Modelling of a Smart Grid system in EcosimPro

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1. Introduction

Power supply is one of the greatest challenges, not only for the future, but also at the present time. One of the key goals involves developing renewable and sustainable sources of energy that are also cheap and reliable, and that can supply enough power to cover demands. Smart networks can be used to manage the power generated from several sources to optimize the available output and minimize the need for high-cost and contaminating fuels. Furthermore, the goal is to obtain distributed generation to produce electricity as close as possible to the consumption point, using the resources available in each site. This way, the power losses during transport are also reduced.

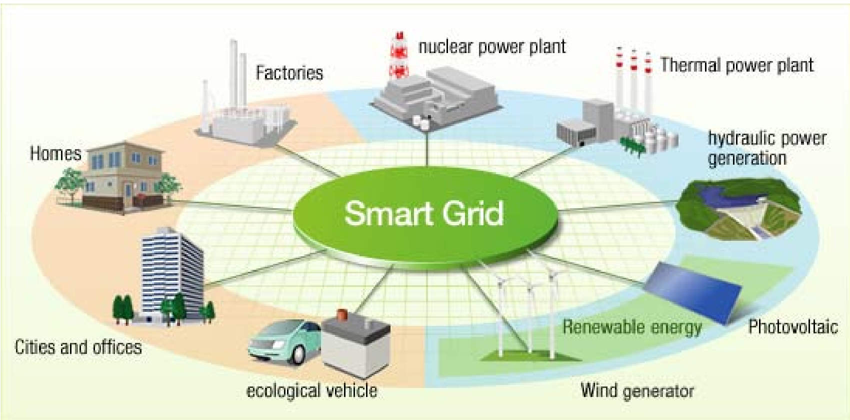

Figure 1. Smart Grid.

This document presents a model of an isolated smart grid developed in EcosimPro with the SMART_GRID library [1]. It shall grow in complexity in future versions, and will try to prove the functionality and potential of the simulation tool in this field. To do this, a solar photovoltaic power generation system, a wind power generation system, a diesel support unit and a battery storage system have been modelled. In isolated networks, one of the power sources needs to be set as the main one to guarantee a level of voltage and frequency in the grid. Normally, this role is carried out by the diesel generator, since it is the only one that is independent of weather conditions. Once the network voltage and frequency have been established, the rest of the power sources may be controlled with more flexibility by means of power converters that allow every device to operate at its optimal operating point at all times.

The developed model simulates the typical consumption during a day in an average facility. An analysis is made to establish how to obtain that energy by reducing the contribution from the diesel generator to a minimum. The system will be managed on a global scale by a master controller in charge of optimizing the generation-storage process to best meet the demands. The environmental conditions, the power demand profile itself and the configuration of each element are open so that they can be easily modified by users.

2. Solar photovoltaic power generation

The solar photovoltaic system includes a detailed model of the solar panels: Depending on the environmental conditions (solar radiation and temperature) and the operating point (supply voltage), the panels return a certain power. In addition, the model of the created panel allows the number of cells in each panel, as well as the number of panels in the plant, both in serial and parallel connection, to be adjusted. This component can thus be used to easily model and dimension complete plants of different sizes. The model is based on the equivalent circuit of the panel. Nevertheless, the behaviour of elements such as the threshold voltage, serial resistance or the supplied power depends on temperature, radiation, ageing and operating point. Furthermore, these dependencies are generally non-linear. The model has therefore been implemented by introducing the equations corresponding to those relationships by means of EL code parallel to the schematic model. This way of working greatly eases the development and expansion of the models. The equivalent circuit of a solar cell has been extensively studied and can be viewed in [6]. The following figure shows the schematic representation implemented in EcosimPro:

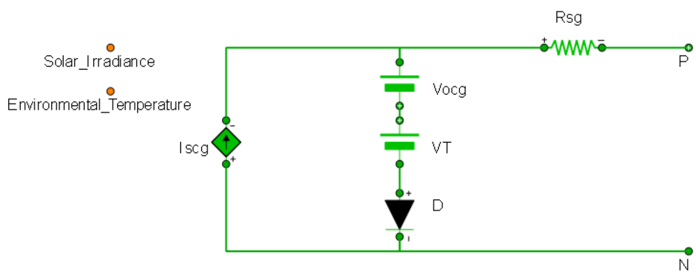

Figure 2. Photovoltaic Cell Equivalent Circuit.

The controller identified as MPPT (Maximum Power Point Tracking) is critical for this system. It always seeks to feed the panels with adequate voltage to guarantee as much power as possible is generated for given radiation and temperature conditions. The capabilities of EcosimPro allow parametric studies to be performed on the components so that each element can be dimensioned in accordance with the needs or the influence of every parameter on its response. Whenever solar photovoltaic panels are being modelled it is interesting to know the power they supply depending on the voltage for different solar radiation and temperature values. EcosimPro allows these studies to be performed automatically once the panel model has been developed. The following figure shows, for instance, the output power and current depending on the panel voltage for several values of solar radiation:

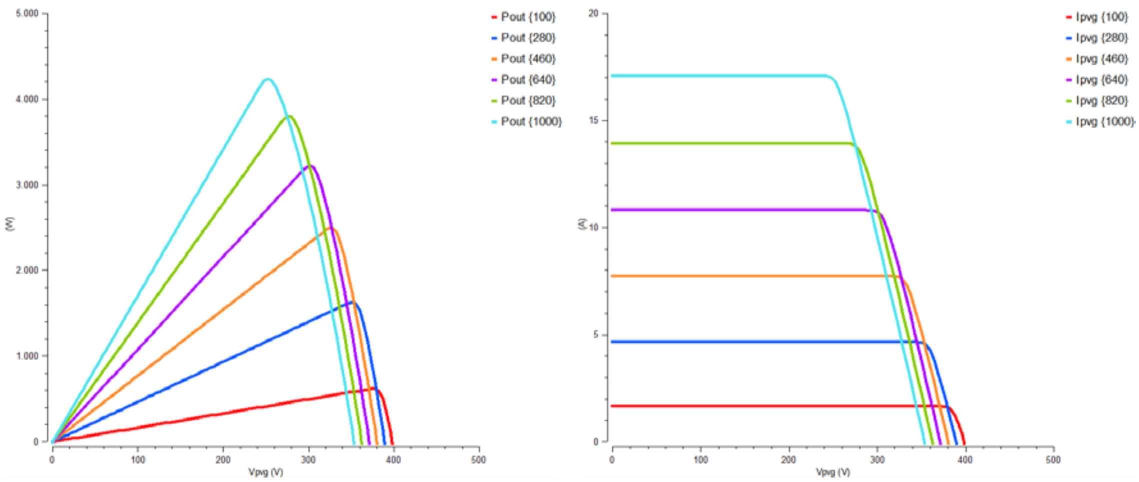

Figure 3. Photovoltaic Panel Power and Current = f(Voltage and Radiation).

The response of the MPPT needs to be readjusted through a second DC/AC converter (see schematic diagram) that follows the criteria of the Master controller. By performing this second adjustment in AC, the master is able to control the power factor of the solar generation. Therefore, by establishing a DC level for the panels and controlling the DC/AC converter behaviour, the active and reactive power to be transferred in AC to the grid will be obtained. In accordance with the above, the complete model of the solar photovoltaic facility implemented in EcosimPro is as follows:

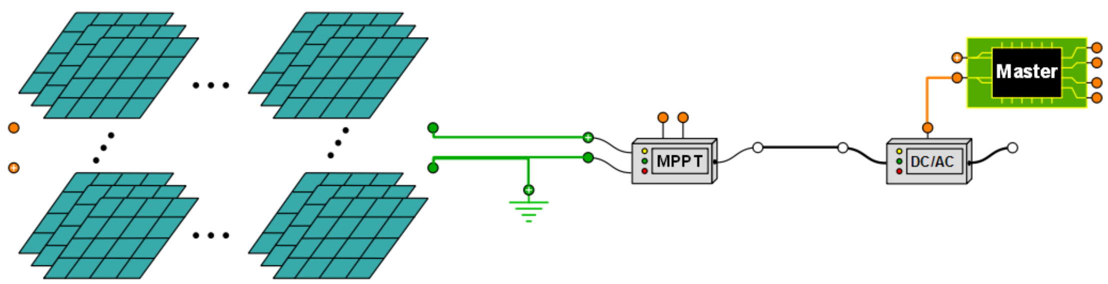

Figure 4. EcosimPro Photovoltaic Plant Model.

The model for the solar photovoltaic panel has been developed to make easier its reuse as much as possible. Thus, the model allows different sized panels and plants to be defined. Furthermore, the object-orientation of EcosimPro would simplify the creation of a plant model with different radiation and temperature conditions among the sections, thus adding a greater realism to the model for the purpose of the generation studies.

3. Wind power generation

In addition, a wind generation system has been modelled. This model includes the aerodynamic unit, which estimates the power obtained from wind depending on the environmental conditions and on the turbine adjustments. This component is the basis for the model, and its equations can be seen in [6]. As in the case of the solar panels, an effort has been made in the model to guarantee the flexibility of the wind power generator. Thus, different turbines can be modelled from a common base once their operating characteristics are known. It is also possible to dimension different sizes of turbines and plants. Furthermore, different ambient conditions can be applied to each section of a facility by replicating the component. The capabilities of EcosimPro also simplify the task and time of parametric studies. The following graphs correspond to the typical parametric study of a wind turbine: They show the wind power use coefficient, *Cp*, depending on the *Lambda* coefficient, which in turn establishes a relationship between the turbine speed and the wind speed. *Cp = f(Lambda)* is represented for several values of pitch angle.

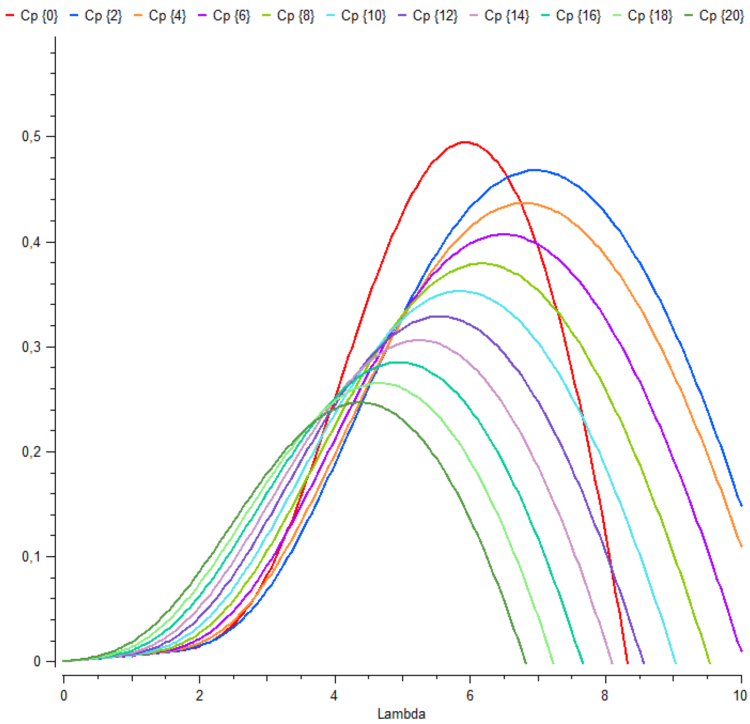

Figure 5. Wind Turbine Power Coefficient.

These studies show the optimal operating points and ease the configuration of the control systems. For instance, for a 8^{o} pitch angle, the optimal turbine speed is given by Lambda at around 6.5. In this scenario, the turbine performance is 40%.

On the other hand, the blade speed is lower than the rated speed of the electrical power generators. Speed-increasing gearboxes are used to overcome this problem. To do this, a system has been modelled to adapt the rotation speed so that it is adequate for the operation of the permanent magnet synchronous generator, which has also been modelled independently. These components share rotating mechanical ports of the EcosimPro ports library so they can be connected to, for instance, the CONTROL [4] or MECHANICAL [5] libraries, thus allowing other effects and controls to be simulated with all the capabilities allowed by these libraries. For instance, these libraries have been used to model a mechanical braking system for the turbine that is activated when it is necessary to keep the generator stopped.

There are essentially two power generation controls for this type of turbine: Power electronics are used to demand a given power level from each generator. The controller that is used establishes this power depending on the wind and the type of turbine so that the power that is obtained is the maximum possible by design. To do this, an inverter adequately establishes the polarity of each generator winding. In addition, it is also possible to control the pitch angle. This angle affects the turbine rotation speed and, therefore, the obtained power. The controls that can be performed on this type of generator are combinations of both possibilities and depend on what needs to be controlled or guaranteed in each case. In the model presented herein, the wind is assumed to be over turbine nominal value so that the electronics have been configured in such a way as to always find the optimal operating point and to control the generated output by means of the pitch angle. The developed model, in the same way as most of the wind power generators currently under development, uses a synchronous generator coupled to an AC/AC converter to obtain the active and reactive power required at any given moment and to allow the turbine to operate at variable speed despite using a synchronous generator. In any case, the Smart Grid modelling has been developed guaranteeing the compatibility with the rest of the EcosimPro libraries. Thus, the MECHANICAL [5] and ELECTRIC_SYSTEMS [2] library can be used to easily create different variants of the wind generator using induction generators or synchronous fixed-speed generators with no AC/AC converter.

As explained in the case of the photovoltaic generators, wind power generation is also controlled by the master to obtain a better power balance and power factor control.

Finally, a power increasing unit allows the number of turbines that make up the farm to be easily dimensioned. The complete model of the turbine is as shown in the following figure:

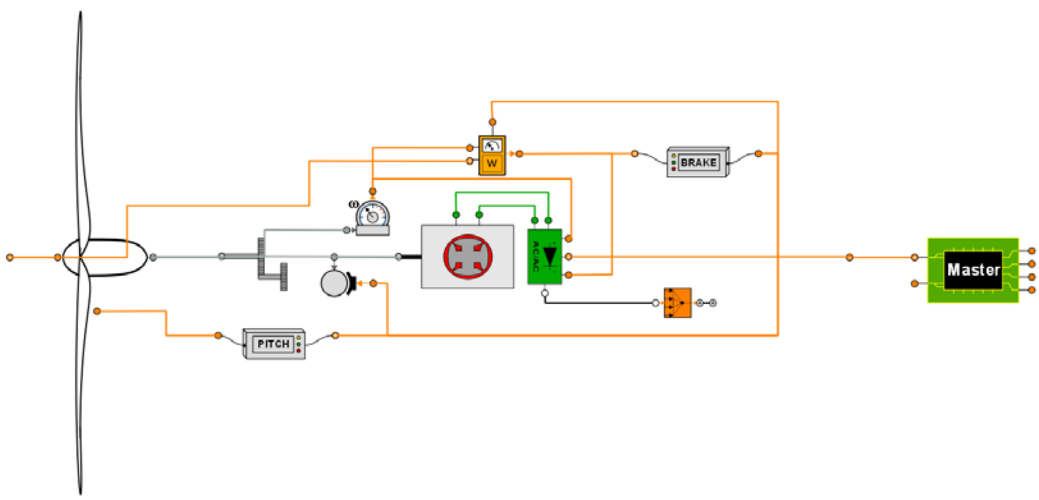

Figure 6. EcosimPro Wind Turbine Model.

4. Diesel generator

The components of the ELECTRIC_SYSTEMS [2], CONTROL [4] and MECHANICAL [5] libraries have been used to model a diesel generator to provide the power required if demand cannot be met and also to guarantee frequency and voltage levels in the grid. The EcosimPro libraries can be used to model the mechanical, electrical and control sections of the generator with different levels of detail. In addition, the interpolation capabilities of EcosimPro ease the incorporation of the characteristic curves provided by the manufacturer into the models. The model presented herein is formed by a synchronous generator with excitation control and a source of mechanical torque with its corresponding control system. These control loops guarantee that the rotation speed and the voltage level in the network are as required. The reference values for speed and voltage are established by the desired network frequency and voltage, respectively, since it is an isolated network.

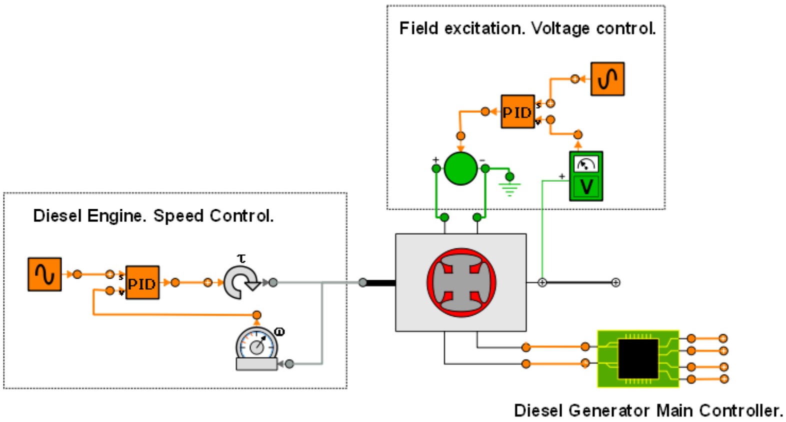

Figure 7. EcosimPro Diesel Generator Model.

The control implemented in the diesel generator model allows the establishment of a power generation requirement other than the projected consumption reference. Thus, it is possible to force a certain overgeneration to recharge the batteries. This capability is especially useful if the situation requires that the batteries be recharged whenever environmental conditions do not provide the required power from renewable energy sources. However, the batteries are normally recharged whenever there is an excess of renewable energy, so as not to use fuel in a process that is rarely urgent.

5. Power storage system

In order to simulate the power storage capacity, the facility is completed with a battery model based on the characteristic curves for state of charge (SOC) and voltage of this type of device. The load and voltage response is not linear throughout the operating range of a battery. The behaviour differs depending on the charge current, the charge status of the battery, etc. The capability of EcosimPro for interpolation in 3D curves allows this type of behaviour to be modelled in a relatively simple way by graphically establishing the battery voltage on the basis of the current it receives and its own status of charge. This type of model is highly flexible and easy to use in comparison with the analytical models based on equivalent equations and circuits. The basis of the model is useful for most batteries and can be easily adapted to any model by modifying the 3D curve for response in accordance with the data from the manufacturer for a given model.

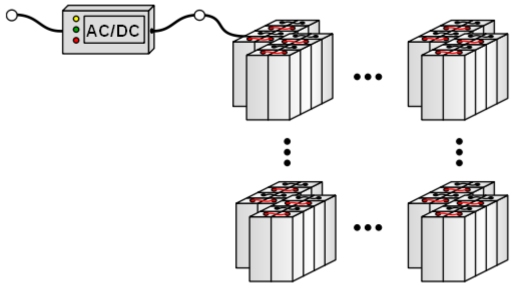

Figure 8. EcosimPro Battery Model.

The case presented herein defines a characteristic with a first area of linear relationship between the SOC and the battery voltage, up to 30% charge. Between 30% and 80% charge, voltage remains constant at around three quarters of its rated value. Finally, the voltage shall increase up to its maximum value when the battery charge exceeds 90%.

On the other hand, direction and current value also affects the charging and discharging process. This characteristic is modelled by adding a third axis to the chart that corresponds to the current. The result is that there are different V = f(SOC) curves, one for each current value. The following 3D relationship between voltage, state of charge and current is established:

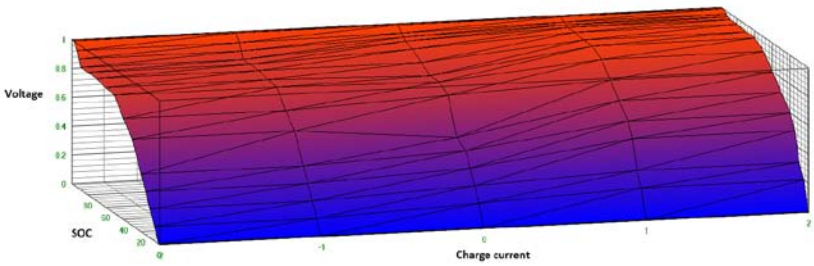

Figure 9. Battery Voltage = f(SOC,Current)

This way of modelling the batteries allows different technologies to be implemented by simply adapting the configuration of the curves to the characteristics of the battery to be modelled. Thus, batteries of different technologies, along with their typical controls, can be included in the same plant. Applying the same philosophy of interpolation in curves, the model is expected to be completed with ageing characteristics that allow this important aspect of the batteries to be contemplated, and their behaviour to be easily reproduced with a minimum of computational load. Furthermore, it is assumed that the battery model has enough dimensioning parameters to replicate its capacity by adding blocks in serial connection and in parallel without increasing the number of components or equations, since only the power, voltage and current values are scaled up.

Finally, the developed battery model incorporates an AC/DC converter to connect the storage system to the network in the most appropriate way at any time and manage the charge and discharge processes.

6. Smart Grid

Object-oriented modelling allows the complexity of the models described above by creating independent components for each of them. In turn, these components can be associated to a symbol for reuse in schematic form in more complex models. Thus, the SmartGrid model that is shown in the following figure has been created by interconnecting the models described in the above points.

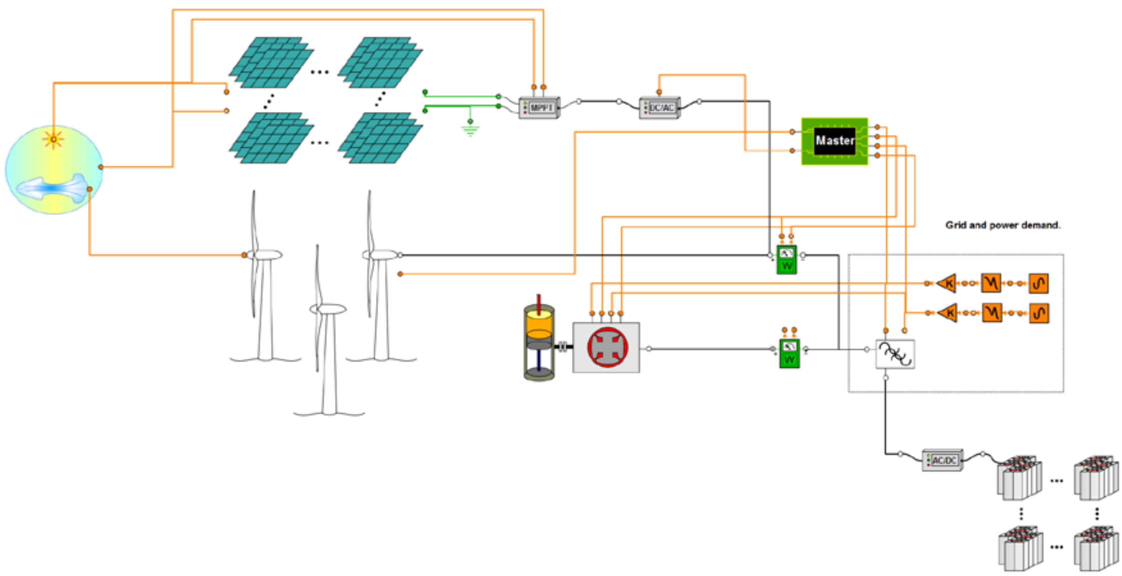

Figure 10. EcosimPro Smart Grid Model.

This model is formed by the parts presented above: Wind power generation, solar photovoltaic power generation, diesel backup and storage batteries. In addition, the following additional components have been created:

Firstly, a prototype for a **master controller** has been modelled. This shall be in charge of managing power generation. This controller shall be the core of the smart network and shall decide on the amount of energy that each part of the network needs to supply. To do this, it needs to have all the information on the network and have certain criteria that allow efficient decision-making: Instantaneous power budget, power factor, generation and consumption predictions, state of the batteries, environmental conditions and projections, cost of generation of each power source or sale price and other financial aspects.

In addition, a **component that simulates the network** has been created. It performs the generated and consumed power budget functions in the local area. During this first stage of the modelling, its functionality has been limited to the calculation of the different between power generation and consumption. The excess or shortage of power has been applied to the charging or discharging of the batteries. However, other effects, such as voltage and frequency variations, shall be included in the model in future projects. This component allows users to model a consumption profile over a certain time by introducing a series of values that define the power demand curve. In the case under analysis, values defining a typical consumption profile over a 24-hour period have been introduced.

Finally, the **component created to simulate the environmental conditions** allows users to configure the behaviour of the main weather variables: temperature, solar radiation and wind. The first two have a bearing on the power and ageing of the solar panels. In addition, the controllers of the photovoltaic plant also require this information to define the most appropriate polarization voltage for the panels. In turn, the wind speed establishes the operation and power produced by the wind section, so this information is sent to the turbine and its control. In order to guarantee compatibility and extend the possibilities of the environmental conditions component, components from the CONTROL [4] library have been used. Thus, signal generators define the behaviour of each variable by means of predefined waveforms (constant, steps, ramps, sines, cosines, etc) or by defining a given pattern with a series of points. The CONTROL [4] library also allows data bases to be reused with real measurements or weather forecasts that have been stored beforehand in external files, and to reproduce these same conditions during the simulation. Furthermore, the generated signals are filtered beforehand to make their behaviour smoother and to introduce time constants that may be configured by the users.

6. Results of the most interesting cases

Based on the above model, a complete day of operation has been reproduced, and the components have been dimensioned in accordance with the following approximate characteristics:

Photovoltaic solar plant:

- Total installed power: 50 KVA.
- Number of modules: 20.
- Open circuit voltage per module: 45 V.

Wind generator:

- Total installed power: 200 KVA.
- Number of turbines: 10.
- Type of generator: Synchronous, variable speed with AC/AC converter.

Diesel generator:

- Maximum power: 200 KVA.
- Rated voltage: 200 VRMS. Network voltage when isolated.
- Rated frequency: 50 Hz. Network frequency when isolated.

Batteries:

- Rated voltage: 200 V.
- Maximum power: 5 KVA.
- Maximum capacity: 2000 Ah.

Typical consumption during a 24-hour period is known and normally evolves up to a first maximum level at dawn, coinciding with the start of operation of many industrial plants, work centers and households. Consumption drops slightly at midday and again climbs at dusk until it drops to a minimum at night. This consumption pattern is established in the local network for the active power. As regards reactive power, a behaviour with a single maximum level at midday is programmed. The controls of each power source are configured to try and guarantee the supply that meets the demands. The diesel generator backup guarantees the setpoint is met, while also modifying its control to generate a certain power excess and deficit to complete a battery charge and discharge cycle.

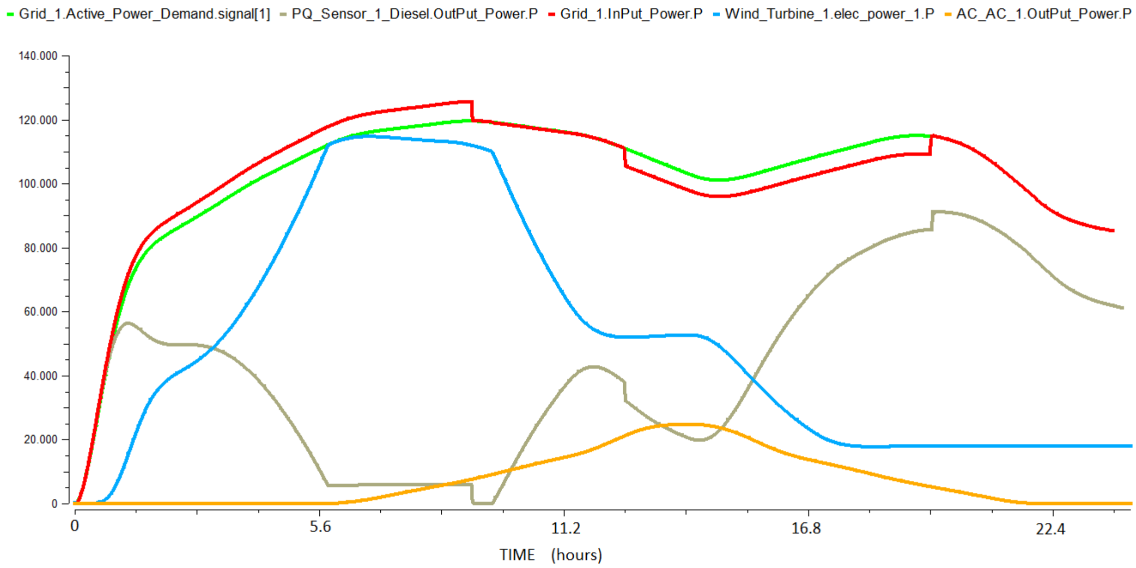

Figure 11. Active Power balance.

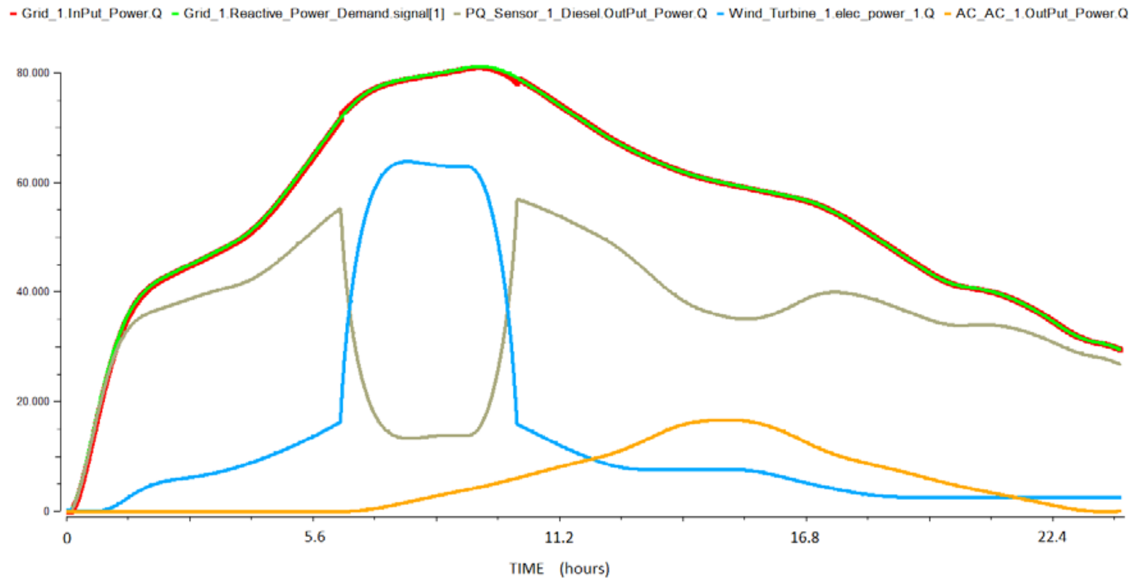

Figure 12. Reactive Power balance.

The above graphs show the active and reactive power balances of the network. The power converters supply the network with the power generated at the required power factor, distributing the supply between active and reactive power as appropriate throughout the network. The study of the above graphs show some general ideas about the case under study.

Firstly, control of the wind power generators has been programmed to obtain mostly active power. However, whenever wind speed increases (after five hours, approximately), the demand for active power is fulfilled and the controllers modify the wind contribution and devote the excess power to strengthening the reactive power generation. This significantly reduces the contribution from the diesel generators. Later, after ten hours, the wind reduces its contribution and the diesel generator needs to again increase its generation.

In addition, the solar photovoltaic plan has started supplying power since dawn. The master controller decides the way in which solar power needs to be supplied. The power converters are used to distribute between active and reactive power, as appropriate. As the sun goes down, the photovoltaic contribution drops until it reaches zero at night.

The wind contribution at night has been set to a small level to simulate highly unfavorable conditions, so the diesel generator needs to supply almost all of the required power.

The modelled wind power generation contributes a maximum power of about 160 KVA. The energy produced by the solar photovoltaic plant is of around 40 KVA, while the energy supplied by the diesel generators is of around 120 KVA at the moment of most demand. All this is done to adapt to an average demand that is slightly below 200 KVA. The diesel power generation guarantees that the necessary levels are observed at all times by supplying the difference between the demand and the sum of the wind and solar power.

The batteries are initially considered to be discharged. A power generation level that is slightly above the demand is established so as to charge the batteries. Once the batteries have been charged, the control actuates by reducing the power generation exactly to the required supply. Under these circumstances, the batteries maintain their charge. At midday, the diesel generator is programmed to generate less power than required, and the batteries discharge their power to the network to maintain the voltage and frequency. The voltage profile in the batteries during the charging and discharging processes is established by the curves introduced in the model and by the charging and discharging current, which in turn is established by the available power.

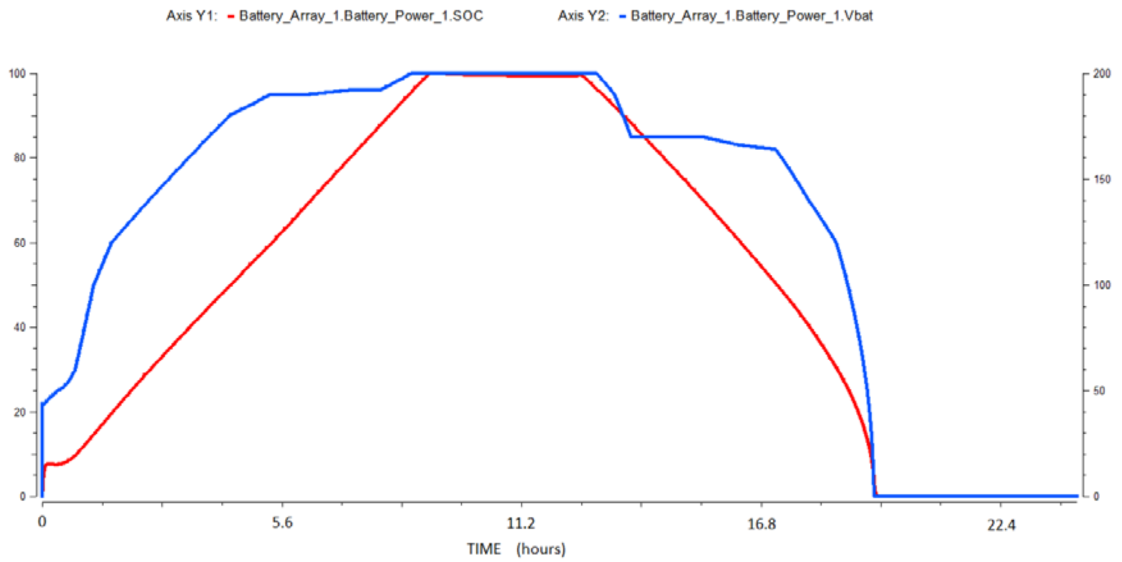

Figure 13. Battery SOC and Voltage.

The graphs show how the state of charge (SOC) is almost linear, and its gradient depends on the charging or discharging current. However, the behaviour of voltage is non-linear and depends on the state of charge and the current. The battery charging and discharging processes take about 8 hours each for the balance of power under analysis and the curves defined for the batteries.

7. Conclusions and potential lines of actuation

The purpose of the described work is to present the capabilities of the EcosimPro tool and the SMART_GRID [1] library for the modelling and simulation of smart networks. Furthermore, the compatibility and usefulness of libraries such as ELECTRICAL [3], ELECTRIC_SYSTEMS [2], MECHANICAL [5] or CONTROL [4] for this type of work has been proven. On the other hand, it has been proven that it is easy to create new components that can be used to perform parametric studies for the dimensioning of networks. These components can later be reused for the simulation of complete networks with different characteristics. The way EcosimPro works (object-oriented modelling, joint schematic-code modelling, graphical interpolation between variables, use of external files, etc) allows users to create and reuse components easily and without too much effort, so modellers can focus on the design of the networks and their control topology.

The focus of the described model has been to search and analyse the power balance for long lengths of time (one or more days). The main goal is to estimate the power generation for given environmental conditions and to calculate the part of the demand that will be met by the diesel generator. Therefore, the fastest dynamics of the power converters and of the consumption and generation points are not considered. However, the capabilities of the ELECTRIC_SYSTEMS [2] library includes the modelling of those particular aspects and the analysis of transient responses in short time intervals. Similarly, other aspects that are not considered in this case, such as voltage drops in the distribution networks, frequency deviations, harmonics due to power converters, etc, could be analysed.

Besides, as indicated at several points in this document, future issues aim to extend the capabilities of the master controller, which will need to incorporate the high-level control strategies that allow the network to be managed. These capabilities include the capability to manage net zero photovoltaic systems, so that only the energy required by the charge is produced and no energy is spilled onto the grid, observing the current requirements.

In turn, the models developed for this first test case shall be extended and improved in future versions, including different technologies, varying locations, additional capabilities in line with other EcosimPro libraries (solar parabolic trough and tower thermal-solar power plants, combined cycle power plants, cogeneration plants, etc). An alternative for the wind section has also been projected. It shall have an almost stationary approach based on the information usually provided to the final user by manufacturers: curves for power, torque, pitch angle and speed. In this way, dual control strategies shall be included in the library by correctly polarising the electrical power generator and adjusting the pitch angle.

Furthermore, the models may be improved and completed with the capabilities provided by the ELECTRIC_SYSTEMS [2] library for the modelling of transformers, transport and distribution lines, connections or other similar aspects.

8. References:

1. SMART_GRID: EcosimPro Renewable Energy and Smart Grid Library, Empresarios Agrupados Internacional (EAI).
2. ELECTRIC_SYSTEMS: EcosimPro Electric, Electronic and Power Systems Simulation Library, Empresarios Agrupados Internacional (EAI).
3. ELECTRICAL: EcosimPro Electric Simulation Library, Empresarios Agrupados Internacional(EAI).
4. CONTROL EcosimPro control and Signal Processing Library, Empresarios Agrupados Internacional (EAI).
5. MECHANICAL EcosimPro Mechanical Simulation Library, Empresarios Agrupados Internacional (EAI).
6. "RENEWABLE ENERGY LIBRARY For Ecosimpro", J. Salazar, F. Tadeo, C. de Prada, University of Valladolid.