Energy Management in Autonomous Microgrid Using Stability-Constrained Droop Control of Inverters

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Abstract—This paper presents an Energy Management System (EMS) for a stand-alone droop-controlled microgrid, which adjusts generators output power to minimize fuel consumption and also ensures stable operation. It has previously been shown that frequency-droop gains have a significant effect on stability in such microgrids. Relationship between these parameters and stability margins are therefore identified, using qualitative analysis and small-signal techniques. This allows them to be selected to ensure stability. Optimized generator outputs are then implemented in real-time by the EMS, through adjustments to droop characteristics within this constraint. Experimental results from a laboratory-sized microgrid confirm the EMS function.

Index Terms—Droop control, Energy Management System (EMS), microgrids, small-signal stability.

I. INTRODUCTION

MICROGRIDS have received increasing attention as a means of integrating distributed generation such as combined heat and power (CHP) into the electricity network. Usually described as confined clusters of loads, storage devices and small generators (< 500 kW), these autonomous networks connect as single entities to the public distribution grid [1]–[3]. The low-voltage non-50/60-Hz power output of many forms of small-scale distributed generation—including wind turbines, fuel cells, reciprocating gas engines, and energy storage—means that power-electronic converter interfaces are required. While such low-inertia interfaces tend to make microgrids sensitive to disturbances, they enable flexible operation of the connected generators [4], [5].

Real-time optimization is therefore feasible in microgrids, through frequent adjustments of generator outputs to minimize costs or meet other targets [6]. Optimization may include power flow to the public network: energy for storage can be bought when prices are low, and then used when the grid connection is unavailable. Energy Management Systems (EMS) have been proposed to coordinate such functions [7]–[12].

An important consideration when implementing optimal generator outputs is system stability. When the microgrid is operated in stand-alone mode, its dynamics are strongly dependent on the connected sources and on the power regulation control of the converter interfaces [4], [5]. This is similar to a conventional grid where the system stability is largely influenced by the synchronous generators. For droop-controlled microgrids, which offer advantages in terms of autonomous operation, analysis has shown that the parameters that determine generator power sharing have a significant effect on stability in stand-alone operation [4]. A deeper understanding of this effect is required, to allow an EMS to apply real-time optimization. This paper presents the application of small-signal stability analysis, previously developed in [4], to an EMS for a laboratory-size droop-controlled microgrid. Experimental results have been collected to validate the proposed control strategy.

II. MICROGRID STRUCTURE

The laboratory microgrid under study, which is fully described in [4] and [13], has three distributed generators (DG) with 10-kW inverter interfaces, and two local load buses, as shown in Fig. 1(a). Each DG is represented by a dc supply. Inverter power controllers regulate the real and reactive power outputs, by providing reference values for the output voltage magnitude and phase. These references are based on two sets of droops: real power versus voltage frequency and reactive power versus voltage magnitude. The real droop power, of particular interest here, is characterized by a frequency set point $f_{set}$ and a droop gain $g_{fP}$ (see Fig. 1). The generator rating $P_{rating}$ limits the extent to which the droop is applicable.

When connected in parallel, generators share real power demand according to their combined droops. This determines the system operating frequency $f_{op}$ [see Fig. 1(b)]. To implement a particular droop operating point—with a certain power sharing at a chosen frequency—an EMS, in real time, can therefore adjust the generator droop settings relative to each other.

The microgrid studied in this paper is a three-phase balanced system with all generators and loads being balanced three-phase entities. Although out of scope of this paper, it is worth mentioning that in a practical scenario a microgrid might include single-phase generators and loads resulting in unbalanced network conditions. The droop-based power controllers of the three-phase inverters, studied in this paper, use low-pass filters to eliminate the double frequency components (and harmonic components) in the measured power that result from these unbalanced conditions. This means the three-phase DG inverters are controlled to share only the fundamental-frequency balanced portion of the loads. Further research is needed to model and study unbalanced system conditions and to determine a suitable sharing/dispatch strategy where unbalance is significant.
III. EMS DESIGN

Three functions form the proposed EMS, which is implemented on a PC: droop stability analysis, droop selection, and generator dispatch optimization [see Fig. 1(a)]. The control loop, which consists of the two latter online functions, optimizes the generator power sharing approximately every 15 s by communicating new droop settings, based on demand read back from the inverter outputs. Droop stability analysis is carried out offline.

A. Droop Stability Analysis

The droop stability analysis uses a small-signal state space model of the prototype microgrid. Such a model has been presented in full in [4], where analysis has shown that the dominant low-frequency eigenvalues are influenced primarily by the elements of the real power controller, and in particular by the frequency-droop gains \( k_p \) (hertz per watts). These affect both system stability and transient performance. While a thorough analysis of droop gains in terms of transients would also be useful, the work presented here focuses on the relationship between droop gains and stability margins.

Fig. 2 illustrates the motion towards the imaginary axis of the two dominant eigenvalue pairs as \( k_p \) is increased, for a case when all inverters employ the same droop settings. \( f_{set} \) is also adjusted alongside \( k_p \), to keep the droop operating point fixed; the EMS would similarly adjust both parameters, to achieve desired generator power outputs and operating frequency. While a thorough analysis of droop gains in terms of transients would also be useful, the work presented here focuses on the relationship between droop gains and stability margins.

Fig. 2 shows that a high droop gain makes the microgrid less stable, with instability occurring at \( k_p^\text{max} \). For \( k_p < k_p^\text{max} \) each droop gain can be annotated as \( k_p^\text{eff} \), with a corresponding stability margin of angle \( \theta \). This angle is also shown in Fig. 2 and decreases as \( k_p^\text{eff} \) increases. Based on this, an EMS could limit \( k_p^\text{eff} \) to some \( k_p^\text{max} \) to achieve a desired level of damping.

However, the eigenvalues in Fig. 2 are specific to a particular microgrid operating point, due to the small-signal analysis. \( k_p^0 \) and \( k_p^\text{max} \) change in real-time with the power flow. Rather than the EMS constantly recalculating these values, a more practical approach is to identify qualitatively the situations that limit the most. This information can be used to construct a limit case, with a set of \( k_p^0 \) and \( k_p^\text{max} \) defined with capital letters as \( K_p^0 \) and \( K_p^\text{max} \). For a particular \( K_p^0 \), any operating condition within the extent of the limit case would then be assumed to exhibit at least the corresponding stability margin \( \theta \). The stability analysis can therefore be carried out offline.

1) Limit Case Analysis: For the limit case analysis, two methods are used. First, it is observed that the microgrid is less damped when all inverters have the same \( k_p^0 \), than if one or more inverters have droop gains below this value [13]. This can be confirmed from Fig. 3, which depicts the trace of two dominant eigenvalue pairs (marked as \( \lambda_1-2 \) and \( \lambda_1-3 \)). It can
Generator load sharing has a less straightforward effect. Results show that \( k_p^{\text{max}} \) is lower when DG1 supplies a large proportion of the demand, for inverter output powers down to 0.5 kW. The largest variation of \( k_p^{\text{max}} \) with respect to the reference case (approximately 8%) arises from the variation of line inductance but this is a relatively small variation and supports the approach of using a single \( K_p^\theta \) and \( K_p^{\text{max}} \) in the EMS. It should be noted that the base case is a planning choice and this can vary from system to system. If we chose another base case, the values in Fig. 4 would change but modeling of the microgrid suggests that the basic behaviors would be the same.

Based on Fig. 4, the limit case considered here is: DG1 generates at full capacity (10 kW) while DG2 and DG3 generate near zero capacity (0.5 kW), at a low operating frequency (49.5 Hz), and with all load placed at BUS3. Fig. 5 shows how \( K_p^\theta \) varies with stability margin \( \theta \) for this situation. Droop gain versus stability margin is also shown for the reference case, and when the limit case has been extended to include worst-case variation in impedance values (assumed to be resistances +10% and inductances −5%). These plots diverge more at low stability margins; the biggest difference in droop gain occurs at \( \theta = 0 \) degrees. At this point, the effect of impedance variations with respect to the limit case can be expressed as \( \Delta K_p^{\text{imp}} \approx -2.7 \times 10^{-6} \) (Hz/W).

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2) Experimental Validation of Limit Case Analysis: The laboratory microgrid was operated according to the limit case, in order to compare its stability performance with that of the small-signal model. Dominant eigenvalues were approximated from load step changes, by visually identifying the oscillation frequency and exponential decay of the inverter power output. At \( k_p = 2.51 \times 10^{-5} \) (Hz/W), the shape of this response (shown in Fig. 6 as a relative change from an initial value) has a frequency of 7.7 Hz and a decay constant of 1.75, giving an eigenvalue with a stability margin of \( \theta \approx 2 \) degrees. Additional droop gains yield eigenvalues that correspond to the stability margins \( \theta \) in Fig. 7. Although slightly less damped, the experimental
fig. 6. step response shape for \( k_p = 2.51 \times 10^{-5} \) (Hz/W). The dominant eigenvalue gives a stability margin \( \theta \approx 2 \) degrees.

fig. 7. droop gain versus stability margin \( \theta \) at limit case operation, for experimental \( (k_p^e) \) and simulated small-signal analysis \( (k_p^{imp}) \) data. \( \Delta k_p^{exp} \approx -2.3 \times 10^{-5} \) Hz/W.

setup agrees well with the model limit case. When shifted down, the simulated curve is a visual fit of the experimental data in the shown region of stability margins. The shift is \( \Delta k_p^{exp} \approx -2.3 \times 10^{-5} \) Hz/W.

To further test the validity of the limit case, the microgrid was again run according to limit case settings, except the operating frequency \( f_{op} \); this was varied from above, to just below, 49.5 Hz. \( k_p = 2.6 \times 10^{-5} \) Hz/W was chosen to place the limit case operation, occurring at 49.5 Hz, on the instability. When adjusted by \( \Delta k_p^{imp} \) and \( \Delta k_p^{exp} \), Fig. 7 shows that this droop gain corresponds to \( k_p = 3.1 \times 10^{-5} \approx k_p^{max} \) Hz/W. As a lower \( f_{op} \) reduces \( k_p^{max} \) (see Fig. 4), the analysis suggests that the microgrid is likely to become unstable for \( f_{op} \) below 49.5 Hz. Fig. 8 confirms this; the inverter power outputs become increasingly oscillatory until one inverter finally cuts out.

These results suggest that it is possible to ensure a stability margin of \( > \theta \) degrees in the laboratory microgrid by applying the corresponding \( \Delta k_p^\theta \) from the model limit case, adjusted by \( \Delta k_p^{exp} \) and \( \Delta k_p^{imp} \) to account for the small modeling inaccuracies and impedance variations. Some limitations should be noted, however. First, while \( \Delta k_p^{imp} \) compensates for impedance variations in the choice of \( k_p^\theta \), the value obtained for \( \Delta k_p^{exp} \) is also subject to such inaccuracies as well as to errors in the approximation of eigenvalues from step responses. Such errors are difficult to eliminate completely, and are often dealt with in the field by selecting a slightly larger stability margin than calculated theoretically.

Second, the value used for \( \Delta k_p^{exp} \) is based on a narrow range of small stability margins. Since Fig. 5 shows that different operating cases diverge more in this range, however, it is reasonable to assume that the difference between the model and the experimental microgrid diminishes at larger stability margins. Finally, the previous stability analysis is specific to the chosen limit case and therefore does not consider, for example, operating frequencies below 49.5 Hz. However, the method proposed in this paper can easily be extended to incorporate additional operating conditions and factors, including nonlinear loads, offline generators, generator dynamics, or different network topologies that may arise due to line outages.

B. Inverter Droop Selection

A desired droop operating point—with a particular generator power sharing (P1, P2, P3) and system frequency \( f_{op} \)—can be achieved with a range of combinations of droop characteristics (see Fig. 1(b)). These options differ with regard to system performance. While high gains \( k_p \) reduce the stability margin (see Fig. 2), low gains increase the response time, which results in poor transient behavior in terms of higher energy storage requirements to deal with increased transient energy exchange. The settings also determine how the droop operating point...
moves in response to external influences such as load changes. For instance, high gains can force a significant step in operating frequency in response to a load change. Similarly, droop gains may prompt a generator that operates near maximum or zero dispatch to exceed its rating or absorb power, which requires appropriate control or protection measures. Consequently, the choice of droops is a tradeoff between stability margin, dynamic performance, and shifts in the droop operating point.

One straightforward method to select droops is to set identical gains $k_p$ in all generators, based on this tradeoff. Generator power sharing then becomes decoupled, determined only by the frequency set points $f_{set}$. For a chosen $k_p$, $f_{set}$ is calculated for each generator as in (1) based on a suitable operating frequency $f_{op}$ and the optimal generator output $P_i^g$ requested by the dispatch optimization. This method is employed in the EMS proposed here. However, equal $k_p$ force generators to share equal in any change in load power until the EMS’s next re-dispatch action. This is not necessarily desirable. Alternative approaches can be envisaged where nonidentical droop gains are used to restrict changes in power output of particular generators or tailor the system performance in other ways

$$f_{set} = f_{op} + k_p \cdot P_i.$$  \hspace{1cm} (1)

Reactive power droop gain is selected as a compromise between two contradicting requirements: a high droop gain for better transient response where as low droop gain for better voltage regulation. Also, due to high R/X ratio of low voltage cables active and reactive power control is not completely decoupled and a precise reactive power sharing can not be achieved [13]–[15]. Some solutions were already reported to over come this problem, such as the one presented in [16]. Sometimes a large variation to voltage magnitude (and hence, large value for reactive power droop gain) can also give a better reactive power sharing. However, since the microgrid system stability is less affected by reactive power droop gain compared to real power droop gain (as explained in [4] and [13]), and the focus of the paper is on economic dispatch of real power in a stable manner, the reactive power droop gains are kept constant throughout this work.

C. EMS—Generator Dispatch Optimization

A generator dispatch optimization is included in the EMS to demonstrate the implementation of several power sharing scenarios. For this purpose, the fuel minimization problem formulation in (2) is sufficient, although more extensive problem formulations or other methods may be appropriate, including issues such as generator dynamics or using real-time data such as fuel or energy pricing. The algorithm finds the optimal dispatch factor $x_i$ for each generator $i$, which is a fraction between 0 and 1 of the generator capacity $P_{rating,i}$. Constraints ensure that power ($P_{demand,i}^e$) and heat demands ($P_{demand,i}^h$) are met, where the heat generated depends on the power-to-heat ratios (PHR) of available CHP generators. They also include restrictions on the generator dispatch factors: an upper bound (UB) to maintain a fast reserve, as is common in traditional power systems, and a lower bound (LB), because a switched off generator has not been covered by the stability analysis and may jeopardize the stability of the system

$$\min_{x_i} \left\{ \sum_{i=1}^{3} F_{rates,i}(x_i) \right\}$$

subject to $$\sum_{i=1}^{3} P_{rating,i} \cdot x_i = P_{demand}^e$$

$$\sum_{i=1}^{3} P_{rating,i} \cdot \left(1/PHR_i\right) \cdot x_i \geq P_{demand}^h.$$  \hspace{1cm} (2)

The fuel consumption rates $F_{rate}$ for the optimization algorithm (see Fig. 9) have been taken from the technical datasheets of a 100-kW microturbine (MTU) [17] and two 300-kW gas engines [18]. The 100-kW microturbine data has been fitted as a fourth-order polynomial and scaled linearly with output power to represent a 200-kW unit. Similarly, the 300-kW gas engine data has been approximated by linear functions and then scaled to a 400-kW lean-burn and a 200-kW rich-burn engine. Dispatch factors for these hypothetical units are applied to the 10-kW inverters, to implement the power sharing on the microgrid. DG1 and DG2 represent the 400 and 200 kW gas generators, while DG3 represents the 200-kW MTU.

IV. EMS EXPERIMENTAL VERIFICATION

Stable microgrid operation and the function of the complete EMS have been verified, for optimal dispatch of the units described in the preceding section. Dispatch factors (constrained by lower and upper bounds of 0.1 and 0.9, respectively) and output powers are shown in Fig. 10, for loads of 20%–85% of installed capacity. The microturbine is assumed to have a power-to-heat ratio of 0.6. Heat demand is set to 50% of its thermal capacity; it is consequently required to operate at a dispatch factor $\geq 0.5$. As expected, the 400-kW lean-burn gas engine is preferred over the less efficient 200-kW unit.

In the droop selection, equal droop gains were used in all inverters ($k_p = 2.39 \times 10^{-5}$ (Hz/W)). Adjusting for $\Delta K^{exp}$ and $\Delta K^{exp}$, this value corresponds to $K^{exp} = 2.89 \times 10^{-5}$ (Hz/W) with a stability margin of $\theta \approx 1.25$ degrees (see Fig. 7). A larger margin would normally be selected, to avoid events such as tripping of generators due to a transient over shoot, but a low margin
was chosen here to show that the microgrid’s stability is maintained even in the worst case scenario. Frequency set points \( f_{\text{set}} \) were selected to give an operating frequency \( f_0 \approx 49.5 \) Hz at the optimal generator power outputs, from (1). As in the limit case in the stability analysis, the full load was applied on BUS3 and DG1 (the 400-kW gas engine) supplied most of the load at high demands.

Fig. 11 shows the stable outputs of the microgrid inverters as the load is increased progressively from 20% to 80% of the (scaled) generating capacity. The output profiles reflect the fact that inverters initially react to a load change based on their existing droops (point B). Within one EMS communication cycle, these droops—and hence power outputs—are adjusted to reflect updated optimal dispatch levels (point C). The profile shapes can be compared to the optimal power levels in Fig. 10.

V. CONCLUSION

This paper has described an EMS for a droop-controlled stand-alone microgrid, which successfully implements optimal generator dispatch levels by selecting droops from a region where the stable operation of the microgrid can be guaranteed. Three key elements make up the proposed EMS: droop stability analysis, droop selection, and generator dispatch optimization. The stability analysis stage illustrates an "offline" method of identifying the stability constraints imposed by droop characteristics, using a small-signal approach. Droop selection then identifies a specific set of droop characteristics from the stability-guaranteed region, in order to implement optimal power outputs. The required power outputs are provided by the optimal generator dispatch, which effectively is a fuel optimization algorithm aimed at reducing the operating costs of the microgrid.

Particular emphasis has been paid to the impact of droop gains on stability, because these parameters have been found to play a significant role in the microgrid’s dynamic performance. The proposed analysis is based on the use of a sufficiently accurate small-signal model and a limit case to establish a single stability constraint. Experimental data has been presented that supports the validity of these methods. Other operating conditions, such as offline generators or different network topologies that may arise due to line outages, can be incorporated in the analysis to extend its use. Finally, by providing a deeper understanding of microgrid stability, the proposed analysis may make it feasible to implement more sophisticated DG droop settings in stand-alone microgrids, to further improve their performance.

REFERENCES


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