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A Review of Droop Control Implementation in Microgrids

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***Abstract*— This article includes a compilation and analysis of relevant information on the state of the art of the implementation of the Droop Control technique in microgrids. To this end, a summary and compilation of the theoretical models of the Droop Control and a summary of implementations have been made and, in general, try to summarize the great variety of experiences developed in this topic. The chosen experiences have been selected according to the research motivations that are available in the future and that are explained throughout this article, since this will serve as a starting point and guide for future research in microgrids and similar novel topics such as Low Voltage Distribution in Direct Current (LV DC) and DC microgrids (DC MG). The LV DC distribution for this article is related to houses in direct current (DC Home).**

***Keywords*— Microgrid, control droop, low voltage power networks, distributed generation.**

I. INTRODUCTION

An distributed generator is defined as a source of electrical power connected to the distribution network or directly to the user. The high penetration of distributed generation units in electrical systems can significantly impact the power and voltage flow conditions of end users [6]. A microgrid can create a small robust system using many of these distributed generation units using local information from each generator. Microgrids offer many advantages over traditionally centralized electrical systems [5]. There are many applications that require a high level of reliability and robustness in the electrical infrastructure. The ability to create a power system that can easily change with small engineering to provide the flexibility to add generators and loads as well as can be done [1].

Therefore, a microgrid is defined as a subsystem of distributed energy sources and their associated loads [1,5]. This criterion allows for local control of distributed generation, reducing or eliminating the need for a central controller. The microgrid can be a subsystem connected to the mains or separated during disturbances [1] or disconnected in case of energy self-sufficiency.

The microgrid concept is driven by two fundamental principles: 1) A systems perspective is necessary for users, electricity companies and society to capture all the benefits of integrating distributed energy sources into an energy system; 2) In the case of businesses to accelerate the adoption of these advanced concepts will be driven, first of all, by reducing the initial cost and increasing the value of the microgrid [4]

Power quality and energy reliability are frequently used in quantifying levels of electrical service. Distributed energy sources have the potential to increase system reliability and energy quality due to decentralization of power [1].

The integration of renewable energy sources into power systems offers unique challenges to designers of electrical systems [1]. Each improvement embodied in the microgrid concept has been specifically created to reduce the cost and improve the reliability of small-scale distributed generation systems (i.e. systems with installed capacities between tens and hundreds of kW) [4]

An important factor in microgrids is the creation of the disconnect switch which allows the microgrid to maintain compliance with the current commercial standard such as IEEE 1547. Such a switch is necessary to realize high reliability and energy quality that microgrids must offer [1]

Remote electrification with isolated supply systems, the increase in the acceptance of the microgrid concept and the penetration of the electrical network interconnected with DER and RES requires the application of inverters and the development of new algorithms. A promising criterion is the implementation of droop f/U within the respective investors. By this methodology an superior system architecture is established, providing redundancy, allowing expansion of the distributed system and avoiding excessive communications spending [2].

II. CONTROL DROOP

For power systems based on rotating generators, the active power and frequency are interconnected. An increase in the load implies that the torque of the load increases without a corresponding increase in the torque of the prime motor, so that the rotation speed and therefore the frequency decreases [1]

In addition, controls micro sources need to ensure that: new micro sources can be added to the system without modification of existing equipment, setpoints can be independently selected, the microgrid can connect or be isolated from the grid in a fast way and without cuts, active and reactive power can be independently controlled, and be able to meet the dynamic needs of the loads. Each micro-source microcontroller can effectively respond to system changes without requiring data from loads, static swith or other sources [4]

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The droop control is used to create references for voltage and frequency which are compared with actual values to create an error signal [1]

As a general criterion of the origin of the droop control, the problem of the transfer of complex power through a transmission line is considered. A transmission line is modeled in Fig. 1 as an RL circuit with constant voltages at the terminals of the line [1]

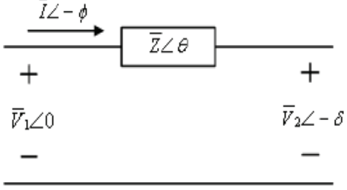

Figure 1. Power flow through the transmission line [1]

The power flow within the power line is described by the equation:

$$S = P + jQ = VI^* = V_1\left(\frac{V_1 - V_2}{Z}\right)^*$$
$$S = V_1\left(\frac{V_1 - V_2 e^{j\delta}}{Z}\right)^* = \frac{V_1}{Z}e^{j\theta} - \frac{V_1V_2}{Z}e^{j(\theta+\delta)} \qquad (1)$$

Using Euler's formula to separate the total power into its real and imaginary components gives the active and reactive power that flows through the line, which is:

$$P = \frac{V_1^2}{Z}\cos\theta - \frac{V_1V_2}{Z}\cos(\theta+\delta) \qquad (2)$$

$$Q = \frac{V_1^2}{Z}sen\theta - \frac{V_1V_2}{Z}sen(\theta+\delta) \qquad (3)$$

If the impedance of the line is equal to $Ze^{j\theta} = R + jX$, the equations can be written as:

$$P = \frac{V_1}{X^2+R^2}\left[RV_1 - V_2\cos\delta + V_2Xsen\delta\right] \qquad (4)$$

$$Q = \frac{V_1}{X^2+R^2}\left[X(V_1 - V_2\cos\delta) - RV_2Rsen\delta\right] \qquad (5)$$

Typical transmission lines are modeled with an inductance that is much larger than the resistance, such that the resistance is usually neglected. The equations can then be written as the well-known equations:

$$P = \frac{V_1V_2}{X}sen\delta \qquad (6)$$

$$Q = \frac{V_1^2}{X} - \frac{V_1V_2}{X}\cos\delta \qquad (7)$$

If the angle δ is small, so the angle of the formula can be used such that $sen\delta = \delta$ and $\cos\delta = 1$. Simplifying and rewriting the equations:

$$\delta \cong \frac{XP}{V_1V_2} \qquad (8)$$

$$V_1 - V_2 \cong \frac{XQ}{V_1} \qquad (9)$$

The equations (8) and (9) show that the power angle depends strongly on the active power and that the voltage difference of the reactive power. That is, if the active power can be controlled, then right there the power angle is manipulated; If the reactive power can be regulated, then the voltage V_1 can be controlled too [1].

In the droop method, each unit uses the frequency - instead of the power angle or phase angle - to control the active power since the units do not know the initial phase value of the other units in the autonomous system. By regulating the flow of active and reactive power through the power system, the frequency and voltage can be determined. This observation leads to the common equations of the droop control:

$$f = f_o - k_p(P - P_o) \qquad (10)$$

$$V_1 = V_o - k_v(Q - Q_o) \qquad (11)$$

where f_o and V_o are the base frequency and base voltage respectively, and; P_o and Q_o are the temporary set points for the active and reactive powers of the machine. The typical characteristic graph of the droop control is shown in Figure 2

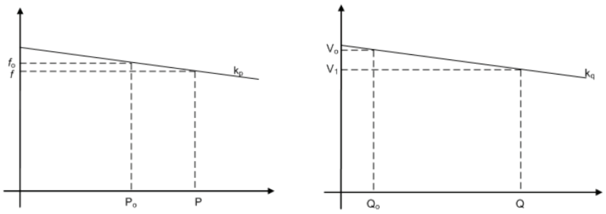

Figure 2. Characteristic Graph of Droop Control [1].

The assumption in the original calculation is that the value of the inductance is very large that the resistance is a good approximation for high voltage transmission lines, but a microgrids operates in low voltage with cables that have non-negligible resistors. To have a more general idea of droop control, both resistance and reactance will be considered [1]

The new droop control equations are:

$$f = f_o - k_p\frac{X}{Z}P - P_o + k_p\frac{R}{Z}Q - Q_o \qquad (12)$$

$$V_1 = V_o - k_q\frac{R}{Z}P - P_o + k_q\frac{X}{Z}Q - Q_o \qquad (13)$$

According to [2], such approaches result in the following characteristics:

- Simple system expansion.
- Increase in redundancy, since the system is not based on a vulnerable system bus.
- For optimization a simple system bus is sufficient.
- More complex control tasks in the components.

Additional redundancy in electrical networks can be achieved by use of voltage source inverters (VSI) in parallel [2].

In [2] the microgrid uses inverters, these are coupled via the inductances resulting from their filters for the suppression of peaks and decoupling of reactances (see Figure 3). The active power P and the reactive power Q of the voltage source can be calculated as:

$$P_1 = \frac{U_{1,eff} \bullet U_{2.eff}}{w_N(L_1 + L_2)}sen\delta \qquad (14)$$

$$Q_1 = \frac{U_{1,eff}^2}{w_N(L_1+L_{2)}} - \frac{U_{1,eff} \bullet U_{2.eff}}{w_N(L_1+L_2)}\cos\delta \qquad (15)$$

Where the phase shift δ between the two voltage sources causes the transmission of active power. The transmission of reactive power is due to the voltage difference $U_1 - U_2$. They assume standard values for inductance L_1 and L_2 resulting in highly sensitive systems where a small deviation of the phase and magnitude causes high currents between inverters. This sensitivity is the reason why the fixed frequency and fixed voltage controlled inverters cannot operate in parallel. There is always a voltage tolerance due to the tolerances of the sensors, references, temperature variation and aging, and also the crystals are not equal. Frequency errors in the crystals are integrated over time resulting in dangerous angle differences [2].

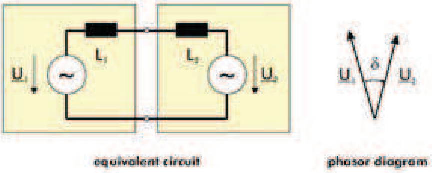

Figura 3. Inductive coupled voltage sources [2].

The obvious method for implementing frequency drops is the use of *P* as a function of *f*. But in a real system, obtaining an accurate measurement of the instantaneous frequency is not easy. Instant active power measurements are easier. Therefore, is proposed that the control of f be a function of P, the output power of the VSI is measured and its quantity is used to adjust its output frequency [2].

In a low voltage line, the electrical resistance predominates over the inductive reactance, therefore, the inductive reactance can be neglected. The active and reactive power of coupled resistance voltage sources - here an inverter and a grid - can be calculated using the notation according to Figure 4:

$$Q_{inv} = \frac{U_{inv.eff} \bullet U_{grid,eff}}{R_{line}} sen\,\delta \qquad (16)$$

$$P_{inv} = \frac{U_{inv,eff}^2}{R_{line}} - \frac{U_{inv.eff} \bullet U_{grid,eff}}{R_{line}}\cos\delta \qquad (17)$$

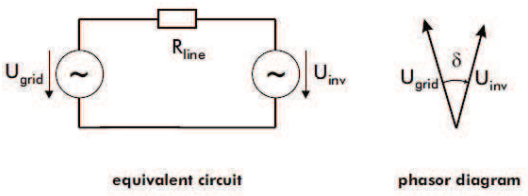

Figure 4. Inductive coupled voltage sources [2].

Eq. 17 shows that the active power flow and voltage are linked in the low voltage grid. The phase difference between the voltage sources causes reactive power flow (see Ec. 16). This fact suggests the use of droops active power/voltage and reactive power/frequency called "opposite droops" in low voltage grids instead of droops reactive power/voltage and active power/frequency called "conventional droops." Table 1 shows the pros and cons of using these two droops concepts. [2].

TABLE I
DROOP CONCEPT COMPARISON FOR LOW VOLTAGE LEVEL [2]

	Droop convencional	Droop opuesto
Compatible con nivel HV	Si	No
Compatible con generadores	Si	No
Control de voltaje directo	No	Si
Despacho de potencia activa	Si	No

According to [2] to derive the operating points of conventional droops in low voltage network the power transfer equation (see Ec. 17) takes into account that the inverter voltage is U_{inv} with a given power P_{inv} and a grid voltage U_{grid}, so, two solutions result from solving the quadratic equation:

$$U_{inv1,2} = \frac{U_{grid}}{2} \pm \sqrt{\frac{U_{grid}^2}{4} + P_{inv}.R} \qquad (18)$$

Eq. 18 gives a result in which the angle of displacement is 180° in both solutions, this creates a parameter $k_{1,2}$ with two values: $k_1 = 1$ y $k_2 = -1$. The power of the inverter is:

$$P_{inv} = \frac{U_{inv1,2} - U_{grid}}{R} \cdot U_{inv1,2} \cdot k_{1,2} \qquad (19)$$

Which is adjusted for changes in inverter voltage U_{inv} with reactive power:

$$U_{inv1,2} - U_{grid} = Q_{1,2} \cdot q_{droop} \qquad (20)$$

and the reactive power is a function of the angle δ:

$$Q_{1,2} \approx \delta \cdot \frac{U_{inv1,2} \cdot U_{grid}}{R} \qquad (21)$$

δ results from the integral in time of the frequency difference between generators to the grid:

$$\delta = \int \Delta f dt \qquad (22)$$

$$\Delta f = (P_{set} - P_{inv}) \cdot p_{droop} \qquad (23)$$

From which an important condition is deduced which is:

$$p_{droop} \cdot q_{droop} \cdot k_{1,2} > 0 \qquad (24)$$

With this, four stable operating points can be derived and are shown in Table 2.

TABLE II
STABLE OPERATING POINTS OF DROOPS CONVENTIONALS IN LOW VOLTAGE NETWORKS [2]

Case	Description	p_{drop}	q_{drop}	k	Commet
1	Inverse conv.	pos.	pos.	1	allowed
2	conv.	neg.	neg.	1	allowed
3		pos.	neg.	-1	not allowed
4		neg.	pos.	-1	not allowed

Cases 1 and 2 (the inverse droop and conventional droop) are characterized by the same sign of both droop factors. Cases 3 and 4 are not allowed (see Figures 5 and 6).

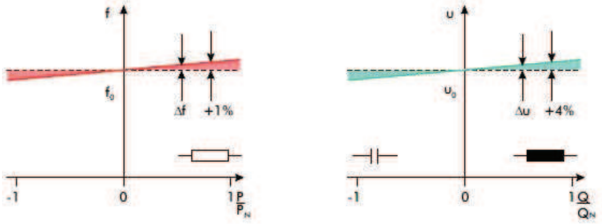

Figura 5. Droops with positive p_{droop} and q_{droop}[2]

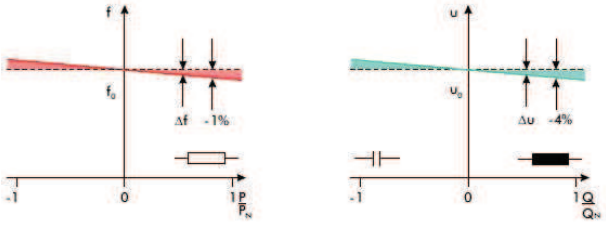

Figure 6. Droops with negative p_{droop} and q_{droop}[2]

With what has been developed for two investors is possible to expand concepts for more investors connected in parallel. In [3] is mentioned that the frequency and voltage control in isolated electrical grids, supplied by several inverters in parallel, can be obtained by means of several control methods, without or with communication. Control methods based solely on local measurements exhibit superior redundancy since they do not depend on communications for reliable operation. A peculiar aspect of these methods is that they only have a proportional controller for frequency and voltage, lacking any form of integral control. Control of a distributed system without the use of communications can be achieved by allowing a small error. Therefore, these techniques are generally denoted as droop control. The small fall is generally considered as long as the error remains within predefined limits. However, it should be borne in mind that the techniques described in the literature to extend the "local droop control" by a "comprehensive global control" through low bandwidth communication, combining both redundancy and integral control.

In [3], the authors present a new control proposal built by three levels of control, in which a primary control ensures the reliability of the supply by means of droop control technique, then a secondary control ensures the quality of energy and a tertiary control, includes the economy in the operation of the microfuent control unit. The primary control does not require communications and uses local information, however, the secondary and tertiary controls use a communications network.

III. IMPLEMENTATION OF DROOP CONTROL CASES

In [1] makes modeling, simulation and experimentation of a microgrid. As a modeling, it has been emphasized in making the model of an electric machine (generator) consisting of a voltage source dependent on the current and in which the current of the stator is negligible. Then they perform a droop control model for the prime motor that drives the electric generator that feeds a variable frequency network, thereby determining its transfer function and implementing a high pass filter to improve stability. The simulations are based on the electric generator model with nominal values of 61.7 kW, four poles, series reactance of 1.68 Ω, mutual inductance 0.0223 H, an initial power factor of 0.85 and voltage between phases of 460 V, in which the scenarios assumed in the model are tested and analyzed. The experimental part has been done on the microgrid configuration implemented by CERTS (Consortium of Electric Reliability Technology Solutions), however, the experiment was strongly limited to only one type of prime and generator engine, with which they confirmed the behavior of the droop control and explored how different droop gains could affect the distribution of energy. The experiment diagram is shown in Figure 7.

In the conclusions of [1], the authors mention that a proportional gain controller improves the stability of the system by damping the effects caused by rapid changes in the load, providing critical time for the system to adjust and prevent synchronism losses; and, in the case of unstable poles of the transfer function, this is changed by high pass filter that improves the response and stability of the system because it moves the unstable poles towards the left semi-plane of the complex plane *s*.

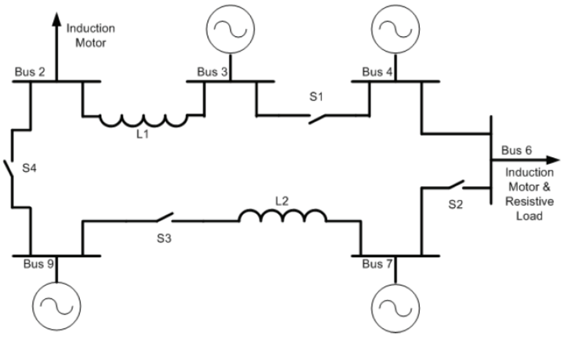

Figure 7. Radial microgrid structure for experimentation [1].

In [2], the authors present simulations performed for the four cases mentioned in Table 2, where compensation for electric lines is used in which the resistivity of the line is involved. They conclude that the droops actually used in low voltage systems due to their "indirect operation", where as shown in Table 2, the only boundary condition is the same sign for the frequency as well as the droop factors of the voltage; As a consequence of this result, the control strategy of the conventional network can be scaled to the low voltage level without any restrictions. This consistency serves as support for the introduction of DER and RES at the low voltage level and, concerns about stability and safety of the power grid can be alleviated. Still the voltage control question remains open, which is supported by the layout of the power grid. However, in order to improve the situation of partial line compensation has been successively demonstrated by means of simulations (see Figures 8 and 9).

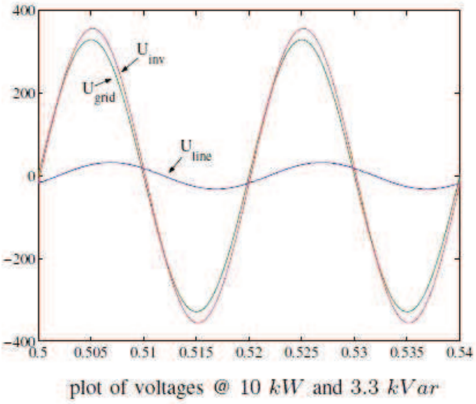

Figure 8. Results of inverse conventional droops [2]

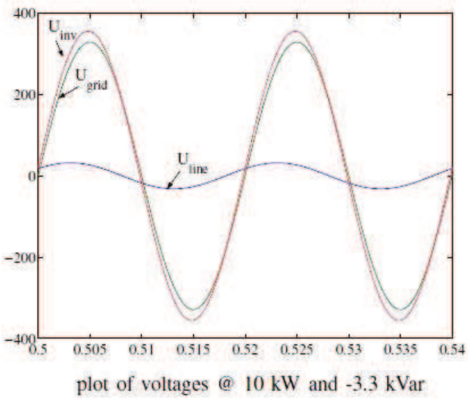

Figure 9. Results of conventional droops [2]

IV. CONCLUSIONS

The importance of this work is in the aspect of knowing in detail the concepts and criteria of the droop control concept and making a general analysis of implementations oriented towards the operation of microgrids and also other elements of advanced electrical systems that will have the same or similar way of operation, such as: electric vehicles, virtual plants, distributed generation, intelligent electric charges, nanogrids, among other new concepts that may appear in the future.

It is found that the development of the droop control includes a basic model of the high-voltage power line extended towards low voltage as a starting point from which equations are concluded that relate active power, reactive power, frequency and voltage. Based on this, that is, by being able to regulate these variables in a system with renewable sources with randomized environmental parameters, inverters are used to control and adapt the generated electrical energy to the needs of the loads in the case of a isolated system and meet the perspectives of interconnection in case of being connected to a general electricity network (utility network).

Because these are engineering solutions in the field of energy to be implemented in the short term globally, it is suggested the development of demonstration projects (which will be conditional on the availability of resources) and / or the development of mathematical and computational models of microgrid in order to reproduce and create new operating scenarios of microgrids.

The present work is the starting point towards investigations oriented to the optimization and management of direct current microgrids (DC MG).

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