Basic Principles for Virtual Synchronous Generator Modelling and Control

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Abstract—**Currently, there is strong interest in incorporating renewable energy generation systems into the overall grid supply; however, the intention of these generation systems represents a significant impact on high level of grid integration of the power system. In contrast to conventional generation systems new renewable technologies needs inverters to connect to the grid and since the vast majority of the control algorithms for the grid have the behavior as "grid-forming", it is not able to add inertia to the grid.**

The problem is evident when a comparison is made between the synchronous generator and the inverters in the renewable energy system. Where the synchronous generator is a type of rotating electrical machine that converts mechanical energy into electrical energy through constant rotation. The developed inertia generates kinetic energy in the rotor, which allows it to be used to dampen the frequency fluctuations caused by the imbalance generated by power consumption in the grid. On the other hand, inverters do not generate inertia and, as they are implemented on a larger scale, they do not have a system that dampens the imbalances caused by frequency variations in the grid.

In this paper, a virtual synchronous generator (VSG) control system is modelled to improve the frequency response of the grid with a high level of generation penetration, reducing the impact at the time of grid integration.

Keywords—**Power system, Electricity grid, Virtual synchronous generators, Virtual inertia, Droop control, Inverters Renewable energy.**

I. Introduction

Nowadays, along the increase of Renewable energies and sustainability, exists a strong trend to incorporate sustainable generator systems to electrical power systems with the aim to reduce the environmental impact due to electrical generation. To accomplish this goal, distributed generation systems take place to contribute the national power supply from the grid distribution. Distributed generation is known as the support of real and reactive power in distribution power network [1] through, as usual, renewable energy systems like photovoltaic, wind, hydroelectric and others generation system.

One of the clean generation systems that has had popularity and better growthless is photovoltaic distributed generation, also with its costs have been decreasing and its performances increasing along of the time [2]. By contrast with conventional generation systems, photovoltaic systems need invertors to connect to the network and, since most of its control algorithm are only as grid voltage followers, they don't apport with inertia to the grid [3] and this absence of inertia causes the system to be more sensitive to frequency changes [4]. Furthermore, must say that invertors traditional controls don't have the capability to contribute on voltage/frequency regulation caused eventually in the power systems. Also, grids with high use of photovoltaic systems could have voltage changes eventual levels and it produce harm operations of the system [3].

As we can see, commonly use of photovoltaic systems is to follow the voltage and inject current to the grid or store energy when the demand needs it, but it has its disadvantages as don't participate in voltage/frequency regulation and don't have inertia. Due to that, several methods have been developed to solve that disadvantage and one of the most popular propose is "droop control". This control technique is based on tradicional control methods for synchronous machines programing a linear relationship between real and reactive power respect to frequency and voltage, respectably, but it still hasn't inertia [6].

To solve this lack of inertia, a recent proposal called "virtual synchronous generator" (also known as synchronous virtual machine, or synchro generator) has emerged, which aims to emulate the inertial response of a synchronous machine by programming its equations of oscillation in the controller of the inverter, as a control strategy [7].

II. Ease of Use

Within the framework of sustainable development, some of the SDG (Sustainable Development Goals) are based on the better and efficient use of resources, and the use of clean and accessible energy (goal 7 and goal 12, respectively) [5], which, for the most part, come from renewable sources, such as photovoltaic solar and wind energy. All this, together with the reduction in installation costs, has accelerated the growth of its uses in the last twenty years [3].

At present, renewable energies are widely classified as either "on-grid" or "off-grid" that refers the way that energy

is developed. "On-grid" talks about to all renewable power stations that are connected to the power systems, such as Eolic farms and solar panel plants, which contribute with energy to the grid. In the other hand, "off-grid" refers to those small renewable energy power plants, such as photovoltaic modules, that feed one specific load as one small building, one house or a small village house [17].

In the first decade of century 21, all electrical generators based on renewable energy and their invertors had the feature to "follow the grid" (grid-following power converters) [19] and now, recently, have been developed new techniques and strategies control for invertors that allow its function in microgrids, as much "on-grids" and "off-grids" emulating synchronous generators inertia. Thus, allows to use of invertors as voltage forming units on isolate microgrids being known as "grid-forming inverters", and with the wide use of these, it will be possible to have full renewable electrical networks. [19]

This inverter types are also known as Virtual Synchronous Generators (VGS) [20]. Within their most important features are to adjust its virtual inertia, stability, power distribution and droop Q-V and P-w features. The inertial characteristic of power generators connected to an electrical network or microgrid plays a fundamental role in maintaining the frequency stability of these power systems [21].

III. METHODOLOGY

The DC voltage source is the main source of power for the microgrid, which could be a solar installation or other renewable source that has DC voltage to operate. This source is connected to an inverter which converts to AC power with a frequency of 50Hz, depending on the system. This VSG controller is implemented to control the inverter in the real and active power to be supplied to the load. The load that is connected to the output of the inverter is connected by an LCL filter, which helps to regulate the shape of the output signal and eliminate harmonic distrosity. [8]
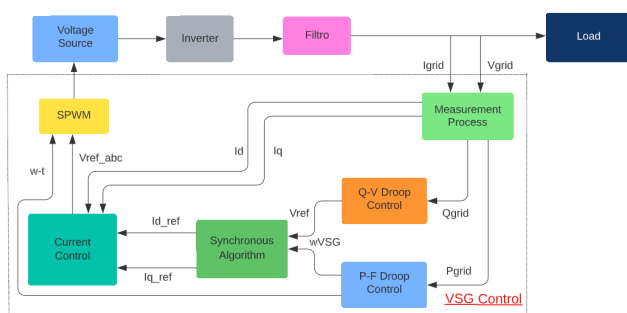

Fig. 1. Block diagram for Active Power and Frequency. [8]

A. Park Transform

Using Park's transform to transform the abc system into the quantities dq, these values are the three-phase voltages and currents; these are measured via a load bus. In addition, the measured real and reactive powers are input signals for

the droop control blocks of: Active Power and Frequency P-F and Reactive Power and Voltage Q-V. These droop controllers are used to perform frequency and voltage stabilisation, the P-F droop controller is used to calculate the phase angle and frequency of the VSG, while the Q-V droop controller is used to calculate the reference voltage.

Next, the reference current for the control block is found using a synchronous algorithm; the current controller calculates the three-phase reference voltage for the SPWM; it delivers pulses from the inverter gate to provide the desired real and reactive power, using the reference voltage and VSG angle given by the P-F droop controller. To minimise harmonics, an LCL filter is used at the inverter output.

B. Active Power and Frequency Control

For medium and high voltage microgrids of a distributed generation system, P-F and Q-V droop controls are used to control the real and reactive power flow [8] [9] [10] [11]. The frequency control has the characteristic of droop at the generator output to stabilise the power generator.

The following equations can be used to express the power droop characteristic [12] [13].

$$F_{ref} - F_{nom} = -m_f(P_{grid} - P_{nom})$$
$$F_{ref} = F_{nom} + m_f(P_{nom} - P_{grid}) \tag{1}$$

where F_{ref} reference grid frequency, F_{nom} nominal frequency, m_f P-F droop coefficient and the measurement process use P_{grid} three-phase grid active power P_{nom} the nominal real power. The Equation is expressed by the block diagram show in figure 2.
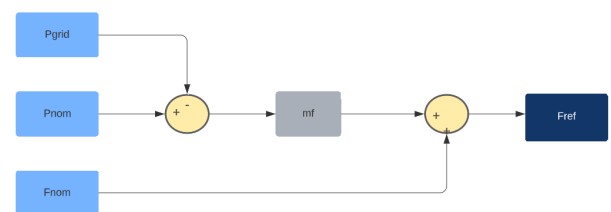

Fig. 2. Block diagram for Active Power and Frequency.

On change of a load demand, a power generator's frequency will drop, which will cause the fuel supply to increase due to the primary engine controller; in order for this to happen, P-F droop control is implemented, as shown in the figure above. [8] The parameters used which has been chosen a nominal/expected frequency Fnom of 50Hz, which is connected to the load side with a power of 50kW. There could be a disturbance/change on the grid/load side, which is introduced by the variables Pref, Pnom and Fnom.

When these three variables are introduced into the system, the gain is found by considering one of these constant variables and varying the other two variables, and the gain is found by plotting the gain using a contour plot. A code has been used with the equation Pnom is a constant value.

C. Reactive Power and Voltage Control

The reactive power supplied by the generator is related to the terminal voltage, having a droop characteristic.

The following equations can be used to express the reactivepower droop characteristic.

$$V_{ref} - V_{nom} = -n_v(Q_{grid} - Q_{nom})$$
$$V_{ref} = V_{nom} + n_v(Q_{nom} - Q_{grid})$$

(2)

where V_{ref} reference voltage, which is expected to be the grid voltage, V_{nom} nominal voltage, n_v constant of Q-V droop coefficient, and the measurement process use Q_{grid} three-phase grid reactive power Q_{nom} the nominal real power.

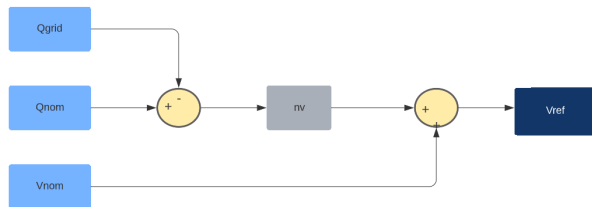The Equation is expressed by the block diagram show in figure 3.

Fig. 3. Block diagram for Reactive Power and Voltage.

The block diagram in figure 3 shows the Q-V droop control, given in equation 2. This control is used for the system voltage control where the reference voltage is derived.

The gains of Q-V droop control and P-F droop control are similar which are found by contour diagram.

D. Current Control

To control the three-phase VSG there are two strategies, voltage control and current control. For current control, a SPWM is used to control the current injected into the grid from the active and reactive power components. On the other hand to control the power flow with a voltage control that uses the phase angle between the grid voltage and the output voltage of the inverter.

In comparison of the controllers it can be said that the current controller is faster and less sensitive [14] also this controller helps us to improve power quality by compensating harmonics and providing overcurrent protection [13].

An LCL filter is connected between the VSG and the grid which does not minimise harmonics but helps to implement the current control loop. The dynamic voltage equation (AC side) is found using the Kirchhoff voltage, assuming the LCL filter is lossless. [8]

E. Synchronous algorithml

Current control in dq coordinates is proposed. This algorithm is based on the virtual generator model. The Q-V droop controller has a virtual generator excitation voltage VE and
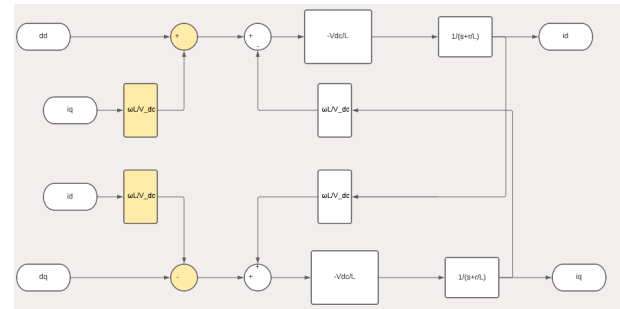

Fig. 4. Current control.

the grid/load voltage V_{grid}/Q_{load} assuming that it produces the reference voltage V_{ref}.

Using a voltage sensor the grid/load voltage is determined, while it is evaluated using the phasor relationship between generator voltage and line current for armature current $Id*$ and $Iq*$ [8].

It is known that in a regular power system most of the load is inductive, due to this the power factor is considered overexcited in the phasor diagram.

For the virutal generator, the synchronous angular velocity ω is given by the droop controller P-F, also the phase angle θ is given by the integral of ω. The excitation of the voltage is evaluated by the dq component.

F. Generator inertial

The inertia of the generator is emulated by the oscillation equation; with this equation, the output power of the VSG is described, and should be noted that the output of the voltage source and the input power must remain the same.

$$\Delta P_{VSG} = P_m - P_e = J\Delta\omega' + D\Delta\omega$$

(3)

Where P_m is mechanical input, P_e is Electrical output, D damping coefficient and J is inertial coefficient

$$P_{in} = P_{out} = P_{load}$$

(4)

The frequency dynamics of the generator is governed by the oscillation equation; as the P-F droop control

$$F_{grid} - F_{nom} = m_f(P_{nom} - P_{grid})$$
$$P_{in} = (F_{grid} - F_{nom})/m_f + P_{grid}$$

(5)

If P_in has any change it will be due to the frequency, where it minimises the frequency oscillations of the generator inertia.

$$P_{in} - P_{out} = J\Delta F'$$
$$F_{grid} = F_{nom} + \int \frac{1}{J}(P_{in} - P_{out})$$

(6)

After a perturbation reduces a maximum deviation of the rotor speed after a disturbance, the frequency response will be slower for larger values of J.

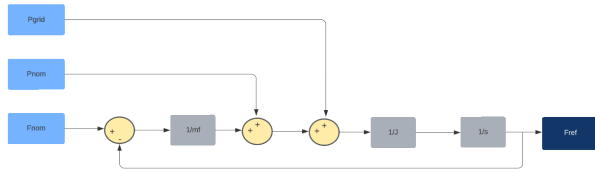$$F_{grid} = F_{nom} + \int_0^t \frac{1}{J}((F_{nom} - F_{grid})/m_f + P_{grid} - P_{out})dt$$

(7)

Fig. 5. Contour diagram for n_v

IV. SIMULATION RESULTS

Simulation test results are presented to evaluate the closed-loop control of the proposed VSG. The dynamic models are implemented in Matlab/Simulink, and the gain of the droop controller for VSG control and the gains of the PI controller have been determined by trial and error. These tests will verify the effectiveness of the design and the possibilities for improvement. [15]
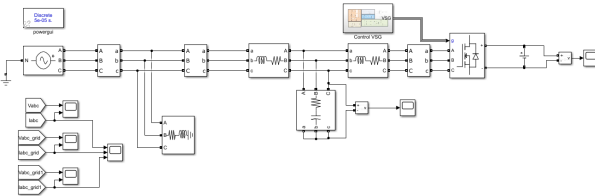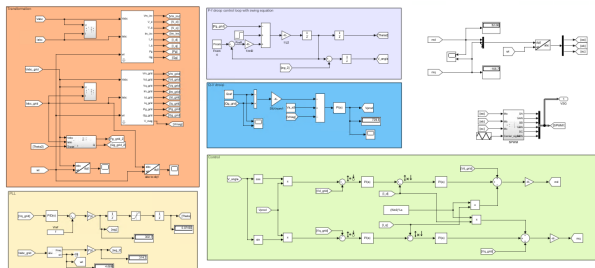

Fig. 6. Simulink design diagram

Fig. 7. Simulink design diagram

Next, we evaluate the characteristics of the system due to a load change in the system. For these experiments, a combination of resistive and inductive loads is connected on the load side. The system will be evaluated under different types of load switching. The initial load of 50kW and 12.5kVAR. The droop coefficient, $m_f = 4.2739x10^{-7}$ and $n_v = 8.6971x10^{-5}$ which were found by contour plot.

The first approach to emulate virtual inertia is to use the oscillation equation in the inverter control loop. Using the oscillation equation we use the inertia in the equation of the P-F droop controller.

Initially, a simulation is carried out to observe the ability of the VSG to track both active and reactive power references. The initial conditions are adjusted to eliminate the transient in the synchronisation of the inverter with the three-phase source, the results can be observed. The simulation starts at t=0s with
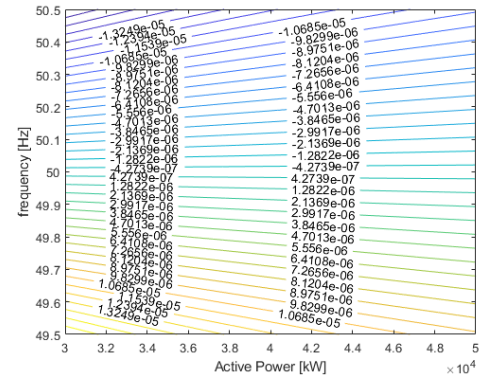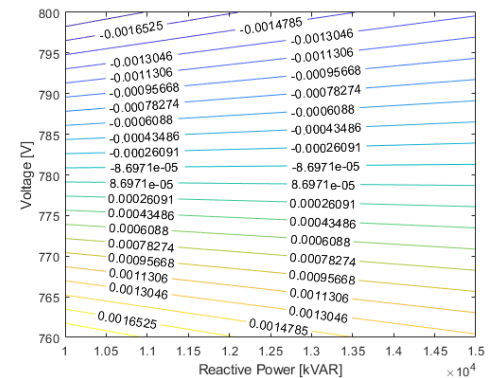

Fig. 8. Contour diagram for m_f

Fig. 9. Contour diagram for n_v

the power settings at P_{set}=12.5kW and Q_{set}=12.5kVAR. At t= 1s the value of the active power increases to P_{set} =50kW the inverter appropriately follows the change of the reference as we see in figure 10, while the reactive power remains with its value in figure 11. Note that during the simulation the inverter follows the reference values very closely. There is a slight coupling between the powers because when a change in one of the powers occurs.
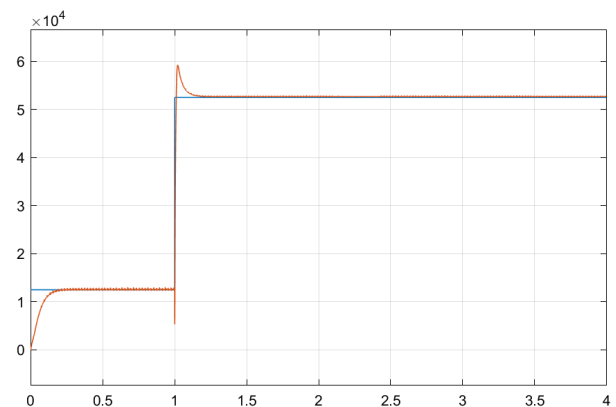

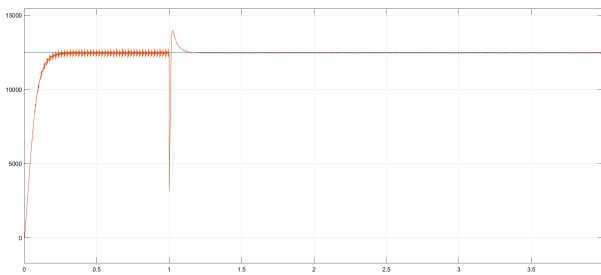Fig. 10. Active Power and Reference Power.

Fig. 11.   Reactive Power and Reference Power.

One of the most important features of the VSG is its ability to stay synchronised with the grid without the use of a PLL. The virtual frequency of the inverter is equal to the grid frequency at all times, i.e. if the system frequency increases or decreases, the virtual frequency will also increase or decrease. Figure 13.a illustrates the behaviour of the inverter's virtual frequency.
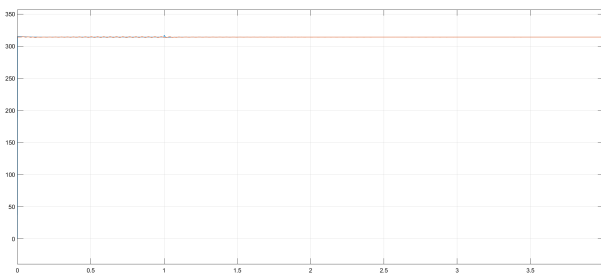

Fig. 12.   Angular frequency

The voltage at the point of connection of the inverter to the grid or load can vary due to various factors. However, the voltage control is generally associated with the amount of reactive power the grid requires at that node. In the grid, the grid operator assigns a voltage level at the connection point, which must be able to regulate the voltage by modifying the value of reactive power exchanged with the grid, in order to maintain the voltage level required by the system operator.

Voltage level required by the system operator, as shown in figure 13.c, this being the variation in the current as shown in figure 13.d. Finally, the active and reactive power of the system is shown in figure 13.b.
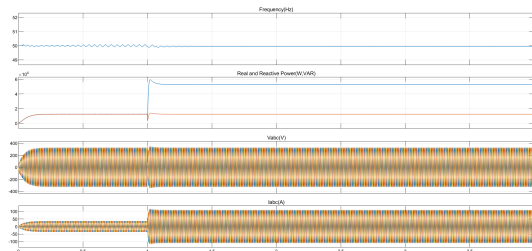

Fig. 13.   Results: a. Frequency; b. Active and reactive power; c. Voltage; d. Current.

V. CONCLUSIONS

The performance with different values of active and reactive power was analysed, as well as its capacity to participate in voltage and frequency regulation, presenting a very good dynamic response, following at all times the reference values P_{set} and Q_{set} and actively participating in frequency and voltage regulation.

Among the central contributions of this chapter we can highlight:

- The detailed analysis of the calculation of the parameters of the VSG.
- The analysis of the operation of the VSG with different values of active and reactive power exchanged with the grid and/or loads.
- The analysis of the performance of the VSG when the frequency and voltage values of the grid are different from the nominal values. different from the nominal ones.

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