A ROBUST CONTROL METHOD TO IMPROVE MICROGRID FREQUENCY STABILITY IN ISLANDED OPERATION

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Abstract

Islanded Microgrids have low inertia due to their small size as well as integration of inverter-based renewable energy resources. Hence frequency stability is one main concern regarding their operation. Load step pre-announcement and a bang-bang controller were proposed and applied in a test islanded Microgrid, consisting of a conventional generator, a photovoltaic generator and a lumped load, to improve the frequency response. In this paper, a possible control architecture for the proposed method is illustrated. A sensitivity analysis is conducted to determine the influence of two parameters, preset and total time, on the performance of the proposed control method. Furthermore, the effectiveness of the implementation of load step pre-announcement and bang-bang controller in the test microgrid with different shares of PV is evaluated through simulation results.

1 Introduction

Microgrids (MGs), which can operate in grid-parallel and islanded mode, are considered to be an effective solution to provide power supply autonomously regarding the increasing amount of integrated renewable energy sources (RES). Hence many MG research projects are carried out worldwide [1]. However, to allow the deployment of MGs, many technical challenges need to be overcome. One important issue that has to be addressed is their frequency stability in islanded operation [2].

For islanded MGs, since there is no additional support from the utility grid, frequency has to be controlled via coordination of distributed generation within them. Besides, due to their small size and low inertia, frequency changes fast when there is a mismatch between power supply and demand. Hence maintaining frequency stability under load steps that are large in comparison to the size of MGs becomes more critical and only implementing standard frequency control may not be sufficient. Therefore, a novel control method, comprising load step pre-announcement (LSP) and a bang-bang controller (BB controller), has been introduced to improve MG frequency stability in islanded operation [2, 3]. A possible control architecture to implement the proposed control method is described in detail in this paper. Besides, steady state load change limit and dynamic operating limit of MGs are defined. Load changes are categorized under the consideration of system frequency dynamic stability and communication requirements regarding control architecture are discussed.

In this paper, the islanded MG model, consisting of conventional generation (CG), a photovoltaic (PV) generator and a lumped load, published in [3] is further investigated. A sensitivity analysis of the impact of time parameters on the performance of LSP and BB controller is conducted. The reliability of the proposed control method is analysed and evaluated. Furthermore, the control effect of the proposed method is validated by simulation results.

2. Control Method and Architecture

The proposed control method, LSP and BB controller, is implemented to regulate the frequency of the islanded MG in addition to the conventional frequency control. LSP receives load change signals and delays the load change for a defined short time period, which is preset time (t_{set}), and maintains the previous loading status to the system. The BB controller is notified about the load change and regulates the conventional generation (CG) to preemptively increase or decrease power output. The activation time of the BB controller is referred to as total time (t_{total}).

2.1 Categorization of Load Steps

The stepwise change of load is investigated as most dynamically challenging case to reach a new steady state operation. Load changes are classified into three categories, namely normal, large and critical load step. These types of load steps are categorized according to their frequency nadir during the dynamic response after power deviations occur in the MG. Normal load step (NLS) indicates a small load change that can be carried out without leading to any frequency instability issues. Frequency disturbances caused by this kind of load step can be covered by frequency control only. Large load steps (LLS) are defined as load changes that can cause severe frequency disturbances after being carried out by the MG. Without the proposed control method, emergency control, e.g. load shedding action or cutting off generation, would be necessary to allow the MG to withstand the frequency disturbance. Critical load steps (CLS) refer to the load changes, which exceed the possible system steady state operating limits. Therefore, no matter which kind of control scheme is applied, the load cannot be realized in the islanded MG under stable conditions.

2.2 Control Architecture

LSP and BB controller can be implemented either in a centralized or decentralized architecture. Figure 1 shows a possible control architecture, in which both LSP and BB controller belong to the microgrid central controller (MGCC) and each element in the MG has a local controller (LC). The LC of the CG provides droop settings locally. The LC of the PV provides a frequency dependent active power control following the German VDE-AR-N 4105 standard [4]. The load switch should be connected to its LC that is able to collect any switch change information of the load. In the load LC, there is a predefined setting that information about the load change should be sent over to the MGCC as soon as the status of the switch changes.

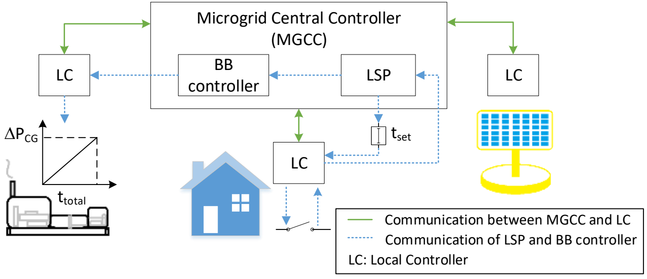


Figure 1. Control architecture of an islanded MG

Depending on control architecture, different amounts of information are assigned to LCs and LCs have different level of autonomy. In case of a centralized architecture, LC actions are coordinated by the MGCC. For a more decentralized control, LCs can be predefined with detailed information to take over some control actions from the MGCC, and thus, reduce the need of communication. For example, the load LC with pre-defined information determines what actions are conducted in case of fluctuation caused by NLS or a switch request from CLS. Only when LLS are carried out, the load LC needs to wait for the instruction from MGCC. Frequent information exchange between the LC and the MGCC can thereby be avoided. The setting of the load LC is illustrated in Table 1.

Table 1. Predefined information in LC

Case	Action	Communication
NLS	Continue operating under normal frequency control	Not needed
LLS	Inform the MGCC about the change and wait for further instruction	Necessary
CLS	Refuse to be switched on/off	Not needed

3. Microgrid Operating Limits

3.1 Steady State Load Change Limit

The steady state load change limit is introduced under ideal circumstances by neglecting frequency instability problems that can be caused by the inability of the MG to reach a possible stable operating point due to dynamical limitations. It includes steady state positive and negative load change limits, which represent the maximum possible positive and negative load change that can be realized from the initial load. Steady state load change limit depends on the initial state of the MG system, the CG operating points and the PV P-f characteristic curve. It defines a baseline for the MG's dynamic operating limit.

3.2 Dynamic Operating Limit

The dynamic behaviour of a system shows the effects of the interaction of its elements. It describes how a system reacts over time to a change that breaks the initial steady state balance. Dynamic stability indicates a system's ability to return to a steady state after a change occurs without violation of the limits. If frequency deviations are within a certain range, frequency can be regulated and stabilized by its control system; otherwise the MG undergoes frequency instability, which may result in a blackout.

The dynamic operating limit indicates the maximum dynamically allowable positive and negative load steps that can be dealt with by the islanded MG at one time. It is influenced by factors like initial loading status, shares of generators, system inertia and the MG's control system. In other words, a load step must be supported dynamically and in steady state, but system dynamics limits the path the steady state limits can be realized. An example of a frequency dynamic response on a load increase is presented in Figure 2.

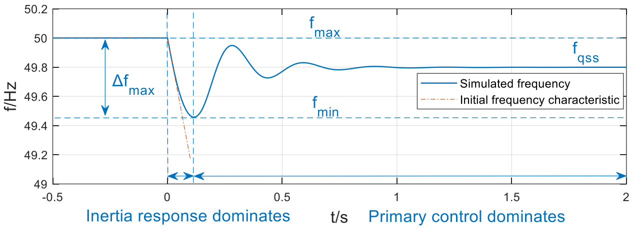


Figure 2. Dynamic frequency response on a load increase

The red dashed line shows the frequency characteristic under initial rate of change of frequency due to the power imbalance. In the moment of the load change, primary control gets activated, and shortly before frequency reaches the nadir, it becomes dominant and continues to adjust the CG active power infeed until the frequency reaches a new stable point, which is defined by the droop setting of primary control. Frequency nadirs where load shedding at 49 Hz and PV disconnection at 51.5 Hz occur are defined as the dynamic operating limits of the system.

3.3 Optimization Criteria

The settings of preset and total time strongly influence the MG dynamic operating limits. Three optimization criteria were used to determine the optimal time parameters [3]. Criterion 1 calculates the frequency band f_{band}, which is the difference between maximum and minimum frequency (f_{max} and f_{min} shown in Figure 2).

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

Criterion 2 seeks to minimize the frequency deviation area between actual frequency f(t) and frequency at quasi steady state f_{qss} from the time of load change (t=0) until the end of primary control (t_{qss}).

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

Criterion 3 is calculated as the sum of f_{band} divided through its reference $f_{band\text{-}ref}$ and c_{area} divided through its reference $c_{area\text{-}ref}$. The reference values are those where preset and total time are both 0.

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

For all three criteria, the smaller the sought-after index value is, the better the time setting is.

4. Results and Discussion

4.1 Sensitivity Analysis

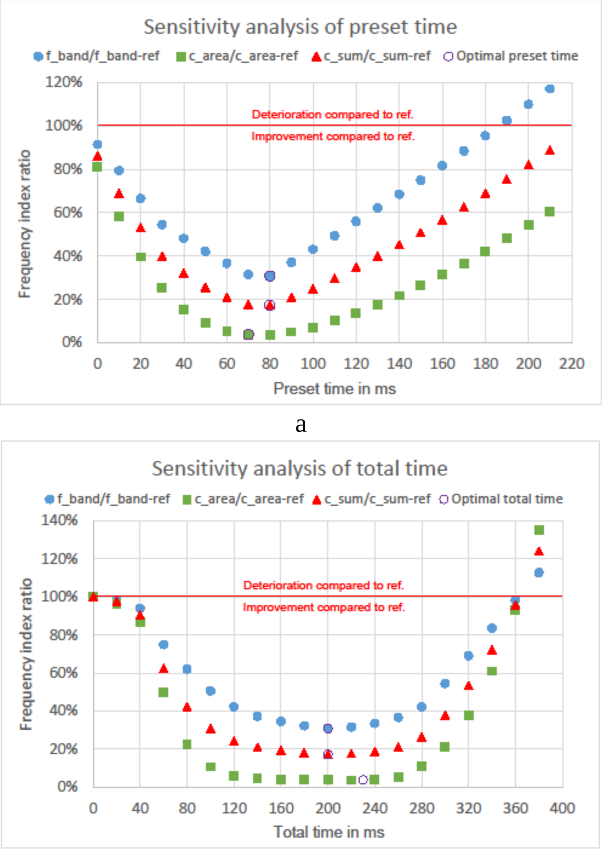
As it is difficult to find a mathematical approximation of the optimal values of time parameters, optimization is done through dynamic simulations of the test MG for a range of preset and total time. It is also important to examine the impact of time parameters of LSP and BB controller being set to be longer or shorter than their optima on frequency deviation of the islanded MG. Thus, a sensitivity analysis is conducted. It is analysed by changing one of the time parameters at a time, while the other parameters are fixed at their base values. The simulated islanded MG having a 25% share of PV presented in [3] is further investigated. For the exemplary islanded MG, the base values of optimal preset and total time determined by criteria 3 are found to be at 80 ms and 200 ms, respectively. The base values, ranges of variation and increments of the time parameters in the sensitivity analysis are given in Table 2.

Table 2. Time parameter values in sensitivity analysis

Parameter	Base value	Range	Increment
t_{set}	80 ms	0-210 ms	10 ms
t_{total}	200 ms	0-380 ms	20 ms

Figure 3 illustrates the influence of the time parameters of the proposed method on the frequency deviation. The optimal time parameters under the three introduced optimization criteria and their corresponding index ratios are marked by purple circles. For instance, following criterion 1, the frequency deviation band between the maximum and minimum frequency during the dynamic frequency response f_{band} is approximately 0.69 Hz, when the preset time and total time are at their optima. In the same MG without LSP and BB controller, equivalent to both preset and total time being 0, the frequency deviation band $f_{band\text{-}ref}$ is around 2.23 Hz. The same procedure is carried out for criteria 2 and 3 to obtain $c_{area}/c_{area\text{-}ref}$ and $c_{sum}/c_{sum\text{-}ref}$.

Comparing the two time parameters of the proposed control method, the frequency deviation is less sensitive to total time near its optimal value than to preset time. As shown in Figure 3, if the time parameters lead to the frequency index ratio below 100%, which is in the region below the red dotted line, the three variables f_{band}, c_{area} and c_{sum} are smaller than their reference values. In this case, LSP and BB controller have a positive effect on the frequency deviation caused by power imbalance in the islanded MG, although time parameters are not at their optimal values. If one of the three frequency index ratios exceeds 100%, the respective setting of preset and total time should not be permitted, because the situation is deteriorated.



a

b

Figure 3. (a) Sensitivity of preset time to frequency stability, (b) Sensitivity of total time to frequency stability

4.2 Effects of LSP and BB control

To show the effect of the proposed control method, a comparison of dynamic operating limits of the simulated islanded MGs having shares of PV of 25% and 50% is presented in Figure 4.

As can be seen, both the steady state and dynamic limits in the islanded MG with 25% share of PV are higher than in the one with 50% share of PV. This is because less dispatchable active power is available to supply load demand if more PV is integrated. For negative load steps, the steady state and dynamic limits are the same. Hence the proposed control method cannot improve the negative dynamic operating limit. In case of a high initial load, or if PV reacts with time delay, the negative dynamic limits can be different from the steady state limit, and thus, an improvement of dynamic operating limit is expected. In addition, the maximum dynamically allowable negative load step limits are greater than the maximum positive load step limits. This is because both CG and PV participate in stabilizing frequency during frequency rise in case of load reduction whereas only the CG is able to increase its power if frequency drops due to more load to be supplied.

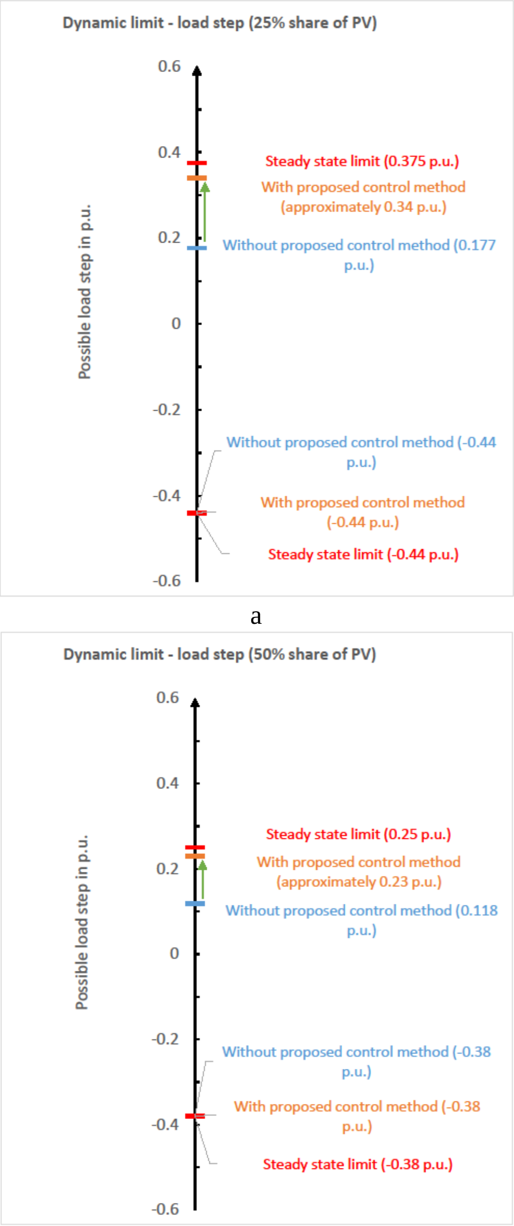


Figure 4. Dynamic limit improvement by implementing LSP and BB controller (a) 25% share of PV (b) 50% share of PV

If only frequency control is applied in the islanded MG, the allowed maximum positive load step is 0.177 p.u. in the MG with 25% share of PV while the allowed maximum positive load step is 0.119 p.u. in that with 50% share of PV. If LSP and BB controller with optimal preset and total time settings are included in the system, the maximum allowable positive load steps of both MGs are 0.34 p.u. and 0.23 p.u. respectively. In comparison to the MG only with frequency control, the maximum allowable load steps can be brought closer to the steady state limits of the MGs with both 25% and 50% share of PV by implementing the proposed control method. The improvement of the dynamic positive load step limit with LSP and BB controller is larger in the MG with 25% share of PV than with 50% share of PV. Since LSP and BB controller only have an influence on the active power output of the CG, their control effect is stronger and more active power can be dispatched if the MG has a higher share of CG and a lower share of PV. The steady state limit of this MG setting is 0.375 p.u., which is the upper boundary for the dynamic operating limit.

5. Conclusion

Implementing LSP and BB controller in the islanded MG improves system dynamic reaction on power disturbances significantly. With optimal time parameters, the control effect of LSP and BB controller is maximized. Furthermore, the sensitivity of time parameters is examined. Three introduced criteria show a wide range of time settings in which the frequency response is enhanced. This illustrates that the proposed control method is robust even when it operates with non-optimal preset or total time. However, the more reliable the choice of time parameters are, the better the control effect of LSP and BB controller is.

The enhancement of the dynamic operating limits by the proposed control method is the most important measure for its effectiveness. For the exemplary MG with both 25% and 50% share of PV, its maximum dynamically allowable positive load step is doubled. The optimized LSP and BB controller bring the dynamic operating limits close to the steady state limits. This means the control method exploits nearly the entire potential of enhancing system frequency response.

6. References

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