OPTIMIZING LOAD STEP PRE-ANNOUNCEMENT AND BANG-BANG CONTROLLER FOR ENHANCED ISLANDED MICROGRID FREQUENCY STABILITY

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Abstract

A novel control method that can assist conventional frequency control to improve frequency stability of islanded microgrids is presented. As two time parameters strongly affect the performance of the proposed method, definition and influential factors of optimal time parameters are studied, focusing on the dependency on non-controlled generation and load variation. A test islanded microgrid is simulated. Using three optimization criteria, correlations between influential factors and optimal system time parameters are investigated. The effectiveness of the control method is presented in terms of dynamic simulation results.

1 Introduction

In islanded mode, microgrids (MGs) tend to have a low inertia in comparison to large traditional power systems, especially when there is a high penetration of power electronic interfaced power sources in the MG. Hence conventional frequency control alone may not be sufficient for stable islanded MG operation. To assist frequency control to keep frequency stable within islanded MGs, a novel control method, including load step pre-announcement (LSP) and bang-bang (BB) controller, was developed in [1]. Two time parameters, preset and total time, significantly affect the performance of the proposed method. They determine the time available to increase or decrease active power of conventional generation (CG) in advance of an anticipated load change, how much CG active power change is realized in total, and hence the magnitude of the resulting dynamic frequency deviation. Preset and total time are optimized following three criteria [1, 2], which seek to minimize the frequency deviation band, a defined frequency deviation area index and an index that combines both.

In this paper, definition and influential factors of optimal time parameters are studied, focusing on the dependency of optimal time parameters on the share of non-controlled generation, e.g. photovoltaic (PV) generation, and on the size of load step. Total time influences the CG active power change during the entire activation time of the proposed method.

2. Control Method

2.1 Concept of control method

The concept of the proposed control method, LSP and BB controller, is to anticipate active power changes, which result in imbalances between load and generation, by proactively delaying them for a specific time interval, so that any dynamic effect on frequency deviations caused by them can be smoothed by a pre-emptive system reaction.

LSP anticipates load changes and delays them by the preset time (t_{set}). Meanwhile, the bang-bang controller ramps up or down the conventional generation for a time, referred to as total time (t_{total}). Active power infeed of conventional generation based on directly coupled rotating machines can be controlled in advance, and thus, frequency control in islanded MGs is supported.

2.2 Frequency limitations of control method

As LSP and BB controller are introduced to provide dynamic support to the islanded MG, their most important feature is that the frequency disturbance caused by them does not create an instability issue. The frequency deviation resulting from the BB control effect before load actually changes should be within a certain range. The lower frequency limit is 49 Hz, which is determined based on the ENTSO-E RG CE general under-frequency load shedding (UFLS) scheme [3]. For the upper frequency limit, 51.5 Hz is used to avoid distributed generation (e.g. PV) disconnection caused by overfrequency according to the frequency-dependent active power characteristic defined by the German VDE-AR-N 4105 standard [4]. This means that the BB controller should not be activated if the frequency would drop below 49 Hz or raises above 51.5 Hz.

Figure 1 shows the frequency limitations during the time interval determined by preset time. At the end of the preset time interval, system frequency should not rise higher than 51.5 Hz or drop below 49 Hz due to the active power change of the CG, so that no cutting-off of the PV generation or load shedding occurs. Since the calculated system frequency should be limited within 49 Hz to 51.5 Hz, possible settings of the preset time for which LSP delays the load switch signal and the CG changes its active power output following the BB control in advance can be determined.

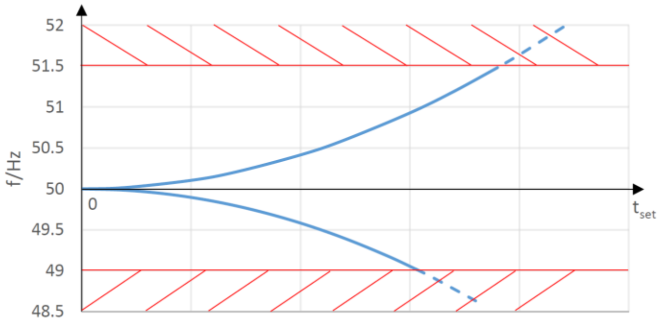


Figure 1. Frequency limitations during time interval determined by preset time

2.3 Optimization criteria

The performance of the proposed method is influenced by the two time parameters. In order to achieve the best control effect, the time parameters need to be optimized. Three optimization criteria that consider the frequency deviation band (criterion 1), the frequency deviation area (criterion 2) or a combination of both (criterion 3), respectively, are defined in [1] to assess the dynamic frequency response and find optimal time settings. With the optimal time settings, the proposed control method maximises the dynamic operating limits. The dynamic operating limits indicate the maximum dynamically allowable positive and negative load steps that can be handled by the islanded MG without violation of the frequency limits [2].

LSP and BB controller can improve system frequency stability for positive as well as negative load steps. However, as the influence of the control method on the frequency behaviour is similar for positive and negative load steps, this paper only focuses on positive load steps. The corresponding findings and description of positive load steps are also equivalent for negative load steps.

3 Influential Factors

According to [1], the optimal preset and total time may differ in the islanded MG depending on the properties of the MG. A sensitivity analysis is conducted to find out how the outcome of a model depends on changes of input parameters and which input parameters are the most sensitive to the outcome.

3.1 Test islanded microgrid

The simulated islanded MG as stated in [1], only consisting of a CG, PV infeed and a lumped load, is used as a study case. The islanded MG is modelled in per unit base and its total size is defined by the maximum load demand that can be supplied by its installed capacity. The parameters of the exemplary MG are given in Table 1.

Table 1. Settings of exemplary islanded microgrid

Parameter	Description	Value
s_{CG}	Share of CG	75%
s_{PV}	Share of PV	25%
P_{CGset}	Initial set point of active power of CG	0.375 p.u.
P_{PVact}	PV's currently available active power	0.125 p.u.
$P_{L\text{-}in}$	Initial load supplied by MG in per unit base	0.5 p.u.

3.2 Sensitivity analysis

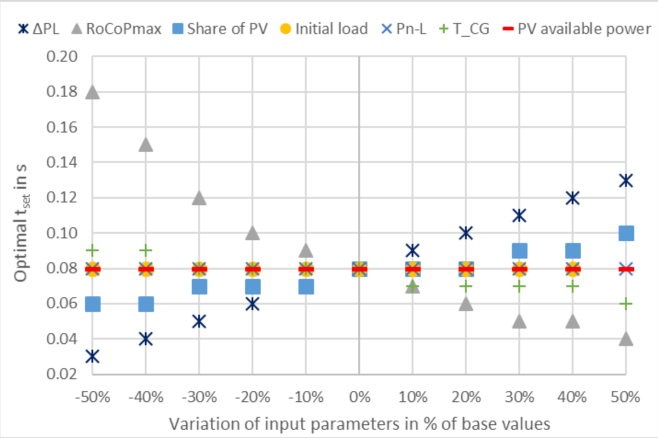
The sensitivity analysis is performed by changing one parameter at a time while keeping the other parameters constant at their base values. The parameters are varied with a step size of 10% of their base value in the range of ± 50% from their base value. The base values of the parameters that are examined in the sensitivity analysis are given in Table 2.

Table 2. Input parameters used in sensitivity analysis

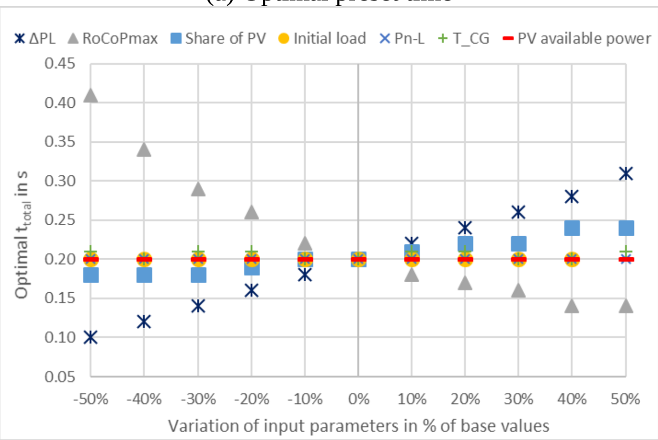
Parameter	Description	Base Value
ΔP_L	Load change	0.15 p.u.
$RoCoP_{max}$	Maximum rate of CG's active power change	± 0.75 p.u./s
s_{PV}	Share of PV	25%
$P_{L\text{-}in}$	Initial load supplied by MG in per unit base	0.5 p.u.
$P_{n\text{-}L}$	Total size of MG	40 kW
T_{CG}	Starting time constant of CG	0.6 s
P_{PVact}	PV's currently available active power	0.125 p.u.

The three optimization criteria show similar results as stated in [1, 2], therefore the optimization criterion 1 that evaluates the frequency deviation band is used for the investigation in this section. Figure 2 illustrates how the optimal time parameters determined by criterion 1 change, while the input parameters are varied. The choice of optimal time parameters is apparently independent from three input parameters, namely initial loading status, total size of MG and amount of active power of PV being available. However, the other four parameters listed in Table 2 have an influence on the optimal settings of the time parameters.

The optimal preset and total time should be set to be higher than the base value in case of a larger load step, and vice versa. This is because a larger load step requires more power from the CG, which results in a longer time of power change. Both time parameters have a linear relation to the load step. If the CG has a larger power gradient, i.e. a faster power change, it needs a shorter time to reach the expected load demand. Thus, both optimal preset and total time are shorter for higher $RoCoP_{max}$ and conversely. In Figure 2, different shares of PV take adjusted $RoCoP_{max}$ into account in order to keep full rate of power change of the CG at ±100% of its rated power per second. For a fixed MG total size, a higher share of PV means a smaller rated power of CG. This leads to the CG needing a longer time to increase its power generation to match the same amount of load change. Hence if the MG has a higher share of PV, the optimal time parameters are longer. The bigger the starting time constant of the CG (T_{CG}), which slows down the frequency change of the MG in case of a power deviation, is, the smaller the optimal preset time. However, the optimal total time does not vary strongly while the starting time constant varies on either side of the base values.



(a) Optimal preset time



(b) Optimal total time

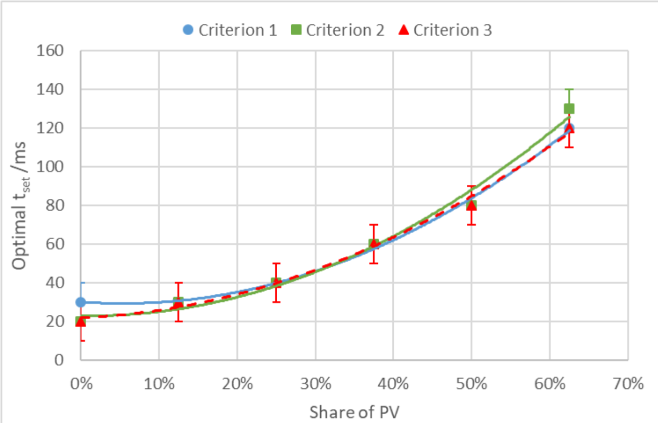
Figure 2. Sensitivity of input parameters to optimal outcomes

4 Simulation and Discussion

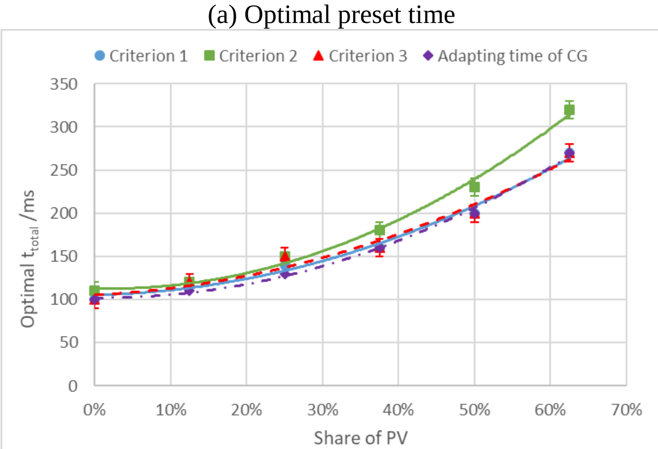
4.1 Analysis of optimal time parameters

As discussed above, the optimal time parameters are influenced by the share of PV, the load step, starting time constant and full rate of power change of CG. For a specific CG, starting time constant and full rate of power change are constant. Therefore, the impacts of share of PV and load step size are further analysed while other input parameters are fixed in this section. The MG with the parameters from Table 1 is used. The full rate of power change of the CG is assumed to be ±100% of its rated power per second and its starting time constant is 0.6 s. The initial load to be supplied is 0.5 p.u. at 50 Hz and the available active power of the PV is 50% of its rated power.

To test how the share of PV influences the optimal settings of the preset and total time of LSP and BB controller in the islanded MG, the load increase is assumed to be 0.1 p.u. Each optimal preset or total time is obtained while the other time parameter is set to be at its optimum. Figure 3(a) presents the relation between share of PV and optimal preset time. The blue, green and red curves represent the optimal preset time determined by criteria 1, 2 and 3, respectively. Since criterion 3 is a combination of criterion 1 and 2, its results are expected to always lay within the range of results of criterion 1 and 2. As can be seen, for all three criteria described in [1], the optimal setting of preset time should be larger for an increase of share of PV. Figure 3(b) shows the correlation between optimal total time and share of PV as well as between adapting time (t_{adp}) and share of PV. The adapting time of the CG refers to the time that it needs to change its mechanical power at full rate until it matches the amount of power that the increased or decreased load demand requires. As the simulation is conducted with 10 ms increments of the time settings, the upper and lower limits of the confidence interval are set to be the neighbouring points.



(a) Optimal preset time



(b) Optimal total time

Figure 3. Correlation between total time and share of PV

As shown in Figure 3, the optimal total time of the proposed control method is estimated to be the same as the adapting time of the CG to match its active power to the expected load change. This is because it is practical for the BB controller to command the CG to change its active power to be equivalent to the anticipated change of the load demand. The CG generating too much or too little active power according to the BB control signal may result in the need of a further change of power in the MG due to the remaining power imbalance.

Unlike for the total time, a mathematical prediction of the optimal preset time was not performed. Optimal preset time is determined by simulations. Since LSP and BB controller are implemented in the CG, they can only influence the active power generation increase or reduction of the CG. A further analysis between optimal preset time and loading status of the CG is conducted. As stated above, the optimal settings of preset and total time are independent from the initial loading status. This is also valid for the initial loading status of the CG under the assumption of linear behaviour of the CG. Therefore, the relation between optimal preset time defined by optimization criterion 3 and expected change of CG loading is presented in Figure 4. The expected change of CG, which is related to both share of PV and size of load step, refers to the difference between CG loading after a load step occurs and its initial loading status.

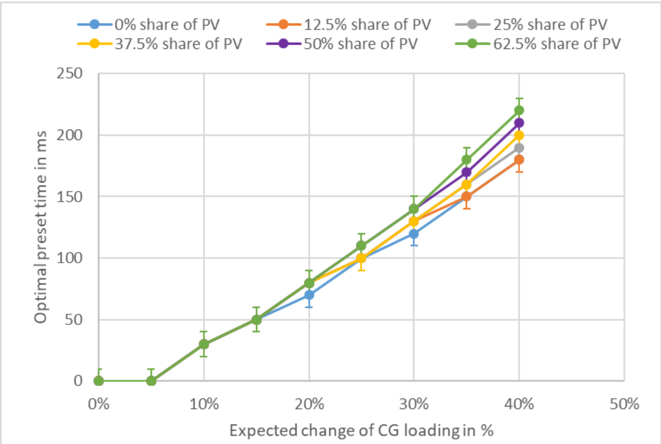


Figure 4. The relation between optimal preset time and expected change of CG loading in case of a load change

As can be seen, optimal preset time shows a nearly linear dependency on the expected change of CG loading for all test cases. However, if the expected change of CG loading is below 5%, the optimal preset time is 0. For load steps that require less than 5% change of CG loading, the proposed control method does not need to be implemented in the MG, as the frequency deviation that is caused is not significant enough. These load steps can also be carried out under conventional frequency control without the risk of leading to frequency instability. However, LSP and BB controller with preset time being 0 and total time being at its optimal value may improve frequency dynamic behavior. In this case, the BB control makes the CG change its active power at a faster rate once the load changes in comparison to the CG only being regulated by frequency control. Therefore, system frequency response is enhanced as already discussed in [2]. If the preset time is not equal to 0 while total time is at optimum, the proposed method changes active power of the CG before the load increase, and thus, increases system frequency by the end of the preset time interval. As for small changes, the frequency maximum is the peak when the load increase occurs. Its size increases for growing t_{set} and it is expected that a higher peak at this moment results in a lower frequency nadir in a given setup. Therefore, the frequency dynamic response in the MG is worse in these cases compared to those where preset time is 0, while total time is at its optimum.

As presented in Figure 4, if load steps require more than 20% change of CG loading, a higher share of PV results in a longer optimal preset time for the same expected change of CG loading. For the test MG setup, a preset time being longer than 70 ms leads to a frequency increase over 50.2 Hz in the MG regardless of the share of PV if the CG has the dynamic properties as previously described in section 3. The optimal preset time is approximately 70 ms when the expected change of CG loading is 20%, see Figure 4. In case of the preset time being higher than 70 ms, the PV starts to reduce its active power infeed following the frequency change by the end of the preset time interval according to the VDE-AR-N 4105 standard under the assumption of the PV generation reacting to frequency deviations instantly. This requires the CG to further increase its active power before the load step takes place. Therefore, if the expected change of CG loading is higher than 20%, it takes longer for the CG to meet the load demand in the MG with a higher share of PV, meaning a longer optimal preset time. This effect gets stronger if the expected change of CG loading increases. For larger load steps, change of CG loading is required to be larger as well. This leads to a higher frequency increase by the end of the optimal preset time interval. Corresponding to larger frequency increase, the PV reduces its active power infeed more strongly. Hence the influence of share of PV on optimal preset time increases when the expected change of CG loading is higher.

4.2 Dynamic simulations

In order to understand the effect of time parameters on the performance of the proposed control method under a load increase, dynamic responses of the test islanded MG with different shares of PV as well as with only conventional frequency control (t_{set} = t_{total} = 0) and with the proposed method including the respective optimal time parameters are simulated. Figure 5 presents the results of the corresponding dynamic simulations of the MG with different shares of PV.

The blue solid and yellow dash-dotted lines in the diagram present the dynamic response of the islanded MG only with frequency control. Since LSP and BB controller are not applied, the CG starts to change its active power under primary and then secondary control to stabilize the system frequency and the PV generation provides active power following the P-f characteristic curve based on the VDE-AR-N 4105 standard when frequency deviates. The red dotted and purple dashed lines represent the dynamic behaviour of the MG implementing not only frequency control but also LSP and BB controller under their optimal time settings.

As presented by the yellow dash-dotted line in Figure 5, with only conventional frequency control, frequency decreases to 48.2 Hz in the islanded MG with 50% share of PV, caused by a 0.1 p.u. positive load step. In this case, a load shedding action is necessary to maintain the frequency stability. If LSP and BB controller are implemented together with frequency control in the MG, the frequency response of the MG can be improved. For the MG with 50% share of PV (purple dashed line), the optimal preset and total time are 80 ms and 200 ms, respectively. In this case, the CG is able to increase its active power at the full rate for 80 ms before the load is actually changed. The load change is realized after the 80 ms preset time. Since the BB controller is still activated after the load change, it continues to command the CG to increase its power output at the full rate. When the total time of the BB controller, namely 200 ms, is elapsed, it stops to override the control of the CG, which then returns to the normal operation mode. Because of the CG's pre-emptively generated power controlled by the BB controller and the effect of LSP, at the end of preset time, the frequency increases to approximately 50.25 Hz. After the load increase, the CG keeps increasing its active power until the end of total time interval. This enables CG to reach the active power required by the load earlier than the MG without LSP and BB controller. Frequency nadir of the purple dashed line is 49.6 Hz, which does not exceed the lower limit of 49 Hz. Therefore, UFLS scheme is not applied.

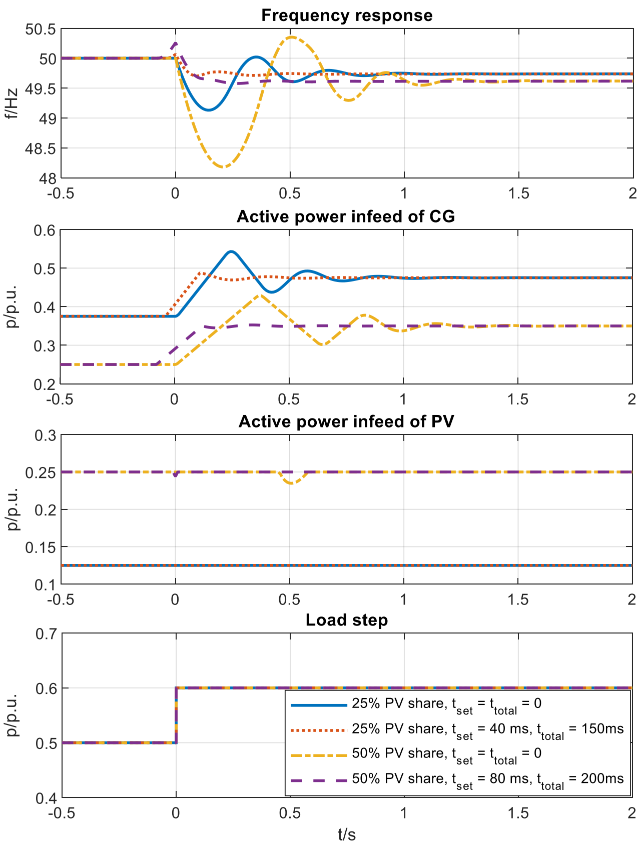


Figure 5. Dynamic simulation of test islanded microgrid

Improvement in frequency stability, to a lesser extent, is observed in the MG with 25% share of PV as well (blue solid and red dotted lines). For both PV shares, the exemplary MG implementing LSP and BB controller features a better reaction on power imbalances and shows lower frequency deviations than the one without LSP and BB controller. The designed LSP and BB controller, thus, enhance the performance of the MG control system.

5 Conclusion

The simulation results illustrate that the dynamic frequency behaviour is significantly improved by the proposed control method with optimal settings of preset and total time for both 25% and 50% share of PV. The performance of the proposed LSP and BB controller is strongly dependent on preset and total time. At the optimal time settings, the performance of the control method is maximised.

The choices of preset and total time are influenced by four parameters, namely size of anticipated load step, full rate of CG's active power change, share of PV, and CG starting time constant. In general, in order to have a positive control effect on MG dynamic behaviour in case of a load change, preset time should be set to be shorter than total time. Otherwise, the CG stops adjusting its active power before the load step takes place and diminish the control effect of LSP and BB controller. Optimal preset time approximately has a linear relation to the expected change of CG loading. Contrary to preset time, the optimal total time is found to be as long as the CG requires to change its active power output to match the expected load change. In this case, no power mismatch is foreseen after total time.

6 References

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