Robust AC Voltage Regulation of Microgrids in Islanded Mode with Sinusoidal Internal Model

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Abstract: This paper shows that the $H^\infty$ control is an effective tool for electric voltage regulation. We here consider robust AC voltage regulation of microgrids in an islanded mode. When a microgrid is disconnected from a utility grid, it automatically switches to an islanded mode to provide necessary power using a battery system until the grid is recovered. In the islanded mode, it is important to regulate the electric voltage generated in the grid to track a predetermined AC voltage reference. A difficulty is that there exists unmodeled dynamics in the grid that may cause large power fluctuations. To resolve this problem, we adapt the $H^\infty$ control with a sinusoidal internal model to robust AC voltage regulation in microgrids. Simulation and experimental results confirm that the proposed $H^\infty$ control can achieve robust tracking performance.

Key Words: AC voltage control, microgrids, $H^\infty$ control, internal model principle.

1. Introduction

A smart grid is a system integrating power electricity networks with information and communication technology to improve not only on network efficiency but also on resilience against unpredictable events such as power outage and security breaches. This technology has become a promising future power system paradigm as discussed in [1]–[3]. A microgrid is a small-scale smart grid that can operate both in a grid-connected mode and in an islanded mode; see e.g. [4]–[9]. The grid-connected mode is used for a cooperative operation of a utility grid and distributed power resources in the networks. On the other hand, the islanded mode is turned on and activated when the microgrid is disconnected from the utility grid, in which the necessary power must be locally provided by distributed power resources or power storage systems in the microgrid. For example, in case of blackout, backup battery systems such as uninterruptible power supply systems and plug-in electric vehicles automatically discharge necessary power for home appliances connected to the microgrid [10]–[15]. In such an islanded mode, battery systems should regulate the electric voltage to track a predetermined AC voltage reference (usually 50 or 60 Hz sinusoids) as promptly as possible, so that the power supply is of the same quality from the utility grid.

A large number of attempts have been made for AC voltage regulation via PI (Proportional-Integral) control. However, it is difficult to achieve robust AC tracking by PI control; when there is a fluctuation, the total system cannot provide the pre-assigned sinusoidal output voltage. Therefore, it is mandated by the internal model principle [16] that one should implement a sinusoidal signal generator (internal model) of the same frequency into the closed-loop to robustly track sinusoids. Since PI control cannot provide any sinusoidal generator, it has the fundamental limitation of missing the robust tracking property, which is crucial to guarantee the AC voltage supply in the islanded mode.

We should also note that a microgrid is exposed to various power fluctuations due to changes of various connected loads. Hence we should guarantee robustness against such fluctuations or unmodeled dynamics, and $H^\infty$ control is best suited for guaranteeing this performance under a prescribed plant uncertainty, as opposed to PI control where guaranteed robustness is hard to achieve due to limitations in design parameters. We thus propose a new approach to AC voltage regulation of microgrids in an islanded mode based on $H^\infty$ control with a sinusoidal internal model that guarantees robust tracking and stability.

We also note that while the objective here is to provide a robust control method with a single-phase sinusoidal voltage tracking, the proposed method can readily be extended to three-phase robust voltage controllers as well.

Some remarks on related work are in order. The authors of [17],[18] considered an AC current control method of PWM inverters with a sinusoidal internal model. They proposed a “PIS” controller that consists of a PI controller and a sinusoidal reference generator (whence “S”). However, their approach amounts to assigning gains to these three components, which places unnecessary extra constraints on the structure of the controller, and hence results in the lack of freedom in designing a controller and limits the capability of dealing with robustness. Though the authors of [19] also proposed AC tracking control based on the internal model principle with a linear quadratic regulator, the robustness issue is ignored in [19]. Zhu and co-workers proposed a robust power system stabilizer using Glover-McFarlane’s loop shaping to achieve good oscillation damping for perturbed plants [20]. However, the internal model for AC tracking is ignored. On the other hand, a PR (Proportional-Resonant) control has been attempted for AC...
voltage control to cope with the drawback of steady-state tracking errors occurring in conventional PI control [21],[22]. Yang et al. also considered an $H_{\infty}$ voltage control scheme for three-phase inverters with a second-order weighting function [23]. In both methods, however, the sinusoidal internal model is approximated as a stable second-order system to avoid computational difficulties, and hence exact tracking cannot be achieved, as opposed to our approach where an exact sinusoidal internal model is incorporated. Repetitive control is also proposed for robust AC tracking [24],[25]. While [24] and [25] proposed $H_{\infty}$ control by a repetitive control framework in the presence of unbalanced and nonlinear loads, the infinite-dimensionality of a repetitive controller makes it hard to implement with practical processors since it should have infinitely many poles to track any periodic signals other than a simple sinusoidal wave. If we want to track only a pure sinusoidal wave with a fixed frequency (e.g. 60 Hz), the proposed $H_{\infty}$ controller with the sinusoidal internal model is much simpler than the repetitive controller. In addition to that, the performance of the repetitive controller depends on how to approximate it to a finite-dimensional controller.

The paper is organized as follows: Section 2 presents a model of a microgrid system in an islanded mode. In Section 3, we give an $H_{\infty}$ voltage controller with the sinusoidal internal model. Section 4 shows simulation results that illustrate the effectiveness of the proposed control in comparison with a conventional PI controller. Section 5 shows experimental results on a microgrid test bench of the proposed $H_{\infty}$ controller. Section 6 gives concluding remarks.

2. Microgrid Model

Consider the microgrid system in an islanded mode shown in Fig. 1. This configuration consists of various loads, a voltage controller, and a battery system such as an uninterruptible power supply system and a plug-in electric vehicle. The battery system in the microgrid starts power supply automatically when it detects power outage of the utility grid.

Figure 2 shows a linearized model of the microgrid in Fig. 1. This model consists of voltage controller $K(s)$, PWM inverter $P_{\text{pwm}}(s)$, inverter filter $P_{\text{filter}}(s)$, voltage-current conversion ratio $k_e$, and total load $P_{\text{load}}(s)$. To achieve robust AC regulation, the voltage controller $K(s)$ is designed to minimize the tracking error $e$ between a given AC reference voltage $r$ and the output voltage $y$ of the total load $P_{\text{load}}(s)$. Throughout this paper, we assume that the frequency of the AC reference $r$ is 60 Hz, and the ratio $k_e$ is 0.1.

We note that a number of elaborate and very detailed battery models have been proposed, which are nonlinear and of relatively high-order; see e.g. [26]. However, such a model is quite complex, and not easy to use. Instead, we here adopt the following simple first-order model for the PWM inverter to reduce the implementation complexity of high-order models as in [27],[28], and deal with such complexity via the robustness of the control system:

$$P_{\text{pwm}}(s) = \frac{1}{T_{\text{pwm}}s + 1},$$

where $T_{\text{pwm}}$ is the time constant of the PWM inverter. The time constant can be identified as $T_{\text{pwm}} = 0.0005\text{ sec}$ by a step response test for a PWM inverter used in our experiment (see Section 5).

Next, we give a detailed model of $P_{\text{load}}(s)$ in Fig. 2. We assume that there are $m$ loads with impedance $Z_i(s)$, $i = 1, 2, \ldots, m$, which is modeled as an RL circuit:

$$Z_i(s) = R_i + L_i s,$$

where $R_i$ and $L_i$ are the resistance and the inductance of the $i$-th load, respectively. The total impedance $Z(s)$ is given by

$$\frac{1}{Z(s)} = \sum_{i=1}^{m} \frac{1}{Z_i(s)},$$

and the total load is $P_{\text{load}}(s) = Z(s)$.

We here note that the loads may have unmodeled nonlinear characteristics, and also the total load varies in time since the connected loads to the grid get switched on and off. We model such uncertainties as an additive uncertainty $\Delta_{\text{load}}(s)$ such that

$$P_{\text{load}}(s) = P_{\text{nom}}(s) + \Delta_{\text{load}}(s),$$

where $P_{\text{nom}}(s)$ is a nominal model of the total load. Examples of $\Delta_{\text{load}}$ will be given in the next section where we give a robust control design.

3. $H_{\infty}$ Control with Sinusoidal Internal Model

We now present an $H_{\infty}$ controller design procedure for robust AC voltage regulation in a microgrid. One of the major objectives is to overcome power fluctuations caused by the loads in the microgrid.

Consider the block diagram of the microgrid shown in Fig. 3, where

$$P(s) = k_e P_{\text{filter}}(s) P_{\text{pwm}}(s) P_{\text{nom}}(s).$$

We model the uncertainties in the microgrid as
\[ \Delta(s) = k_i P_{\text{filter}}(s) P_{\text{pwm}}(s) \Delta_{\text{load}}(s). \]  

Note that, by (2), we have

\[ P(s) + \Delta(s) = k_i P_{\text{filter}}(s) P_{\text{pwm}}(s) P_{\text{load}}(s). \]

By suitably describing an upper bound for \( \Delta_{\text{load}}(s) \), and hence \( \Delta(s) \) as well, we can achieve robust voltage regulation under model uncertainties and load changes in the microgrid.

Another objective of the design is robust tracking of the voltage to a prespecified sinusoid against model uncertainties. To this end, we incorporate an internal model of the sinusoidal generator into the controller \( K(s) \) as proposed in [16]. Hence we assume the controller of the form

\[ K(s) = \frac{k_1}{s^2 + \omega_n^2}, \quad \omega_n = 2\pi \times 60 \text{ rad/sec}, \]  

where \( k_1/(s^2 + \omega_n^2) \) is the internal model of the AC reference with angular frequency \( \omega_n \) (here corresponding to 60 Hz) and gain \( k_1 \), and \( K_0(s) \) has no poles at \( s = \pm j\omega_n \).

Figure 4 shows the block diagram for designing the controller \( K_0(s) \). In this diagram, \( r \) is the reference AC voltage signal, \( u \) is the control input, \( y \) is the output voltage, and \( z_e \) and \( z_T \) are the outputs to be controlled for AC voltage tracking and robustness against uncertainty. \( W_T(s) \) gives a description of an upper bound of the complementary sensitivity function that covers the model uncertainties in the frequency domain. We employ the tracking error \( z_e \) for the output of the internal model instead of the actual tracking error \( e \) to make the \( H^\infty \) design problem well-posed, avoiding eigenvalues on the imaginary axis introduced by the sinusoidal internal model. Note that the tracking error \( z_e \) is equivalent to the actual tracking error \( e \) weighted by the internal model \( k_1/(s^2 + \omega_n^2) \) (Fig. 4), and hence, the tracking performance is guaranteed by minimizing the \( H^\infty \) norm from \( r \) to \( z_e \).

For loads in the microgrid, we consider a desk lamp (DL), a washing machine (WM), and a television set (TS), which are switched on and off in time.

Table 1 shows the parameters of the RL circuit model (1), and Table 2 gives all possible respective changes of the loads.

Each uncertainty \( \Delta_i(s) \) is then given as

\[ \Delta_i(s) = k_i P_{\text{filter}}(s) P_{\text{pwm}}(s) (P_{\text{load}}(s) - P_{\text{nom}}(s)). \]

For example, we consider the following inverter filter \( P_{\text{filter}}(s) \) and the nominal model \( P_{\text{nom}}(s) \):

\[ P_{\text{filter}}(s) = \frac{\omega_0}{s^2 + 2\zeta \omega_0 s + \omega_0^2} \]  

\[ P_{\text{nom}}(s) = k_i P_{\text{filter}}(s) P_{\text{pwm}}(s) P_{\text{load}}(s) \]  

with \( \omega_0 = 5774 \), \( \zeta = 0.43 \). Then the model uncertainty \( \Delta_i(s) \) is given by

\[ \Delta_i(s) = k_i P_{\text{filter}}(s) P_{\text{pwm}}(s) (P_{\text{load}}(s) - P_{\text{nom}}(s)) = \frac{N_{\Delta_i}(s)}{D_{\Delta_i}(s)}, \]  

where

\[
\begin{align*}
N_{\Delta_i}(s) &= -1.886 \times 10^{-5} s^4 - 3.784 \times 10^{-10} s^3 \\
&\quad - 1.912 \times 10^{-5} s^2 - 0.01315 s - 1.547, \\
D_{\Delta_i}(s) &= 2.829 \times 10^{-19} s^6 + 2.859 \times 10^{-12} s^5 \\
&\quad + 2.154 \times 10^{-8} s^4 + 1.347 \times 10^{-4} s^3 \\
&\quad + 0.2579 s^2 + 108.35 s + 9437.
\end{align*}
\]

Figure 5 shows the Bode gain plots of these variations, as well as a weighting function \( W_T(s) \) that covers all such load variations. The function \( W_T(s) \) is given by

\[ W_T(s) = \frac{-4.2s - 1910}{1.4 \times 10^{-5} s^4 + 0.032 s^2 + 22.88 s + 5004}. \]  

The gain \( k_1 = 12 \) is adjusted to obtain a satisfactory tracking performance in the transient. The gain \( k_1 \) and the weighting function \( W_T(s) \) in (7) were tuned to achieve the best performance on the microgrid test bench at Panasonic Corporation (see Section 5). In this experiment, due to physical constraints of the test bench, we took a relatively large margin for robust stability as shown in Fig. 5.

The \( H^\infty \) norm of the system from the reference \( r \) to the outputs \( z_e \) and \( z_T \) measures the performance for steady-state tracking and robustness against model uncertainties simultaneously.

Table 2 The corresponding loads to the plant model \( P_{\text{load}}(s) \).

| \( P_{\text{load}}(s) \) | DL, WM, TS |
| --- | --- |
| \( P_{\text{load}}(s) \) | DL |
| \( P_{\text{load}}(s) \) | TS |
| \( P_{\text{load}}(s) \) | WM |
| \( P_{\text{load}}(s) \) | DL, TS |
| \( P_{\text{load}}(s) \) | DL, WM |
| \( P_{\text{load}}(s) \) | TS, WM |

![Fig. 5 Bode gain plots of \( W_T(s) \) and \( \Delta_i(s) \).](image-url)
We thus consider the following $H^\infty$ (suboptimal) control problem. Since it is not always possible or desirable to actually minimize the $H^\infty$ performance index, it is customary to content ourselves with a suboptimal controller that gives a performance close to optimal. For brevity, in what follows, we say “$H^\infty$ control” meaning such an $H^\infty$ suboptimal control.

**Problem 1 ($H^\infty$ Control Problem for $K_0(s)$)** Find a controller $K_0(s)$ that minimizes (or nearly minimizes) the $H^\infty$ norm of the system from $r$ to $z = [z_T; z_v]^T$.

Figure 6 shows the block diagram for $H^\infty$ controller design. In this block diagram, $G_o(s)$ is defined as

\[
G_o(s) = \begin{bmatrix} 0 & W_f(s) \\ 1 & -P(s) \end{bmatrix}.
\]

Then the generalized plant $G(s)$ is given by

\[
G(s) = \begin{bmatrix} 0 & W_f(s) \\ \frac{k_1}{s + W_f(s)} & -\frac{k_1}{s + W_f(s)}P(s) \end{bmatrix}.
\]

With this generalized plant formulation, Problem 1 is numerically solvable via an LMI-based algorithm as in [29] using Robust Control Toolbox of MATLAB.

Let us summarize the procedure of the proposed $H^\infty$ controller design as follows:

1) Construct the generalized plant $G(s)$ shown in Fig. 6.

2) Find a controller $K_0(s)$ by solving Problem 1 with an LMI-based algorithm.

3) The controller $K(s)$ with the sinusoidal internal model is then given by Eq. (4).

The obtained $H^\infty$ controller $K(s)$ is of 9th-order. Due to the hardware constraint of the microprocessor of the test bench, we have reduced the order of $K(s)$ via the balanced truncation, see e.g. [30], to obtain a reduced 6th-order controller $K_r(s) = \frac{N_r(s)}{D_r(s)}$, where

\[
N_r(s) = 3.4 \times 10^5 s^3 + 1.1 \times 10^9 s^2 + 2.6 \times 10^{13} s + 1.2 \times 10^{16},
\]

\[
D_r(s) = s^6 + 2.0 \times 10^4 s^5 + 1.9 \times 10^7 s^4 + 2.8 \times 10^{11} s^3 + 1.3 \times 10^{14} s^2 + 4.0 \times 10^{16} s + 1.8 \times 10^{19}.
\]

Figure 7 shows the Bode gain plots of the closed-loop system with respect to the 9th-order controller $K(s)$ and the reduced 6th-order controller $K_r(s)$. It is seen that the reduced order controller $K_r(s)$ gives almost the same performance as the original controller $K(s)$. In particular, both controllers show the same tracking performance at low frequencies. It is also seen that the reduced order controller $K_r(s)$ achieves zero steady-state error at the reference angular frequency $\omega_n = 2\pi \times 60$ rad/sec (here corresponding to 60 Hz). Though the performance of the 9th-order controller $K(s)$ and the reduced order controller $K_r(s)$ is slightly different at high frequencies, the gain of the closed-loop system quickly falls in both cases. Thus we see that the reduced order controller $K_r(s)$ can effectively attenuate high-frequency noise.

4. Simulation

We show the effectiveness of the proposed robust AC voltage regulation by simulation. We develop a numerical model of the microgrid system by the SymPowerSystems Toolbox of MATLAB/SIMULINK.

4.1 Simulation under Load Variations

We first show a simulation result under the load variations described in the previous section. We consider three kinds of loads: a desk lamp, a washing machine, and a television set in Table 1. In this simulation, the desk lamp is connected at the initial time. The washing machine and the television set are turned on at $t = 0.1$. Then, at $t = 0.2$, the television set is turned off.

Figure 8 shows the output voltage $y$ of the microgrid with the reduced-order $H^\infty$ controller $K_r(s)$ (see Section 3). Figure 9 shows an enlarged view of Fig. 8 in the steady state. This figure shows that the output voltage of the microgrid well tracks the AC reference.

We compare the performance of the exact internal model $k_1(s^2 + \omega_n^2)$ with that of a second-order weighting function proposed in [23]. The authors in [23] considered an $H^\infty$ controller with the following stable second-order weighting function:

\[
W_{so}(s) = \frac{k_0 \omega_n^2}{s^2 + 2\xi \omega_n s + \omega_n^2},
\]

where $\xi$ is a damping factor of the weighting function and $\omega_n = 2\pi \times 60$ rad/sec is the angular frequency for the reference sinusoidal voltage. When the damping factor is sufficiently small, that is, $\xi \approx 0$, the second-order weighting function (8)
Fig. 8 Output voltage $y$ with the $H^\infty$ controller $K_r(s)$ and the RLC filter $P_{\text{filter}}(s)$.

Fig. 9 Steady state output voltage $y$.

Fig. 10 THD performance of $H^\infty$ controllers with the exact internal model $k_1/(s^2 + \omega_n^2)$ and the second-order weighting function $W_{so}(s)$ proposed in [23].

is equivalent to the ideal internal model $k_{so}\omega_n^2/(s^2 + \omega_n^2)$. In this simulation, the damping factor of the second-order weighting function (8) and the gain are $\xi = 0.01$ and $k_{so} = 0.05$. The $H^\infty$ controller for the second-order weighting function (8) is designed by the LMI-based algorithm as in Section 3.

Figure 10 shows the comparison of the THD performance of the exact internal model $k_1/(s^2 + \omega_n^2)$ and the second-order weighting function $W_{so}(s)$ proposed in [23]. From this result, we conclude that the $H^\infty$ controller with the exact internal model achieves the better sinusoidal tracking than that with the second-order weighting function $W_{so}(s)$ even under large load variations.

4.2 Robust Performance

We compare the performance of the proposed $H^\infty$ controller $K_r(s)$ with that of a PI controller. In this simulation, a capacitor input type rectifier is connected to the microgrid. The circuit model of the rectifier is shown in Fig. 11, where $C_{dc} = 1.8 \times 10^{-3}$ F and $R_{dc} = 45$ Ω. We verify robust performance of these controllers against uncertain input time-delays.

Figures 12(a) and 12(b) show the output voltages by a PI controller and the proposed $H^\infty$ controller, respectively. The PI controller has the proportional gain $k_P = 0.002$ and integral gain $k_I = 640$. (These constants have been chosen empirically by a number of trial-and-error experiments to achieve the best tracking performance in the test bench at Panasonic Corporation; note that the gain $k_I$ is quite high.) Figure 13 shows the THD (with time) with the proposed $H^\infty$ controller with input-delay 0.03 sec. On the other hand, the PI controller makes the system diverge at this delay, hence is not shown here; it can tolerate the delay only up to $5 \times 10^{-4}$ sec—way too small compared to the $H^\infty$ control. Figure 14 also shows a comparison of the input by the $H^\infty$ controller against that by the PI controller.
Fig. 13  THD performance via $H^\infty$ control with input delay = 0.03 (sec).

Fig. 14  Inputs of $H^\infty$ controller and PI controller.

Fig. 15  Output of the response against the truncated $H^\infty$ controller.

Since the input by the former is generally larger than that by the latter, it has a sharp peak for the first 0.01 sec. To show the performance of the $H^\infty$ controller, we truncate the input signal of the $H^\infty$ controller with the saturation point at 70 V, which corresponds to the maximum of the input by the PI controller. The corresponding response of the $H^\infty$ controller is shown in Fig. 15. While the response is slightly slower than that shown in Fig. 12(b), it still behaves well even under such an input truncation.

5. Experiments

We here verify the validity and utility of the proposed method via experiments on a microgrid test bench. To this end, we have developed an experimental system shown in Fig. 16. We connect a home-use air conditioner as a nonlinear load that consumes a relatively large amount of power (920 W).

Figure 17 shows the output voltages and currents with the proposed $H^\infty$ controller. The THD of the proposed $H^\infty$ control is 8.1%, which is allowable for real microgrids. Although the $H^\infty$ controller is designed for linear models, this result shows that the proposed $H^\infty$ control can well regulate output voltages and reduce wave distortions for nonlinear loads.

6. Conclusion

We have considered an application of $H^\infty$ control to robust AC voltage regulation in microgrids. We have designed an $H^\infty$ controller for a battery system that includes the internal model of a desired AC reference voltage signal to achieve zero tracking error. The designed $H^\infty$ controller takes account of robustness against load uncertainties and changes in the microgrid, which cannot be achieved by the conventional PI controllers. Simulation and experimental results have shown that the proposed $H^\infty$ optimal control achieves desirable robust performance for AC voltage regulation.

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