Modelling, Control, Integration and Analysis of Energy Storage System for Smart Grid

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Abstract. Smart grids and intelligent networks play a vital role in making the system more efficient with minimum loss of energy during transmission. It also allows various kinds of renewable energy sources to the system by support energy system and allows large number of electric or hybrid vehicles to charge or send power back to the grid. The main goal of this study is to performing real time simulations of the use of this system. Describe the simulation of the hardware in real-time using loop method and applies it to two models of photovoltaic systems using batteries and converters, analysing their behaviour in interaction with the grid and verifying the assistance provided by the batteries.

Keywords: Micro Grids, Smart Grids, Power Electronic Converters, Renewable Generation, Simulink.

1 Introduction

In general, the electrical network is the system of power lines, transformers and infrastructures that delivers electrical energy from the production centres to all users [5]. These networks are more responsible for transmitting and distributing the electricity produced in power plants to homes, industries, and other end users [4]. However, the current networks have been designed and used since the middle of the last century [3]. The electricity grid infrastructure Corresponds to energy generation and supply the objectives, but has to improve from the user point of view and energy management [1].

Currently, there are a number of problems, which are discussed below, along with their possible solutions [2]. One of the main problems is the growth in demand, together with a strong increase in renewable energy [6]. This creates a need for power that is increasingly firm due to high demand, and more flexible due to the integration of renewable energies

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that are variable [7]. Therefore, the solution arises need for systems that provides a safer, cheaper and more sustainable supply of electricity [8]. Another problem is the increasingly expensive price of the fuel used by traditional energy generation plants, in addition to the cost of building the plants themselves [10]. The effective immersion of clean energy would reduce these costs [9]. On the other hand, there is a problem that creates during demand peaks, which makes it necessary to develop special kind of plants than can meet the energy needs, assuming extra costs [5]. As a solution, it will be useful to have smart meters at all consumption points, mainly in domestic uses [13]. These consumption meters could also represent a solution to renewable integration, in addition to being intended for users (microgeneration) also for the injection into the network (with its related payment) of the energy generated during peaks time period [14]. These initiatives should be supported by all companies and accompanied by reforms in regulations and legalization, encouraging new efficiency-oriented policies [2].

Another of the problems associated with the fee of energy is, in addition to the expense of raw materials, the threat posed by dependence on suppliers, as it can lead to price increases or supply restrictions [10]. The ease of integrating renewable energies (whose generation is usually local) and sustainable and controlled consumption can reduce these dependencies and costs [3]. Environmental aspects are also present, especially due to the use of fossil fuels, which contribute to the emissions of smoke and gases that cause the greenhouse effect [6]. The reliability of the energy production and distribution is considered as an important factor [8]. Although nowadays the modern electrical system is highly reliable, they still provide a great economic and social loss due to no electricity supply, causing failures due to congestion and overloads [5]. By implementing intelligent and automatic systems can allow electric companies can monitor the grid in real time [1]. This makes quick response, early detection of possible faults, and reduces the impact of a failure [7]. Moreover, if the network is directly connected to the end user, the status of their supply lines, energy usage, and continuously monitors the delivery condition [4].

All these solutions are aimed to change the energy model that is more than necessary and justified today [9]. The change is towards new distributed systems in which any agent that is connected to the network has the possibility of providing energy, making it possible to create micro-generators that minimize the strong dependence on current energy generation and contribute to the current environmental problem [3]. It is here when we find the origin of the Intelligent Networks or Smart Grids, as a set of solutions to all these problems raised [2]. This type of network helps to reduce the energy transmission losses makes it easier to connect different renewable energy source, support energy storage system, and supports to large scale connection of electric or hybrid vehicles that use energy both for charging and for transferring energy to the grid [6]. Fig.1 illustrates a diagram that represents a Smart Grid, as a sample of the development of the electrical network [8].

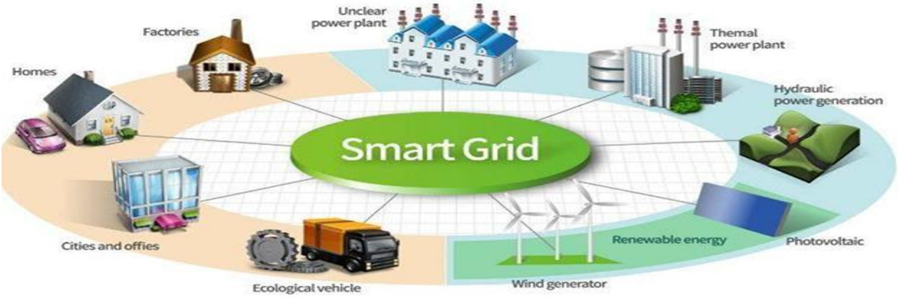

Fig.1. Diagram of evolution of the electrical network towards the Smart Grid

2 Literature Review

The Energy Management System (EMS) is an important part of Smart Grids. Its main job is to balance how much electricity is produced and how much is used. It does this by controlling and managing the flow of power to make sure energy is used efficiently and reaches where it's needed. In this study, different research works about EMS are reviewed to explain how it is used, what its main functions are, and how it helps achieve specific goals like saving energy, reducing costs, or improving power reliability. From [4] and [5], energy management systems can be classified in different ways. However, in this work, the classification is based on the role and operational functions. The main objective of an EMS is reducing the operating costs, minimize the harmful emissions, increase the voltage stability, improving the performance of the system and enhance the efficiency. To reduce the operating costs [6-8], an energy management system optimizes electricity generation, based on real time demand. It focuses on more economical source and avoids using costly power sources, especially at peak hours. Additional it can adjust the distribution system schedule for future low operational expenses. The use of distributed generation also helps to reduce transmission losses by generated power. However, the energy management system is more responsible for managing and coordinating the integration and operation of these distributed energy source.

For example, in a household that uses distributed generation, electric vehicles, and regular electric appliances, to improve the efficiency the energy can be planned more intelligently. Instead of charging the electric vehicle during peak hours, it can be scheduled to charge at night when overall electricity demand is low. During peak demand hours the electric vehicle battery can even supply power back to the home, helping to reduce stress on the grid. Energy management systems usually perform some key functions such as monitoring, optimization, forecasting, control, and management. Among these, the functions that contribute the most to energy savings are control (about 30%), optimization (about 25.6%) and management (about 25%). Still, the best combination of functions in EMS is control/optimization, with an average saving of 21.27%, and the lowest prediction, with 10% energy saving [4]. Overall, the optimization function in energy management system focuses on planning and selecting the most efficient schedule for energy usage inside the building. It helps to make smart decisions about when and how energy should be used to reduce the cost and wastage. Examples are seen in [10-12]. The control function involves the actual operation and regulation of energy consuming devices, ensuring they work efficiently and according to planned strategy [13]. According to [14] 5G technology, a new communication network structure is being developed and 5G offers advantages like low latency, high stability, increase availability, and better reliability requirements than other communication technologies. This advancement is expected to impact many industries, including the energy sector, by enabling faster and more reliable data exchange. According to [15], the advanced metering infrastructure plays a main role in modern power systems. It responsible for collecting, analysing and storing energy consumption data from end users and send it to utilities that are responsible for billing, managing the network and demand forecasting. This work aims to explore limit the adoption of electricity generation combined with energy storage system. This work seeks to explore the main challenges that limit the adoption of electricity generation combined with Energy Storage Systems (SAEs). Additionally, it proposes possible solutions and discusses both technical and economic aspects related to their application in smart grids.

3 Description of the proposal

The motivation of this dissertation concerns the optimal use of a storage system for network support services, and considers the specific objectives of the dissertation the efficient selection of a storage device considering its technological characteristics, costs, impacts and regulatory barriers and how energy storage fits into grid modernization. To achieve this end, this document is divided into two stages: theoretical and experimental. Thus, in order to determine the behaviour of the use of energy storage devices in communion with the network, simulators are used to characterize the waveforms and show how much independent production configurations can harmoniously integrate with the network. For the behaviour study, the TyphoomHil 600 simulator was used using a Texas Instrument F28335 digital signal controller.

3.1 Typhoon HIL 600

Typhoon Hil is a scientific research simulator and Hardware in Loop package for real time testing of power systems. In this way, it is possible to build models and perform tests in different scenarios, in four steps: defining the converter model in the schematic editor and compile the circuit to be studied, run it, Capture signals. Automate the previous steps via Python test scripts and let the emulator comprehensively test the controller 24/7.

3.2 Digital Signal Controllers (DSC)

For the simulations, a Texas Instrument DSC (TMS320F28335) was used, as shown in Fig.2.The test is carried out in the laboratory.

Fig.2. Texas Instrument Controller

4 Case study Description

The aim of this chapter is to present two case studies, through the presentation of simulation results obtained through technical feasibility. Through these results, conclusions are drawn about the behaviour of two typical configurations of photovoltaic production with the use of energy storage.

The results were obtained through the implementation of the simulation presented in the Typhoon HIL 600 simulator, a program that allowed the following studies to be carried out: Analysing the effects of power injection into the electrical grid; Evaluate the solutions found to help the network; Study the impact that energy storage has on the power grid.

4.1 Case study 1

In order to check the behaviour of the network in a bidirectional system, a system was simulated where it can receive energy from the network, as well as feed it through photovoltaic production linked to a battery system. The battery that works in parallel with solar production, and its energy flow is controlled through the double active bridge converter. The PV (Photovoltaic) system is controlled using boost converter.

The cumulative power (power exchanged with the grid) is routed to the grid using the two-level three-phase voltage inverter. Thus, the energy from the grid can continue to feed the battery, as well as the photovoltaic system and/or battery can supply the grid. The typology of the simulated circuit is shown in Fig.3.

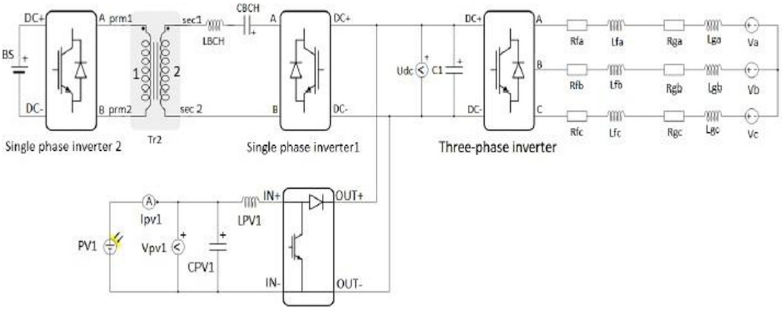

Fig.3. Case study 1

Thus, the functions of the elements of this circuit are:

- Photovoltaic panels represented by PV1- It has the function of producing energy through solar energy, having a current meter in series Ipv1 and a voltage meter in parallel Vpv1.
- Boost 1 converter isa DC-DC converter that increases the voltage from its input to its output load. It is a class of switching power supply containing two semiconductors. Accompanied by two energy storage elements such as a CPV1 capacitor and an LPV1 inductor, these work as a power supply filter in order to reduce voltage ripple at the converter input.
- Transformer Tr2- It has the function of reducing the voltage coming from the network or from the PV1 production, to supply the battery with the desired voltages for it.
- Single phase inverter 2- controls the current input to the battery
- Single phase inverter 1- controls the voltage coming from the grid or photovoltaic

production.

- Three phase inverter - is responsible for converting continuous energy at its input into alternating energy to be injected into the network. Capacitor C1 filters the tremor component of the three-phase inverter input current.
- The simulation and implementation of the proposed method in single power system is done using proposed configuration. The source voltage is 380 V with the frequency of 60 Hz, the load is considered to be a thyristor based rectifier feeding a resistive inductive load and a linear load.
- The simulations are made to balanced and sin wave supply voltage with different events to prove the capacity of the proposed system in helping the network. The inductance of the coupling transformer is 1mH and the proposed switching frequency is chosen equal to Fswitching = 10 kHz. The parameters used in the simulation are provided in Table 1.

Table 1. Test parameters of case study 1

Parameters	Values
Battery capacity	7.5 kWh
DC-link condenser	1100 F
inductor filter	= 4.8 mH, = 4.3 F
Switching frequency	DC-DC Converters: = 20 kHz
Voltage switching frequency	DC-AC Converters: = 10 kHz DC-link = 400 V
Mains rated voltage	= 230V
Nominal frequency of the PV network	= 50 Hz Output filters RL 20 Ω; 0.1mH ; 2.7μF System Power
Condenser	2kW
Transformer	2.7mF

4.2 Case study 2

To see how a grid-tie system behaves, another typical microgrid production system was simulated, where the PV photovoltaic system produces energy and this passes through a DC-AC inverter system, energy converted into alternating current that can feed the two loads Load1 and Load2, as well as the electrical network. In addition, the photovoltaic solar system can power the battery by converting its alternating current into direct current when it goes to the battery inverter system, represented by the diagram in Fig.4. And the parameter of case study 2 was shown in Table 2.

Thus, when photovoltaic production is in high production, it can charge the battery and loads, as well as inject energy into the grid. Likewise, the network can supply loads, as well as charge the battery. In this case, the battery works as a backup in order to keep the system as independent as possible from the mains.

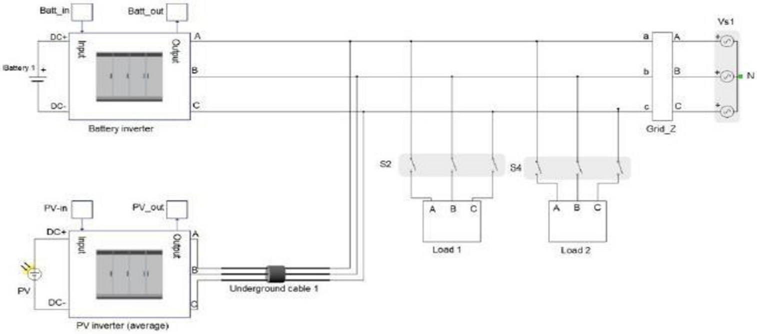

Fig.4. Case study 2

Table.2 Test parameters of case study 2

Parameters	**Values**
Battery capacity	7.5 kWh
Mains rated voltage	380 V
Rated network frequency	50 Hz
RL output filters	20 Ω; 0.1mH ; 2.7µF
PV system power	2.5kW
Condenser	2.7mF

5 Results and Discussion

In this chapter, the most relevant results of this dissertation will be presented, through simulations. To this end, several simulation scenarios will be described that validate the models and, consequently, the photovoltaic systems connected to the grid. Initially, the curves presented in the simulation of case study 1 and their impact during the time intervals will be presented. In case study 2, four simulation scenarios of voltages, currents and powers involving the photovoltaic system in question are presented along with the due discussions regarding the results obtained.

5.1 Results of case study 1

The Fig.5 shows the waveform that represents the power delivered to the photovoltaic system as a function of the load variations defined in three scenarios with different time periods:

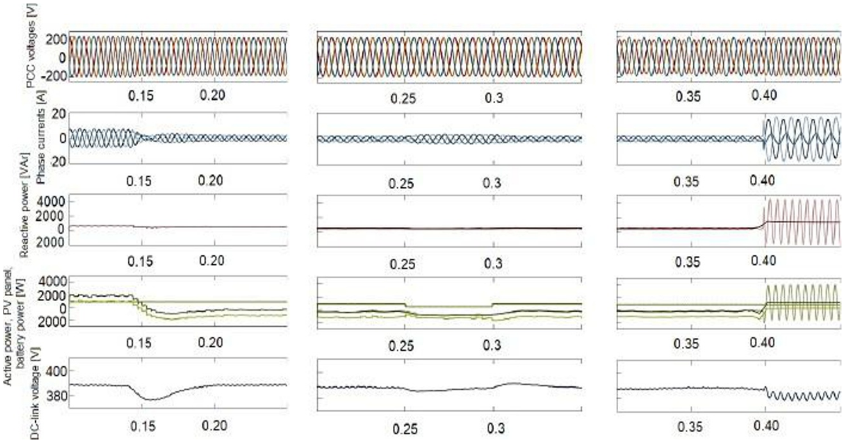

Fig.5. Results of case study 1- all scenarios

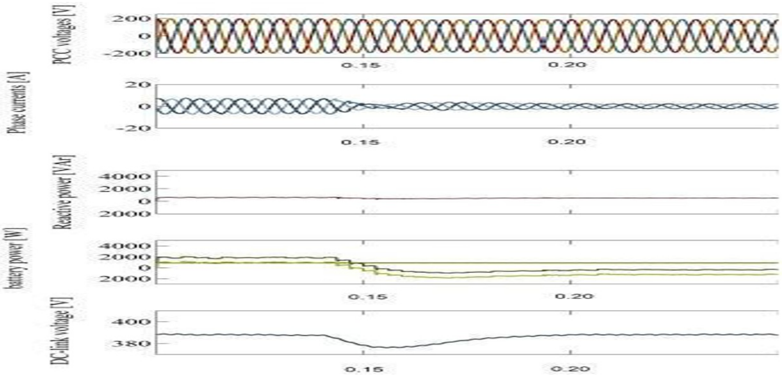

Fig.6. Results of case study 1 - scenario 1

In the first interval of 0 to 0.15 seconds shown by Fig.6, it shows the battery being charged through the electrical network. The three-phase current is 10A. Already in the second interval of 0.15 to 0.20 seconds, the battery stops consuming energy from the electrical network. Soon the current reduces by half (5A) and the battery voltage reduces a lot accompanied by active energy. However, in the third interval, which corresponds to the period from 0.20 to 0.25 seconds, it remains inert. In the fourth interval between 0.25 to 0.30 seconds there is a small increase in current consumption. In the space of time between 0.30 to 0.35 seconds, the consumption of three-phase current is reduced again, as shown in Fig.7.

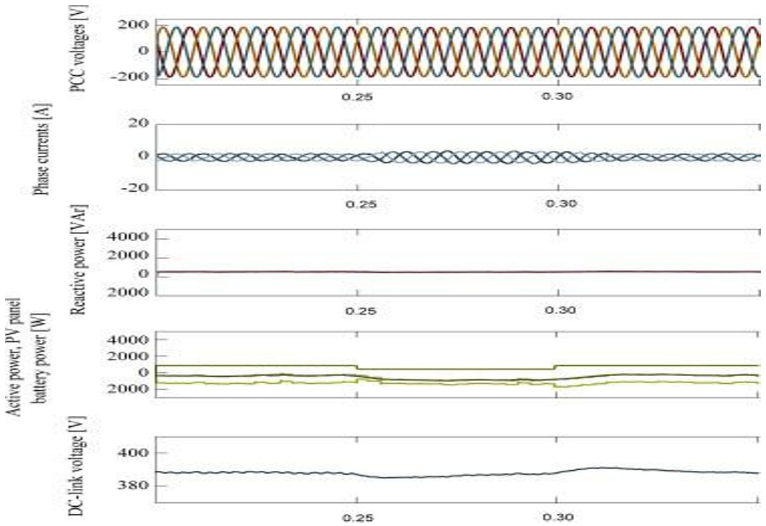

Fig.7. Results of case study 1 - Scenario 2

After a time of 0.40s onwards, the current significantly increases showing a phase unbalance. The reactive power grows and there is a ripple of battery voltages.

It can be seen, in the first interval, the battery has 2kw of power and the photovoltaic system 1kw, where the battery absorbs energy from the alternating current. From the second interval on, both produce again and notice that when the extra load was turned on, there was a disturbance at the end of the interval. It is observed that the three-phase voltage waveform of the PCC (point common coupling) remains in good state until the fourth interval.

Fig.8 presents the three-phase voltage and current of the PCC and the mains current during the battery start-up and during the application of the compensation strategies. The current from the three-phase mains was the full load current and it became sinusoidal, but not balanced, because the battery only compensates for the empty current. The battery, when it delays the delivery of active power, proves to be useful in controlling the PCC voltage, as well as in the reactive power, proving to be an attractive solution for smart microgrids. The simulation results showed that the battery in this system has its effectiveness. Neither injection behaviour nor instability occurred during steady state. The battery acts to limit the sending of active power, helping the PCC voltage by reducing the negative effects of voltage rise from active power injection.

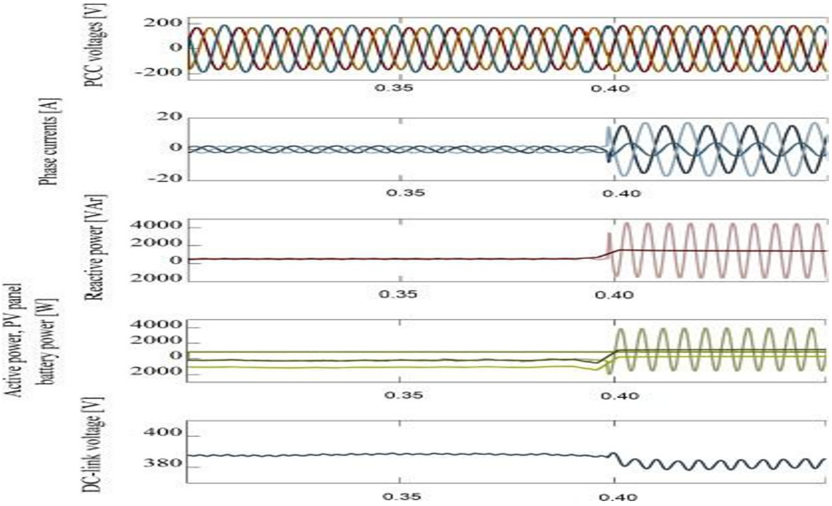

Fig.8. Results of case study 1 - Scenario 3

5.2 Results of case study 2

Scenario 1 considers only the generation of the photovoltaic system, scenario 2 only consumption, and scenario 3, both (generation and consumption of loads load 1 and 2) and scenario 4 only consumption load 1. For scenarios 2 and 3, an attempt was made to use or maintain photovoltaic production at 250kW in all installed scenarios to obtain more expressive measurement values.

Scenario 1

In scenario 1, the system was simulated when only the photovoltaic system is producing energy which is shown in Fig.9. In the period from 0s to 0.28s, the photovoltaic system delivers active energy of 100kW. Contactors S1 and S2 are disabled, so loads 1 and 2 are not absorbing the energy produced. Thus, it can be seen that the waveform of the voltages delivered to the three-phase grid_Z bus remains continuously without deformations with a voltage of 380V. However, the battery output currents present deformities throughout the analysed period. The measurement of currents at the output of the PV average system came out with 420A, with sinusoidal shapes without major distortions.

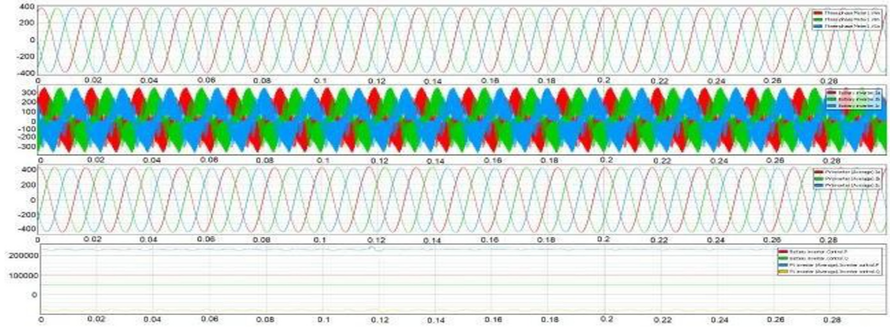

Fig.9. Results of case study 2 -Scenario 1 response

Scenario 2

In this situation, the system was simulated consuming electricity from the grid. In the same period of time from 0s to 0.28s, the photovoltaic system delivers active energy of 250kW and reactive energy of -9kVa. Contactors S1 and S2 are still disabled, so loads 1 and 2 are not absorbing the energy produced. Thus, it can be seen that the voltage waveform delivered to the grid_Z three-phase bus remains continuously without deformations. However, the output currents of the battery present deformities throughout the analysed period, considering that it has a sine wave with 400V with active energy of 100kW and reactive energy of 50kVa which is shown in Fig.10.

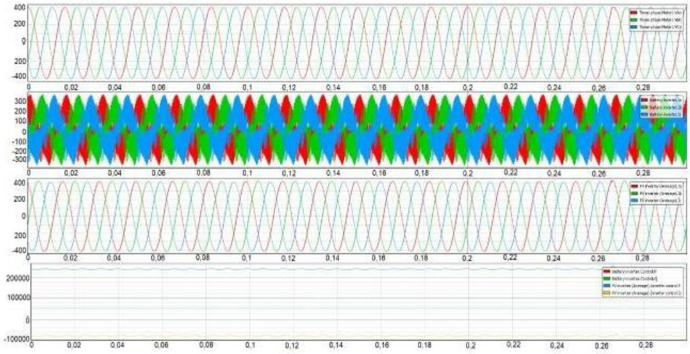

Fig.10. Results of case study 2 - Responses from scenario

Scenario 3

In Fig.11, the system was simulated when only the photovoltaic system is producing energy. In the same time as the previous test, the photovoltaic system delivers active energy of 100kW. Contactors S1 and S2 are still enabled, therefore loads 1 and 2 absorb the energy produced. Thus, it can be seen that the voltage waveform delivered to the grid_Z three-phase bus remains continuously without deformations at 380V. However, the output currents of the inverter battery show a significant improvement throughout the analysed period, considering that it has a sine wave with 420A. The photovoltaic system maintains its production throughout the analysed period. The reactive load increases substantially. Even with a very large reactive load, an improvement in the sine curve can be observed.

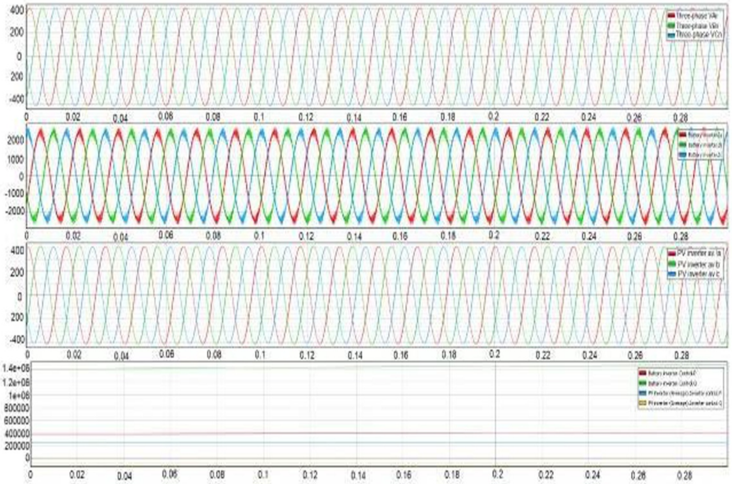

Fig.11. Results of case study 2 - Responses from scenario 3

Scenario 4

In Fig.12, the system was simulated when only the photovoltaic system is producing energy. In the period from 0s to 0.28s, the photovoltaic system delivers active energy of 100kW and reactive power of -1kVa, proving to be inductive. Contactors S1 have the contact closed and S2 is disabled, so only load loads 1 absorbs the energy produced. Thus, it can be seen that the voltage waveform delivered to the three-phase grid_Z bus remains continuously without deformations at 400V.

The photovoltaic system maintains its production throughout the analysed period. There is an increase in reactive power. With active power P of 10kW. Even with the reactive load Q of the inverter output still high at 800kVa, where the sine curve improves in relation to scenarios 1 and 2, however it presents a slight worsening in its shape compared to scenario 3, considering that this one is with sine wave with 1000A. The output currents of photovoltaic production are with sine waves without deformities of 380A.

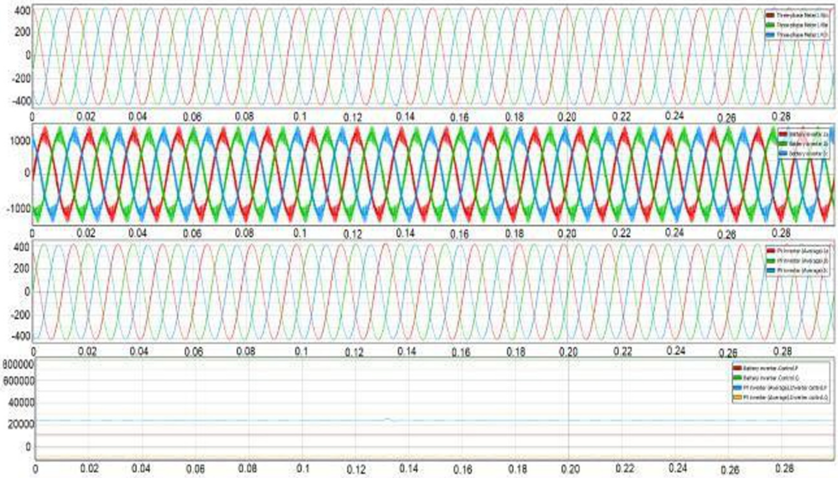

Fig.12. Results of case study 2 - Responses to scenario 4

Conclusions

In this work, two typical models of photovoltaic production with the use of lithium batteries as backup were studied and developed, evaluating the behaviour of the two models when coupled to the electrical grid. The simulations were able to describe the function of storage systems. The proposed emulator performed the macroscopic representation of the phenomena produced by the simulated topologies. The need to implement behaviour simulations is necessary in order to prove its benefits to the network. In case study 1, the introduction of battery use proved to be effective due to the delay of active energy in the network, not causing disturbances. The association of loads and generators in a microgrid in case 2 allowed us to state that the control of the sources is localized and does not interfere or does not depend on the conventional system, as well as, it can also supply reactive energy if the grid needs it. With regard to the application of batteries in microgrids, it was possible to confirm their effectiveness as a solution to some problems, such as reactive power control. Furthermore, this technology can also be used as a load regulator, being able to balance generation with consumption at any time. The simulation carried out by the emulator proved that both bidirectional systems together with the network, fulfil their functions in a harmonious way with this one and the use of the battery in both cases represents a great help in regulating the reactive power, levelling the load and guaranteeing the quality of energy in a distributed generation system. Thus, the study proves to be conducive to breaking the stigma of the functionality and benefits of this type of technology. These functions allow for a series of advantages not only in terms of energy use but also in economic terms, as producers can postpone some investments in power plants and consumers see better management of their energy, which will be reflected in energy savings and reliability. Finally, based on all the results obtained, it can be ended that the two implemented models satisfy the purpose of simulating in some detail the phenomena that occurred in their operation, beneficially influencing the implementation of storage systems, as well as analysing their interaction with the electrical network.

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