LOAD STEP PRE-ANNOUNCEMENT AND BANG-BANG CONTROLLER IMPLEMENTED IN ISLANDED MICROGRIDS TO IMPROVE FREQUENCY STABILITY

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ABSTRACT

Unlike large traditional electrical power systems, islanded Microgrids usually have a low inertia, especially when a high share of inverter coupled generation is integrated. Frequency stability is one main concern in islanded Microgrid operation. Load step pre-announcement and a bang-bang controller are introduced and implemented to improve the frequency response of islanded Microgrids. In order to achieve the best performance of the proposed control method, two parameters, preset and total time, have to be optimized. In this paper, an islanded Microgrid, including a conventional generator, a photovoltaic generator and a lumped load, is used as a study case. Three optimization criteria regarding the two parameters are presented, analyzed and compared. Furthermore, the effectiveness of the implementation of load step pre-announcement and bang-bang controller is validated using simulation results.

INTRODUCTION

High penetration of distributed generation (DG) into electrical power systems poses great technical challenges to network operation, stability and control. This stimulates the interest in Microgrid (MG) research worldwide [1]. The MG concept has been introduced as an effective solution for the control of grids under high penetration of DG. Although a more detailed definition of MGs is still under discussion, MGs can be described as decentralized electrical power systems comprising DG, local loads and storage, plus necessary control [2]. One specific feature of MGs is that they can be operated both in grid-parallel and islanded mode.

Unlike large traditional power systems, islanded MGs usually have a relatively low inertia because of integration of renewable energy sources, especially inverter-based distributed generation. This leads to a high rate of change of frequency under unbalanced conditions, which means that frequency changes fast during a power mismatch. Thus, frequency stability is one main concern in islanded MG operation. To maintain the frequency within the allowable limits and stabilize the system in case of disturbances, frequency control is one important control method that is currently applied in large power systems during normal operation [3]. However, any imbalance that occurs between power generation and load demand in islanded MGs may lead to severe frequency deviations due to the low inertia. Only implementing standard frequency control may not be sufficient to stabilize the system frequency in case of large power deviations.

This paper focuses on how to improve frequency stability within islanded MGs by implementing an additional control method. An islanded MG, consisting of conventional generation (CG), a photovoltaic (PV) generator and a lumped load, is simulated. CG means generation based on directly coupled rotating machines. Frequency control, including primary and secondary control, is applied in the CG to stabilize the system frequency. The PV generator is regulated following the VDE-AR-N 4105 standard [4], where its active power infeed varies depending on the actual system frequency.

PROPOSED CONTROL METHOD

In order to support frequency control as well as to improve the frequency response of an islanded MG, a control method, including load step pre-announcement (LSP) and a bang-bang controller (BB controller), has been introduced in [5]. This proposed control method is further developed regarding the optimization of its time parameters.

Load step pre-announcement

LSP receives signals from the load side and announces possible load changes in the islanded MG. If a load requires to be switched on or off, LSP will delay the switch signal for a defined short time period, which is referred to as preset time (t_{set}), and maintain the previous loading status to the system. Within this preset time period, LSP notifies the BB controller to regulate the power output of the CG preemptively, so that the CG starts increasing or decreasing its power output at full rate before the load change is actually realized.

Bang-Bang controller

A BB controller can be used as a feedback controller, which switches between two states, on and off. In the studied MG, it reacts on the signal from LSP depending on whether there is a significant load change or not. After receiving a signal from LSP, the BB controller commands the CG to change its operating point within a pre-defined time, e.g. it increases CG generation at maximum rate in case of a load increase. Likewise, it

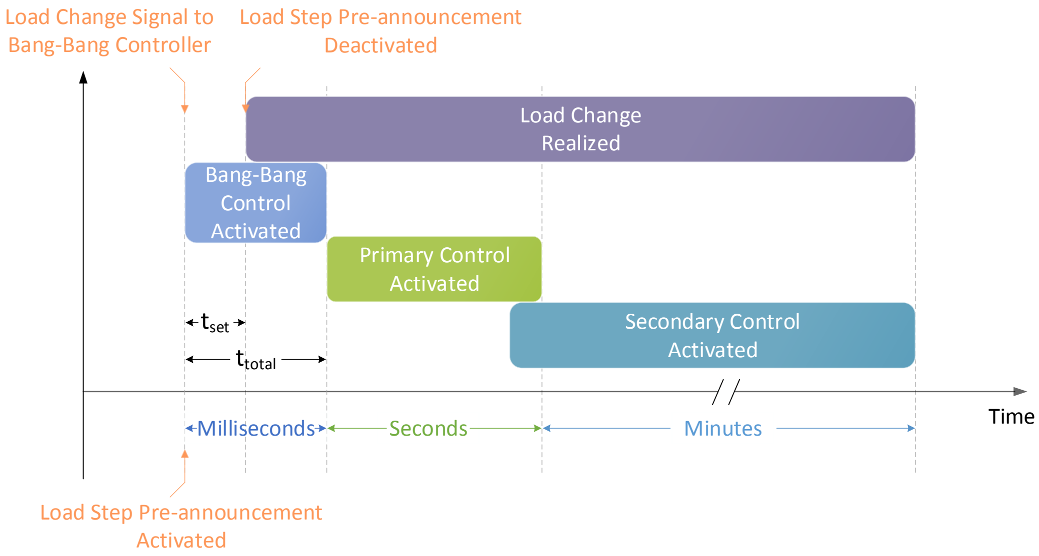

Figure 1. Active time ranges of LSP and BB controller

requires the CG to start decreasing its power output when a load decrease is announced by LSP. If no load change signal is sent, the BB controller does not take any additional control action. However, in order to avoid any instability that may occur and not to interfere with the function of primary and secondary control, the BB controller should only be active within a certain time period and a secure limit. In this way, the rapid change in power generation will not trigger over- or under-frequency protection of the CG, cause disconnection of the PV generation or lead to load shedding actions.

Time parameters and limitations

Preset time is one important parameter that defines the effect of the proposed control method. Unlike proposed in [5] that both LSP and BB controller work only within the preset time period, the BB control signal may last longer than t_{set} in this investigation. This means that the control signal will not necessarily stop when the load change occurs. The operating time of the BB controller, which includes the preset time and an additional time period, is called total time (t_{total}). The active time ranges of LSP and BB controller are shown in Figure 1. When preset time runs out, load step will be released by LSP. Due to the extension of its activation time, the BB controller stays active after the load change is realized. When the total time period is over, the BB controller will be deactivated and the CG will work again in its normal operation mode. The total time of the BB controller is the second important time parameter along with preset time. It can vary from several up to hundreds of milliseconds. Preset and total time should be set individually depending on the properties of the system.

LSP and BB controller should support the frequency stability of islanded MGs while not causing other instability issues as stated above. Therefore, a secure frequency limit should be set up for activating the BB controller. For instance, a pre-defined activation time of the BB controller (t_{total}) that can lead to a frequency drop below 49 Hz is not allowed to avoid the under-frequency load shedding (UFLS) scheme defined in [6]. For the upper frequency limit, 51.5 Hz is used in line with the frequency-dependent active power characteristic determined by the German VDE-AR-N 4105 standard [4] to avoid PV disconnection caused by over-frequency.

OPTIMIZATION CRITERIA

As mentioned in the previous section, preset and total time of LSP and BB controller determine when the load step is about to be released, how much the CG active power is increased or decreased before the load change, how much active power change of the CG is realized during the entire total time, and the magnitude of frequency deviation. The selection of these two time parameters influences the control effect of the proposed control method. Both optimal preset and total time are influenced by dynamics and share of CG. Determining optimal time parameters for the proposed control method is achieved through three criteria.

Criterion 1

The frequency responses during the dynamic simulations of the islanded MG under different shares of PV are observed depending on the time parameter settings. As presented in Figure 2, the frequency deviation band is calculated as the difference between maximum and minimum frequency (f_{max} and f_{min}) that occurred in the whole dynamic frequency response,

$$f_{band} = f_{max} - f_{min} \qquad (1)$$

For the first criterion, the smallest value of the frequency deviation band (f_{band}) is sought-after. The smaller this frequency band between maximum and minimum frequency is, the better the dynamic behavior of the islanded MG is in case of a load change.

Criterion 2

The area between final frequency at quasi-steady state f_{qss}

after primary control and actual frequency f(t) in the time interval from when the load change occurs until the end of primary control t_{qss} is calculated. This frequency deviation area is marked as the red shaded regions in Figure 2. Since negative regions could cancel out positive regions in the integral, the square of the frequency difference between system frequency and frequency at quasi-steady state is integrated. So,

$$c_{area} = \int_0^{t_{qss}} [f(t) - f_{qss}]^2 dt \qquad (2)$$

where c_{area} represents the size of the frequency deviation area after a load change. The optimal setting of time parameters regarding criterion 2 is, thus, determined by the smallest frequency deviation area index c_{area}.

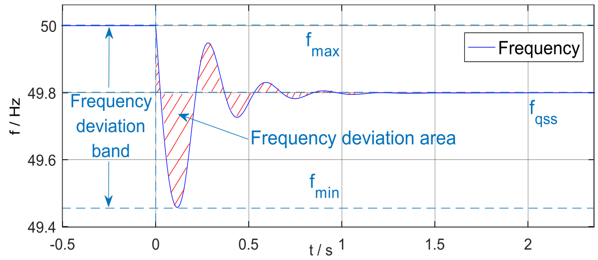

Figure 2. Optimization Criteria

Criterion 3

The third criterion combines criteria 1 and 2 and searches for the smallest sum of frequency deviation band and frequency deviation area index. Since the units of frequency deviation band and frequency deviation area index are different, it is necessary to use a reference value. Hence,

$$c_{sum} = \frac{f_{band}}{f_{band-ref}} + \frac{c_{area}}{c_{area-ref}} \qquad (3)$$

where $f_{band-ref}$ and $c_{area-ref}$ are the frequency deviation band and the frequency deviation area index recorded in simulations of the islanded MG without LSP and BB controller, which is equivalent to that the preset and total time are 0.

In criterion 3, c_{sum} is the sum index of these two relative values and, corresponding to criterion 1 and 2, its minimum value indicates the optimal time parameters of the proposed control method.

DYNAMIC SIMULATIONS

The islanded MG is simulated in per unit (p.u.) system. The total size of the islanded MG, which is defined by the maximum load demand to be served, is used as the base value. As an example, the islanded MG with a 25% share of PV and 75% share of CG is assumed to supply 0.5 p.u. load initially at nominal frequency and undergo a 0.15 p.u. load increase at t = 0. Combinations of preset and total time in 10 ms steps are tested in this exemplary MG. Since similar optimal preset and total time are found following the three criteria, only the simulation results of criterion 3 are presented in Figure 3.

Among the results, the areas, where either maximum frequency is above 51.5 Hz or minimum frequency is below 49 Hz, are removed for a better overview. As described in the previous section, the smallest c_{sum} defines the optimal setting of preset and total time. It equals 0.35, which is 17.5% of the reference value of the sum index $c_{sum-ref}$ = 2. As can be seen, this is the case for preset time being 80 ms and total time being 200 ms, respectively.

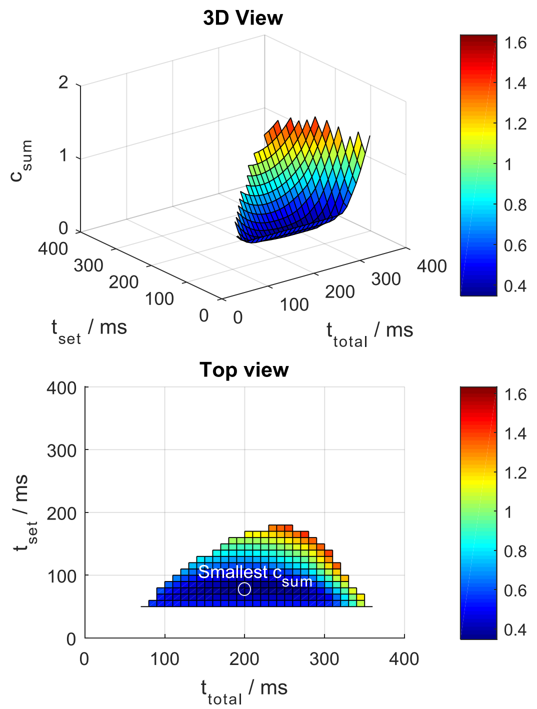

Figure 3. Optimization of time parameters (criterion 3)

To illustrate this, dynamic simulations of the exemplary MG introduced above with different settings of time parameters as listed out in Table 1 are shown in Figure 4.

Table 1. Settings of time parameters in 4 test cases

Test cases	Parameters
Case 1	$t_{set} = t_{total}$ = 0 ms
Case 2	$t_{set} = t_{total}$ = 40 ms
Case 3	$t_{set} = t_{total}$ = 80 ms
Case 4	t_{set} = 80 ms, t_{total} = 200 ms

The blue dashed line in the diagram presents the dynamic behavior of the islanded MG only with frequency control (case 1). The red dash-dotted, yellow dotted and purple solid lines illustrate the dynamic behavior of the MG implementing frequency control as well as LSP and BB controller. The red and yellow lines indicate the dynamic behavior of the MG for cases 2 and 3 ($t_{set} = t_{total}$). The purple line shows the optimal dynamic behavior of the MG with the optimal time parameters determined by criterion 3 (case 4).

As shown in Figure 4, a frequency drop to approximately 48.2 Hz in the islanded MG only with frequency control is caused by a 0.15 p.u. positive load step (blue dashed line). This can result in load shedding actions to support the frequency stability. In case 2, where the MG includes LSP and BB controller (red dash-dotted line), the CG is controlled by the BB controller to start to ramp up 40 ms before the load is released. The system frequency increases and reaches approximately 50.07 Hz at the end of the preset time. As the CG already started increasing its output, the frequency decreases by approximately 0.5 Hz less than it does in the MG without LSP and BB controller after the load change takes place. As a comparison, the result for case 3, where preset and total time are longer, is shown by the yellow dotted line. Frequency reaches approximately 50.25 Hz by the end of activation time of LSP and BB controller. Under frequency droop control after the BB controller is deactivated, the CG decreases its active power from the power set point if frequency raises from its nominal value, and vice versa. As the CG's active power is increased while the BB control regulates it, once the BB control stops, the CG reduces its active power until the active power meets the requirement of the frequency droop control. This is observed for the MG with LSP and BB controller in case 2 as well.

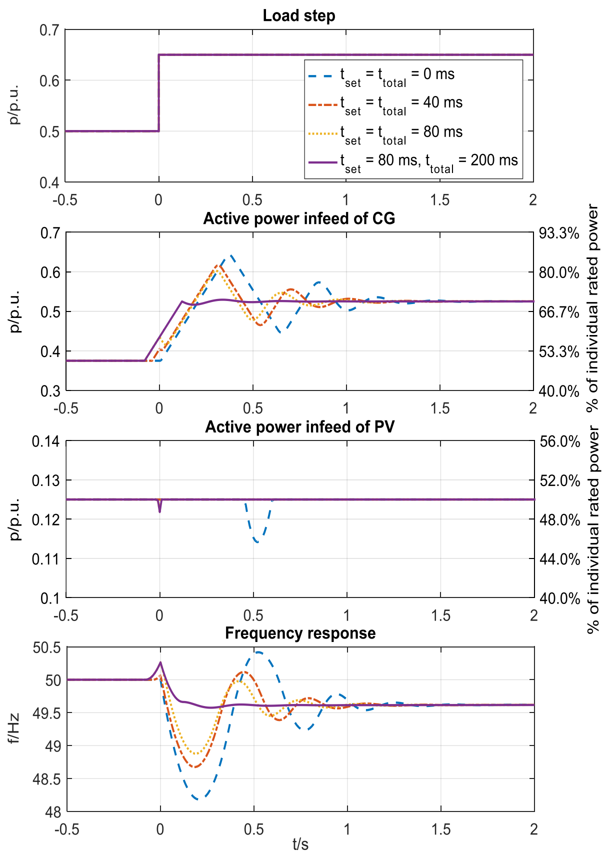

Figure 4. Dynamic simulation of exemplary islanded MG

As illustrated by both the red dash-dotted and yellow dotted lines in Figure 4, the frequency nadirs are below 49 Hz. The power reductions of the CG that occur after the BB control signal stops during the dynamic process diminish the control effect of LSP and BB controller because more active power than supplied at t = 0 is expected to be required at quasi-steady state. The optimal preset time defined by criterion 3 for LSP to hold the load switch signal is 80 ms and the optimal total time for the BB controller to be activated is 200 ms as shown by the purple solid line for case 4. Because of the CG's pre-generated power, system frequency increases to approximately 50.25 Hz at the end of the 80 ms preset time, which is the same as that presented by the yellow dotted line. After the positive load step is realized, the CG continues to ramp up, which allows it to reach the amount of active power required by the load earlier than in the other three cases. Frequency dip in the purple line is about 49.6 Hz, which does not exceed 49 Hz. Hence possible under-frequency load shedding can be avoided. The CG keeps increasing its active power as long as the total time of the BB controller does not run out. This avoids the power drops that occur in cases 2 and 3, respectively.

CONCLUSION

The exemplary islanded MG with the designed LSP and BB controller being implemented features a significantly enhanced dynamic reaction on power disturbances and shows lower frequency deviations. In addition, the settings of two important time parameters - preset and total time - influence the control effect of the proposed method. In the example, an extension of the activation time of the BB controller helps the CG to reach the active power required by the load earlier than if $t_{set} = t_{total}$. With optimal time parameters, the control effect of LSP and BB controller is maximized. The upper dynamic operating limit of the exemplary MG is increased from 0.18 p.u. to 0.34 p.u. The steady state limit of this MG setting is 0.375 p.u., which is the upper boundary for the dynamic operating limit. Therefore, larger load steps can be realized with this proposed scheme.

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