ISLANDING OF A MICROGRID OPERATING AT CONSTANT FREQUENCY WITH TWO GRID-FORMING INVERTERS

Lasse Peltonen*[1]*, Pertti Järventausta*[2]*, Pertti Järventausta*[3]**

[1]Faculty of Information Technology and Communication Sciences,
Tampere University, Tampere, Finland
[2]Faculty of Information Technology and Communication Sciences
Tampere University, Korkeakoulunkatu 7, Tampere, Finland
[3]Faculty of Information Technology and Communication Sciences
Tampere University, Korkeakoulunkatu 7, Tampere, Finland
**pertti.jarventausta@tuni.fi*

Keywords: MICROGRID, CONSTANT FREQUENCY OPERATION, GRID-FORMING, INVERTER-BASED, ISLANDING

Abstract

This paper shows how inverter-based microgrid operating at constant frequency performs under various transient and dynamic events, including islanding, fault inside the microgrid, loss of its primary grid-forming unit and rapid load changes. The microgrid comprehends one grid-forming unit, one grid-supporting/grid-forming unit, one grid-feeding unit and variable loads. Firstly, transient response of the microgrid during islanding to stand-alone operational mode is analysed. Results show how the main grid-forming unit can restore the voltage and balance active and reactive power fluctuations in stand-alone mode. Secondly, a fault inside the microgrid is applied when the microgrid operates in steady state and stand-alone mode. During the fault, the main grid-forming unit disconnects, and the grid-supporting unit changes its mode to grid-forming and restores the voltage and stabilizes the microgrid. All the production units can operate independently monitoring only their terminal quantities so communication between the units on primary control level is not needed. The usability and robustness of the chosen control methods are studied by using PSCAD/EMTDC.

1 Introduction

Microgrid-related studies have gained more attention in recent years [1]. Several types of stability studies, including various types of generating units and control methods, have been conducted. Directly grid-connected synchronous machines are still very common in microgrids. Due to this, most of the microgrid studies deal with dynamic responses in which microgrid possesses at least one directly grid-connected synchronous generator among inverter-connected units. In these cases, it is natural to use frequency as a control variable.

In microgrids comprising only inverter-based units, frequency is not determinated similarly as in synchronous machine-based power system, where frequency indicates the rotational speed of the electrical machines and frequency variations changes in their kinetic energy. Therefore, in inverter-based grids, frequency does not have the same physical relation to rotational masses of the power generating units. Based on the authors best knowledge, in most of the only-inverter related microgrid studies, the control of microgrid is still based on frequency. In these suggestions, the operation of microgrid is made e.g. to mimic the operation of synchronous generator. Examples of using frequency as a primary level control variable are shown in [2] and in [3].

Whether frequency is used or not as a primary level control variable, control of microgrids can be classified into two different categories: a) with a high-speed communication between the units b) without a high-speed communication between the units [4,5,6]. In many cases, primary level control methods using communication are generally not considered as a robust, reliable nor cost-effective solution [7]. Therefore, the primary control level solutions based on high-speed communication are not treated in this study. Rarely studied approach on only inverter-based microgrids is a method where frequency is not used as a control variable and microgrid operates at constant frequency [8]. This study concentrates on only inverter-based microgrids.

The paper presents transient response of islanding and the post-fault dynamics of the microgrid operating at constant frequency. The following two system events can be regarded as the most challenging when the stability of a microgrid is on concern: 1) islanding to stand-alone mode due to a fault on external grid, 2) fault inside the microgrid in stand-alone mode. Therefore, these two main scenarios are studied. Evaluation concentrates mainly on the primary control level. It is shown that with the chosen control method microgrid performs well under various transient and dynamic events. The usability and robustness of the chosen control methods are studied by using PSCAD/EMTDC.

This paper is organized as follows. Section 2 presents aspects related using frequency as a control variable and discusses aspects when microgrid operates at constant frequency. Section 3 introduce the model and control methods used to analyse the transient response of the microgrid. Section 4 describes the two simulation scenarios and study sequences. Section 5 presents the main results of the study. Finally, conclusions are presented, and future work is discussed in Section 6.

2 Problem formulation

2.1 Aspects related using frequency as a control variable

Large-scale power system's control is based on well-known *P/f* and *Q/U* -relations. There is only very little cross-coupling between frequency and voltage controls because the grid is mainly inductive [6]. In microgrids, this control method may not work in robust manner mainly because of the different *R/X* -relation. If traditional control methods are used in microgrids, strong cross-coupling between active and reactive power control is possible. It is raised in [9] that microgrid control could be based on *P/U* and *Q/f* -relations. It is also suggested that the microgrid can be made to mimic inductive system so that the control methods applied to large-scale power systems can be used [9]. Also, it is suggested that microgrid could mimic the operation of large-scale power system by adding virtual inertia [5,6]. In all cases, fast, accurate and reliable frequency estimate is needed to use frequency as a primary level control variable.

Compared to large-scale power systems, the frequency estimation in microgrids can be more challenging due to higher grid impedances which will have negative impact on voltage quality. Also, high switching frequency of inverters will cause high-frequency ripple in voltage waveform. In stand-alone mode, faults (e.g. short-circuits) will have a major influence on the whole microgrid area. As a result, all frequency estimates will undergo heavy transients during and right after the fault which will have major impact on transient response of microgrid. Also, the load changes are more abrupt and relatively much bigger compared to large-scale power systems. All this means that the successful control of microgrid is highly reliable on the performance and robustness of PLLs (Phase-Locked Loop), which in practice also implies a need for fast, accurate and reliable frequency estimate.

2.2 Aspects related using constant frequency operation

In a constant frequency microgrid, the most relevant target is to keep smooth and constant voltage profile. Because of the absence of one control variable (frequency), the control of active and reactive power between the production units might be more challenging in some cases. On the other hand, reactive power control on primary control level might not be necessary at all. Also, it might be possible to reduce oscillation problems originate from cross-coupling in two-variable control (*f, U*). Still, the control responses of production units must be robust in wide variety of dynamic and transient events. In case of inadequate active power, it is the voltage that will drop. Production unit's apparent power is limited its $S_{n,max}$. Therefore, reactive power output affects mainly on the unit's limit to deliver or absorb active power.

The performance of PLLs on constant frequency operation is still very important because production units must be tightly synchronized with each other's to maintain the stability of microgrid and to supply or absorb reference powers. As the microgrid's ideal frequency will be 50 Hz, narrow band-pass filter for phase voltage measurement might be possible to track the phase angles more accurately than in solutions using variable frequency as a primary level control variable [10]. However, it is evident that frequency estimate is affected by the changes on the voltage angle.

3 Target of the study and description of the study models

3.1 Target of the study

Purpose of this research is to study how inverter-based microgrid operating at constant frequency performs under various transient and dynamic events, including islanding, fault inside the microgrid, loss of its primary grid-forming unit and rapid load changes. Based on these severe changes, the robustness of the control of the microgrid can be demonstrated in various scenarios. It is shown that the microgrid can be controlled without using variable frequency as a control variable. The purpose is not to derive rigorous stability analysis nor tune the controller's parameters for best response.

As stated earlier, the microgrid operates without high-speed communication on primary control level. Communication is needed only on secondary control level when the control mode of the production units change based on the state of the circuit breaker and when $BESS_1$ (Battery Energy Storage System) sends power orders to $BESS_2$. Target is to show how one grid-forming unit acts as a voltage source converter while other production units extract the voltage phase angle from their terminals by using PLL which will exclude the need for high-speed communication on primary control level.

In [11] deduction was that grid-forming unit could form the grid, only if it delivered active power to grid. If the grid-forming unit absorbed active power, it was unable to form the grid. Based on different scenarios in this study, the intention is to show that grid-forming unit can form the grid whether it is delivering or absorbing real and reactive power. Further, it was stated in [11] that for a large microgrid, separate reactive power compensation is necessary. It is not clear how large microgrid was in question, but again, the purpose is to show that reactive power balance could be handled without needing separate reactive power compensation using only the existing production units.

In [10] it is stated that "reactive power reference is treated as proportion of active power reference. This ratio is acceptable for a wide range of variables, so long as it keeps less than 40%." The simulation results show that reactive power of production units is limited only by total apparent power. The surplus or deficit of microgrid's active and reactive powers are balanced by the grid-forming unit. There is no need for calculation active power reference for grid-forming unit because the control method reacts in such way that that active and reactive powers are balanced automatically. Also, it is shown that it is possible to control microgrid in which does not rely on the grid's impedance calculation [1,7].

3.2 Microgrid model for the study

The simulation model was established so that it was feasible for transient analysis of the microgrid operating at constant frequency. Fig. 1 illustrates the model which was used in all the simulations. The microgrid comprehends one grid-forming unit (*$BESS_1$*, *$S_n = 3.0$ MVA*), one grid-supporting unit (*$BESS_2$*, *$S_n = 2.5$ MVA*), and one grid-feeding unit (*PV*, *PhotoVoltaic, $S_n = 2.0$ MVA*). The *$BESS_2$* also possessed grid-forming mode. The active and reactive power loads were balanced three-phase, constant impedance loads. The equivalent *110 kV* grid was modelled as a voltage source equivalent. The simulation model also comprehended five transformers and four circuit breakers. The *X/R* -relation in the microgrid was unity. The microgrid's frequency was measured at the terminals of the *$BESS_2$*.

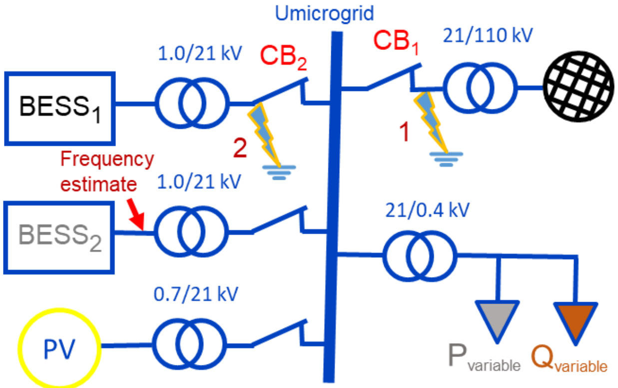

Fig. 1 Schematic picture of the three-phase microgrid

Fig. 1 shows the location of the faults in which the first one (1), initiated islanding. The second fault (2) commenced when the microgrid was operating in stand-alone mode. The circuit breaker labelled as "*CB_1*" was used to form the microgrid and the circuit breaker labelled as "*CB_2* ", was used to disconnect the *$BESS_1$* after the fault inside the microgrid commenced.

3.3 Proposed control method and power sharing

3.3.1 Grid-forming unit - $BESS_1$: When the *$BESS_1$* is parallel to grid, it adjusts its active and reactive power outputs using DQ-control method [4]. The main task of the grid-forming unit in stand-alone mode is to form the microgrid by acting as a voltage source converter. By doing so, it enables other production units, which act as a current source converter, to synchronize on the microgrid's voltages. The other main task of the grid-forming unit is to keep the U_{rms} of the microgrid on its nominal value (*1.0 p.u.*). The U_{rms} is controlled directly with PI-controller by controlling the $u_{d,ref}$. The input of the PI-controller is the voltage error between the reference and the measured voltage (U_{rms}). This method enables very fast control response.

Active and reactive power sharing between the production units is based on the difference in the voltage angle and U_{rms}. In stand-alone mode, the grid-forming unit's reference reactive power current component, $i_{q,ref}$, was set to zero. The reactive power imbalance is automatically compensated by the *$BESS_1$* based on the phase shift of the voltage and current in the microgrid. Fig. 2 shows simplified control principle of the grid-forming unit operating in stand-alone mode.

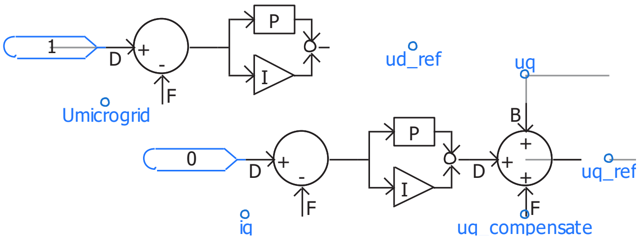

Fig. 2 Simplified control principle of the grid-forming unit

The applied frequency is dictated by the grid-forming unit's internal signal generator. In a case of constant frequency operation, the frequency can be chosen freely. In the study, value of 50 Hz is used. While in stand-alone mode, grid-forming unit can control grid-supporting unit's active and reactive power by using secondary level communication link.

3.3.2 Grid-supporting and grid-feeding units - $BESS_2$, PV: Control method of *$BESS_2$* operating in grid-supporting mode was DQ-control while parallel to grid and in stand-alone mode. In this study, its power reference is generated by the orders sent by the *$BESS_1$*. The *PV* operated in DQ-control mode whether the microgrid was operating in parallel to grid or in stand-alone mode. Both units extracted the voltage angle for synchronization using SRF-PLL (Synchronous-Reference Frame-PLL). The voltages are measured on the grid side of the LCL-filters. The *$BESS_2$* also possessed grid-forming mode but was always in supporting-mode when the *$BESS_1$* was connected to microgrid. When the *$BESS_2$* was operating in grid-forming mode, its control was identical than that of the *$BESS_1$*.

4 Chain of the events

4.1 Islanding
Before islanding, $BESS_1$ delivers *1.0 MW* and *0.5 Mvar* to the grid. The same values for $BESS_2$ are *0.75 MW*, *0.25 Mvar* and for *PV 1.5 MW* and *0 Mvar,* respectively.

When the three-phase short circuit commences in the main grid at the time of *1.0 second*, the circuit breaker CB_1 opens when the measured U_{rms} at the PCC (Point of Common Coupling) goes below *0.25 p.u.* and microgrid islands. $BESS_1$ changes its mode instantly from grid-supporting to grid-forming, when the CB_1 opens.

Now it is $BESS_1$'s task to form the microgrid. $BESS_2$ and *PV* target to maintain their active and reactive power outputs on the values they were before islanding. After the islanding, in stand-alone mode, active and reactive power loads change several times in stepwise between *1.25* and *3.75 seconds*. $BESS_1$'s task is to balance the load fluctuations by delivering or absorbing active and reactive powers. Fig. 3 shows the results of the depicted transient events.

4.2 Fault inside the microgrid
When microgrid operates in stand-alone mode and steady state, deep, three-phase short circuit commences at the time of *4.5 seconds* at the $BESS_1$'s terminals. At the beginning of the fault, $BESS_1$ is disconnected due to internal malfunction. Based on the open-state of the circuit breaker CB_2, $BESS_2$ changes its mode instantly from grid-supporting to grid-forming mode. The fault is cleared in *150 milliseconds* and now it is $BESS_2$'s task to restore the voltage and balance the load fluctuations. *PV* stays connected during the fault. After the fault is cleared, *PV* continues delivering its initial powers (*1.5 MW*, *0 Mvar*). Fig. 4 shows the results of the depicted transient events.

5 Simulation results

5.1 Islanding
Fig. 3 shows the microgrid's voltage, active and reactive powers of all the units, and the frequency estimate from *0.85 seconds* to *3.75 seconds*. Before the time of *1.0 second*, microgrid operates parallel to the grid. Fault commences at the time of *1.0 second* and U_{rms} reaches *0.25 p.u.* few tens of milliseconds later and the circuit breaker CB_1 opens. $BESS_1$ takes the grid-forming mode and restores the voltage rapidly. $BESS_2$ and *PV* undergo transients during the voltage dip but can restore their initial output powers soon after islanding. $BESS_1$'s internal signal generator keeps the frequency tightly at 50 Hz, but frequency estimate is affected heavily by the voltage transients caused by the fault and islanding. Just after the islanding, there are minor fluctuations on $BESS_1$'s, $BESS_2$'s and *PV*'s output powers, but otherwise the microgrid is stabilized within *200 milliseconds*.

Fig. 3 shows that steady state is reached after the islanding at the time of *1.2 seconds*. Between *1.25 seconds* and *3.5 seconds* both active and reactive power loads are fluctuating. At the time of *2.25 seconds*, total load rises above the $BESS_1$'s maximum power (S_n) limit. Consequently, U_{rms} drops to 0.9 p.u. After *250 milliseconds* of this excess active power increase, the $BESS_1$ sends order to the $BESS_2$ to increase its active power output from *0.75 MW* to *2.0 MW*. This restores U_{rms} to its nominal value (*1.0 p.u*).

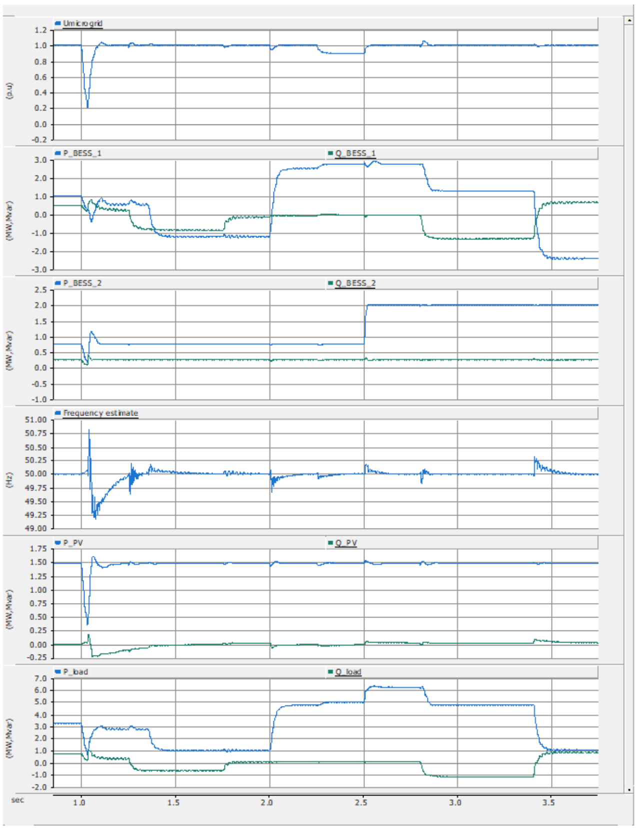

Fig. 3 Microgrid's voltage, active and reactive powers of the all units and frequency during islanding and in stand-alone mode.

Otherwise $BESS_1$ can maintain smooth voltage profile in the microgrid during the load fluctuations. $BESS_1$ can also balance the load fluctuations irrespective of whether it is delivering or absorbing active or reactive power. Fig. 3 shows that the frequency estimate becomes temporarily distorted in cases of largest load fluctuations.

5.2 Fault inside the microgrid
Fig. 4 shows microgrid's voltage, active and reactive powers of the *BESSs*' and frequency from *4.4 seconds* to *5.2 seconds*. Fig. 4 shows that microgrid operates in steady state until the time of *4.5 seconds* is reached. At the time of *4.5 seconds*, deep, three-phase short circuit commences at the terminals of $BESS_1$ and $BESS_1$ is disconnected. $BESS_2$ changes its control method to grid-forming mode based on the state of circuit breaker CB_2. After *150 milliseconds* the fault is cleared. Fig. 4 shows that c. *75 milliseconds* after the fault is cleared, voltage is restored and the microgrid is stabilized.

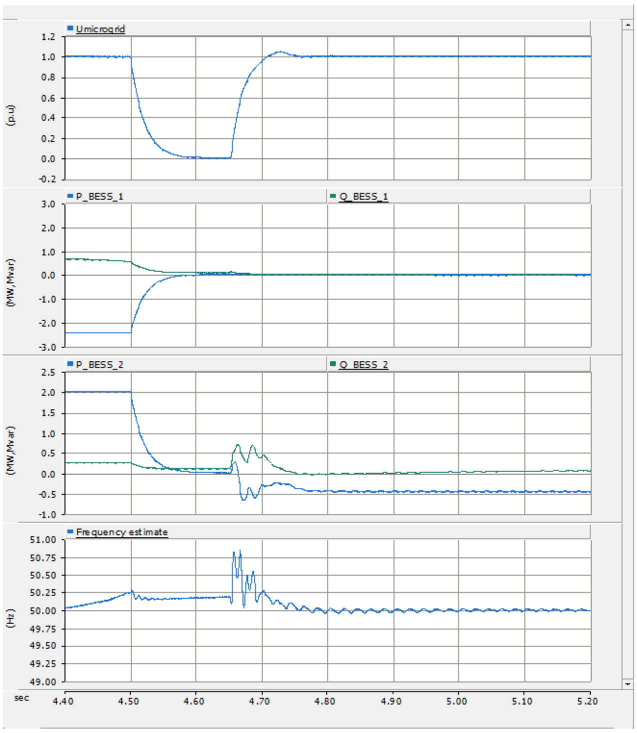

Fig. 4 Microgrid's voltage, active and reactive powers of the *BESS*s' and frequency during and after fault inside the microgrid.

6 Conclusion and discussion

Simulation results show that with the chosen control method, the grid-forming unit ($BESS_1$) can restore the voltage after islanding and the microgrid stays stable and continues its operation at constant frequency. In stand-alone mode, the microgrid can perform well under various transient and dynamic events, including three-phase fault, loss of its primary grid-forming unit and rapid load changes. Grid-forming units can balance load changes without the need for power reference calculations on the primary control level. All the production units can operate independently just monitoring their terminal quantities so that communication between the units are not needed on the primary control level.

The simulation results show that the microgrid is stable under the studied scenarios. Still, the simulation results cover only small fraction of all the possible transients so deductions on overall robustness of microgrid's performance cannot be done. In the study, $BESS_1$ and $BESS_2$ changed their mode to grid-forming instantly based on the states of circuit breakers. In practice, there will be tens to few hundred milliseconds delay when the change of the modes take place.

7 References

[1] Khanabdal, S., Banejad, M., Blaabjerg, F. & Hosseinzadeh, N.: 'Virtual Flux Droop Control with Constant Switching Frequency for Power Sharing Between Parallel Inverters in Islanded Microgrids', 2019, 4, (30), IEEE 27th Iranian Conference on Electrical Engineering (ICEE), pp. 868-874

[2] Lan, Z., Wang, J., Zeng, J. et al.: 'Constant Frequency Control Strategy of Microgrids by Coordinating Energy Router and Energy Storage System', Mathematical problems in engineering, 2020, 8, (14), pp. 1-8

[3] Thomas, V., Kumaravel, S. & Ashok, S.: 'Virtual synchronous generator and its comparison to droop control in microgrids', IEEE International Conference on Power, Instrumentation, Control and Computing (PICC), 2018, 4, (18), pp. 1-4

[4] Bijaieh, M.M., Anubi, O.M. & Konstantinou, C.: 'Distributed Adaptive AC Droop Control in D-Q Coordinates for Inverter-Based Microgrids', IEEE Power & Energy Society General Meeting (PESGM), 2020, 8, (2), pp. 1-5

[5] Negri, S., Tironi, E. & Danna, D.S.: 'Integrated Control Strategy for Islanded Operation in Smart Grids: Virtual Inertia and Ancillary Services', IEEE transactions on industry applications, 2019, 5, pp. 2401-2411

[6] Toub, M., Bijaieh, M.M., Weaver, et al..: 'Droop Control in DQ Coordinates for Fixed Frequency Inverter-Based AC Microgrids', Electronics (Basel), 2019, 10, (15), pp. 1168-1187

[7] Janjornmanit, S., Panta, S. & Thonglek, V.: 'An approach of controlling the inverter-based generator for use in an islanded microgrid', International Journal of Power Electronics and Drive Systems (IJPEDS), 2020, 9, (3), pp. 1610-1616

[8] Zhang, D.: 'Issues on Load Shedding in a Microgrid Operated at Constant Frequency', ICEMS 20th International Conference on Electrical Machines and Systems, 2017, 8, (11-14), pp. 506-511

[9] Jia Liu, Miura, Y. & Ise, T.: 'Comparison of Dynamic Characteristics Between Virtual Synchronous Generator and Droop Control in Inverter-Based Distributed Generators', IEEE Transactions on Power Electronics, 2016, 5, pp. 3600-3611

[10] Tang, X., Zhang, D.: 'Small Signal Stability and V-P Control of Islanded AC Microgrid at Constant Frequency', ECCE 10th International Conference on Power Electronics, 2019, 5, (27-30), pp. 1-6

[11] Zhang, D., Tang, X. & Fletcher, J.: 'Voltage Profile Improvement in Autonomous AC Microgrid Operated at Constant Frequency and Equivalent Parallel Operation of Inverters', IEEE Region 10 Conference (TENCON) 2020, 10, (16), IEEE, pp. 506-511