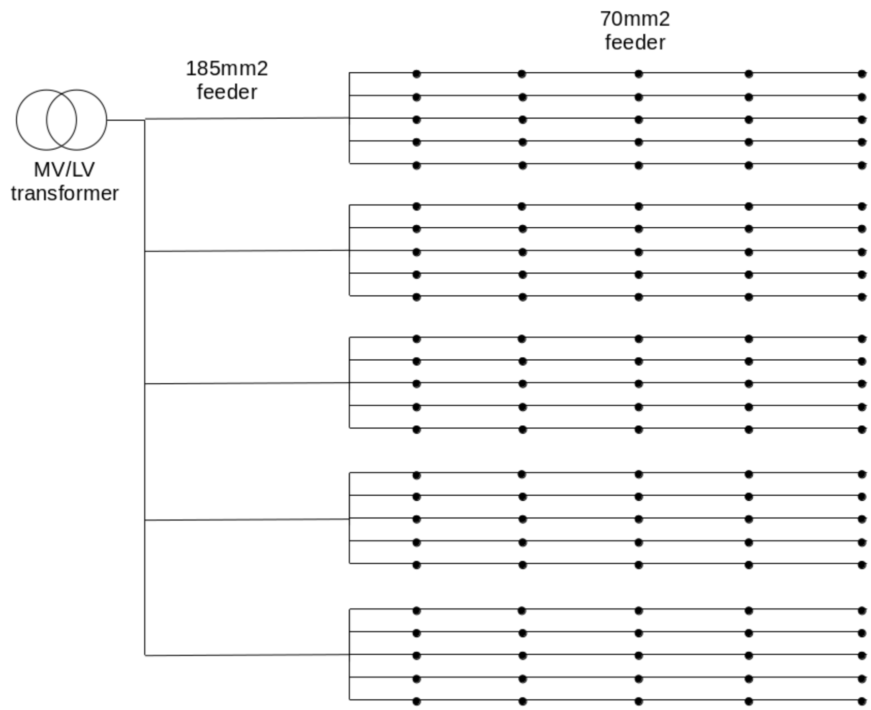


Figure 4.1: grid model structure

the transport of energy to the end of the line.

To make the model more simple and to shorten the times of the simulation the final users of the grid have been grouped: in each point of connection three “units” are modelled: each unit is composed by an equivalent load, an equivalent solar panel and a battery (Figure 4.2).

The load profile of each user is not the same every day and is different from house to house so the use of the equivalent consumer is necessary. The equivalent consumer is a user that employs an amount of energy equivalent to the mean consumption of the population considered and it’s calculated approximately as the total consumption of a geographical area divided by the number of users located in this area. The same can be said about the solar panels output so, equally, the equivalent solar panel is a plant that produces an amount of energy equivalent to the mean production of the population considered. Load and solar panels models are discussed in the next sections of this chapter.

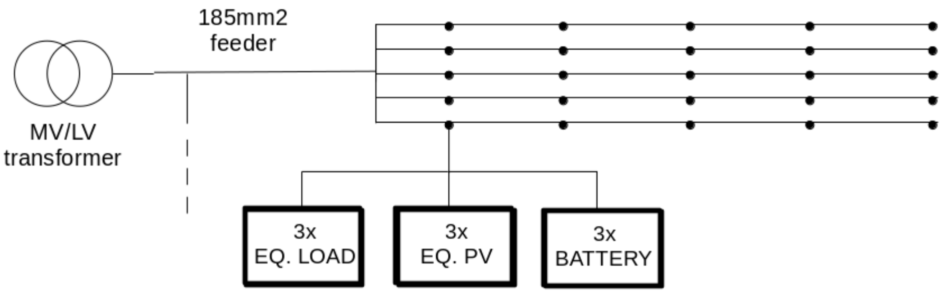


Figure 4.2: components of the line “units”

As said before this model structure is optimal to simulate situations with different configurations that could be different for the lenght of the cables, the amount of energy consumed or produced by the the loads or solar panels respectively or the number of units connected. In this thesis, it was choosen to simulate different cable lenghts, that could be assumed longer in a rural context and shorter and more branched in an urban context, and different solar energy production to reproduce the situation in which the solar irradiation is not at full power due to cloudiness more or less intense.

The model of the line in *MATLAB* was constructed using the libraries of Simpowersystem where is already implemented a model for the line section called *PI section line*. The block implements a single-phase transmission line with parameters lumped in PI sections. An approximate model of the distributed parameter line is obtained by cascading several identical PI sections, as shown in Figure 4.3.

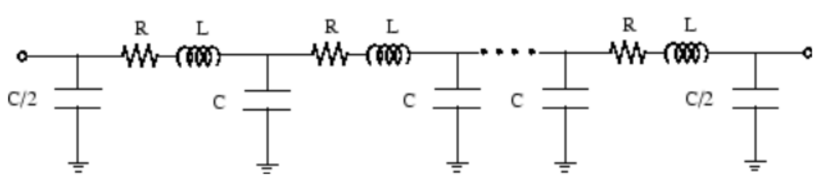


Figure 4.3: pi section line scheme

The resistance, inductance and capacitance are uniformly distrubited along the line. For short line sections ($< 50km$ as in the present case) the RLC elements of the line are given by $R = r \cdot l_{sec}$, $L = l \cdot l_{sec}$, $C = c \cdot l_{sec}$ where r, l, c are respectively the resistance, inductance and capacitance per unit length of the cable and l_{sec} is the length of the line section being considered. Besides the values of r, l, c, the length of the line and the number of PI sections are settable parameters.

4.2 Transformer model

In this thesis the transformer has been modelled as a voltage source connected in series with an impedance. These elements represent the behavior of the transformer itself and of the grid, with all the elements connected to it, that is upstream of the substation and connected to the medium voltage winding of the transformer. The maximum error resulting from this semplification of the system is expected to be less than 10%.
The impedance of the transformer has been calculated according to the following formula:

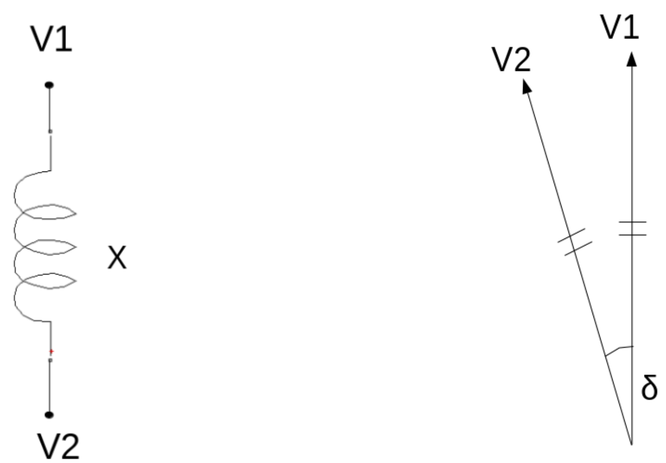
$$Z_{act} = Z_{pu} \cdot \frac{V_B^2}{S_B} \tag{4.1}$$

where
- Z_{pu} is the percentage impedance of the transformer: the percentage impedance of a transformer is the volt drop due to the winding resistance and leakage reactance expressed as a percentage of the rated voltage. It is also the percentage of the normal terminal voltage required to circulate full-load current under short circuit conditions; For a transformer of rated 11 kV the percentage impedance is about 5% so this is the value considered.
- V_B is the rated voltage;
- S_B is the nominal power of the transformer. Between the three power typical of the maltese grid listed in the previous chapter (500 kVA, 1 MVA, 1.5 MVA) it was chosen to use in the grid the maximum one in order to simulate the line with the maximum number of units connected possible. In simulations where a smaller number of users are connected and a smaller transformer is suitable, its rating can be easily changed.

The MV/LV transformers in Malta have at the second winding four wires: the three phases and the neutral that is earthed at the substation.

4.3 PV power plant

The photovoltaic panels have been modelled as a controlled voltage source connected at the point of common coupling (PCC) of the plant. The voltage waveform has been determined considering the simplified scheme shown in Figure 4.4a



(a) pv semplified scheme

(b) voltage phasors

Figure 4.4: PV semplified scheme

where:
-V1 is the line voltage at the point of common coupling;
-V2 is the voltage at the inverter of the PV panels;
-X is a not real, made-up reactance that is needed to provide the difference in phase between the two voltages V1 and V2, given in reality by the power injection of the solar power plant.

The power flowing from the PV panels to the grid can be therefore written as:

$$P = \frac{V1 \cdot V2}{X} \cdot \sin(\delta) \tag{4.2}$$

where δ is the angle between the two phasors of the voltages V1 and V2 shown in Figure 4.4b. The norm of the two phasors of the voltage at the PCC and at the inverter differ very little and can be therefore assumed to be equal: $V1 = V2 = V$. Considering this assumption, the power flowing from the PV panels to the grid can be written as:

$$P = \frac{V^2}{X} \cdot \sin(\delta) \tag{4.3}$$

The power injected by the solar panels in the grid is a known value that changes during the day and has the trend shown in Figure 4.5: a real maltese power plant installed in the city of Sliema with a nominal power of 3.0 kWp was taken as reference for the domestic PV installations. A tipical production curve of this unit in a sunny day in the winter period was considered (7 november 2013); the production starts around 7.00am and ends when the sun sets at around 5.00pm.

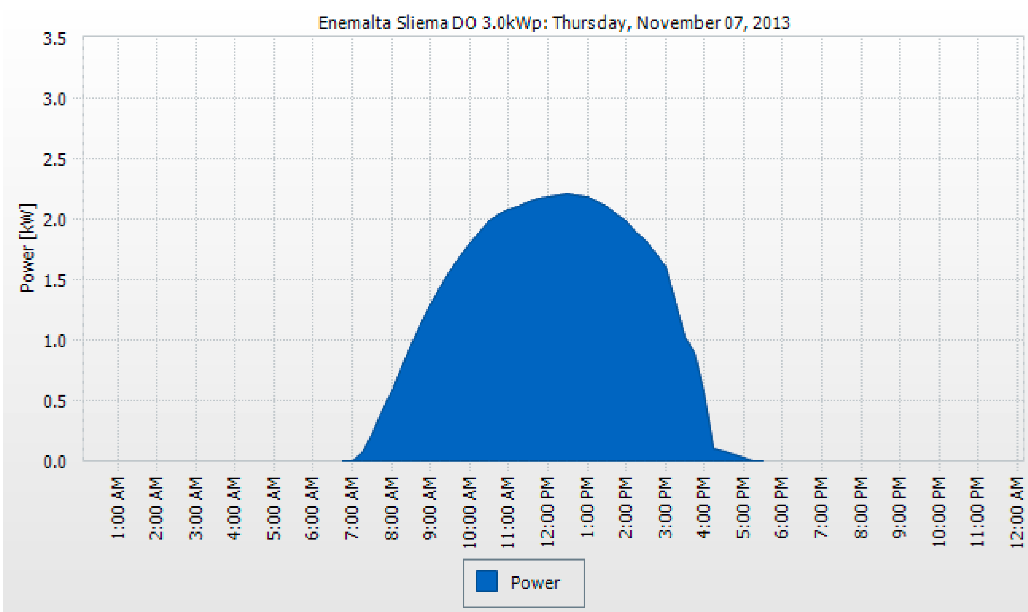


Figure 4.5: solar panels' power

The peak value of the production is about 2.2 kW in the central hours of the day.
From equation 4.3, the difference in phase of the two voltages due to the immission of power by the PV power plant can be derived:

$$\delta = \arcsin\left(\frac{P \cdot X}{V^2}\right) \tag{4.4}$$

This value is then used to build the sinusoidal wave of the controlled voltage source. It has to have the same amplitude of the voltage at the point of common coupling, the same frequency and a difference in phase given by the angle δ found in equation 4.4. The voltage amplitude is given by a voltage measurement block whose output signal is then processed by a RMS block that gives the Root Mean Square value of the sine wave and finally multiplied by $\sqrt{2}$ to obtain the peak value.
A PLL was used in the simulation to get a wave with the same frequency and phase of the voltage at the Point of Common Coupling. A Phase-Locked Loop, usually known with its acronym PLL, is a control system that generates an output signal whose phase is related to the phase of the input signal. It is basically constituted of a variable frequency oscillator and a phase detector. The phase detector compares the phases of the signal produced by the generator and of the input signal and adjust the oscillator to keep the two phases matched. Keeping the phases locked together means also keeping the input and output frequences the same. The sine wave of the controlled voltage source was then constructed as follows:

$$|V1| \sin(\omega t + \theta + \delta) \tag{4.5}$$

where
-$|V1|$ is the peak amplitude of the voltage at the point of common coupling;
-$\omega t + \theta$ is given by the PLL and represent the frequency ($\omega = 2 \cdot \pi \cdot f$) and the phase (θ) of the voltage at the PCC.
-δ is the difference in phase between the voltage at the PCC and at the inverter of the PV plant given by equation 4.4.

In this thesis the reactive power injected or absorbed by the solar panels is not considered and is set equal to zero. Reactive power regulation is another possible mechanism to control the voltage profile (both overvoltages or undervoltages) along the line because of the bigger or lower current that would be consumed or generated. This argument could be better discussed in a future work.

4.4 Load

The typical current consumption of a domestic load in Malta is a function of time characterized by two peaks during the day: the first one around 8.00 in the morning when people wake up and have breakfast and the second one during the evening around 19.00-20.00, when families are at home, cooking and using many energy consuming devices such as TV, computers and water heaters. The part of the day when there is less energy consumption is obviously the night when only few devices such as the refrigerator are working.
Current consumption data of a typical MV/LV substation were taken and used in the simulation. The trend of the consumption for a week is shown in Figure 4.6 where different colors represent the three phases of the distribution grid one of which is then considered separately from this point forward.

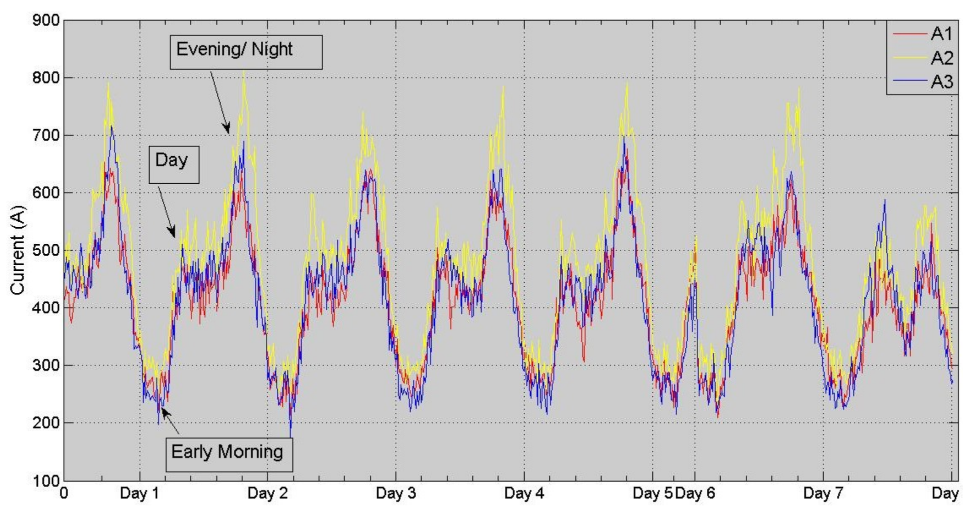


Figure 4.6: domestic load trend

In this thesis the domestic loads have been modelled as a controlled voltage source taking current from the grid and therefore absorbing energy. The model construction logic is the same as the PV panels: the voltage imposed at the PCC is given by the equation 4.5 where $|V1|$ and $\omega t + \theta$ are the peak amplitude at the PCC, taken from the voltage measurement, and the frequency and phase of the voltage, given by the PLL, and δ is given by equation 4.4 where the power P is the power absorbed by the loads, and is therefore negative.

As well as for the photovoltaic panels, reactive power absorption or injections by the load are not considered and the power factor of the generator is selected equal to 1.

4.5 Storage apparatus

The model of the storage apparatus was constructed, similarly to the load and the solar panels, as a controlled voltage source. The voltage imposed at its terminals is calculated again with equation 4.5 with the same parameters $|V|$ and $\omega t + \theta$ while the power P is adapted to the situation: it can both be negative or positive and therfore absorbe energy or produce energy as appropriate. When the voltage is high it works as a load, taking power from the grid and charging in order to lower the voltage at the point of connection; when the load is high and the production of the PV plant is low or null, and therefore the voltage tend to drop, it acts as a generator injecting energy in the grid and discharging.

It was chosen in this thesis to control the connection of the battery with a logic based on the voltage measurement at the point of connection. Others possibilities exist: a control based on the amount of power production, an energy control logic etc.
To determine when the battery has to take energy from the grid or has to give energy an algorithm was implemented (Figure 4.7) and is here explained. The control logic is based on two measurements: the voltage at the point of common coupling and the power generated by the solar panels.

Voltage control regulation (battery charge): when the voltage at the PCC goes over a prefixed limit (Vmax) the battery begins to charge acting like a load and absorbing part of the energy produced by the PV installation or also all of it if the situation requires a big decrease of voltage. Whithout the contribution of the generation plant, the grid can become a passive system (if all the energy produced is absorbed) or not but in any case the voltage profile is expected to decrease monotonously along the line at every time step;

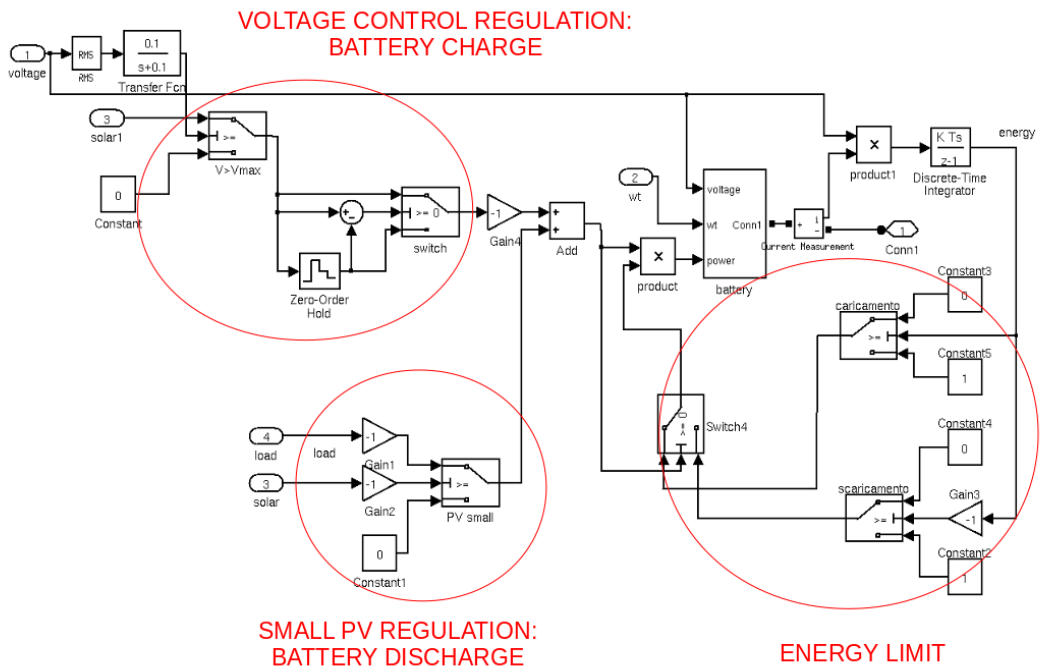


Figure 4.7: battery algorithm

Small PV regulation (battery discharge): if the PV production is low, and therefore it can be assumed that the voltage value is within the upper limit, than the battery is made work as a generator injecting so much current that the load doesn't need to take energy from the grid. This will make the voltage value increase.

The discharging of the battery could also be implemented with a combined check of the PV production and voltage measurement and a logic similar to the one used for the charge. The battery would be then connected when the solar plant doesn't inject power in the grid and the voltage is under a limit imposed. This method allow to discharge the battery expecially when the load is high and the battery is consequently at the lowest values of the day. The autoconsumed energy would be increased and the efficiency of the whole apparatus would be greater.

Considering the conditions necessary to use them, these two control logics are never implemented together and their outcomes can be therefore summed and put as an input to the source that controls the behavior of the battery with no risk of joined effects. These control logics are shown in Figure 4.8.

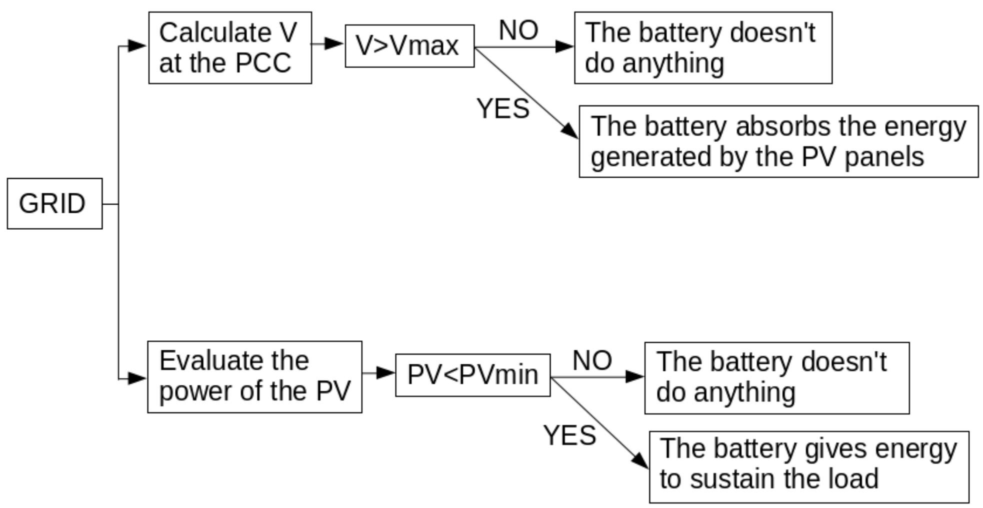


Figure 4.8: battery control logic

In addition to these regulation logics, another one was built to set a limit to the energy absorbed or provided by the battery. At the beginning of the simulation, the level of the energy stored in the battery is equal to zero, equivalent to a SOC (State Of Charge: the amount of energy in % that can be stored in a battery) of 50% of the usable storage capacity. From this point it can therefore be charged till *+Capacity/2* or discharged till *-Capacity/2* . If the capacity limit is not violated the battery block keeps implementing the regulation resulting from the first algorithms; if the limit is violated the battery stops working as a load or as a generator and the voltage at the PCC is no longer affected by the storage behavior. This control logic is shown in Figure 4.9.

Both these algorithms are implemented in every point of connection of a battery, that is supposed to be at each point of connection of PV panels; the small PV regulation and the energy control are implemented at every time

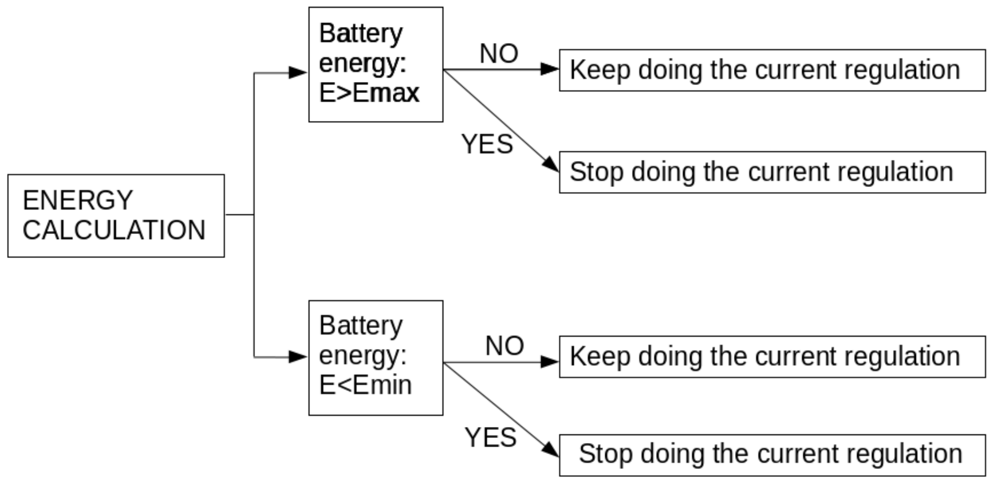


Figure 4.9: battery energy limit

step of the simulation but regarding the voltage control regulation the timing becomes more articulated.
If implemented at each simulation step, the battery would continually be attached and detached from the grid because the voltage control, when the battery is connected, would measure a low voltage on the line and would therefore command to detach it. Vice-versa, when the battery is disconnected, the voltage would rise and the controller would reconnect it in the next time step. This behavior is to be avoided because the fast and continuous connecting and disconnecting of the battery could cause the deterioration of its components and shorten its life.
Another control part is therefore inserted in the model: when the voltage goes over the limit, its porpuse is to mantain the regulation (keep the battery connected) for a certain interval of time, than disconnect it, measure again the voltage and act accordingly: if the limit is still violated the controller has to reconnect immediately the battery; if the voltage remanis under the limit it has to keep the battery inactive until the next violation.

A further improvement of this solution, in order to decrease the number of times the battery has to be connected and disconnected, can be the following: after the second or third interval of time in which the battery has been attached and detached from the grid, if the voltage still reaches a level that is beyond the limit then the battery has to stay connected for a longer period since the situation suggests that the voltage will stay over the maximum. The duration of this longer period has to be carefully chosen because if too long the battery could keep absorbing energy when is not necessary for the overvoltage mitigation and its size would be overestimated compared to the one required for its real correct use.

Chapter 5

Operative procedures

The models described in the previous chapter allows to have all the information about the LV network needed for the development of this work. The *Simulink* environment permit to calculate in each node the magnitude of the voltage, the active and reactive power flows and the cumulated energy for each device: transformer, PV panels, loads and batteries. With these data it is possible to proceed to the different analysis carried out in this thesis that are here described.

5.1 Hosting capacity evaluation

The maximum hosting capacity (HC) is the maximum amount of photovoltaic power that can be connected to the system and can be calculated in relation to three technical bonds:

- slow voltage variations: this is the increase or decrease of voltage due to the variation of the total load of the system. The adjective "slow" implies that the variation is valued in steady state conditions and enough time is passed so that the system has reached a new equilibrium state.
- fast voltage viriations: quick variation of the rms (root mean square) of the voltage kept for a finite and not specified time. These are usually caused by a sudden variation of the load or manouvers on the system.
- thermal limit: this is a structural limit of the elements componing the line. If used at a higher level than the nominal ones causes a stress condition on the matereals and a decrease of their life.

In this thesis only the first case is considered.

As previously explained, the energy generation causes a voltage increase at the point of connection of the plant. In order to ensure the distribution service quality, the regulation imposes a limit to the variation of $\pm 10\%$ of the nominal voltage of the system.
In a passive grid the voltage decreases monotonously along the line and the main risk is the violation of the lower limit at the nodes placed at the far end of the line, while for the upper limit it is sufficient to guarantee that it is not violated at the transformer bus. The behavior changes when the grid becomes active: the maximum voltage is no longer at a known point but can change according to the amount of installed power and the position of the plants.

To evaluate the maximum hosting capacity was implemented an algorithm that will be repeted in each node of the the LV grid.
The installed capacity is increased by steps of fixed size and the voltage measured in each section of the line. If the voltage at any node and at any time step reaches or exceedes the limit, the installed power is judged excessive and cannot be tolerated by the grid. The maximum capacity that doesn't cause the reaching of the limits is the maximum hosting capacity.

This algorithm can be implemented for different configurations of the grid: multiple generators connected by each load or a single generator connected at one point of the grid. In the first case the distributed generation penetration is simulated. In the second case different situations are possible and produce different results: as said before, the case that produce the biggest increase of the voltage profile is when the generation plant is connected at the end of the line more distant from the substation.

5.2 Hosting capacity improvement by means of storage system

With the introduction of batteries in the grid, the hosting capacity is supposed to increase: if a certain amount of the power produced by the PV panels is stored in the battery it doesn't influence the voltage level. The bigger the storage system is the bigger the amount of energy that can be stored is and therefore the bigger the solar panels can be without reaching the voltage limits. The increase of HC is therefore supposed to be at least equal to the maximum power that the battery can absorbe.

To evaluate the increase of hosting capacity an algorithm similar to the previous was implemented: the simulations were run with the batteries and the voltage measured at each node. If the voltage reaches or overcome the limit, the amount of power installed is excessive and can't be tolerated by the grid. The maximum capacity that doesn't cause the reaching of the limits is the maximum hosting capacity.

5.3 Storage design and definition of voltage threshold

The storage apparatus is defined by two principal characteristics: the power that can be delivered instantly and the total amount of energy that can be absorbed and injected in one cycle of charge/discharge. The choise of these two parameters influence, as said, the increase of hosting capacity and the definition of the voltage at which the battery has to be connected to the grid (Vmax). The second regulation can be with fixed Vmax or with fixed battery size.

5.3.1 Fixed voltage threshold

If the maximum voltage achievable is fixed, the battery has to be big enough to absorbe all the energy produced by the solar panels in the period of time in which the voltage is over the limits. This period is approximately composed by the two time spans before and after the insolation peak. The battery has to absorbe the energy produced and then give it back to the load when the production of the PV is null. The size of the battery has therefore to be at least equal to this value of energy absorbed.

5.3.2 Fixed storage energy size

If or when the battery size is fixed, the voltage at which the battery has to be connected can be regulated and adapted to the different production and consumption trends of different days. In Figure 5.1 this algorithm is represented.

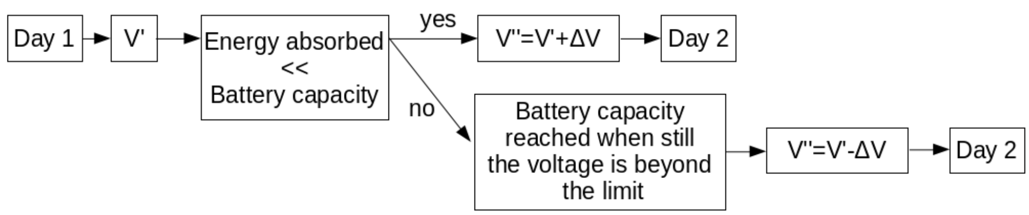


Figure 5.1: algorithm for the choise of Vmax

On day 1 Vmax is fixed at the value V'. At the end of the day, meaning with day the hours in which the solar panels produce energy, it has absorbed a certain amount of energy. If this is much less than the total capacity of the battery the voltage maximum of day 2 can be lowered so that more of the energy produced by the solar plant can be stored and don't influence the voltage of the grid. If instead, the battery is completely filled before the end of the period in which the production causes overvoltages, it could happen that in the moment of maximum need (when the production is at the peak and the voltage reaches the maximum) the battery is not available to mitigate the problem. The Vmax has therefore to be rised so that the battery at day 2 begins to absorb energy later in the morning and is not full at the peak production.

Chapter 6

Simulation and results

In this chapter the results of the simulation will be presented. The analysis is divided in three main parts:

- passive grid: only loads are connected to the grid so the system results to be passive as it was designed to be at the beginning of the electrification process. The influence of the loads and trend of the voltage along the line will be analised.

- active grid: the PV panels are inserted in the simulation next to the loads. The trend of the voltage will be once more analised and, in addition to it, energy analysis will be carried out. In particular, energy losses along the line, energy absorbed and produced by the loads and solar panels and the energy autoconsumed directly by the load without passing through the grid will be considered.

- active grid with batteries: storage systems are added in the simulation to mitigate the problem of overvoltage caused by the PV. Again voltage trend will be discussed and energy flows analised.

6.1 Passive grid

The grid considered (Figure 6.1) is a portion the one previously presented, constitued by one feeder with five derivations to which the loads are connected (as said before each load represent three equivalent users).
The line parameters used in the simulation are listed in table 6.1.

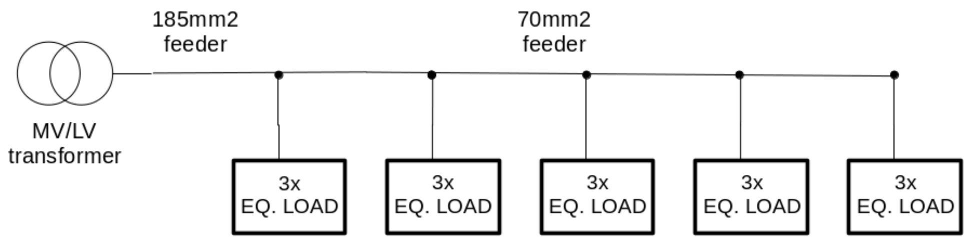


Figure 6.1: passive line model with one feeder

	length [km]	r [Ω/km]	x [Ω/km]
transf to node 1	0.5+0.1	0.164 / 0.26	0.0753 / 0.23
node 1 to node 2	0.1	0.26	0.23
node 2 to node 3	0.1	0.26	0.23
node 3 to node 4	0.1	0.26	0.23
node 4 to node 5	0.1	0.26	0.23

Table 6.1: line characteristics

The first section, that represent the feeder outgoing the substation and the first segment of the further diramation, is composed by 500 meters of underground cables and 100 meters of aerial lines that have different parameters; the following sections are all aerial lines only. Every section is supposed to be of the same length with the resistance and reactance typical of the lines of the maltese islands.

6.1.1 Voltage analysis

Figure 6.2 shows the trend of the voltage along the line for the different nodes of measurement of the line during the whole day where time is measured in minutes and voltage in volts.
The higer voltage is, as expected, at the beginning of the power line (blue line), at the node coloser to the connection to the LV winding of the transformer and it decreases as the distance from the substation increases. It reaches the minimum at the far end of the line, at the last node considered (light blue line). This effect is given by the increasing impedance of the line between the transformer and the point of measurement as verifiable from

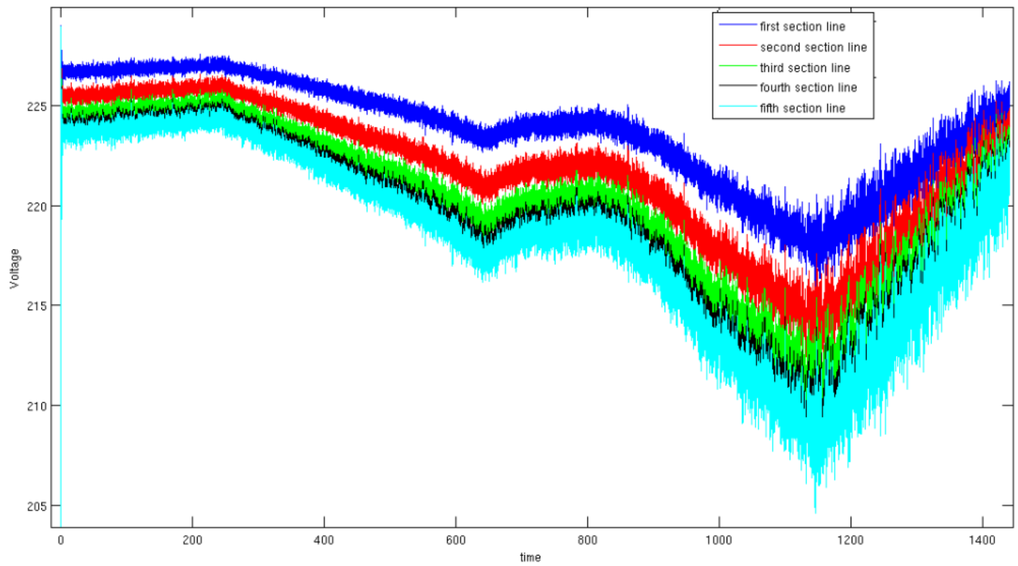


Figure 6.2: voltage profile, over a whole day, in passive grid

equation 6.1.

$$\Delta V = r \cdot p + x \cdot q \tag{6.1}$$

Being the power absorbed p positive because of the absence of generation, the voltage drop is proportional to the impedance of the line given by r and x. The more the line is long the more the impedance grows and by consequence the voltage decreases.
The trend in time follows the trend of the reversed load consumption: the more the load grows the more the voltage drop is big. The minimum voltage, in time, is reached at the moment of maximum load demand at the beginning of the evening when the amount of energy absorbed is bigger.

6.2 Active grid

Being this thesis focused on the photovoltaic panels impact on the voltage grid, it was chosen to limit the simulation time to the period when the sun is shining and the production of energy is not null. From this point on, therefore, the graphics and the data will be referred to the central part of the day, from approximately 6.30 am to 6.30 pm.

We pass now to the analysis of the active grid. The line model considered in this case is shown in Figure 6.3 where both loads and solar panels are connected. Each of them represent three equivalent consumers and three equivalent producers respectively.

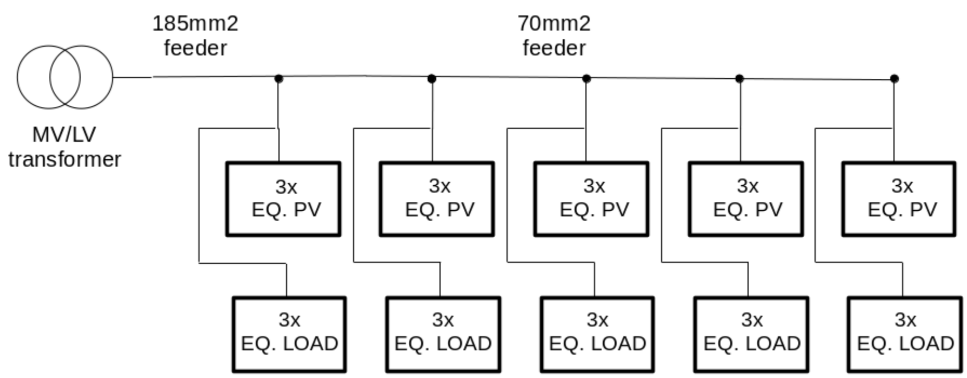


Figure 6.3: active line model with one feeder

The line parameters (length, resistance, reactance) are the same as the previous case. In the base case analised, the solar panels have a nominal power of 3 kWp, typical size for photovoltaic plants installed in domestic locations, (hereafter referred to as 100% of PV power) and the day is supposed to be sunny and clear so that the power produced in the moment of peak insolation meets the demand of the loads near which they are installed at the peak of the demand. Later on, other simulations with different levels of photovoltaic power are analised to simulate a more cloudy day, a different penetration of PV plants or a higher capacity installed in each node, ranging from 25% to 125% for the case of distributed generation and the two cases of 200% and 300% of the base power for the concentrated generation.

6.2.1 Voltage and hosting capacity analysis

The first analysis carried out about the simulation results are about the voltage trend and the influence of various parameters on it.

Distributed PV power

In Figure 6.4 the voltage trend with installed PV is shown. Again time is measured in minutes and voltage in volts.

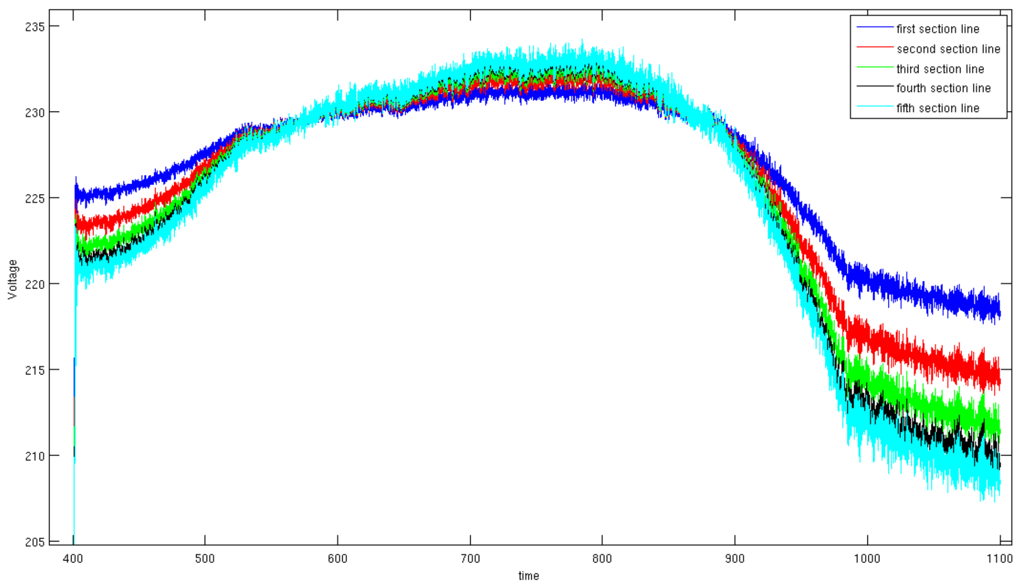


Figure 6.4: voltage profile with installed PV plants

Considering the time dependance, it can be seen that, when the solar panels work and there is injection of power, the voltage increases. To explain this behavior the simplified equation of the voltage drop can be again used (equation 6.1. The active power term (power absorbed by the loads) is positive until the generated power becomes bigger than the load demand at the node of connection. When this happens the energy flow is no longer from the substation to the end of the line but it turns upstream and the term of the equation change sign. The reactive term, considering in this thesis a power factor equal to one, is constant and null and doesn't influence the voltage trend. With high generation capacity matched with low consumption, the voltage drop is therefore negative and the voltage increases.

Figure 6.4 also shows the different effect of the distance of the point of measurement from the substation: in the left and right part of the graphic, where the production of PV is low, and therefore the active power term of equation 6.1 is positive, the lowest voltage is at the portion of the grid more distant from the substation where the impedance is maximum. The voltage decreases therfore along the line in the same way it does when the grid is a passive one.
When the production of PV is high in the middle of the day, on the other hand, the $r \cdot p$ term is negative because of the higer power injection that exceeds the demand. The voltage is therefore, as said, increasing and its absolute value is bigger once more where the impedance of the line is higer, that is at the end of the line more distant from the substation. That's why the lines of the voltage trend cross each other and their order is inverted.

Voltage analysis for different PV power

In the following figures, the voltage trend for different levels of PV production is shown (time is measured in minutes and voltage in volts). The effect of the PV is lower and lower as the production decreases and the voltage approaches the trend seen in the passive grid. It can be seen that for a level of PV equal to 75% the voltage at a certain point in time around 800 seconds (corresponding to approximately 1.30 pm) reaches the same value in each portion of the line. This means that the photovoltaic panels produce approximately the same amount of power needed by the load and therefore no energy supply is required from the substation, no current flows in the line and the line losses are consequently annulled. The same effect occurs with higher levels of PV production twice a day, when the power produced and absorbed are equal and the voltage trends cross.
The level reached by the voltage reaches a high value that requires the introduction of measures for its mitigation in the cases of 100% and 125% of the base power. These two cases will therefore be studied in the next section when the storage system will be introduced.

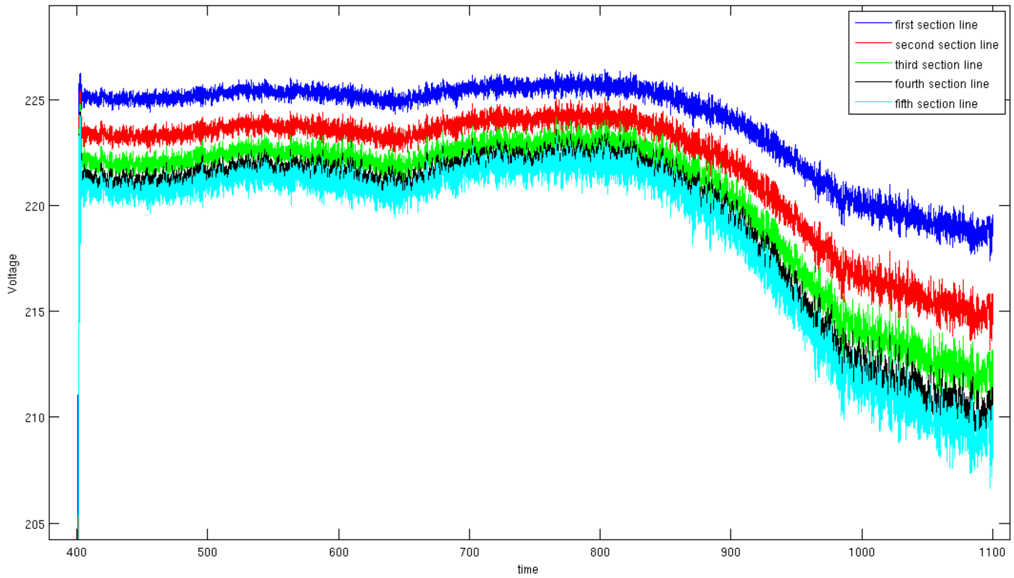


Figure 6.5: voltage trend with PV=25% P_{nom}

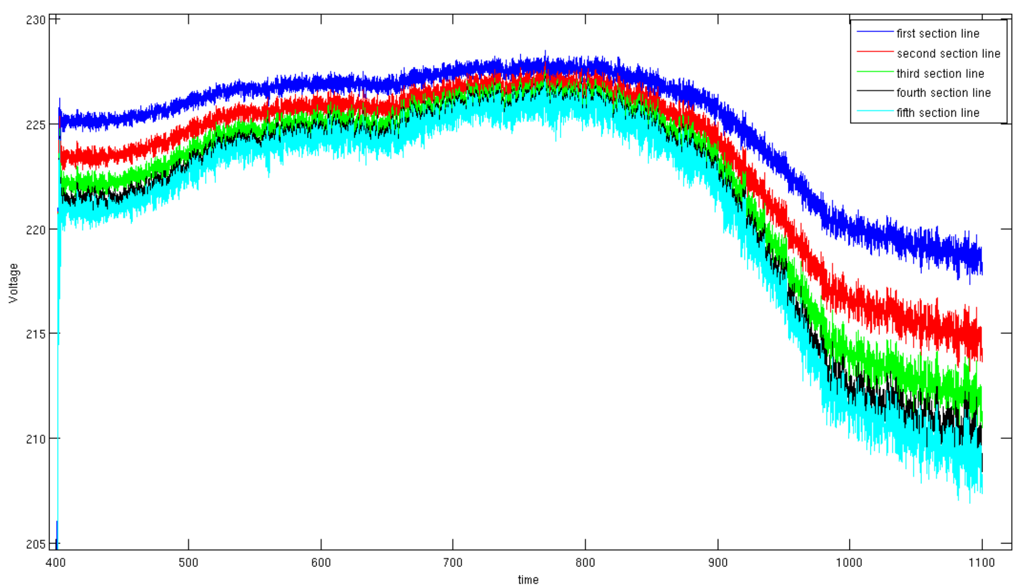


Figure 6.6: voltage trend with PV=50% P_{nom}

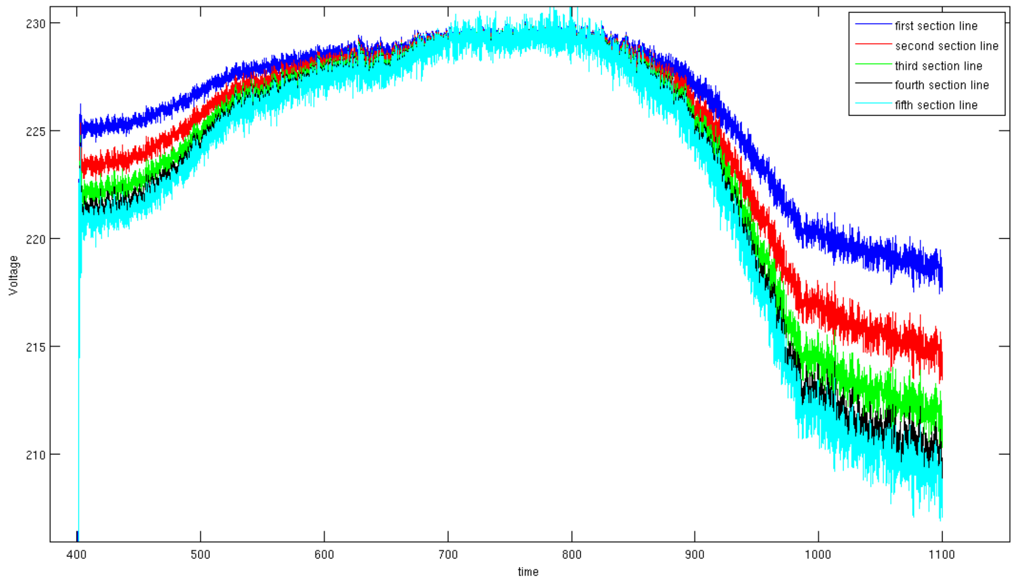


Figure 6.7: voltage trend with PV=75% P_{nom}

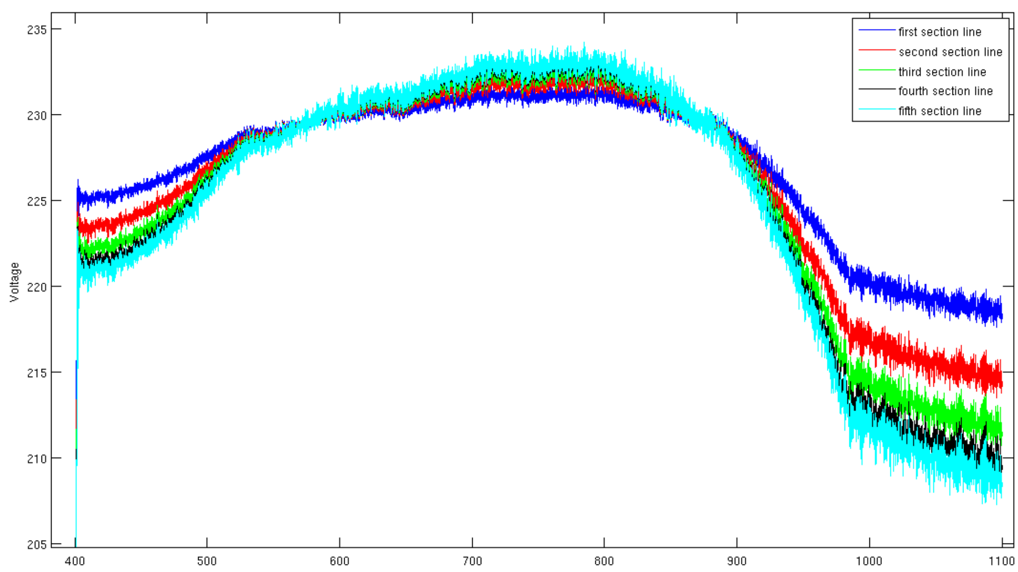


Figure 6.8: voltage trend with PV=100% P_{nom}

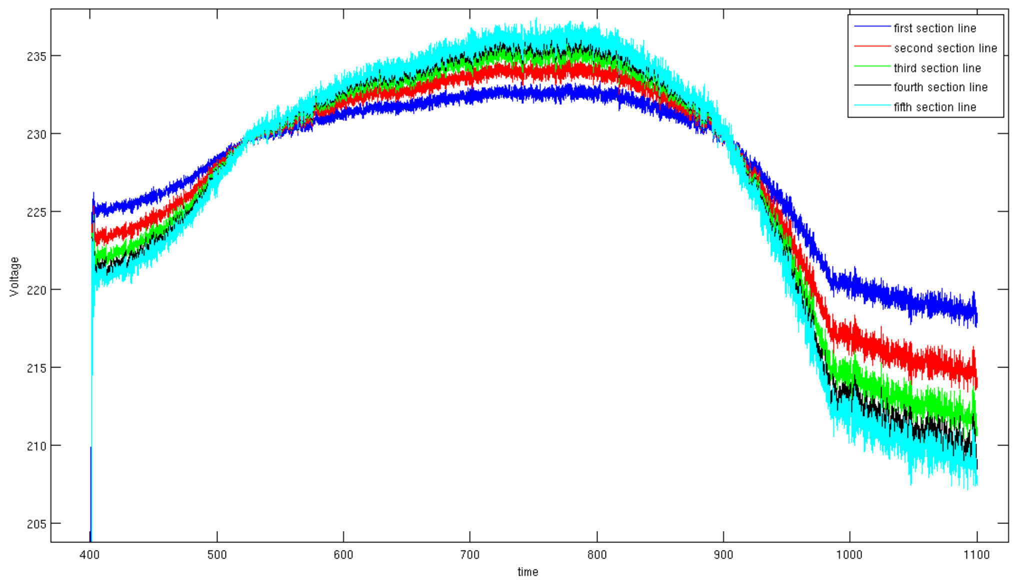


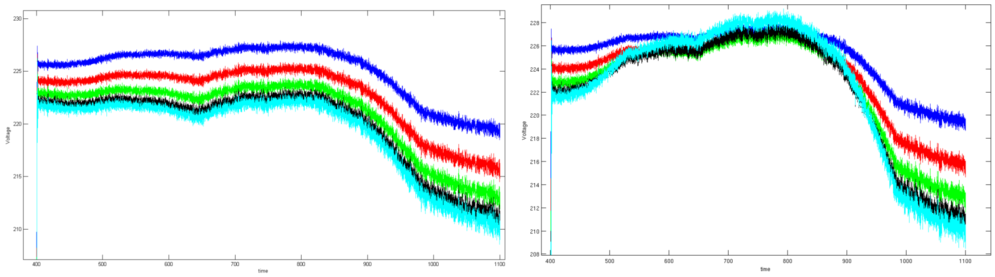
Figure 6.9: voltage trend with PV=125% P_{nom}

Concentrated PV power

Two limit conditions were analised in this section: the generation concentrated at the first node of the line near the substation and the generation concentrated at the end of the line in the most distant section of the line from the transformer. The following figures show the voltage trend in each node for two different pv penetration values: 200% and 300% of the base power. Time is measured again in minutes and voltage in volts.

It can be easily noted that the voltage profile changes if the photovoltaic plant is situated at the beginning or at the end of the line: if the power is injected at the first node, the voltage of all the line is increased of more or less the same value and the lines representing the value of the voltage in Figure 6.10a and 6.11a are almost parallel. The upper voltage limit can be therefore reached only in the first node and only this point has to be kept under observation.

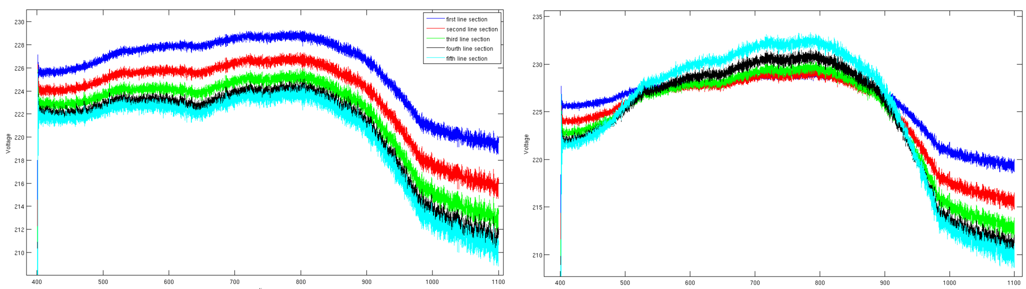
If the power is injected at the end of the line, on the other hand, the point most influenced is the node of injection itself that will register the biggest voltage increase. This will be greater than the increase in the case of photo-



(a) beginning of the line

(b) end of the line

Figure 6.10: voltage trend with PV=200% P_{nom}



(a) beginning of the line

(b) end of the line

Figure 6.11: voltage trend with PV=300% P_{nom}

voltaic panels connected at the beginning of the line, equal power, because of the bigger value of the line impedance. The neighbouring nodes experience as well an increase of voltage but the effect will be lower and lower as the distance from the power injection increases.
In both cases of power connected at the beginning of the line and in the case of 200% of PV power injected at the end of the line, the voltage increase doesn't reach a warning value regarding the upper voltage limit. In the case shown in Figure 6.11b, on the contrary, the voltage increases more and the necessity of the introduction of a storage system can be studied.
Since domestic installations are considered, it was chosen not to exceed the value of 300% of pv power that would be sufficient to cover three times the

consumption of an average house.

In case of concentrated generation the installation of storage systems is therefore not necessary.

Hosting capacity analysis

From the previous pictures it is possible to determine the hosting capacity (maximum installable power that doesn't causes the reaching of the upper voltage limit) of the LV grid considered.

	power in a single node	total power
DG	1.65 kW	8.25 kW
PV at the beginning of the line	6.6 kW	6.6 kW
PV at the end of the line	4.4 kW	4.4 kW

Table 6.2: Hosting capacity

The total HC is therefore maximum in the case of distributed generation even though in each node the power installed is lower than the other situations. The minimum HC is found when the PV plants are connected to the end of the line because the impact on the voltage is amplified by the electric distance from the substation.

6.2.2 Energy analysis

As regarding energy, three different analysis are carried out: autoconsumed energy, line losses, transformer energy.

Line losses

As previously said, the connection of generation plants in the low voltage distribution grid has a benefic effect on the line losses: part of the energy needed by the loads is generated by the photovoltaic plants and therefore less energy is required to be supplied from the substation. Because of the lower current flowing in the grid the line losses decrease.
Table 6.3 shows the line losses with different PV integration, made 100 the

value of the base case.

PV integration	line losses
0% PV	14.8 kWh/day
25% PV	10.96 kWh/day
50% PV	8.5 kWh/day
75% PV	7.05 kWh/day
100% PV	6.99 kWh/day
125% PV	7.89 kWh/day

Table 6.3: line losses

The value of the line losses decreases when passing from 0% to 100% but when the power injection becomes too high the effect of the PV panels is the opposit, the energy produced flows towards the substation and the line losses begin to increase.

Autoconsumed energy

Because of the different trends of the power consumption of the loads and the power production of the photovoltaic panels not all the energy produced can be consumed by the correspondent load. Only part of it is autoconsumed and the rest is injected in the grid. Table 6.4 shows the amount of energy autoconsumed related to the total energy consumed by the load in the simulation time

	sec 1	sec 2	sec 3	sec 4	sec 5
25% PV	11.87%	12.08%	12.23%	12.33%	12.38%
50% PV	30.52%	30.71%	30.85%	30.96%	30.98%
75% PV	48.5%	48.66%	48.74%	48.79%	48.79%
100% PV	57.1%	57.23%	57.33%	57.38%	57.4%
125% PV	60.45%	60.77%	60.7%	60.77%	60.79%

Table 6.4: autoconsumed energy

When PV production is low the energy generated covers only the 11-12% of the energy needed by the load. As the production increases, the value of the energy autoconsumed increases too but at each step of increased PV power the autoconsumption increases less.

Transformer energy

From the analysis of the cumulated energy flowing from the transformer it can be seen the flow of current to the LV grid or to the MV grid. Figure 6.12, 6.13, 6.14, 6.15, 6.16, 6.17 are reported the treds of the cumulated energy for different PV power. Time is measured in minutes while energy in $W \cdot minute$. In the first three cases the energy is continuously increasing in time and the flows are from the substation to the LV grid. In the 75% PV case, the trend becomes flat in the central part of the day when as seen before the power of the solar panels and of the loads are equal. No energy is required in this situation from the substation. For higer power installed in the LV grid, part of the energy produced is not consumed and has to flow back from the transformer to the MV portion of the grid. In the 100% PV case the energy sent back almost equals the energy absorbed from the substation in the first part of the morning taking the cumulated energy of the transformer to zero. In the 125% case the situation is extremised: the excess energy is much more than the needed in the first period and is then required in the LV grid as the load reaches its maximum. This behaviour is responsable for the increase of energy losses presented before and could be avoided with the use of storage systems that could absorbe the excess energy when produced and give it back when needed.

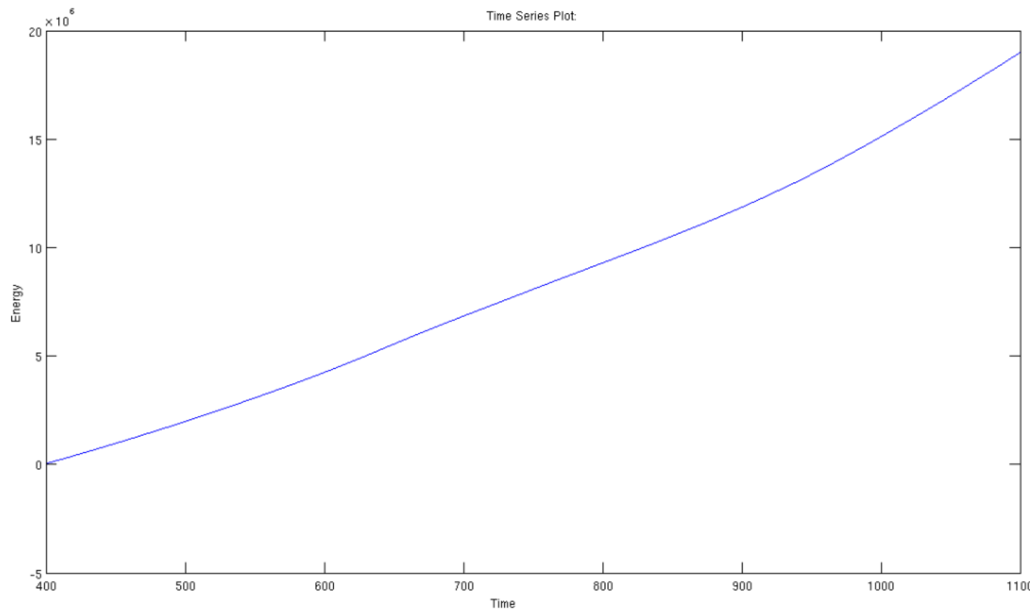


Figure 6.12: energy flowing from the transformer with no PV

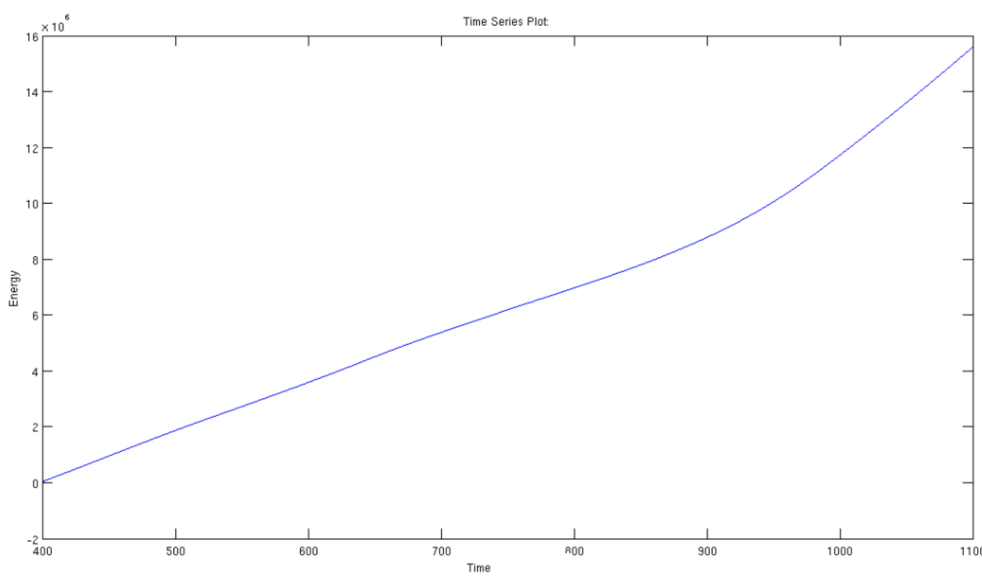


Figure 6.13: energy flowing from the transformer with PV=25% P_{nom}

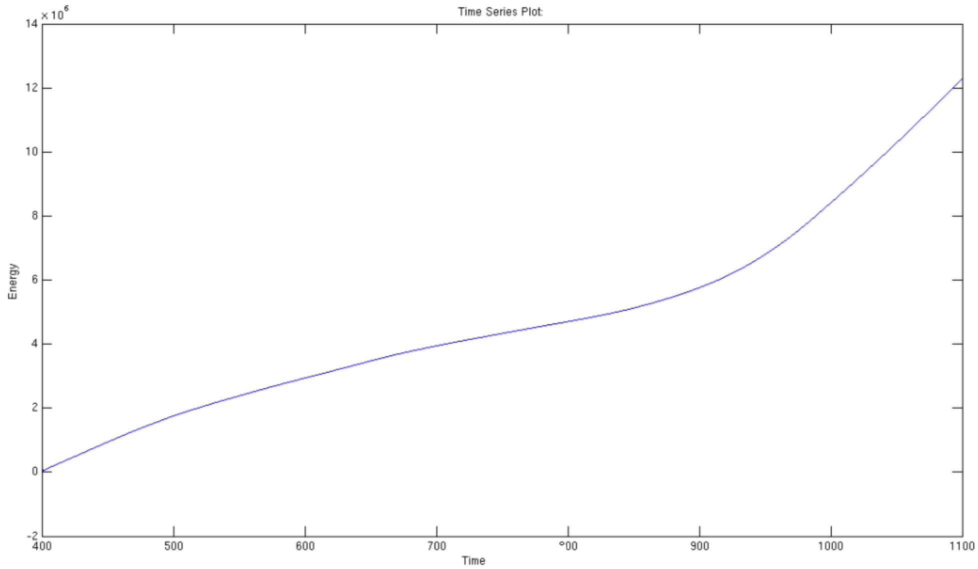


Figure 6.14: energy flowing from the transformer with PV=50% P_{nom}

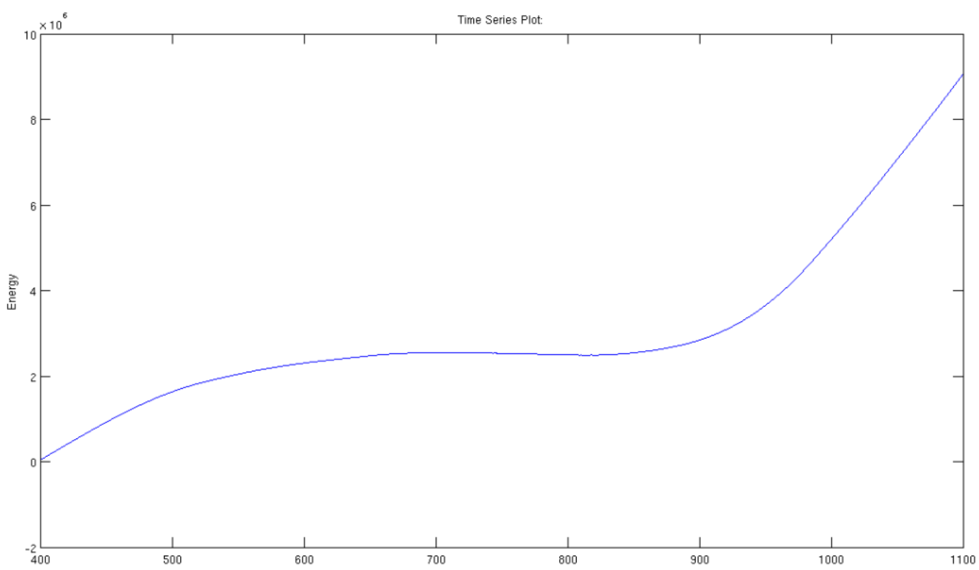


Figure 6.15: energy flowing from the transformer with PV=75% P_{nom}

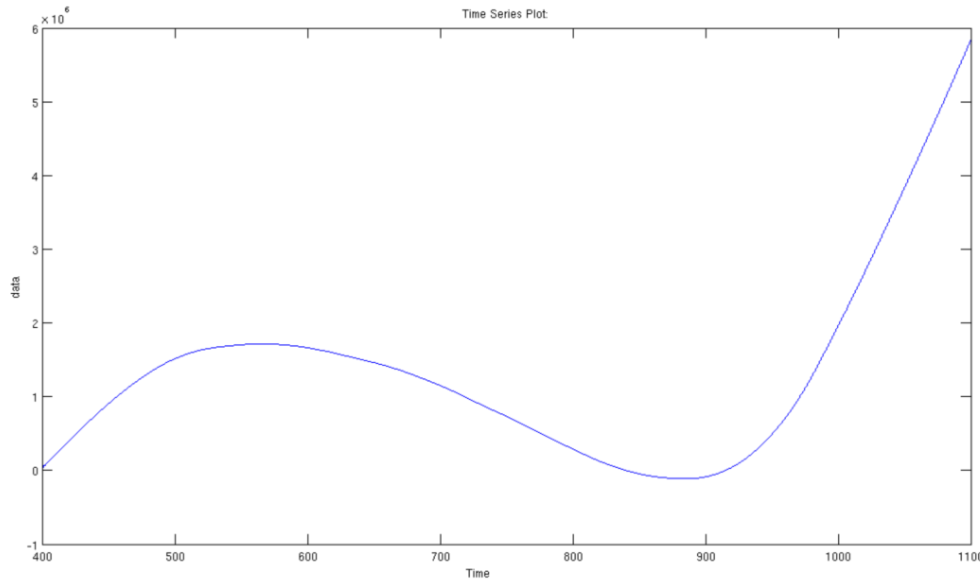


Figure 6.16: energy flowing from the transformer with PV=100% P_{nom}

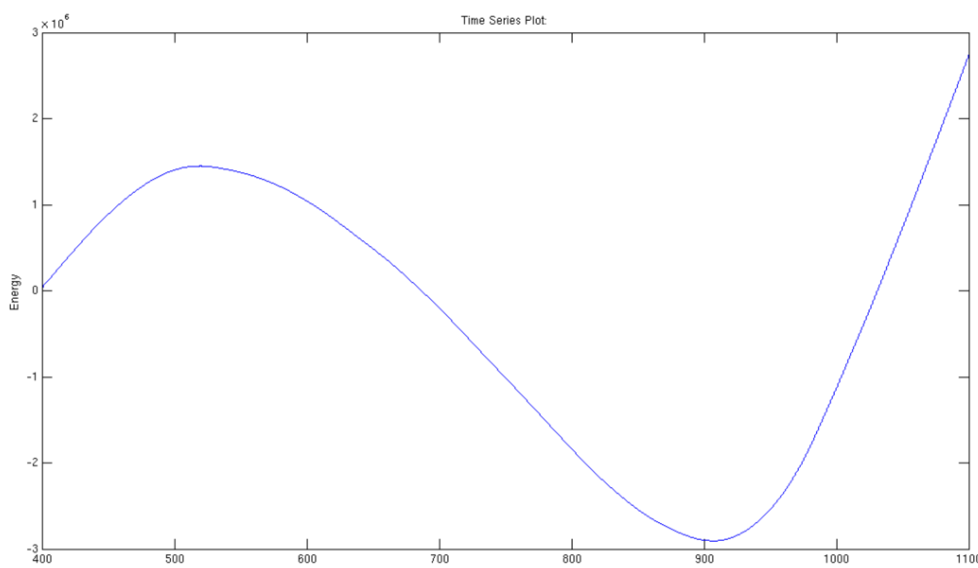


Figure 6.17: energy flowing from the transformer with PV=125% P_{nom}

6.3 Active grid with storage apparatus

In this section, battery models are introduced in the simulation to mitigate the problem of overvoltage violation seen in the previous parts of this chapter. The line model considered in this case is shown in Figure 6.18 where loads, solar panels and batteries are connected.

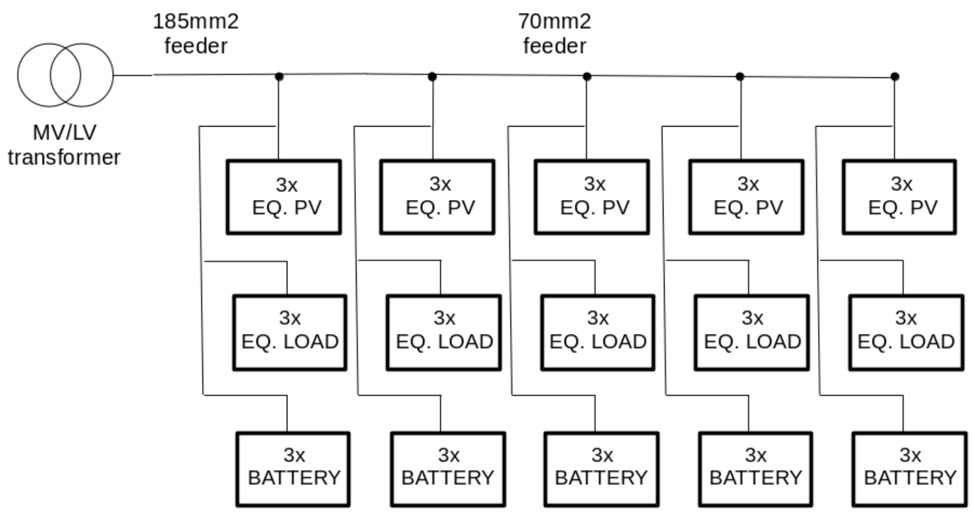
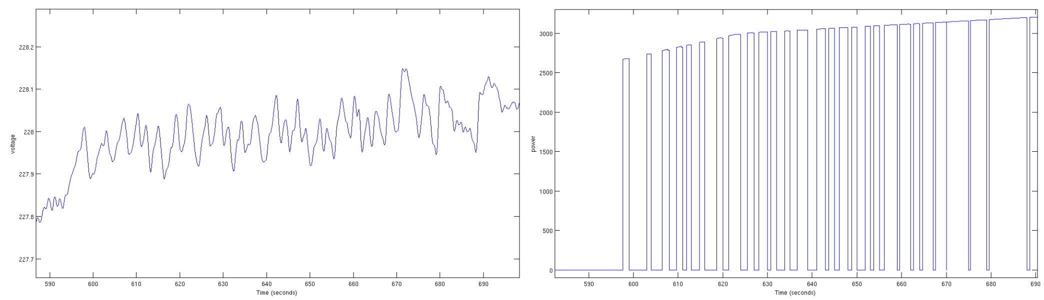


Figure 6.18: active line model with one feeder

The parameters of the line are the same as the previous cases and solar panels also have the same nominal power.
Batteries are supposed to have the power of absorbing half of the power produced by the solar plants in the moment of peak insolation and a total energy capacity sufficient to store all the energy produced in the period of time in which the battery is required to mitigate the overvoltage problems. It will be later checked if is really possible having batteries with the combination of power and energy so calculated.

6.3.1 Storage model

A more detailed description of the behavior of the model of the battery is necessary here because of its particular performance. In figure 6.19 the voltage of the line and the output power of the battery are shown for a small interval of time.



(a) voltage (b) power of the battery

Figure 6.19: battery behavior

From figure 6.19a it can be seen that the voltage profile, due to the calculation process, is very much variable around the mean value. The amplitude of the variations is narrow (less that 0.2 V) but, being the battery programmed to connect to the grid when the voltage reaches the maximum, when the voltage bounce around the upper limit it happens that the voltage changes frequently from “high” to “low”. This causes the battery to connect and disconnect frequently as shown in figure 6.19b. As the mean voltage increases, the period the battery stays attached to the grid increases and even at the end of this reduced period of time it can be seen the desired behavior of the battery: it absorbs energy for a certain time, than disconnect from the grid. The measured voltage is still over the limit and therefore the battery is reconnected to the grid almost immediately.
To calculate voltage profiles, power trends and energy flows, it is therefore necessary to create a new profile of the power absorption/injections of the battery connecting all the peaks of figure 6.19b so that the ideal behavior is approximated.

6.3.2 Voltage and hosting capacity analysis

The voltage profiles are calculated with the assumption just made of almost ideal battery behavior and assuming also that the battery, when connected, absorbs half the power produced by the solar power plant. This value is

chosen arbitrarily, but it was established that 50% was enough to reduce the voltage to an acceptable level.
Figure 6.20 shows the trend of the voltage during all the day when the battery is connected to the grid. Time is measured in minutes and voltage in volts.

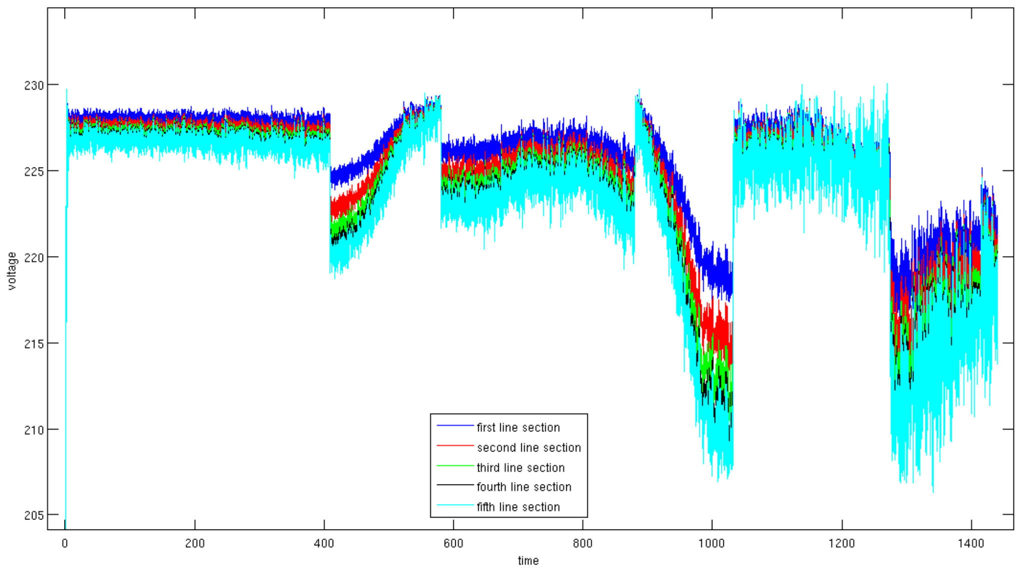


Figure 6.20: voltage profile with the base power for 24h

It is necessary to remind that the battery is supposed to have a state of charge at the beginning of the day equal to 50% of its total capacity and it is therefore initially connected to the grid supplying the load with energy. When the solar panels start generating, the battery is disconnected and the load takes energy from the PV plant and the grid if necessary. The battery is then connected again to the grid when the voltage exceedes the upper limit set at 230 V, absorbing energy and allowing the voltage to decrease to a not worning level. Then it is disconnected when the voltage returns under the maximum and finally riconnected again for the discharge when the solar plant is not producing energy and the load is at its maximum. The discharge process ends when the battery reaches its maximum capacity (around time 1260 in the graphic, corresponding to approximately 9.30pm). It is immediately disconnected from the grid and the voltage is no more influenced by the storage behavior.

As said before, the focus of this thesis is on the period of time when the solar panels produce energy; The analysis from this point on will then be limited to the part of the day in which solar radiation is present.

Figures 6.21 6.22 and 6.23 show the trend of the voltage for a PV power equal to 75%, 100% and 125% of the base power. Time is measured in minutes, voltage in volts. It can be seen that the use of storage systems succeed in mitigating the problem of overvoltage for the three cases considered. The voltage profile is no more inverted when the solar insolation is high but it decreases monotonously along the line during all the period considered thanks to the battery absorbing the energy produced.
The moments the battery is connected and disconnected to the grid, the voltage profile has almost a discontinuity because the energy absorbed pass from zero to the regime value very quickly. This sudden change, could be seen by the users of the grid as a disturbance, the same way faults are seen, with possible consequences on the operation of different devices connected.

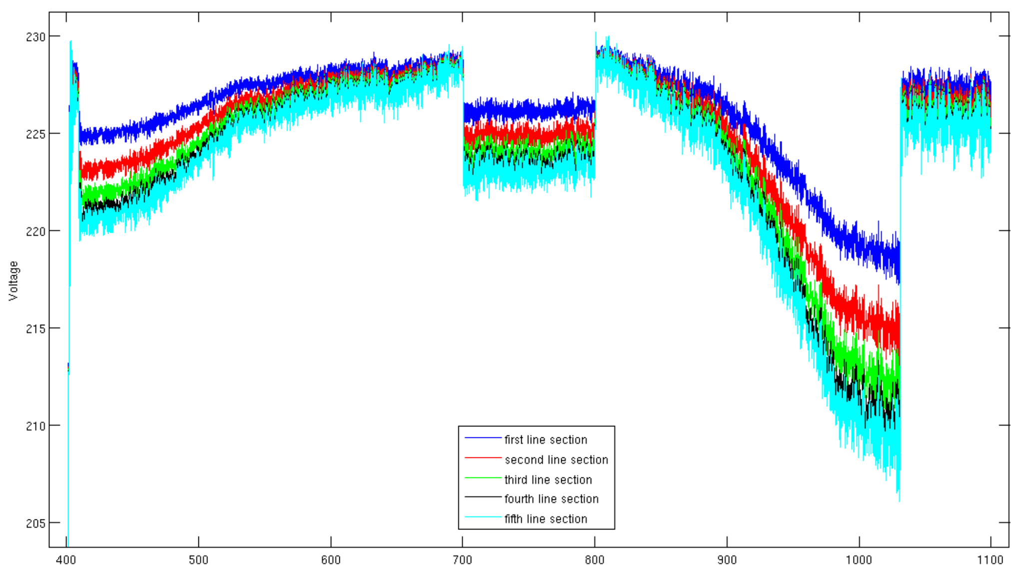


Figure 6.21: voltage profile with PV=75% P_{nom}

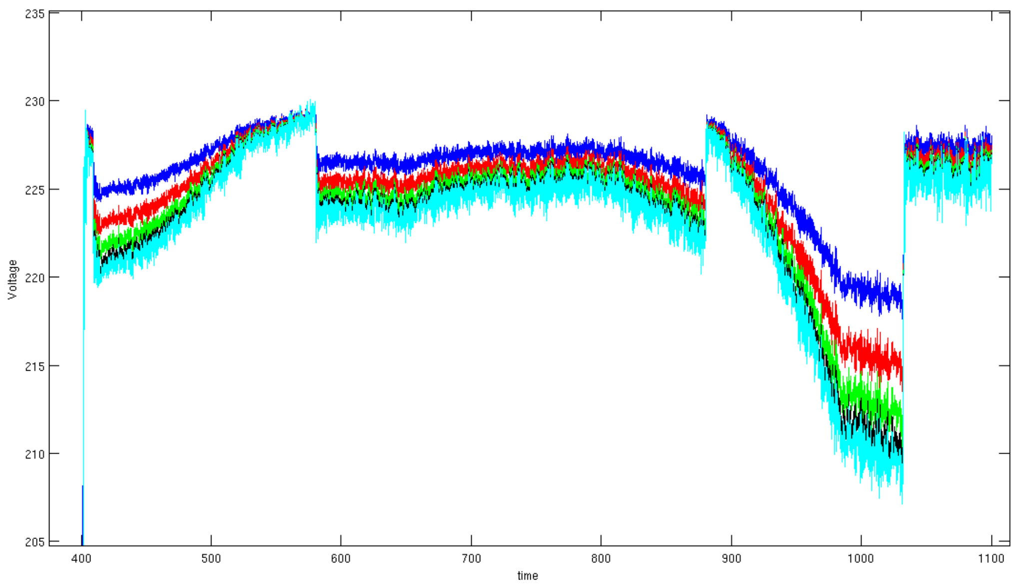


Figure 6.22: voltage profile with PV=100% P_{nom}

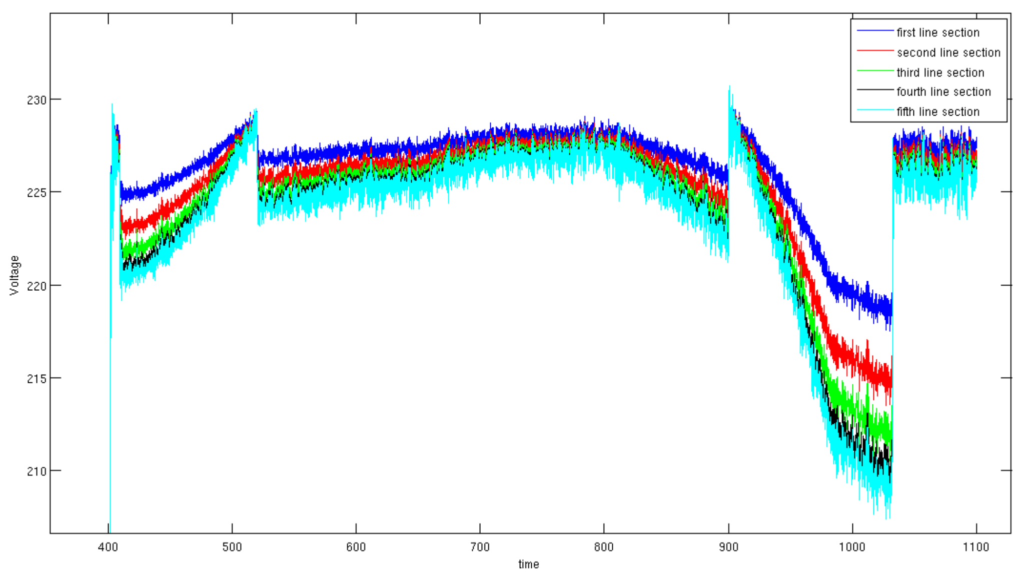


Figure 6.23: voltage profile with PV=125% P_{nom}

A future work can be therefore aimed to the reduction of this step in the voltage profile with the implementation of a more gradual profile of the power absorbed by the batteries.
It can be easily seen that the hosting capacity is increased compared to the case without batteries: the voltage profile never reaches the upper limit also in the case of 125% of PV power installed. But it is necessary to verify that the battery simulated can be effectively a real one. Acid lead batteries has a limitation on the ratio P/E : to guarantee a certain power, the energy capacity has to be greater than the power itself of a factor equal to at least three or four. The ratio P/E has therefore to be maximum 0.333. Table 6.5 shows the value of the ratio for the batteries connected to different section of the line for different PV power installed.

	sec 1	sec 2	sec 3	sec 4	sec 5
PV=75%P_{nom}	0.3337	0.336	0.338	0.3398	0.3406
PV=100%P_{nom}	0.1760	0.1765	0.1771	0.1776	0.1781
PV=125%P_{nom}	0.1578	0.1577	0.1575	0.1573	0.1570

Table 6.5: P/E ratio

In the case of 75% of PV power installed, for no section the battery is feasible. The energy needed with this level of photovoltaic penetration is quite low because the time the voltage is over the limit is reduced to less than two hours while the power needed is still quite high. The combination of these two conditions cause the ratio P/E to be inadequate for the realisation of the battery. For a PV penetration of 100% and 125%, on the other hand, the energy capacity of the battery is much bigger than the previous case because of the longer time the battery has to be connected to the grid and compensate the increase in power. For this reason the values of P/E are acceptable.

6.3.3 Energy analysis

Line losses

Line losses with the use of batteries are supposed to decrease compared to both the case of passive and the case of active grid. The presence of photovoltaic panels has been already established to have a positive effect on line losses with a limit on the amount of power installed: if too much energy is produced the energy flow is inverted and goes from the grid to the substation causing the increase of losses. Batteries, absorbing this excess energy, are able to reduce the energy flows along the line and consequently the losses.

Table 6.6 shows the amount of energy lost in the line in the presence of storage systems compared to the line losses without batteries. Both are referred to the amount of energy lost without batteries and PV plants similarly to the previous section.

PV power installed	line losses without battery	line losses with battery
PV=75%P_{nom}	7.05 kWh	5.59 kWh
PV=100%P_{nom}	6.99 kWh	5.43 kWh
PV=125%P_{nom}	7.89 kWh	4.84 kWh

Table 6.6: line losses with batteries

As expected, line losses decrease with the use of batteries of approximately 10%. It can be also noted that, in the case of 125% of PV power installed, the line losses without battery start increasing while the presence of storage allow the losses to keep decreasing.

Autoconsumed energy

Autoconsumed energy is here calculated considering the battery as a load: its energy flow is therefore summed to the load's one and the autoconsumption is calculated. When the battery charges its absorbed energy is positive like the load and if it takes energy from the solar plant the autoconsumption increase; when it discharges the energy absorbed is negative and is subtracted from the load consumption. This second case, however, happens when the solar production is low or null so it doesn't influence the autoconsumption but reduces the energy absorbed from the grid.
Table 6.7 shows the autoconsumed energy for different PV integration levels in the various sections of the line related to the total energy consumed during the simulation time.

As expected the autoconsumption increases with the increase of power installed meaning that more energy produced is consumed by the load near the panels. The presece of batteries amplifies this effect: when the energy capacity of the battery is not high because of the short time in which is needed

	sec 1	sec 2	sec 3	sec 4	sec 5
PV=75%P_{nom} no bat	48.5%	48.66%	48.74%	48.79%	48.79%
PV=75%P_{nom}	48.95%	49.06%	49.13	49.16	49.12
PV=100%P_{nom} no bat	57.1%	57.23%	57.33%	57.38%	57.4%
PV=100%P_{nom}	67.88%	67.93%	67.96%	68.01%	67.97%
PV=125%P_{nom} no bat	60.45%	60.77%	60.7%	60.77%	60.79%
PV=125%P_{nom}	86.62%	86.72%	86.8%	86.84%	86.81%

Table 6.7: autoconsumed energy with batteries

to mitigate the overvoltage problems, the benefit resulting from its use is limited, but for higher PV penetration and bigger batteries the advantage becomes significant.

6.3.4 Economic analysis

Costs

At present time, the cost of the batteries are still quite high: a lead-acid battery cost between 100 and 150 euro/kWh and the inverter and the auxiliary facilities between 1000 and 2000 euro. The batteries considered in this thesis would therefore have a cost for each user listed in table 6.8 considering a cost of 125 euro/kWh and 1500 euro of fixed costs.

PV power	battery capacity	battery cost
75% PV	7.5 kWh	2400 euro
100% PV	18 kWh	3750 euro
125% PV	26 kWh	4700 euro

Table 6.8: battery cost

Assuming one cycle per day for the battery and a total life of 2500 cycles, the money savings resulting from its use in 2500 days should at least cover the cost; if the expence for the storage system and its installation would result bigger, than the use of batteries would be not economically convenient for the user and the diffusion of this systems, that in any case bring advantages for the transmission and distribution system, would require incentives.

Benefits

For the users, economical benefits resulting from the installation and use of batteries include the increase of hosting capacity, that enhance the energy production that is rewarded by the MRA, and the increase in autoconsumed energy thanks to the fact that the solar plant can produce energy continuously, without being detached from the grid when and if the voltage reaches the upper limit.

In Malta for a domestic consumer the tariff for the supply of electricity is 0.2023 euro/kWh [2]. The feed-in tariff scheme described in chapter 2 pays the electricity produced 0.15 euro/kWh. The benefit of autoconsumed energy is therefore abuot 0.5 euro/kWh. With this information we can proceed to the calculation of the economical benefit given by the batteries during the 2500 days of their life. Results are shown in table 6.9.

	sec 1 [euro]	sec 2 [euro]	sec 3 [euro]	sec 4 [euro]	sec 5 [euro]
PV=75%P_{nom}	31.78	28.33	27.5	26.85	23.5
PV=100%P_{nom}	760.42	757.71	756.04	755.21	751.25
PV=125%P_{nom}	1866.67	1862.71	1859.58	1857.29	1852.92

Table 6.9: battery's economic benefit in Malta

In no case shown in the table the use of batteries is economically convenient because the revenues doesn't compensate the cost of the storage. Two things can be said about it:

- Battery costs can be expected to decrease in the next years and new technologies can enter the market and become a valid alternative to the lead acid batteries considered in this work.
- These calculations have been made, in the case without batteries, considering the PV panels connected to the grid also when the voltage reached the maximum permetted level. The energy produced and autoconsumed is therefore much more than in the case of detaching the plant when the voltage reaches the limit as the actual procedure provide. If this was considered the increase in autoconsumed energy would be greater and the revenues too would be greater and maybe enough to cover the costs of the battery.

Chapter 7

Conclusions

In a situation with high penetration of PV, overvoltage problems can occur in the line where the generation plants are connected. The target of this work was to evaluate the influence of distributed photovoltaic plants connected at the low voltage grid on the voltage profile and on energy flows along the line and then evaluate the technical and economical feasability of a possible solution: the introduction of storage systems.

A model of the line and of each device connected to it has been necessary to simulate the system and evaluate the various phisical quantities used for the analysis. Because of the big diversity and possible configurations of the low voltage lines, it was impossible to study a real grid obtaining results applicable to other systems. The line model was therefore simplified and constructed in order to be able to represent different configurations with the change of the line parameters only.

Results show that with increasing photovoltaic power installed the voltage trend increase and reaches in some cases (100% and 125% of PV power) the upper voltage limit. At the same time, the energy analysis shows that the energy losses caused by the impedance of the line decrease as the solar panels installed produce more energy. This benefit has, however, a limit: if produced energy exceedes the consumption of the loads, its flow becomes inverted and runs from the end of the line to the substation. Energy losses in this case increase once more.

The following step was to introduce the storage systems in the simulation

and analyze its impact on the voltage profile, hosting capacity and energy losses.
Results show that the use of batteries to store part of the energy produced by the solar power plant helps reducing the overvoltage violations in the part of the day when the production is high and the load low. Consequently the hosting capacity of the line increases and more power can be installed in the grid without causing problems to the operation of it.
Line losses also benefit from the use of batteries because the energy produced in excess by the solar panels is not sent in the power line but remains stored near the production site. The same can be said of the energy provided by the battery to the load and therefore not requested from the grid.
Finally, with the use of batteries, autoconsumption is increased: the energy generated by the solar plant and not directly consumed by the load is stored in the battery and used when the PV decreases its production and the load demand increases.

Finally, an economic analysis was carried out to evaluate the convenience of the use of batteries. Results show that with the actual costs of the storage systems and not considering the disconnection of the solar plants when the voltage reaches the limit that cause the decrease of the autoconsumption, batteries don't bring economical benefit. The change of these two mentioned conditions can however change the results of the study.

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