

Micro-Grid Integration of Clean Energy Simulation for a Non-interconnected Region

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Abstract

This paper develops a simulation of a small electrical network (Microgrid) that integrates renewable energies, the model of the micro network is made up of a solar energy source, a wind energy source, an energy storage element, a non-renewable source such as a diesel generator. The model of the microgrid represent a non-interconnected area from the electrical network in Colombia. The non-interconnected areas sometimes depend on unreliable connections to the grid integration of renewable energies could be the best option to guarantee energy in these sectors and allow generating projects with social impact. A possible solution to this deficit of energy is to supplement the production of energy with renewable energy plants from resources as sun or wind. The simulated model allowed to study the effects of the network in island mode and in interconnected mode, showing the imbalances that can be obtained by integrating renewable energies and storage systems. It is verified that with an inclusion of more than 30% of power in renewable energies there is the possibility of having load imbalances, which affect the frequency and cause instability in the network. It also verifies how a control system can regulate the load balance but must interact with the other energy sources.

Keywords: Energy Non-interconnected Renewable Smart grid

I. INTRODUCTION

This document develops a model for simulate a microgrid that represent a non-interconnected area from the electrical network in Colombia. It was made to explore the effects that renewable energies have on the electrical network as a power supply with residential loads. It explores the behavior of this energies and verified if the control systems can maintain the balance of load. The simulation is done in two different modes as interconnected or non-interconnected electrical network. Colombia has a good potential to produce electricity with renewable energies, it does not have seasons and also this country has a location with high annual averages of wind speeds and irradiance from the sun. However, it has difficulties integrating remote regions into the national electricity grid. It non-interconnected zones lack the possibility of energy 24 hours a day. A possible solution to this energy deficit is to supplement the production of energy with renewable energy plants from resources as sun or wind.

II. WHY IS IMPORTANT THIS SIMULATION

Non- Interconnected Zone in Colombia

The government define the term non-interconnected zones (ZNI) in Colombia as following: "For all purposes related to the provision of the public electric power service, ZNI is understood to be municipalities, townships, towns and hamlets not interconnected to the national electric system (SIN-sistemainterconectadonacional)" [1]. It ZNI can be defined as microgrid with non-renewable generation sources that can be improved with the inclusion of renewable energies (unconventional) and take advantage of everything that is developed for smart grids and apply the technology in island mode to optimize the fuel from diesel plants that is commonly used as an energy source of energy in these zones. The main characteristics of the non-interconnected zones in Colombia are: areas with unmet basic needs > 77%, are scattered areas (Low Population Density), with a low average consumption level. They have a low payment capacity and a very low level of collection. It has high costs of providing electricity service. High level of losses. Low level of micro measurement. This makes them a perfect scenario for the efficient use of available natural resources and the use of renewable energies. The non-interconnected areas sometimes depend on unreliable connections to the grid such as the Puerto Carreño in the Vichada zone that depends of a very weak medium voltage circuit from Venezuela. This problem is very important for the development of pilot tests where the application of renewable energies is the best option to guarantee energy in these sectors and allow generating projects with social impact right now. According to the Institute of Planning and Promotion of Energy Solutions for Non-Interconnected

Zones IPSE, the non-interconnected areas in Colombia are in 32 Departments. Where there is currently coverage over 17 departments, which is equivalent to 52% of the national territory is included 90 Municipalities, 20 Special Biodiversity and Border Territories, 1,448 localities ZNI, Municipal Headquarters: 5 departmental capitals[1].

III. CHALLENGES IN THE INTEGRATION OF RENEWABLE ENERGIES

The main effect of the inclusion of renewable energies in the network is that they are basically more prone to instability or variations in their quality parameters, it microgrid need to react quickly with control actions on their own maneuvering equipment and eventually involve all those that are interconnected. The first challenge of the electric networks that integrate renewable energies, is to regulate the power that is delivered to the end user at the moments when there is no availability of alternative sources (for example: in the absence of sunlight or absence of wind). This means that the planning of the required energy must consider the seasons of the year, and probabilistic studies of the wind projections that are available or the solar radiation that is expected at a certain point. Some renewable energies depend on natural phenomena, the available energy is conditioned to the available resource at a given moment [7-11]. An electrical network based only on renewable energies such as wind energy, solar radiation will have problems to feed the load in a constant manner as shown in Figure 1, production and consumption varies over time. Elements that allow the regulating of energy delivered to the end user must be integrated in the microgrid, because in case of absence of solar radiation [12] or wind [13] these systems are unusable to generate energy and the energy received by the end user will be zero [14]. The variability of the network and the fast reacting that now is required for maintain the balances between the load and the renewable energy sources is the principal problem to be simulated. In some remote places there are microgrid composed only of renewable energy that must provide energy to the user 24 hours a day, these must necessarily have devices that allow to the energy generated to be stored or be supplemented with other sources of generation [15] for its proper functioning.

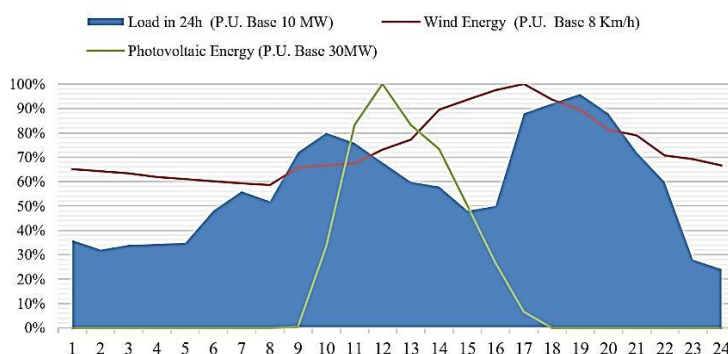


Figure 1. Typical energy production and consumption in a Day (24H)

The solution for integrating renewable energies and regulating fluctuations is called smart grids. This is a type of network that can coordinate the available energy sources and restore the stability in the network. Smart grid will help to increase the level of penetration of renewable energies, IRENA (International Renewable Energy Agency) [16] declare that with levels of penetration higher than 30%, this information exchange technology is essential for the proper functioning of electrical grids.

IV. THE MODEL OF THE MICROGRID

Electrical connection like a non-interconnected zone

The simulation model is designed to represent the electric grid of the non-interconnected area of Puerto Carreño in Colombia. The Figure 2 [17, 18] shows the single line diagram, this electrical grid has the following characteristics: The microgrid has a connection from an electrical network at 34.5 kV, this energy is sent to a distribution substation at 13.2 kV (Grid Connection), the Diesel power plants in 480V are connected to the grid through a step-up transformer to the 13.2kV medium voltage busbar, the loads are connected by a pole-mounted reducer transformer that reduces the voltage from 13.2 kV to 208/120 V to be used by the residential load.

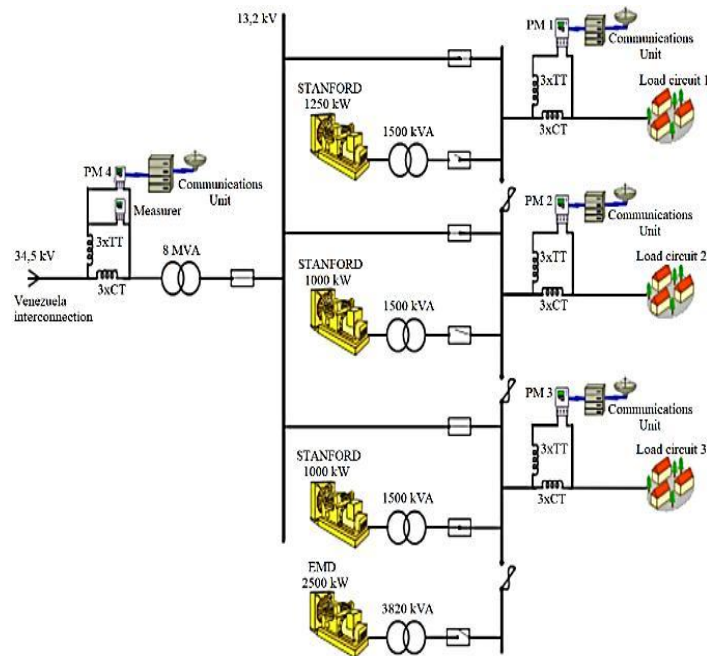


Figure 2. Puerto Carreño grid, single line diagram

For the electrical network, the simulation emulates the connection of the power system of Puerto Carreño, where the loads are approximately 5 MVA, the network arrives from Venezuela through a medium voltage line. The generators are connected to the network through an elevator transformer. The nominal rates and capacities are proposals in the model showed in the Table 1. In the upper part of the table the source is indicated. The first row is the nominal phase -phase voltage that will be used for the electrical connection, in the lower part is show the nominal power of each source or load.

Table 1. Voltages and Powers of the sources that make up the micro network.

	Diesel generator	Wind farm	Photovoltaic Park	Storage	Load
Nominal Voltage [Vn]	480 V	13.8k V	13.8 kV	208/120 VAC	208/120 VAC
Nominal Power [Sn]	10 MVA	2 MVA	2 MVA	400kVA	5MVA

The electrical connection consists of three nodes (BUS_1, BUS_2, BUS_3) shown in Figure 3, the first is the diesel generation node at 480 V AC, this point has a small load that represents the auxiliary services of the machine and from where the parameters for frequency regulation will be taken. The distribution substation is represented as the BUS_2, where the diesel generator is connected through the 20 MVA Yg / Yg elevator transformer. In this busbar the sources of the electric network, the wind farm plant and the photovoltaic farm are connected. The busbar at 13.8 kV and has a reference to ground through a ZIG-ZAG transformer of 10 MVA, this is installed in case the diesel source was isolated and the system is floating. This bus feeds the load node through a reducing transformer from 13.8 kV to 208V with a capacity of 20 MVA Yg / Yg. The BUS_3 represents the lines of distribution up to the loads. The loads are connected to 208/120 VAC as well as the 400-kVA distributed storage system [19]. An important point in this design is that it took into consideration the high cost of large distributed storage systems, which at this time reduces the storage capacity of this technology, since they will not be implemented in the current solutions until their price is more affordable, this would give an approximation to the real environment that may be in the near future In order to simulate the effect of renewable energies a level of penetration of renewable energy sources exceeding 30% was proposed, this is represented as follows, 2 MVA of the wind farm plus 2 MVA in the solar plant for a total of 4 MVA, which is equivalent to approximately 40%; the non-renewable generation source is 10 MVA; The storage capacity is 400 kVA (Energy Storage 4%) and finally the consumption of the load is 5 MVA.

Simulation considerations

For the simulation of this microgrid, the Matlab program was used, especially the Simulink tool and its Simscape™ Power Systems tool block. The electrical network was modeled on the examples of this library and the tool blocks that this program offers. The simulations are done with phasors for better times of simulation and because this representation facilitates the implementation and calculation of the three-phase power systems. The network of the project was adapted and presented in Figure 3, the electric model of the network was proposed and interconnected to run a load flow, this allows to simulate different scenarios, it was decided to use a time range of 24 hours where the load flow is run on three nodes Bus_1 Diesel plant, Bus 2 renewable sources and Bus 3 load and storage systems. The model of the Matlab example library with simulation for 24 hours, was adapted to correspond to the network designed for this specific microgrid.

The simulation of the exchange of information is between the storage system and the diesel plant, since the grid network is modeled as an infinite source and over which there is no control. Wind power plants and solar energy behave as independent systems or disturbances where it is not possible to anticipate the energy they will produce. The control strategy consists of keeping the frequency and voltage on BUS_3 as close as 60 Hz and at 208 VAC. The simulator does not allow to use an OSI exchange model based on the IEC 61850 standard [20, 21], to replace this concept in the simulation it is assumed that the information has no delays and that it is exchanged directly, that is, there is an ideal process bus for the reception and sent information to each controller. The information was exchanged using global tags, these can be visualized by other components. Due to stability problems in the load flow generated when executing the switch maneuvers (Transient that occur in the opening or closing maneuvers - TRV), there were some difficulties, which caused that the program did not find the solution when simulating the load flow. As a solution to this problem, the maneuvers were disabled, and the switches were removed from the generation sources. Only the switch associated with the ideal source (Grid) is implemented, which will be controlled to make the disconnection in the case of island mode.

The simulation models are:

- Mode Island: When the switch associated with the network is opened and the system is working alone through the generator and renewable sources.
- Cogeneration: The network is connected, and the controller is modeled to minimize the use of fuel but maintaining stability in the frequency

The load is of residential type and two different ways of simulating it were implemented, one as a constant system and the other with a variable load profile during daylight hours. Profiles were also generated for the wind and for the sunlight that feed the renewable energies, taking as a base the local information of the installation through the historical data of the IDEAM and its virtual atlas [22, 23].

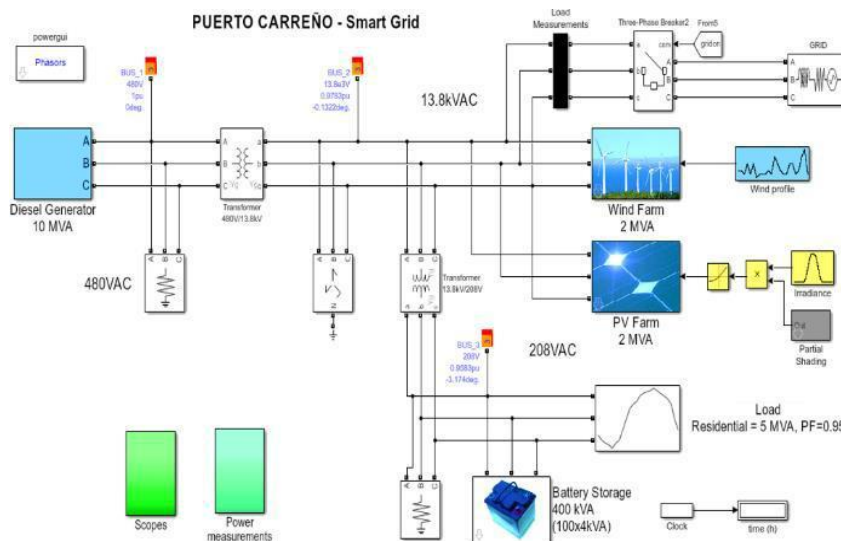


Figure 3. Microgrid simulation diagram

The choice of generation sources is made by recreating the Colombian scenario, which has several interconnected and non-interconnected areas that can make use of renewable resources and could be implemented in these areas in the future.

Diesel plant

The model for the diesel plant is shown in Figure 4(a), it consists of an engine that sends mechanical power to a synchronous machine, the governor is responsible for regulating the power according to a control criterion, in this case is the speed of the rotor (associated with frequency). The parameters of a machine are taken under the norm IEEE recommended practice for excitation system models for power system stability studies, developed by .Sybille (Hydro-Quebec), TarikZabaiou (ETS) - power_machines [24]. The engine is represented inside the governor which generates power that delivers to the synchronous machine, it also has an excitation system which is responsible for controlling the voltage of the machine (associated with the amplitude) and power. This model is taken from the Matlab library and adapted for this simulation. The regulator of the machine has a feedback from the output of the synchronous machine block and calculates the error, to send the desired torque and thus close the control loop. This model has a phasors meter that later is used to decompose the active power (), reactive () and apparent () provided by the system. The calculation of the power used in the simulation assumes that it is a balanced system, in which by the interposition theorem there is only the positive sequence for which this calculation method is applied. The Figure 4(b) show the calculation system. The power factor (angle) is taken from the difference of the angles of the phasors representing the current and the voltage.

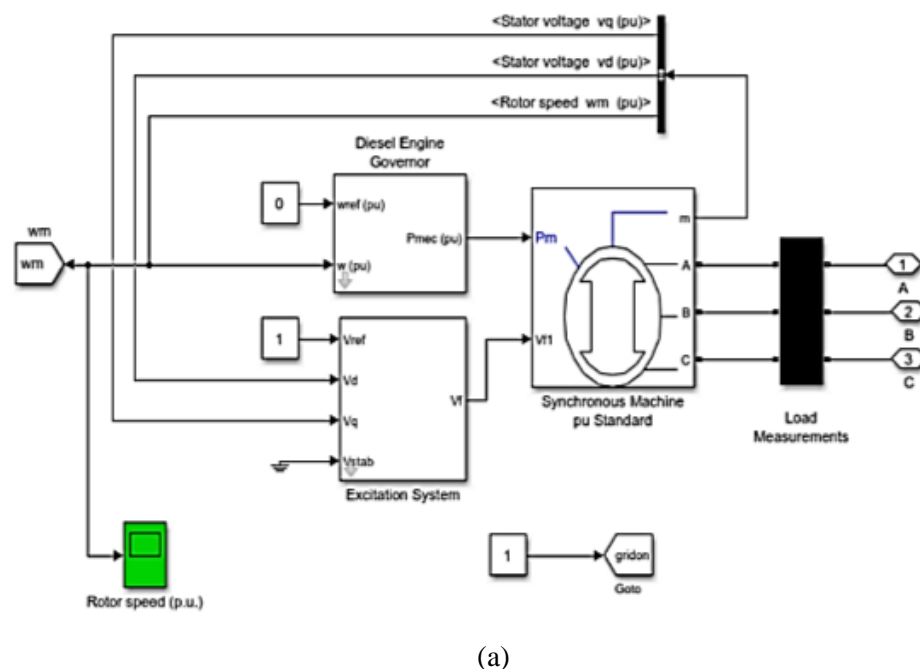


Figure 4. Models for simulation, (a) Simulation model for the diesel plant implemented in matlab, (b) Calculation of the power based in voltages and currents

Win plant

The wind generator is represented as a cubic relation between the wind and the power output with a certain efficiency and a fixed reactive power. For the simulation, a velocity profile was generated based on the averages shown in the IDEAM virtual atlas, where the wind speed increases at nighttime. For the generator, a simplified system was used, which converts the power of the DC system into a three-phase power generator balanced in AC; this modeled inverter through a relationship between the voltages that the system has and the currents that

must be injected into the system and the powers in DC, allows the simulation to be faster and generate the three-phase power in the system with only knowing the power in DC generated. In order to better approximate the model of the wind farm, the example proposed by Matlab is implemented, by incorporating a protection over speed of the park, at the moment that the programmed limit is exceeded, the system cuts the power generation, until the wind speed decrease below the adjusted value. In the Figure 5 is showing the model that is used to generate an apparent three-phase power in AC with a desired power in DC [25].

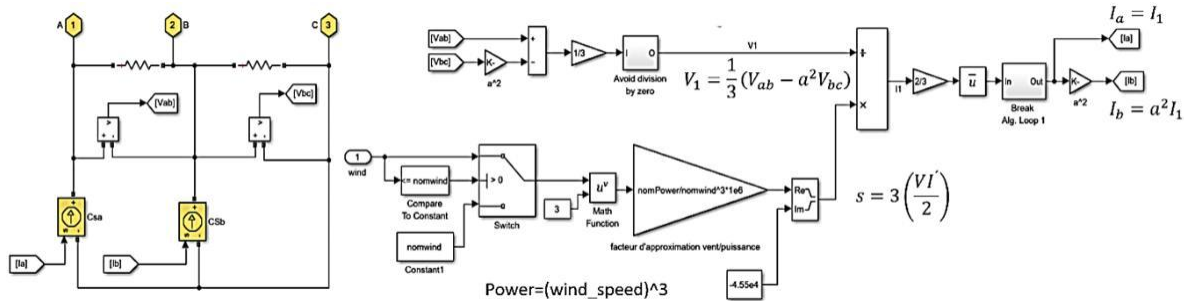


Figure 5. Wind plant model

Once you have the three-phase power S for the balanced system, you proceed to calculate the positive sequence currents I_1 and I_2 that will give the value of the three-phase current generated by the source. This concept is used throughout the simulation to represent DC to AC power converters. This model is used to generate an apparent three-phase power in DC with a desired power in DC. After generator sends the power quantity, the system must adapt the voltage to a value that allows it to be connected to the transmission network in 13.8 kV simulating the required substation in this type of plant, it also includes a load that represents the losses and elements consumed by the own systems. The ideal source is placed so that the system can calculate values of and as reference at the beginning of the simulation, see Figure 6.

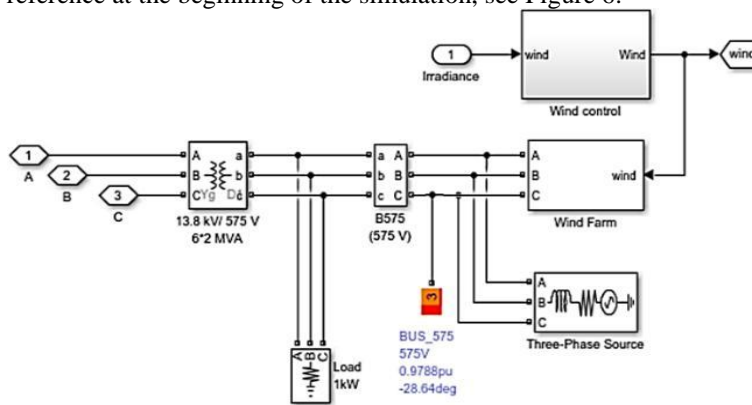


Figure 6. Electrical connection for the wind plant

In this simulation, the reactive generation capacity is limited, as is the case with wind turbines in real life. In summary, the implemented model allows:

- Simulate the trips by over speed.
- Deliver three-phase power as a relation to wind speed.
- Limit the reactive power delivered ()

Photovoltaic plant

The model for the solar generation plant is composed of a relation between irradiance and power, where the power is calculated depending on the area to be used and the efficiency of the cells the concept is shown in Figure 7. With this assumption simplifies the model, assuming that the modules and arrays of cells are grouped and deliver a DC voltage with a certain power. The output of the three-phase generator is connected to a load that represents the own services, in addition to the ideal source for the calculation of the voltages and shown in Figure 8. This output at 575 V is raised to 13.8 kV through the elevator transformer, which connects to the network. In this model, the generation of reagents is also limited. To simulate the electrical behavior of the PV Plant.

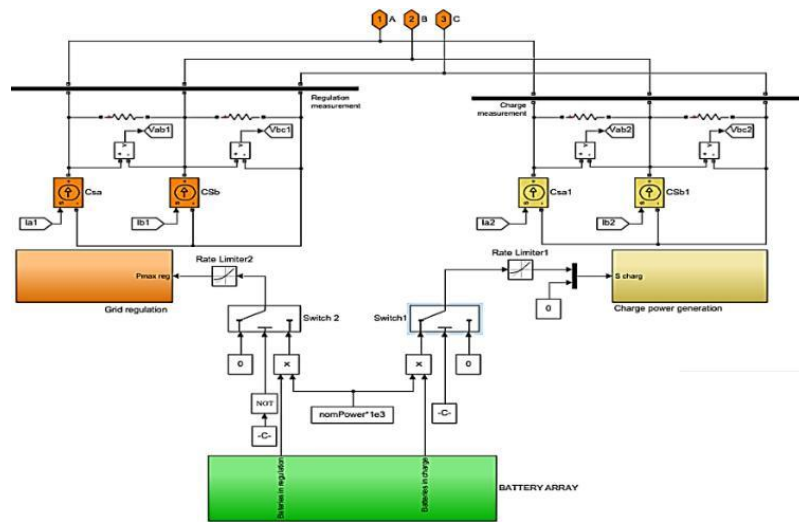


Figure 6. Energy storage model based in a matlab example

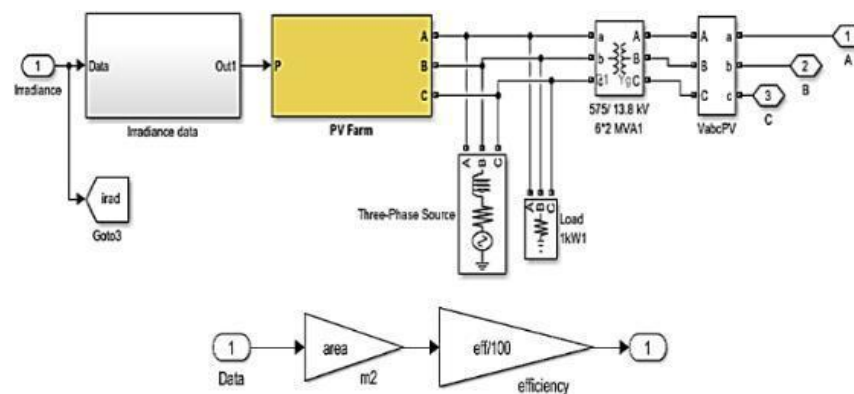


Figure 7. Electrical connection for the PV plant

Energy storage

The energy storage system was represented in a set of battery modules, grouped in blocks to increase the variability, a random function is included to represent in the model that the blocks are in different states of charge, and the blocks can be randomly in charge and regulation mode. The controller takes the blocks that are in regulation mode ($SOC > 85$) and they have power to contribute to the network, the blocks that are below the limit value, absorb power from the electrical network.

Two different converter blocks are used that represent the system, the first is an AC/DC converter for the chargers and the second is the DC/AC converters for take energy from the batteries to the electrical system. The modules have the possibility of being connected or disconnected from the network through the switch to simulate the connection or disconnection of the storage systems offering the possibility of switching each battery block and disabling the regulation. The Figure 8(b) show the storage model.

Residential load

To represent the residential load, two options were taken, the first option allows the simulation of a constant load and the second allows simulating a variable load profile over time. The second option is a residential charge that increases consumption at night and reduces in the early morning hours Figure 9.

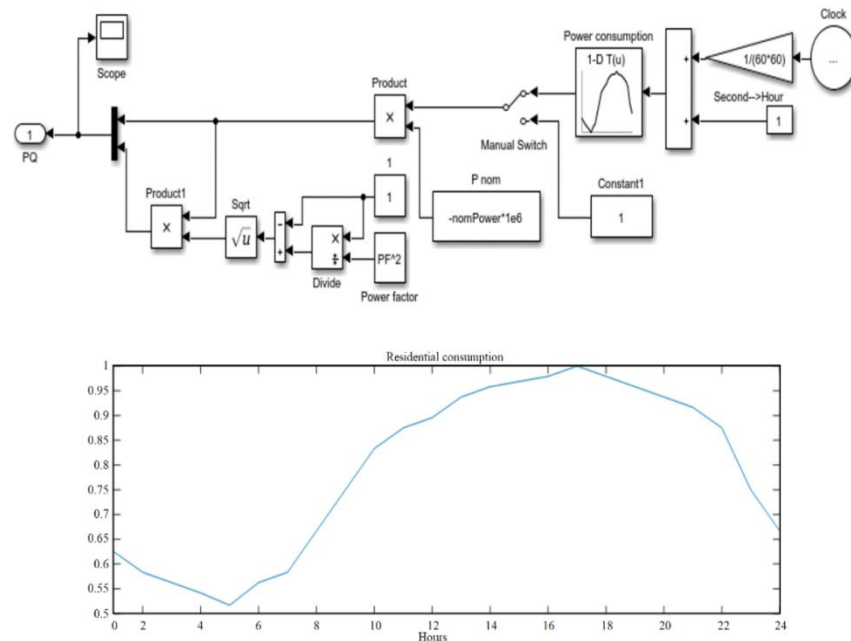


Figure 8. Power consumption for a residential load in 24 hours

V.SIMULATION

The microgrid that was implemented for the simulation has two elements that can regulate the amount of energy delivered to the load, the first element is the Diesel plant and the second is the energy storage equipment. The source of the electrical network (GRID), although it delivers energy cannot be regulated, only open or close maneuvers can be carried out controlling with the associated maneuvering equipment. The diesel generator controller informs the other systems of the speed of the rotor (), so that in this case the controller of the storage system can verify the available accumulated energy and initiate control of the frequency of the network. These two controls work in parallel to keep the network stable . When the system is in cogeneration reducing the consumption of the network, the governor is programmed to maintain the stability of the network with the motor to the minimum () = 0 and only regulating reagents, which makes the generator only work in cooperation with the storage system in cases where the network presents events that may destabilize the micro network, in this case, the plant contributes reagents to the network and complements what is consumed to maintain the stability of the frequency.

In island mode simulation, the microgrid behaves like a weak network; that means, it has small generation sources sensitive to power oscillations, this makes the system very sensitive and exposed to instabilities when loads behave very dynamically. In this case, the plant controller must send the necessary commands to try to maintain the stability of the network. In parallel, the controller of the storage system verifies the behavior of the frequency () and provides energy to keep the system stable. They are basically two controllers working in parallel to keep the frequency within the

operating range. Variations in the active power mainly affect the frequency of the system. Variations in reactive power are less sensitive to changes in frequency and locally affect the magnitude of the voltage [6]. The main regulator in this mode is the governor of the machine that tries to maintain the frequency by supplying power to the network. The design of this type of regulators is basically based on PD controllers, the recommended regulator was implemented as IEEE recommended [24]. It is show in Figure 10, the parameters of a machine are taken under the IEEE standard Recommended Practice for Excitation System Models for Power System Stability Studies, developed by .Sybille (Hydro-Quebec), TarikZabaiou (ETS) - power machines. Adjustments were made to avoid overshoots and minor adjustments for the specific load to adjust the parameters to the size of the network and the load [26]. In cogeneration mode the parameters of the governor are modified to try to maintain the stability of the network by reducing the fuel consumption of the machine but keeping the frequency in a stable state. It seeks to maintain the lowest contribution of the machine to the network by taking energy from renewable energies and the electricity grid.

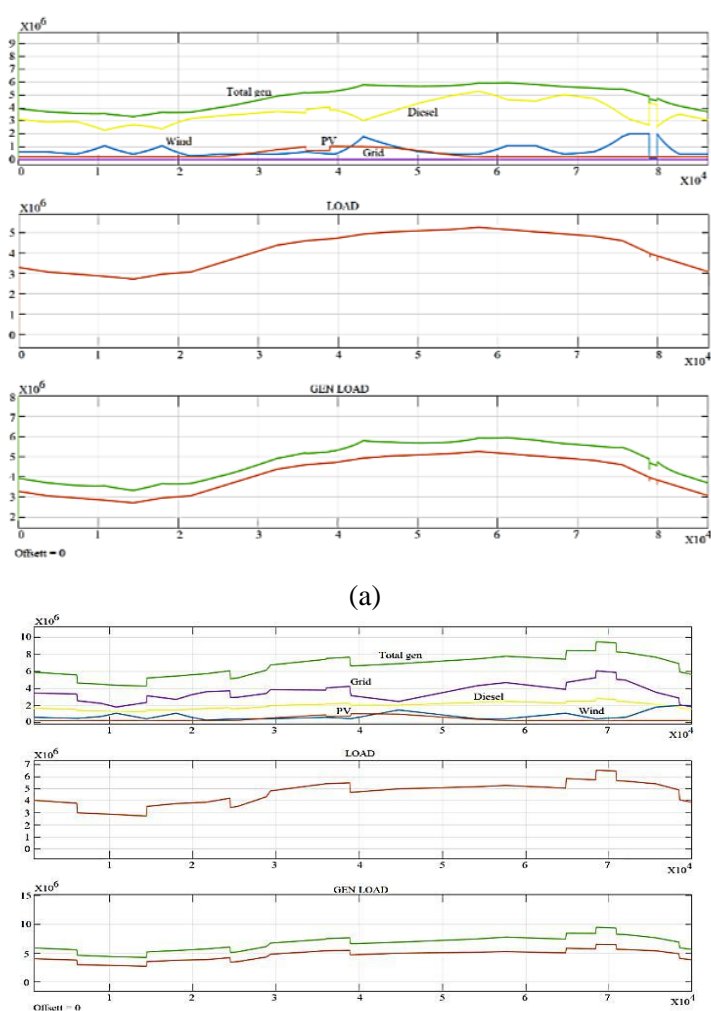


Figure 9. Results island mode, (a) apparent power simulation result (S) in 24h,

(b) system in mode interconnected with the storage system, generators, and load

Interconnected mode

In this case the governor and exciter of the machine should try to keep the machine at a value no higher than 2 MVA, with which the consumption must be reduced by operating at a lower load point. The machine is intended to regulate the Apparent power of the network. The results are shown in Figure 13 the generator power only exceeds the target value of 2 MVA at the moments of greatest demand. Overpasses are made, in this case the

fluctuations of the wind farm. The electrical network (Grid) in violet color has a behavior similar to the load, but the plant is responsible for regulating the stability of the network in times of rapid changes where the grid is insufficient. The grid goes to load the storage system for a greater extent and the diesel plant behaves is much smoother in the interconnection mode with the network [30].

The charge and discharge regulator of the network put some instabilities in the network show as jumps slightly softer than in the interconnected mode. However, the controller is being able to charge faster and demand more energy without affecting the frequency and therefore the load. The controller manages to maintain the frequency in the operation points, with an error of less than 1%, in the cases of the overshoots of the loads or the heaviest changes. The most critical points of operation of the system mode connected are show in the Figure 13, upper box island mode without energy storage, down box in with energy storage.

The frequency regulation keeps the values within less than 0.01Hz of error, behaving in an adequate way to the expected. The power remains stable and the frequency regulation system manages to operate the network in island mode and with more complex scenarios such as cogeneration, with or without storage systems. The frequency oscillates in load shedding. The peaks are compensated by the batteries and decrease (0.009 to 0.004 Pu). Although the oscillations by battery charging processes increase throughout the day.

VI.RESULTS

The plant manages to compensate the variability of renewable energies the load is variable, and the load flow remains stable There are losses in the system of almost 1MVA, representing the lines, transformation systems and auxiliary power consumption. With power greater than 6 MVA in renewable plants it is not possible to regulate the frequency. If the storage system is tun on the systems show a vary over time, there are batteries in charge and others in discharge. The peaks due to load discharges are larger (20%) when being fed by the batteries, to keep the frequency stable. The Diesel screen is placed to work at 2MVA, minimizing the frequency = 0, to decrease the contribution of the plant. The network sends power to the network (violet).The operation of the plant is much more stable and the electrical network compensates for what the load needs.The sources manage to maintain the load balance.The frequency oscillates in load shedding. The peaks are compensated by the batteries and decrease (0.009 to 0.004 Pu). Although the oscillations by battery charging processes increase throughout the day

VII.CONCLUSION

The simulated model allowed to study the effects of the network in island mode and in interconnected mode, showing the imbalances that can be obtained by integrating renewable energies and storage systems. The proposal with renewable energy sources integrated into the network in alternating current, allowed a modeling of phenomena that occur in the existing network; however, the load flow may not converge if there are many harmonics and power oscillations due to the maneuver of equipment such as switches, so the control cannot be based only on maneuvering equipment and it is suggested on the regulators of voltage and power of each source.

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