OPENDSS MODELING FOR STEADY-STATE ANALYSIS OF DISTRIBUTED GENERATION CONTROL TECHNIQUES

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Abstract—The main objective of this paper is to achieve the static analysis of generation controllers in microgrids through simulation in OPENDSS. These controllers were previously designed in power system transient simulators, such as PSCAD / EMTDC, which allow the evaluation of dynamic performance with a certain level of computational cost. Thus, OPENDSS modeling must faithfully reproduce the stable performance of these controllers so that the simulator can be used to investigate high penetrations of distributed generation with relatively low computational costs. To this end, efforts were initially focused on determining a microgrid to be implemented; and then, through the static analysis in OpenDSS, to compare the results, which will confirm those obtained in the dynamic analysis of the Sliding Droop controller, which will allow to obtain conclusions of the state of the network in a steady state before executing the dynamic simulations. The steady-state results obtained by the proposed approach were validated by the dynamic simulation. Therefore, the methodology proposed in this paper is promising for islanded microgrid analysis considering Sliding Droop control.

Keywords—Microgrids; Distributed Generation; OpenDSS; Steady-state analysis;

Resumo—O objetivo principal deste artigo é modelar na análise estática os controladores de geração em microrredes através da simulação no OPENDSS. Esses controladores foram projetados anteriormente em simuladores de transitórios de sistema de energia, como PSCAD / EMTDC, que permitem a análise de regime dinâmico com um certo nível de custo computacional. Desta forma, a modelagem no OPENDSS deve reproduzir fielmente o desempenho estável desses controladores para que o simulador possa ser usado para investigar altas penetrações da geração distribuída com custos computacionais relativamente reduzidos. Para este fim, inicialmente os esforços se concentraram em determinar uma microrrede a ser implementada; para em seguida, poder, através da análise estática no OpenDSS, comparar os resultados, os quais confirmarão àqueles obtidos na análise dinâmica do controlador Sliding Droop, que permitirá obter conclusões do estado da rede em regime permanente antes de executar as simulações dinâmicas. Os resultados em regime permanente obtidos pela abordagem proposta foram validados pela simulação dinâmica. Portanto a metodologia proposta neste artigo é promissora para análises de microrredes isoladas o controle Sliding Droop.

Palavras-chave—Microrredes, Geração Distribuída, OpenDSS, Análise em regime permanente

1 Introduction

Recent studies by the International Energy Agency affirm that in 2015 more than 1 billion people worldwide were without access to electricity. This portion represents more than 13% of the world's population, and therefore different ways of getting electricity to these people are discussed (Kevin Bullis, 2012). In some situations, due to natural factors such as relief, seas and mountains or even low local population density, the traditional solution of building new power transmission and distribution assets is not feasible.

One of the alternatives implemented is the local power generation, i.e., the use of distributed generators in these remote areas, such as diesel generators, wind turbines and photovoltaic generation. Such generation units would be interconnected with the consumer units through the local power grid.

Recently, the penetration of energy generators in regions close to consumers is increasingly going from being an idea to becoming a reality, creating electrical systems based on distributed energy resources (DER).

Distributed Energy Resources is a concept that refers to storage systems and distributed generators spread through the city (L. Philipson, 2002). Distributed generators are generators, sometimes based on renewable power sources, which are spread in the distribution grid. That being said, the concept of microgrid in power system is also established.

The microgrids are low voltage power grids, composed of a set of distributed generators, loads and power storage systems (C.A. Cañizares, 2014). It has the ability to operate either isolated from the main grid or connected to it (if there is), supporting the transition between these two states. The microgrid shall operate by coordinating its elements for reliable power supply, and its connection to the main grid shall be established through point of common coupling (PCC).

The connection of DC sources to the grid can be done through the so-called Voltage Source Converters (VSCs), which sources the active and reactive power injection in order to keep the system voltage stable, generally based on the use of Insulated Gate Bipolar Transistor (IGBT) automatic switching (G. Asplund, 1997), (T. Kalitjuka, 2011). According to (Q.C. Zhong, 2009), the VSCs can be used to mimic the behavior of synchronous generators and are called, in this situation, the Static Synchronous Generator (SSG).

The present paper has the main aim of contributing with ways of obtaining information from a microgrid through static analysis, as a way of to guide or simplify the performance of the dynamic study. This study leads to emphasize the importance of this simulation tool, OpenDSS, regarding the low computational effort required by it, when compared to other simulation software as, for example, it is explained and compared in (Mohammad H. Moradi, 2017) achieving convergence quickly. It is also evidenced, in the same way, the need for the simulator to show the true behavior of the application of the technology studied here, in steady state, in distribution systems, since it is desired to obtain conclusions of the state of the network in this situation before performing the dynamic simulations. For this, the results obtained in (B.W. França, 2017), in the simulation of a microgrid, whose Sliding Droop controller is implemented, will be verified using the static analysis performed by the OpenDSS Software. This is an acceptable form of validation of this study, evidencing that the tool proposed here, in advance of traditional and conventional control systems, aims to improve the techniques of distributed generation control, from the exhaustive studies that the static simulation with OpenDSS can provide; It is said to be exhaustive simulation studies, once again noting the low computational cost required by the software, thus being able to stress it without to compromising speed and performance.

Thus, the paper is organized as follows: after this introduction, in Section II is presented the concept of droop curve, with bias for power sharing. Section III presents the equations for the sliding droop controller, emphasizing the position that follows the sum of the reference of ω (operating frequency) and its details. In section IV, the software used, the OpenDSS, and the modeling of the studied grid are briefly presented. In section V the procedure performed is exposed and the simulation, in section VI the simulations results will be seen and discussed. Finally section VII presents the conclusions and possible future work.

2 Droop Curve

The droop curve P-ω of a synchronous generator is as well-known technique to provide active-power sharing. Based on the principle of equilibrium between the electric power generation and the load consumption, a relation between the power supplied by generators and the operating frequency is established. It has been shown in (C.A. Cañizares, 2014) that, by means of an unbalance between the mechanical power in the generator axis and the electric output power of the generator, the electrical frequency of the system is modified. In systems with the presence of more than one generator, the droop curve determines the power sharing between the generators, then establishing the contribution portion of each one to the system.

Two droop curves P-ω of two static synchronous generators operating in the same grid are shown in Figure 1, where ω_{01} and ω_{02} are the no-load frequencies, ω is the grid frequency, and, P_1 and P_2 are the electrical output power, respectively.

Figure 2 illustrates P-ω droop curves of two generating units. P_{set} represents the setpoint power, or the maximum power available by the distributed generation unit, at a reference frequency ω_{ref}. As shown in (B.W. França, 2017), the use of P_{set} instead of the nominal power of the generation unit is in accordance with intermittent power generation of DG, such as wind and photovoltaic. These kind of generation do not always function at nominal power. Therefore, the change in the nomenclature is employed as a way of distinguishing from the nominal capacity and for emphasizing the variability of available energy.

It is easy to note, through the concept of triangle similarity, that under the conditions in which both droop curves have the same slope, the expression (1) is not true.

$$\frac{P_1}{P_{set1}} = \frac{P_2}{P_{set2}} \tag{1}$$

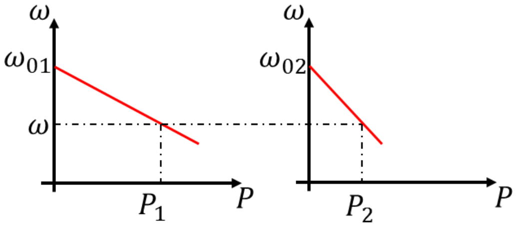

Figure 1.Droop curves of two generating units operating in parallel

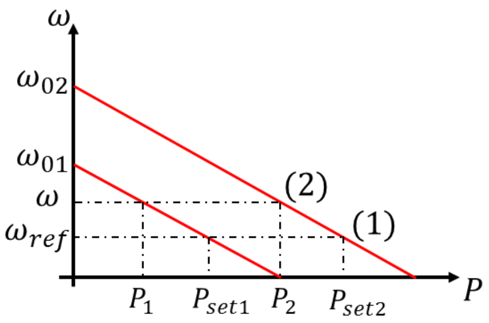

Figure 2. Two operating points of the system represented in the droop curves.

According to (B.W. França, 2017), the power sharing through static synchronous generators with classical static droop curves is acomplished only for specific load and generation scenario, as established in expression (1). The intermittent variability of generation and consumption lead to a situation that would require a communication system in order to still ensuring power sharing with the aforementioned DG control technique. Thus, the Sliding Droop controller, designed to enforce equation (1), was proposed.

3 Sliding Droop Control

The Sliding Droop Control was proposed in (B.W. França, 2017) in order to avoid the need of communication systems to perform power sharing and suitable frequency and voltage regulation. The name "Sliding Droop" comes from the characteristic of proper positioning the droop curves through varying the no-load position, as shown in the P-ω droop curve of Figure 3.

The main idea of this controller is to slide the droop curve to place it in a position that matches the operating point at a frequency given by the sum of the fixed reference ω_{ref} with a given offset, represented by $\delta\omega_{ref}$.

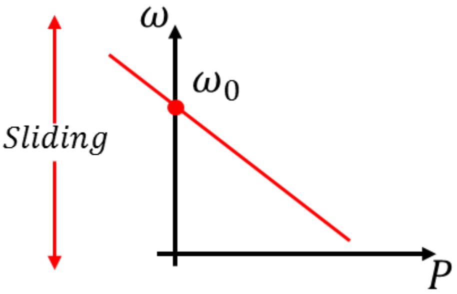

Figure 3. Droop curve slip.

The function that determines the deviation $\delta\omega_{ref}$ is given by:

$$\delta\omega_{ref} = k_{s\omega}\left(1-\frac{P}{P_{set}}\right), \quad P \le P_{set} \quad e \quad 0 < P_{set} < 1\,pu \qquad (2)$$

where, $k_{s\omega}$ is the maximum allowed frequency deviation in steady state

As shown in (B.W. França, 2017), if the microgrid is connected to the main grid, the stable condition in steady-state is with the frequency ω equal to the grid frequency. Since the grid frequency is regulated, according to (2):

$$\delta\omega_{ref} = \omega - \omega_{ref} = 0 \qquad (3)$$

$$\Rightarrow P = P_{set} \qquad (4)$$

Thus, in a microgrid operating in grid-connected mode and with the reference value properly adjusted, the generation power of DG will be given by the set-point power.

Since the reference frequency ω_{ref} and the operating frequency ω in steady state are the same for all distributed generators, respectively, the expression below can be applied to all DG units of the system.

$$\omega = \omega_{ref} + \delta\omega_{ref\ i} \qquad (5)$$

where,

i – distributed generator index, ranging from 1 to the total number of generators n.

Therefore:

$$\delta\omega_{ref\ 1} = \delta\omega_{ref\ 2} = \ldots = \delta\omega_{ref\ n} \qquad (6)$$

Substituting (2) into (6):

$$\left(1-\frac{P_1}{P_{set1}}\right) = \ldots = \left(1-\frac{P_n}{P_{set\,n}}\right) \qquad (7)$$

Finally, by simplifying the expression (7):

$$\frac{P_1}{P_{set\,1}} = \frac{P_2}{P_{set\,2}} = \ldots = \frac{P_n}{P_{set\,n}} \qquad (8)$$

The expression (8) implies the expression (9) below:

$$\frac{P_i}{P_{set\,i}} = \frac{P_1 + P_2 + \ldots + P_n}{P_{set\,1} + P_{set\,2} \ldots + P_{set\,n}} \qquad (9)$$

Assuming a microgrid operating in islanded mode, equation (2) can be written as follows:

$$\delta\omega_{ref} = k_{s\omega}\left(1 - \frac{P_{load}}{\sum_{i=1}^{n} P_{set\,i}}\right) \tag{10}$$

where,

P_{load}– total power consumed by the loads connected to the microgrid.

Thus, by adopting the same value of $k_{s\omega}$ and also a constant and equal slope of the droop curves for all DG units, the power sharing is achieved without the need of a communication system. Moreover, the proper design of $k_{s\omega}$ ensures reduced frequency deviation in steady-state. It is important to highlight that theoretically the same method can be applied for QxV droop curves of DG units connected at the same bus as a mean of reactive-power sharing.

4 The OpenDSS Software

The OpenDSS software is a simulation tool for electric power distribution systems. Since it is applied to distribution system applications, studies on the impact of distributed generators are suitable performed in this software.

The open source characteristic encourages its usage and, consequently, enhances the available resources for the complete modeling of distribution systems. Therefore, OpenDSS is considered to be an attractive tool both in academia and in the professional environment of companies in the electricity sector in general. In Brazil, it is important to highlight the fact that the Brazilian Electricity Regulatory Agency (ANEEL) proposed the use of the OpenDSS to calculate regulatory technical losses by the distribution utilities (Technical Note n° 0057/2014-SRD / ANEEL).

This software, in addition to performing static simulations, also performs dynamic and quasi-static simulations. In this manner, the desired output data is logged through the system response for a given load curve. Quasi-static simulation is useful, for instance, in studies of the impact of photovoltaic generation growth in distribution systems, since the intermittent pattern of such power supply, which varies according to climatic conditions and time of day. In this work, a quasi-static simulation is performed to evaluate photovoltaic generation in distribution systems.

The grid modeling requires data of the physical parameters of the electrical grid in study. Thus, line parameters such as resistance, reactance, and line length are inset on OpenDSS main code. This dataset is usually in a three-phase mode although single-phase dataset can be easily adapted to equivalent three-phase system. Subsequently, the generators connected to the system buses were modeled; all of the generators were modeled initially to inject active power with unit power factor; and finally the modeling of the load, where a constant power model was adopted, that is, the load consumes the same active and reactive power throughout the simulations.

OpenDss simulation can be interfaced with other software to enhance its functionalities. MATLAB, VBA, Python are some of these software that are used with OpenDss. For instance, the connection of OpenDSS with MATLAB is very simple and allows the exchange of data in quasi-static simulations in order to update the input orders of generator and then perform optimal power flow studies in distribution grids with distributed generation. The code block of Figure 4 is provided by the OpenDSS documentation itself, which should be used in a MATLAB script to achieve interface between them.

This explanation of the connection of MATLAB and OpenDSS was necessary for the broad understanding of this study. Although this research group elaborated it in previous works, it was not object of study in this part of the work. It was important to emphasize it to clarify how MATLAB accesses the OpenDSS and simulates the studied system.

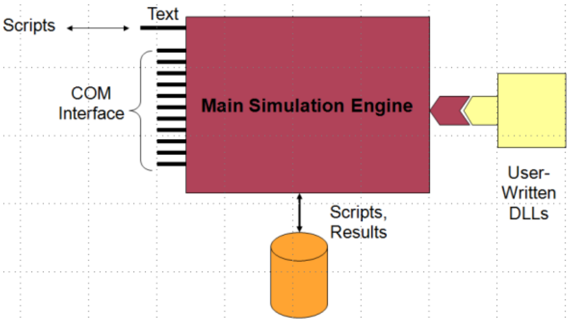

Figure 4. Interface between MATLAB and OpenDSS. (Adapted from Roger C. Dugan)

5 Steady-state analysis with OpenDSS

In this paper, the aim is to perform static analysis of generation controllers in microgrids through simulation in OpenDSS. In the simulations, the voltages in each bus are verified through the static simulation, as well as the active power injected by the generators, through expression (9).

The generation controller is based on (B.W. França, 2017), where dynamic analysis were employed to validate the proposed controller. However, further research is needed to evaluate the impact of such controller in terms of power quality and contingencies, e.g. possibility of voltage violation, in steady-state, depending on the DG level of penetration.

In this way, the microgrid model and the iteration method developed in this work have to faithfully reproduce the steady-state response of the generation controller proposed in (B.W. França, 2017). The input data are the generators setpoints and loads connected in the grid for a modeled grid. Therefore, the results of active power flow and voltage profile have to match with those obtained in steady-state for the dynamic simulation. In addition, it is also necessary to know the reactive powers injected by each generator in all the simulations studied.

The first step was to model the grid used in the study through OpenDSS. The modeled grid is shown in Figure 5 and Table1 shows the network parameters, DG units and impedances in pu.

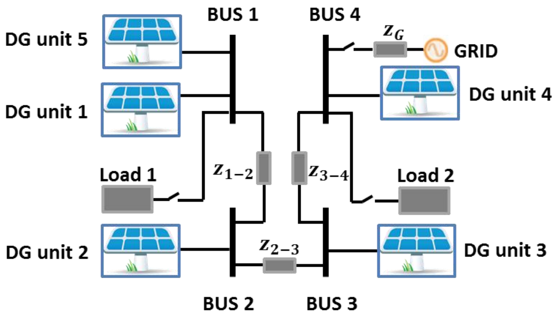

Figure 5. Microgrid used for modeling.

The information of the setpoints of the generators, and of the injected reactive powers can be found in

Table 2 and Figure 6, respectively.

Table1. Network parameters.

Parameter	Value
Theoretical installed capacity of each DG unit	3,5 kVA (1pu)
Load 1	(0,7 + j0,2) pu
Load 2	(1,0 + j1,0) pu
Z_{1-2}	(0,1 + j0,2) pu
Z_{2-3}	(0,03 + j0,1) pu
Z_{3-4}	(0,1 + j0,1) pu
Z_G	j0,03 pu

Table 2. Setpoint of distributed generators.

Setpoint	Generating Units				
	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5
Setpoint (pu)	1.0	0.5	0.5	1.0	0.5

The procedure performed follows the steps described below, in order to achieve all steady-state conditions in Figure 6:

1) For a time greater than 200s, the reactive powers of each generator, provided by Figure 6, were inserted into the OpenDSS. In addition, the active-power setpoint of the generators were also inserted in the OpenDSS. Finally, the simulation was run and the voltages in the bus were obtained.

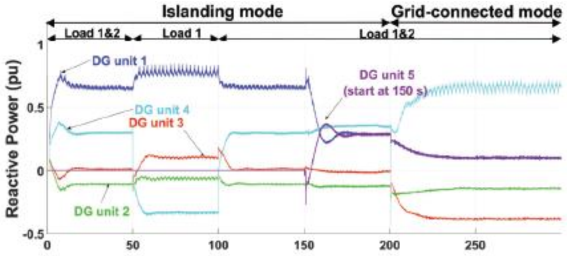

Figure 6. Injection of reactive power in the different simulations. (adapted from B.W. França)

2) For a time between 150 and 200s, the microgrid is disconnected from the main grid. In this case, the reactive power injected by each generator was inserted in the OpenDSS and reactive-power values were obtained through Figure 6. In addition, the value of the active power of each generator was updated according to (9). Finally, the main grid was disconnected in the OpenDSS, assigning bus 2 as the reference bar, since there must be a reference bus. The system was simulated to obtain the voltages in the other buses.

3) For a time between 100 and 150s, the generator 5 is disconnected. The same procedure of item 2 of obtaining the reactive powers injected by each generator through Figure 6 was performed. In the same way, the active power of each generator was updated through (9). Finally, the generator 5 was disconnected from OpenDSS, and the system was simulated to obtain the voltages in the buses.

6 Simulation results

Table 3 presents the power injected by each generator in each simulation, obtained through (9).

Table 4 shows the voltages obtained in OpenDSS simulations. Figure 7 and Figure 8 present the results of the dynamic analysis obtained in (B.W. França, 2017).

The results obtained for the power injected by the generators correspond to the values verified in Figure 7. In addition, the results obtained for the bus voltages in the different load and generation scenarios also corresponded to that expected by Figure 8.

Table 3. Active power injected by the generating units.

Time t (s)	Injected active power (pu)				
	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5
t > 200	1	0.5	0.5	1	0.5
150 < t < 200	0.569	0.284	0.284	0.569	0.284
100 < t < 150	0.663	0.332	0.332	0.663	--
50 < t < 100	0.499	0.250	0.250	0.499	--
0 < t < 50	0.663	0.332	0.332	0.663	--

Table 4. Voltages in the buses during the simulations.

Time t (s)	Voltage (V)			
	Bus 1	Bus 2	Bus 3	Bus 4
T>200	0.994	1.001	1.009	0.980
150<t<200	0.993	0.999	0.997	0.992
100<t<150	0.984	1.001	0.995	0.992
50<t<100	0.982	0.997	0.995	1.007
0<t<50	0.984	1.001	0.995	0.992

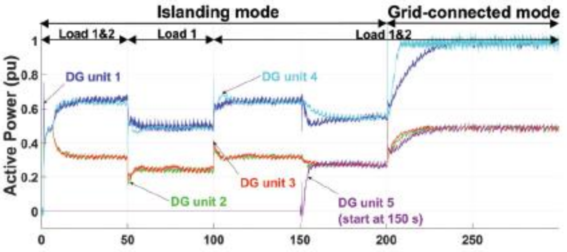

Figure 7. Active power injections obtained in dynamic simulations. (adapted from B.W. França)

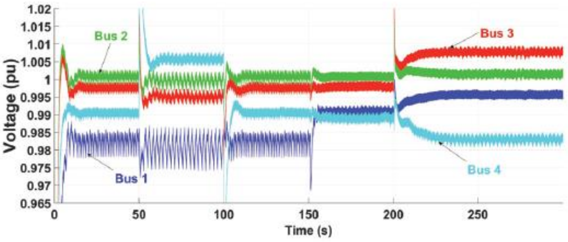

Figure 8. Voltages in the buses obtained in the dynamic simulations. (adapted from B.W. França)

In addition, it is important to note that, due to the hard task of static simulation in an islanded operation mode in the OpenDSS, it was necessary to adopt bus 2 with an approximate voltage of 1 pu to carry out the simulations.

7 Conclusion

The present paper presented static analysis of generation controllers in microgrids through simulation in OpenDSS. With this tool, steady-state analysis of a microgrid controlled through Sliding Droop control technique was implemented, in order to obtain information that, at first, would only be accessible through dynamic simulation of the system. The results obtained from the dynamic analysis in (B.W. França, 2017) were used to validate the microgrid modeling and the simulation procedure.

Two limitations were faced throughout the development of this study. The first was the need of previously having the information of the reactive power injected into the grid by the generators in each of the situations studied. The second was the current difficulty of simulating, in a static way, a microgrid in islanded mode in OpenDSS. To overcome these limitations, a new reference bus was chosen, and the reference voltage adopted in it was set as approximately 1 pu, according to the values verified in the dynamic.

As future works, it is intended to improve the methodology so that other kind of generators can be also controlled by this DG control technique. For instance, the costs of fuels used by these generators could be also analyzed in parallel with the analysis of the reduction of electrical losses in the system, which will result in a new point of operation for the generators. It is also possible to propose new control methods by using OpenDSS and its interfaces, so that a static analysis can be performed without any dependence of data from dynamic studies obtained by other software.

Therefore, it is considered that the present paper intended to contribute in a general way to the research in the area of micrigrid and distributed generation. It should be further improved under the condition of having more accurate data on reactive powers in steady state.

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