STUDY AND IMPLEMENTATION OF "DROOP CONTROL" METHODS FOR INTERFACING VOLTAGE SOURCE INVERTERS TO MINIGRID

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ABSTRACT: This contribution presents control methods for the regulation of the voltage and the frequency on AC minigrids, fed by voltage source inverters (VSI). In order to avoid a complex communication network for the synchronization of the various VSI on a minigrid, a conventional method called "Droop Control" consists in the emulation of rotating alternators for each VSI. Then the VSIs generate AC voltages with an active power dependent frequency, and a reactive power dependent voltage. Such a method is presented and simulated on a given minigrid.
A second less-conventional method is introduced, where the characteristics on the minigrid line impedances are taken into account. Thus is obtained the projection of the active and the reactive power in a new referential depending on the line characteristics. By maintaining a "Droop Voltage" control on the new parameters, it is shown that the global stability is increased.
Keywords: minigrid, droop control, line impedance

1 INTRODUCTION

The actual estimation of people who do not have the access to the main power network in developing countries is estimated to be close of 1.64 billion. In developed country, many islanded sites are still not connected to a main grid.

In such cases, photovoltaics, diesel/alternators, co-generation, or micro-hydro are solutions used to provide locally electrical energy, in addition with batteries. In all cases, such sources deliver electrical energy thanks to voltage source inverters (VSI). The VSI are needed for interfacing accumulators, photovoltaïcs or wind mills to a grid. They are also needed for allowing an efficient active and reactive power management from the sources to the loads, and eventually complex energy transfers from one accumulator to another.

The size for such installations varies from one single home up to a whole village, and sometimes more. In these last two situations, it is a "real" electrical network that has to be managed. Such networks are named "minigrids" or "microgrids".

A minigrid can be connected to the main grid. In that case control strategies are simple for the VSIs as they are synchronized to the main. In case of islanded minigrids, control strategies are more complex as each VSI of such minigrids have to be arbitrary synchronized in order to control the voltage and the frequency [1].

In order to avoid a complex communication network for the synchronization of the various VSIs on a minigrid, a conventional method is called "Droop Control". It consists in the emulation of rotating alternators for each VSI. Then the VSIs generate AC voltages with an active power dependent frequency, and a reactive power dependent voltage. Such a method is presented and simulated on a given minigrid, and the following characteristics are outlined: even if such a method allows a correct management of the active and reactive power injected by each VSI on a minigrid, instabilities can occur in case of parameters fluctuations as well as non controlled reactive power exchange between each VSI of the minigrid. This needs a difficult and point to point fine tuning.

A second less-conventional method is introduced, where the characteristics on the minigrid line impedances is taken into account. Thus is obtained the projection of the active and the reactive power in a new referential depending on the line characteristics. By maintaining a "Droop Voltage" control on the new parameters, it is shown that the global stability is increased.

2 MODELING OF A MINIGRID.

2.1 General equations

The key point of this study is to analyze various strategies to control the Voltage Source Inverters (VSIs) of a minigrid. The aim is to adjust the RMS value and the frequency of the voltages generated by these VSIs in order to control the active and reactive power fluxes into the minigrid. Moreover, this has to be done without any communication network for the synchronization of each VSIs.

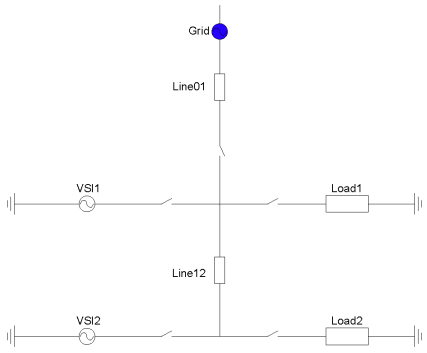

Figure 1: Example for modeling a minigrid

An efficient simulation tool is needed, that we have especially developed for this project. Focusing on the

voltage and frequency control on a minigrid, one has decided not to implement the various energy sources of a minigrid (photovoltaics, batteries, etc..).

As an illustration, we can refer to the example of a minigrid as presented in Figure 1, made of two energy sources (VSI1 and VSI2) interconnected with two loads (Load1 and Load 2).

VSI1 and VSI2 represent each the association of one source with its associated inverter. They are considered as black boxes, and modeled as AC voltage sources. The RMS voltage and the frequency these voltage sources deliver are adjusted as a function of the active and reactive power they have to provide. Such active and reactive powers are identified thanks to a power balance on each node where the VSIs are connected. The power at each node is the sum of the power of the loads and the circulating power on the line between two nodes.

The active and reactive power that circulate threw a line (Line12 in Figure 1) are defined by the equations:

$$P_{12} = \frac{RU_1\left(U_1 - U_2\cos\delta\right) + XU_1U_2\sin\delta}{R^2 + X^2}$$
$$Q_{12} = \frac{XU_1\left(U_1 - U_2\cos\delta\right) - RU_1U_2\sin\delta}{R^2 + X^2} \quad (1)$$

Where U_1 and U_2 are respectively the RMS values of the voltages generated by VSI1 and VSI2. The real part of the line impedance is R while X is the imaginary part. Finally, δ is the phase-shift between the voltages generated by the two VSIs, that can be expressed as follow:

$$\delta = 2\pi\int\left(f_1 - f_2\right)dt \quad (2)$$

Where f_1 and f_2 are the frequencies of the two VSIs generated voltages.

The active and reactive power absorbed by the load can be expressed the same way:

$$P_{load} = \frac{U^2}{R_{load}}$$
$$Q_{load} = \frac{U^2}{X_{load}} \quad (3)$$

Where U is the RMS value of the voltage forced on the node where the load is connected. R_{load} and X_{load} are respectively the real and imaginary parts of the load impedance.

2.2 Matlab/Simulink model

Following such a modeling of a minigrid, based on the power balance on each node on the line, one can establish a Matlab/Simulink model as it is presented in Figure 2. Such a model is the direct implementation into Matlab/Simulink of the minigrid presented in Figure 1, with two VSIs, two nodes, and an access to a main grid.

As it has already been mentioned, such a model realize the computation of all the active and reactive components of the powers in each part of the line and at each load, as a function of the RMS voltages and frequencies generated by each voltage source on the minigrid. In the example presented here, the voltages and the frequencies are those one generated by the main grid, as well as by the two VSIs.

Each of the characteristics of the voltage sources are adjusted to match the correct energy balance at each node of the minigrid.

It is obvious that the voltage and the frequency of the grid are strict datas, with no possibility of controlling them. They are then considered as constant values.

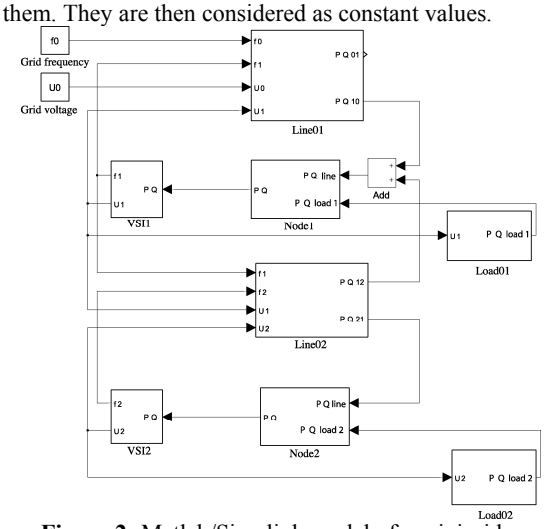

Figure 2: Matlab/Simulink model of a minigrid

On another hand, the RMS values and the frequencies of the voltages generated by the two VSIs must be adjusted to control the power flows into the minigird. This is allowed by the control of each of the inverters.

When the grid is present, then the VSIs must be synchronized to the main. In the case of an islanded mode of the minigrid, the VSIs must be controlled in order to maintain the specified RMS value and the frequency for each load, keeping also the control of power fluxes into the lines.

As the RMS value and the frequency of the voltages generated by the VSIs must be set to match the correct power balance at each node of the minigrid (from equations (1), (2) and (3)), it becomes then straightforward to control them as a function of the active and reactive powers they have to deliver.

This introduces the two control methods we will present in this contribution.

2.3 Case of study: minigrid for tests

In order to compare the two control methods we will present in the next sections, one have chosen to consider a reference minigrid more complex than the minigrid considered previously to introduce the modeling and the simulation tools we have developed.

This reference minigrid will be simulated for each of the proposed methods. It is presented in Figure 3.

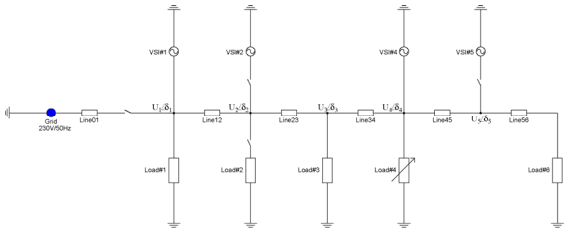

Figure 3: Matlab/Simulink model of a test-minigrid

This minigrid can be connected or isolated to the main grid (230Vrms/50Hz grid). It is made of 6 loads and 4 VSIs.

Each of the loads is a 800W/400VAR load, with the exception of Load#4 which varies linearly (1200W/s and

400VAR/s) in a specified time. The experiment map proposed to compare the two control methods we study is presented in Figure 4. It illustrates, versus the time, when the various devices of the system in Figure 3 will be or not connected to the grid.

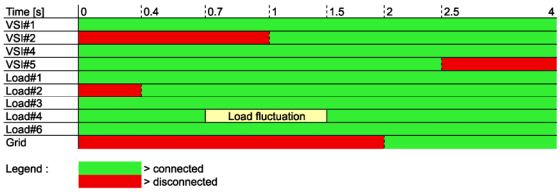

Figure 4: Experiment map

As an example, for the beginning of the test up to 2s, the minigrid is islanded (Grid disconnected). For the Load#4, its consumption in active and reactive powers will vary as described above between 0.7s and 1.5s.

For the parameters of the line, one have consider the typical impedance parameters for a low voltage line (230Vrms/50Hz):

$$R = 0.642\Omega / km$$
$$X = 0.083\Omega / km \quad (4)$$

3 DROOP CONTROL METHOD (Pf-QU)

3.1 Principle of the Droop control method

As underlined previously, the voltages delivered by each VSIs of a minigrid define the power absorbed by each loads, as well as the power transferred into the line. It appears then logical to reverse this approach, in order to adjust the voltages as a function of the power that each VSI must inject into each node of the minigrid.

A conventional method, named “droop control”, consists in controlling each inverter to allow the emulation of rotating alternators. It is well know that in conventional networks, each active power change reflects in a frequency variation as the rotating speed of alternators is changed. The control of the rotating speed of alternators enable the control of the frequency and finally of the active power injection into the grid.

The same way, each impact on a grid due to reactive power changes leads to voltage variation. Controlling the voltage level leads then to the control of the reactive power injected into the grid.

By analogy with conventional networks, one can control each VSIs of a minigrid following the general equations [2]:

$$f - f_0 = -K_p (P - P_0)$$
$$U - U_0 = -K_q (Q - Q_0) \quad (5)$$

For each VSI of the minigrid, the frequency of the AC voltage generated is dependent on the active power, while the voltage is dependant on the reactive power.

For the frequency, 3 main parameters must be defined: the frequency f_0, generally 50Hz, the reference power P_0 that defines the active power generated by the VSI to obtain de reference frequency f_0, and a gain K_p that defines the magnitude of the frequency variations versus the difference between the generated power P and the reference power P_0.

For the voltage, 3 main parameters must also be defined: the voltage U_0, generally 230Vrms, the reference reactive power Q_0 that defines the reactive power generated by the VSI to obtain de reference voltage U_0, and a gain K_q that defines the magnitude of the voltage variations versus the difference between the generated reactive power Q and the reference reactive power Q_0.

For a given minigrid such as that one in Figure 3, one must then tune 6 parameters in order to obtain the stability, a high dynamic response during transient, and an efficient following of the active and reactive power needs. This is available if it is decided that all the VSIs on the minigrid must have the same behavior.

3.2 Behavior of the minigrid – Islanded mode

The last comment is purely theoretical. The stability and a fine tuning are the main drawback of such a method, and need an a priori knowledge of the minigrid on which the VSis will be connected. Each parameters must be different for each VSI, depending on its position on the minigrid and depending on the loads seen by the converters. It must in particular be anticipated the voltages drop on the line for adjusting the parameters U_0 for each VSI.

The same way, the parameter P_0 is difficult to adjust in order to control active power fluxes into the line.

The Figure 5 presents the balance of all the active and reactive powers delivered by each VSI of the minigrid in Figure 3, following the experiment map in Figure 4, in the case of a full islanded mode.

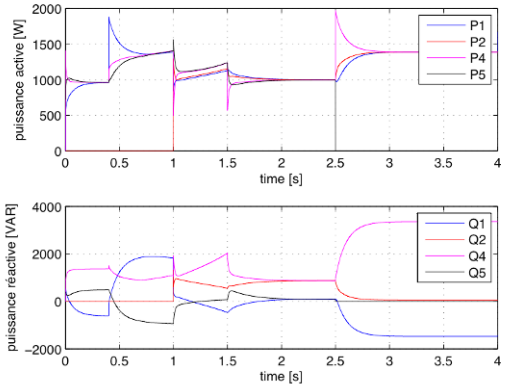

Figure 5: Active and reactive power in islanded mode

One can see that the active power injected by each VSI follow strictly the needs of each loads. However, the reactive power is not so well controlled, especially for the VSI#1 and the VSI#4. It seems that such an excess reactive power is not due to loads, but due to a reactive power exchange between these two VSIs.

The analysis of such a drawback can be made thanks to the Figure 6, that presents the frequency and voltage variations associated with the active and reactive powers shown in Figure 5.

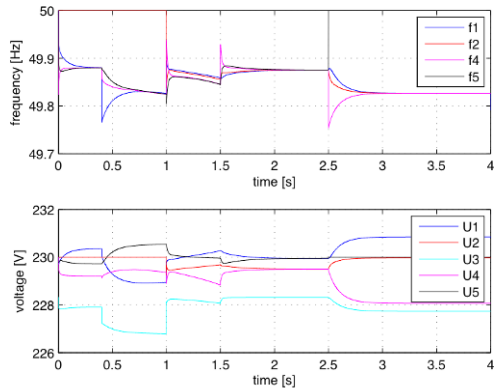

Figure 6: Frequency and voltage in islanded mode

The non-negligible active power that circulates through the line induces high current and then high voltages-drop. As the voltage on each node defines the reactive power injected by each VSI, this reflects by a huge reactive power exchanged between various VSIs, independently from the needs of the loads.

As said in introduction, the voltages drop on the line must be anticipated for adjusting the parameters U_0 for each VSI. The aim is to minimize the extra reactive power that could eventually circulate threw the line.

3.3 Behavior of the minigrid – Connected mode

The connection on the main grid can also be a problem as illustrated in Figure 7 while following strictly the experiment map of Figure4. Some strong instabilities can be seen by a strong reactive power exchange between the VSI of the considered minigrid.

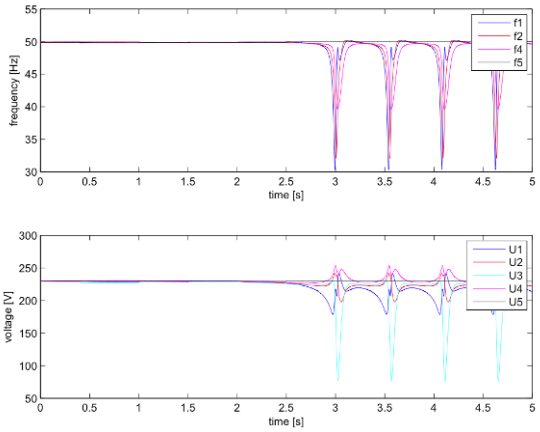

Figure 7: Frequency and voltage instabilities when the minigrid is connected to the main at t=2s

Such instabilities can be avoided thanks to the correct tuning of the parameters K_p and K_q. However, the fine tuning is difficult as a compromise must be done between stability and the dynamic for the response of each VSI at each change of load and configuration.

Such a tuning is strongly dependent on the topology of the minigrid, and there is no "standard parameter" that could be defined, ensuring the direct connection of a VSI on a minigrid with no problem of stability and with no problem of circulating reactive power.

4 MODIFIED DROOP CONTROL METHOD (P'f-Q'U)

4.1 Principle of the modified droop control method

A way to solve this problem is to adapt the initial equations to control the output frequency and voltage of the VSIs with 2 parameters P' and Q' respectively, defined by the following equations [3]:

$$\begin{aligned} & f - f_0 = -K'_p \left(P' - P'_0\right) \\ & U - U_0 = -K'_q \left(Q' - Q'_0\right) \\ & with \quad \begin{pmatrix} P' \\ Q' \end{pmatrix} = \frac{1}{Z_{line}} \begin{pmatrix} X_{line} & -R_{line} \\ -R_{line} & X_{line} \end{pmatrix} \begin{pmatrix} P \\ Q \end{pmatrix} \end{aligned} \tag{6}$$

The two new parameters P' and Q' are homogenous to active and reactive powers are they are defined from P and Q. However, the definition of P' and Q' takes into account the impedance of the line. From equation (1), one can then deduce:

$$\begin{aligned} P'_{12} &= \frac{U_1 U_2 \sin\delta}{Z_{line}} \\ Q'_{12} &= \frac{U_1 \left(U_1 - U_2 \cos\delta\right)}{Z_{line}} \end{aligned} \tag{7}$$

As P' depends directly on the phase-shift δ , it appears logical to control directly the frequency from P'. Once this has been set, one must affect the control the RMS voltage from the new parameter Q'.

4.2 Behavior of the minigrid

Compared with the previous method, this new control scheme appears to be more accurate for the management of the power delivered by each VSI. The active and reactive powers delivered to the loads are the main requirements for each VSI, while the reactive power transfer from one VSI to another is minimized. This is illustrated in Figure 8.

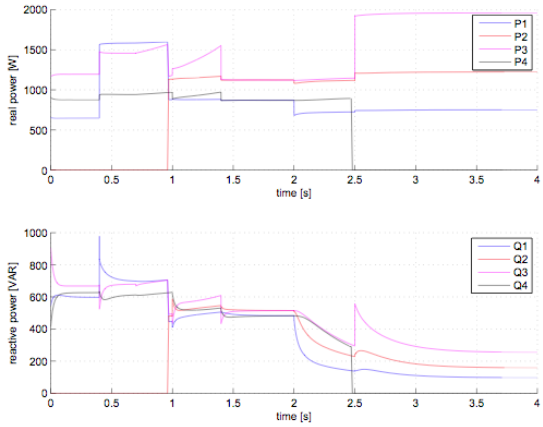

Figure 8: Active and reactive power profiles

The Figure 9 shows the limited excursions of the frequency on the minigrid, as well as the rms values of the voltages at each node.

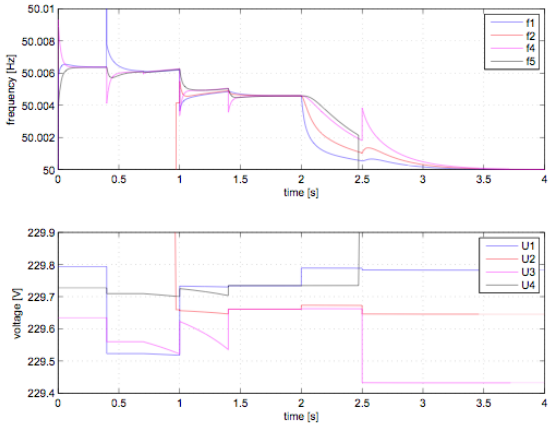

Figure 9: Frequency and voltage profiles

One must underline that these results have been obtained by choosing:

$$f_0 = 50Hz$$
$$U_0 = 230V$$
$$P'_0 = 0W \quad (7)$$
$$Q'_0 = 0VAR$$

For the parameters K'_p and K'_q, an interesting point is that they enable to set independently the operating point of the system and its dynamic: K'_p is adjusted to guaranty the values of voltage and frequency in normal mode, while K'_q is set in order to provide a fast response in transient mode.

The main advantage of such a method is to give a global stability, without any particular tuning for adapting the VSIs control to a special minigrid. The main drawback is during the connection of the minigrid to the main grid, where the reactive power coming from the main can be important depending on initial conditions before the connection. The state of the minigrid must be identified before the connection to the grid, and parameters adjusted in order to lower the reactive power exchange between the grid and the minigrid.

Moreover, still during the connection of the minigrid to the main grid, it is not possible to set the active power provided by each VSI to a given value.

5 CONCLUSION

In the general frame of minigrid, two methods based on the droop control theory have been proposed. Such methods enable the control of the frequency and the voltage generated by VSIs without dedicated communication network.

The droop control method named Pf-QU has a correct behavior if the minigrid is in islanded mode. However, some non-negligible reactive fluxes can be generated between various VSIs, with no possibility of control. Moreover, the connection to a main grid can lead to strong undamped oscillations of the voltage and frequency references computed by each VSI and power exchanges.

In order to solve such drawbacks, the P'f-Q'U method has been proposed. It consists in taking into account the impedance of the lines. The main advantage is that the VSIs controlled that way are in any case stable, in islanded mode as well as in grid-connected mode. In some cases however, some important reactive power fluxes can be observed between the grid and the minigrid.

6 REFERENCES

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