Robust Control of Microgrid Frequency with Attached Storage System

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Abstract—In this paper, we propose a robust control strategy for reducing system frequency deviation, caused by load fluctuation and renewable sources, in a smart microgrid system with attached storage. Frequency and voltage deviations are associated with renewable energy sources because of their inherent variability. In this work, we consider a microgrid where fossil fuel generators and renewable energy sources are combined with a reasonably sized, fast acting battery-based storage system. We develop robust control strategies for frequency deviation reduction, despite the presence of significant (model) uncertainties. The advantages of our approach are illustrated by comparing system frequency deviation between the proposed system (designed via μ-synthesis) and the reference system which uses governors and conventional PID control to cope with load and renewable energy source transients. All the simulations are conducted in the Matlab™ and Simulink™ environment.

Index Terms—Energy storage, Power systems, Smart grids.

I. INTRODUCTION

Microgrids are essentially modern, small-scale (electrical) power distribution systems. They afford numerous benefits, such as enhancing system reliability, reducing capital investment and carbon footprint, and diversifying energy sources [1]. Microgrids contain several generators, whose sizes may range from several tens of kilowatts to a few megawatts [2]. They are different from traditional centralized electricity networks, which transmit vast amounts of electrical energy across long distances at very high voltages. However, they are similar in utility scale power distribution grids, which generate, transmit and regulate electricity to the consumer locally. To improve the efficiency of microgrids and to reduce fossil fuel usage and pollution, renewable energy sources may be integrated with traditional microgrids. Renewable energy sources include photovoltaic power, hydro power and wind power. These are clean and abundantly available energy sources. Due the cost effectiveness of wind turbine generation (WTG), it is one of the fastest growing clean power sources [3]. However, since the output power of WTG is proportional to the cube of the (varying) wind speed, it significantly impacts system stability, and can cause large frequency and voltage (F&V) deviations in a microgrid [4].

For critical installations such as military bases, security concerns have increased interest in utilizing microgrids that allow the facility to operate in islanded mode for extended periods with renewable energy sources involved. It is critical to maintain the F&V deviations within a small range to satisfy military operating requirements. High-speed, grid-attached storage systems such as batteries have been proposed for reducing F&V variability. However, due to high cost, battery sizes must be minimized and therefore may saturate during transients, aggravating F&V deviations. In such situations, conventional control approaches are no longer sufficient to constrain these deviations within a small range, and at the same time limit the battery size. More sophisticated robust control algorithms are needed to achieve better performance despite unexpected disturbances and model uncertainties. A variety of control methods have been proposed for tackling this kind of problem. Proportional-integral-derivative (PID) control has been well studied by a number of researchers [5], [6]. PID control methods are well understood, but have limited ability to tradeoff overshoot, rise time and damping oscillations. \( H_\infty \) control is considered in [3], [7]. Note that \( H_\infty \) control does optimize system tradeoffs, but robustness to model uncertainties is not addressed. Fuzzy logic control is utilized in [8]–[10], but it is difficult to develop a good (simulation) model for Fuzzy logic control, which can facilitate fine tuning the controller. In the work proposed here, we emphasize a robust control approach, which can simultaneously deliver a-priori performance guarantees, whilst controlling against inherent system uncertainties.

Our work develops robust control strategies for both the battery and conventional generation systems, with controllers designed to minimize battery size while at the same time significantly reducing frequency variation, despite variable loads in the microgrid, and the incorporation of a WTG source. Our controllers are designed to cope with load transient, WTG output fluctuations, and model uncertainties. They are compared with conventional PID control approaches, and it is shown that relatively small amounts of storage can dramatically decrease frequency deviation, but only if saturation conditions are avoided by dynamically coordinating storage with other generation sources.

Following the introduction in section I, the rest of the paper is organized as follows. In section II, the system configuration is presented. Some theoretical background of \( \mu \)-synthesis is briefly presented in section III. In section IV, the
\(\mu\)-synthesis controller is designed. Simulations are conducted in the Matlab\textsuperscript{TM} and Simulink\textsuperscript{TM} environment, and the simulation results are presented and discussed in section V. Finally, some concluding remarks are presented in section VII.

II. SYSTEM SETUP AND MODELING

A typical setup of a microgrid with storage system is shown in Fig.1. The energy sources include both conventional and renewable generation systems. On the common bus-bar are energy sources, variable loads, and also a battery-based storage system. The attached storage system is used for suppressing the high frequency load transients caused by renewable energy sources. In order to maintain the nominal frequency in such a system, more advanced control techniques are required to deliver the system performance requirements.

In order to minimize the frequency deviation (\(\Delta f\)), a mathematical model is used for system analysis and controller design. This model consists of three parts: conventional generator (CG), storage system (SS) and Wind Turbine Generator (WTG). The corresponding Simulink\textsuperscript{TM} models are shown in Fig.2, Fig. 3 and Fig. 4. Note that in order to limit the model complexity, simple first order transfer functions are used for modeling (and controller design). Since \(\Delta f\) is caused by the imbalance between the power generated and the power consumed by the load, signals in the model are first normalized to per-unit, and then shifted to deviations around ‘0’ (corresponding physically to deviations from nominal 60Hz [11]). Hence, the load variation, the SS output variation and WTG output variation are denoted as: \(\Delta P_{\text{load}}, \Delta P_{\text{batt}}\) and \(\Delta P_{\text{wind}}\) respectively. These three signal are summed at the summing block in the CG model along with the CG output variation \(\Delta P_{\text{gen}}\).

In our model, \(\Delta P_{\text{batt}}\) and \(\Delta P_{\text{gen}}\) are controlled power deviations, as shown in Fig.2 and Fig.3; the control signals are ‘\(u_g\)’ and ‘\(u_{\text{batt}}\)’ respectively. \(\Delta f\) is considered as the error signal. The controller receives measurements ‘\(y\)’ and outputs actuation/control signals ‘\(u\)’. Although \(\Delta P_{\text{batt}}\) is a controlled output, the output is limited by a saturation block so as to prevent fast charge and discharge. In addition, the State of Charge (SoC) variation of the SS is modeled by integrating its output power deviation. It is controlled indirectly by commanding \(\Delta P_{\text{batt}}\). Meanwhile, \(\Delta P_{\text{load}}\) and \(\Delta P_{\text{wind}}\) are considered as perturbations to the system in the robust controller synthesis methodology. There is no control over these two signals. Here, the controlled outputs are used for minimizing \(\Delta f\), regardless of how the perturbations vary.

A real wind profile is used here with a sample time of 50ms simulated for 500s. The WTG actual output power (\(P_{\text{wind}}\)) is normalized by its rated output (\(P_{\text{wg}}\)) and again shifted to deviations around “0” (in the linear model). \(P_{\text{wind}}\) is “0” unless the angular speed of the gearbox output is higher than the synchronous angular speed. A fixed pitch angle \(\beta\) of 10\(^{\circ}\) is used. Our controller does not command the WTG, rather the WTG produces power according to the given wind speed profile (and hence acts as an unknown “disturbance” as far as our system is concerned). Tip speed ratio (\(\lambda\)), power coefficient (\(C_p\)), windmill output (\(P_{\text{wm}}\)), Slip (\(s\)) and WTG output power (\(P_{\text{wg}}\)) as shown in Fig.4, and are given as: \(\lambda = R_w \cdot \omega/V_{\text{wind}}\); \(C_p = f(\lambda, \beta)\) [14]; \(P_{\text{wm}}=C_p(\lambda, \beta)V_{\text{wind}}^3\rho A/2\); \(s = (\omega_0 - \omega)/\omega_0\); \(P_{\text{wg}} = \frac{(R_2-s_s)(1+s_s)R_2}{(R_2-s_s)^2+s_s(1+s_1+s_2)\lambda_s}\) where \(V_{\text{wind}}\) is the wind speed, \(A\) is windmill rotor cross section area, \(\omega_0\) is synchronous angular speed, and \(\omega\) is angular rotor speed for a windmill [15]. All the modeling parameters are listed in Table. I.

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![Fig. 1. Structure of microgrid with attached storage system.](image1)

![Fig. 2. Conventional generator (Small Power System) model [12] [13].](image2)

![Fig. 3. Battery model [3].](image3)

![Fig. 4. Wind turbine generator model [4].](image4)
TABLE I
MODEL PARAMETERS

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<th>Parameter</th>
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<td>Governor time constant $T_g$</td>
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<td>Diesel engine time constant $T_d$</td>
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<td>Inertia constant $M$</td>
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<td>Damping constant $D$</td>
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<td>Speed droop $R$</td>
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III. UNCERTAINTIES AND ROBUST CONTROL

No mathematical model can exactly describe a physical system. This modeling error can dramatically affect the performance of a control system. The difference between the actual system and its mathematical model (used to develop controller designs) is known as model uncertainty. The two types of uncertainty which are taken into consideration while designing a robust controller are:

1) **Modeling Errors**: These arise due to inaccurate dynamics in the model of the plant (particularly at high frequencies).

2) **Unmodeled Dynamics**: These arise due to neglected or unknown dynamics of the plant.

These perturbations are usually lumped together in a structured uncertainty description $Δ$ where $Δ = diag(Δ_i)$ is block diagonal (see Fig. 5).

$H_2$, $H_∞$ and $µ$-synthesis controllers are all designed based on optimal/robust control theory. Among them, only $µ$-synthesis control is specifically designed to cope with system uncertainties. In our work, the D-K iteration approach is used for $µ$-synthesis controller design. Note that $µ$-synthesis controllers are designed so as to deliver both robust stability and robust performance. Of course, $µ$-synthesis sacrifices some nominal performance (as compared to optimal control methods like $H_∞$) but provides robustness to model uncertainties. Robust control theory has been studied extensively in the literature, and we refer interested readers to [16] and [17] for detailed information. The Robust Control ToolBox™ from Matlab™ is used in this paper for design and analysis/simulation purposes. Finally, note that we utilize conventional PID control for comparison purposes.

IV. CONTROLLER DESIGN

A. Uncertainty weights selection

Nominal models of the small power system and battery are shown in Fig.2 and Fig.3. Multiplicative model uncertainties of 5% and 3% are added to model blocks ‘Diesel’ and ‘Rotating Mass and Load’ to represent modeling errors as shown in Fig.6. Unmodeled high frequency dynamics can also be included as additional perturbations [18], but we do not do so here. Measurement noise is added to the frequency deviation and SoC signals. In addition, control signal penalty weights are also included. Note that there are three control signals; the first one is designated for low frequency diesel engine control, the second one is assigned for high frequency battery control, and the third is used for maintaining the battery at 50% of its SoC. These signals are separately penalized (because of different desired constraints).

B. Performance weights selection

The WTG output is not assumed to be under our control. Its power is directly fed to the same summing point as the load. Hence the net load, which needs to be fulfilled by the generator and battery, is due to both the physical load and the WTG output. The net load profile exhibits both high and low frequency variations. The low frequency load variations are taken care of by the diesel generator. The battery has the ability to deliver/absorb power to/from the system more quickly (via charge/discharge), and so it is used to damp the high frequency variations. Hence our controller profile needs to utilize primarily the diesel engine at low frequency, primarily the battery (charge/discharge) at high frequency, but then also monitor the battery SoC (which is a low frequency signal) and avoid draining/overcharging it. Fourier Transform analysis is applied to the load and WTG output. The frequency spectrum analysis shows that the notable amplitudes of load profile are below 1Hz. The WTG output spectrum shows that its amplitude is widely spread between 1Hz to 10Hz.

The weights are selected in such as way as to reflect the above frequency content of the (desired) signals, with weighting functions active in the desired frequency ranges. If the constraint is to be imposed across all frequency, then a constant gain is used. Hence, the weights on the control error for generator ($W^e_g$), battery ($W^e_b$) and SoC ($W^e_{SoC}$) are selected as:

$$W^e_g = \frac{20}{s+0.0001} \quad \text{(1)}$$

$$W^e_b = \frac{20s+1}{s+0.001} \quad \text{(2)}$$

$$W^e_{SoC} = \frac{50s+0.001}{0.5s+0.1} \quad \text{(3)}$$
The weights on the control input are selected in the same way. The control weight for controlling the diesel engine \( W_{cg} \) and battery \( W_{cb} \) are given as:

\[
W_{cg} = \frac{s + 0.1}{5s + 1}
\]

\[
W_{cb} = \frac{0.2s + 0.1}{100s + 1}
\]

Weights on load \( W_l \) and WTG \( W_w \) outputs are also applied, where \( W_l = W_{cg} \) and \( W_w = W_{cb} \). The selected weights with model uncertainties are shown in Fig. 6.

**C. Design of \( \mu \)-synthesis controller and \( H_\infty \) controller**

Using the system uncertainties presented in section IV-A, and the performance weights we have developed in section IV-B, the state-space design interconnection can be built, and the \( \mu \)-synthesis controller computed, using the Robust Control Toolbox\textsuperscript{TM}. The structured uncertainty \( \Delta \) (normalized so that \( \| \Delta(s) \|_\infty < 1 \) [19]), together with the uncertainty weights, sets the robustness requirements. Note that the PID controller is tuned based on the nominal plant, so that robustness is not specifically addressed, although of course classical control tuning approaches (gain and phase margins etc.) implicitly try to cope with uncertainty.

**V. Simulation and Discussion**

The load and WTG output deviation in pu \( (\Delta P_L \text{ and } \Delta P_w) \) are shown in Fig.7 and Fig.8. \( \Delta P_w \) is about 30% of \( \Delta P_L \). In this section we show a series of simulation results for the \( \mu \)-synthesis and PID controllers.

From Fig.7 and Fig.8, we can see that from 240s to 310s, the load decreases and WTG output increases, which implies there is surplus power in the system. This causes the system frequency \( f \) to increase and so \( \Delta f = f_0 - f \) will decrease, where \( f_0 \) is the nominal frequency. This is also shown in Fig.11. The load and WTG output variations have steep transients in this time interval \( (\Delta t) \), and the load and output power are compared in Fig. 10. The figure shows individual generation/load power deviations from their respective nominal values, e.g., at 248s in Fig.10, the generator increases its output power by 7% to match the 5% increase in load and 2% decrease in wind generation. The generator output is following the load and
provides the major portion of power. The battery is reacting to the high frequency transients.

Fig. 10. Power variations with maximum rated battery power.

At 307s, load increases by 0.1 pu and WTG output decreases by 0.02 pu. Hence the biggest load transient occurs as shown in Fig. 11. Without the help of the battery, high frequency net load transients must be taken care of by generators. However, the diesel engine cannot react as quickly as a battery, and so $\Delta f$ increases. As shown in Fig. 13, $\Delta f$ reaches almost 3% which is unacceptable. In general, for microgrids, $\Delta f$ should be limited to within 1%, otherwise most conventional breakers will trip.

Fig. 11. Frequency deviations.

Fig. 12. Power variation without attached battery.

Fig. 13. Frequency deviations without attached battery.

Fig. 14. Frequency deviations with 50% attached battery.

Fig. 15. Frequency deviations with 25% attached battery.

Fig. 16. Frequency deviations with 10% attached battery.

Fig. 14 shows that for this particular load and WTG output, in order to limit the $\Delta f$ to within 1%, the battery needs to be operated to at least 50% of its maximum rated output power. If not, breakers will trip and start disconnecting the loads. Fig.15, Fig.16 and Fig.17 show that with the decrease of battery maximum output power, the system frequency deviation increases, since the slower diesel generator (longer time delay) now has to handle fast transients (and it is not as effective as the battery in doing so).

As shown in Fig. 17, even a battery with very limited power output can still reduce $\Delta f$ significantly. Here the output power...
of the battery is limited to 3% of its maximum rated output. Compared to the system without any battery, it limits the maximum $\Delta f$ within 1.4%, and all other variations are kept within 1%.

As we mentioned in the previous section, the PID controller is tuned without specific consideration of uncertainties, especially the unmodeled dynamics. Hence, when the PID controller is used for controlling the plant with uncertainties, a bigger frequency deviation (1.1%) takes place, as can be seen in Fig.18.

![Frequency deviation with 3% attached battery.](image)

![Frequency deviation with PID controller.](image)

VI. ACKNOWLEDGEMENT

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VII. CONCLUSION

In this paper, we have shown that by combining a small battery with a sophisticated robust control algorithm, one can significantly reduce system frequency deviation. This new approach is much more robust, and has better performance, as compared to conventional PID control. Our approach utilizes $\mu$-synthesis for the controller design, and careful weight selection is crucial, to enforce good tradeoffs in the controller. The resulting closed-loop microgrid system does not control the devices independently, but rather employs the generator to handle large slow load transients, allowing the battery to smooth out the fast transients, so that the overall system performance is optimized.

REFERENCES


