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Robust Frequency Control of Islanded Microgrids Using an Extended Virtual Synchronous Generator

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Abstract—Integration of inverter-interfaced distributed generators (DGs), e.g., as microgrids, into traditional power systems, reduces the total inertia and damping properties, and accordingly increases uncertainty and sensitivity to the fault in the system. The concept of virtual synchronous generator (VSG) has been recently introduced in the literature as a solution that mimic the behavior of conventional synchronous generators in large power systems. Parameters of the VSGs are normally determined via comparing the virtual and the conventional synchronous generators. This paper introduces a new extended VSG (EVSG) by combining the concept of virtual rotor, virtual primary and virtual secondary control. A H∞ robust control method is proposed for optimal tuning of the extended VSG parameters. A Microgrid test bench is used to verify the proposed control methodology.

Index Terms—Frequency control, microgrid, robust control, virtual inertia, virtual synchronous generators.

I. INTRODUCTION

In the conventional power systems, the generation is centralized and few synchronous generator (SG) units provide energy for the grid. The SG units provide inertia (due to rotating heavy mass) and damping (due to mechanical friction and electrical losses in stator, field, and damper windings) properties for the system [7]. These properties are initial and intrinsic potential of the system that opposes with changes against faults and disturbances. Recently, integration of inverter-based distributed generators (DGs) and renewable energy sources (RESs) into power systems (due to energy crisis and environmental issues) is rapidly growing, which adds great challenges to the systems performance and stability. Therefore, new control strategies are essential for these systems. To facilitate the integration of DGs/RESs in the distribution system, the concept of microgrid (MG) is proposed in the literature, e.g. [1]. The control strategies for MGs are presented in a hierarchical structure (i.e., primary, secondary, tertiary, emergency, and global control levels). While the upper levels require communication to provide a good performance, droop control, as a communication-less decentralized method, is a widely adopted in a primary level [2]–[4].

High penetration of the DGs/RESs decreases total inertia and damping of the conventional bulk power systems. Thus, systems become more sensitive to the fault and disturbance, and system’s stability margin is decreased. However, most of presented control methods, e.g., conventional droop control, provide barely any inertia/damping support for the grid. To cope with this problem, the concept of virtual synchronous machine/generator (VSM/VSG) has been introduced recently. In fact, VSG mimics the behavior of conventional synchronous generators (SGs). A comprehensive survey on VSGs and the existing topologies are given in [7], [8]. Modeling of the virtual synchronous machine-based grid interface converters for integration of RESs is presented in [5]. Dynamic performances of virtual synchronous generator are investigated in [6]. Furthermore, authors in [5]–[20] address modeling and application of VSGs. Almost all the VSG-based methods are common in emulating the inertia/damping properties of conventional SG via swing equation, virtually. For simpler explication, all of these methods are called VSG control in this paper.

Recently, robust control methods, e.g., H∞, μ-synthesis, and mixed H2/H∞, have gained more attraction in microgrid applications [21]–[24]. The main problems of these robust control methods is high-order of the designed controllers especially for the high-order plants. This paper introduces the concept of virtual inertia for microgrids via an extended VSG. The EVSG combines the concept of virtual rotor and virtual primary/secondary controls. A new method based on H∞ robust control is proposed then, to optimal tuning of the EVSG parameters. The proposed approach is evaluated via a MG test system. The H∞ robust controller (Kp) is designed for the underlying system, correlated with the EVSG parameters, and the obtained optimal parameters is then applied to the DG with low inertia.

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The rest of this paper is organized as follows. Section II describes a brief review about frequency control and the basis of VSG for inverter-based systems. In Section III, a MG test system is introduced as a case study. The H. robust control for this MG system is designed in Section IV. In Section V, a new method based on H-robust control is proposed for tuning the virtual parameters optimally. Simulation results and some scenarios verifying the effectiveness of proposed approach is presented in Section VI. Section VIII concludes the paper.

II. FREQUENCY RESPONSE AND EVSG MODELING

A. Frequency Control

The relation of frequency deviation and difference between generated active power and load is expressed by the well-known swing equation [7]:

\[ \Delta P_m(t) - \Delta P_i(t) = 2H \frac{d \Delta f(t)}{dt} + D \Delta f(t) \]  

(1)

where \( \Delta f \), \( \Delta P_m \), \( \Delta P_i \), H, and D, are frequency deviation, mechanical power change, load change, inertia constant, and load damping coefficient, respectively. Block diagram of this equation in the Laplace domain is shown in Fig.1. Once H and/or D decreased (increased), the rate of frequency deviation and frequency deviation in stable state will increase (decrease), respectively.

In the conventional SGs, frequency control is applied in three phases as follow:
1) Rotating mass (rotor) prevent against frequency deviation (inertia and damping properties).
2) Primary control as governor response, and
3) Secondary control.

Here, the aim is emulating this three control levels for inverter-based systems (e.g., microgrids), virtually.

B. Inverter Model

Inverter is a power electronic interface that convert a dc voltage to ac voltage. It can follow a reference signal by controlling the IGBT gates (e.g. PWM method). Traditional modeling for DC/AC PWM inverters is a first-order element in the s-domain [25]. Generally, the inverters have two separate operation modes, acting as a current source or as a voltage source. Given the value of line/filter parameters, the output voltage and frequency, as well as real and reactive powers of the inverter can be controlled using local feedback applied to the inverter [3, 25]. Therefore, inverters can follow reference power with small time constant, thus, they can be modelled as first order transfer function, as shown in Fig.2.

C. Virtual Rotor

According to the swing equation in (1), the power signal reference \( P_{ref} \) for an inverter can be obtained as

\[ P_{ref} = -(Hs + Di)\Delta f \]  

(2)

where \( H \) and \( D \) are virtual inertia constant and virtual damping factor, respectively. Negatives sign in (2) shows negative feedback. In this paper, \( H \) with \( D \) are considered as virtual rotor parameters.

D. Virtual Primary and Secondary Control

Inverter can be considered as synchronous generator with small time constant. Therefore, similar primary and secondary controllers can be designed for inverters.

Primary control, as initial governor response, and secondary control (here considered a simple integrator) can be expressed as

\[ \frac{1}{R_i} + \frac{K_i}{s} \]  

(3)

where \( R \) and \( K \) are virtual droop characteristics and virtual integrator gain, respectively.

E. Extended Virtual Synchronous Generator (EVSG)

Combining the virtual rotor and the virtual primary and secondary controllers, the inverter behaves as a controlled synchronous generator that in this paper expressed as extended virtual synchronous generator (EVSG). The designed controller for the EVSG is shown in Fig.3. In this figure, \( H_i \), \( D_i \), \( R \) and \( K \) are virtual parameters of the EVSG controller \( K_{evsg} \).

III. CASE STUDY

A MG test system consists of conventional diesel engine generator (DEG), PV systems, wind turbine generator (WTG), fuel cell system (FCs), battery energy storage system (BESS), and flywheel energy storage system (FESS). The DGs are connected to the MG by power electronic interfaces, i.e., inverters. Inverters are used for synchronization with ac sources, i.e., DEG and
The main goal of the frequency controller is to eliminate the frequency deviation, and, accordingly regulating the system frequency in presence of disturbance. In this study, natural changes in wind speed ($\Delta P_w$), and solar radiation ($\Delta P_s$), and load profile ($\Delta P_l$), are the sources of disturbance. It should be noted that a trade off should be taken into account between the effort and energy of the controller as an important parameter and disturbance rejection.

With above performance consideration the whole system can be presented as Fig. 5. To build the system and subsystems the \textit{sysic} command in MATLAB is used. The $W_c$ and $W_u$ are weighting functions that shaped and normalized the output and control signals. The effects of weighting functions in controller design are essential. There is no analytical method to determine the weighting functions optimally [7]. In this study, the weighting functions are selected by trial and error as follow

$$
\begin{align*}
\nu_c &= \frac{0.005 x^3 + 0.05 x^2 + 50 x + 125}{x^3 + 100 x^2 + 300 x + 1} \\
\nu_u &= \frac{5 x + 50}{x^3 + 2000 x + 1.7e4}
\end{align*}
$$

C. Optimal $H_\infty$ Controller Design

The $H_\infty$ controller is an optimization control problem, which minimize the $H_\infty$ norm from disturbance signals ($w$) to the controlled output signals ($y$) in the nominal closed loop system. The controller is described as transfer function of $T_{w2}$. Since there is no an analytic method for solving this optimization problem, it is usually sufficient to find a stabilizing controller such that the $H_\infty$-norm of $T_{w2}$ satisfies the

$$
\|T_{w2}(s)\|_\infty = \|F_c(G,K)\|_\infty \leq 1
$$

In this paper, the \textit{hinfsyn} command in MATLAB robust control toolbox is used to design the $H_\infty$ Controller. The order of designed controller is 22.

D. Nominal Stability and Performance

The nominal stability (NS) is satisfied because the
closed-loop system $T_w$ is internally stable for the designed $K_{\text{ref}}$. For evaluating the nominal performance (NP), the controller must satisfy the performance criterion for all frequencies

$$
\sup_{w\in\mathbb{R}} \delta(T_w(jw)) \leq 1
$$

(8)

Fig. 6 shows that the $\infty$-norm inequality of (8) is satisfied and is always less than one. Thus, the closed-loop system successfully reduces the influence of the disturbance, and the required performance is well achieved.

E. Closed-Loop Robust Stability and Performance

The RS and RP are satisfied for closed-loop system if and only if the closed-loop system be internally stable and satisfy the performance criterion, respectively, for all possible plants in presence of uncertainty. For the structured uncertainty, there exist two theorems for RS and RP based on structured singular value ($\mu$)-synthesis:

1) Robust stability,

Consider $M - \Delta$ configuration in Fig. 7(a) Assume

$$
\Delta^* = \{ \Delta(\cdot) \in \mathbb{R}^n_{\geq 0}, \Delta(s_0) \in \mathbb{L}^{\Delta, \mathbb{C}}, \text{Re}(s_0) \geq 0 \},
$$

(9)

$$
M = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}
$$

(10)

where $M$ is the system that contains the designed controller, and $\Delta$ is uncertainty block that expressed in general form as

$$
\Delta = \text{diag} \left[ \delta_{11}, \ldots, \delta_{1n}, \delta_{21}, \ldots, \delta_{2n}, C, A \right], \Delta_s \in \mathbb{L}^{\Delta, \mathbb{C}}
$$

(11)

The closed loop of system for all $\Delta \in \Delta^*$ and $\|\Delta\|_\mu \leq 1$ is internally stable if and only if the nominal system be stable

$$
\sup_{w\in\mathbb{R}} \mu_s(M) \leq 1
$$

(12)

2) Robust performance,

Consider $M - \Delta_r$ configuration in Fig. 7(b) Let

$$
\Delta_r = \begin{bmatrix} \Delta_s & \Delta_p \\ 0 & \Delta_p \end{bmatrix}, \Delta_s \in \mathbb{L}^{\Delta, \mathbb{C}}, \Delta_p \in \mathbb{C}
$$

(13)

where $\Delta_s$ and $\Delta_p$ (apocryphal uncertain block) represents uncertainty and performance requirements, respectively. The closed loop of system for all $\Delta \in \Delta^*$ and $\|\Delta\|_\mu \leq 1$, guarantees a RP if and only if

$$
\sup_{w\in\mathbb{R}} \mu_s(M) \leq 1
$$

(14)
According to this two theorems, the upper bound for RS and RP are below the unit at all frequencies, as shown in Fig. 8 and Fig. 9. Therefore, the RS and RP (for ±90% change in \( H \) and \( D \)) are satisfied. The \( \mu \) command in MATLAB robust control toolbox is used to determine bounds of \( \mu \).

The frequency response of the system for different scenarios i.e., without any controller, with fine-tuned PI controller, under \( H \)- robust controller (\( K_{rob} \)), is shown in Fig. 10.

V. OPTIMAL TUNING OF EVSG PARAMETERS BASED ON \( H_{\infty} \) ROBUST CONTROLLER

Conventionally, the parameters of VSGs are defined using the parameters of conventional SGs, or based on trial and error method. A robust control method is introduced here for optimal tuning of these parameters.

A. Proposed Method

The basis of this method is that the frequency response of \( K_{evg} \) matched with frequency response of \( K_{rob} \). Notice that, the structure of EVSG controller is more simple than a high order robust controller and this is a great advantage. Once both systems are minimum phase, by matching magnitude of the systems, phases will be matched automatically. Since the \( K_{rob} \) and \( K_{evg} \) are minimum phase, we try to match the magnitude of two controllers in the operating frequency range.

For \( \omega \in (0.1, 562) \text{ rad/s} \), and using of proposed method, the virtual parameters are obtained as follow:

\[
H_1 = 0.9, \quad D_1 = 10.4, \quad K = 12.9, \quad R = 2.8
\]  

Bode diagram of \( K_{evg} \) and \( K_{rob} \) for these new defined parameters are plotted in Fig. 11. As depicted in this figure, the bode diagrams of two controllers are well matched for the operating frequency range.

VI. TIME-DOMAIN SIMULATION RESULTS

In this section the \( K_{rob} \) controller in Fig. 4, is replaced with the optimally-tuned EVSG controller in the previous section, i.e., \( K_{evg} \). The presented MG case study is used to verify the effectiveness of the proposed approach. The following time-domain simulation results show the frequency response of the system in the presence of disturbances (\( \Delta P_l, \Delta P_w, \) and \( \Delta P_s \)) and high perturbation of \( H \) and \( D \) parameters as system uncertainty.

**Scenario I- Performance assessment in the presence of disturbances:**

In this scenario, we assume that solar irradiation, wind speed, and load deviations are changed. The results are provided for step change, as well as random and frequent changes of \( \Delta P_l, \Delta P_w, \) and \( \Delta P_s \). The considered test scenarios are as follows:

1) 0.1 pu step changes are applied to the system for \( \Delta P_l, \Delta P_w, \) and \( \Delta P_s \) at 1 s, 5 s and 8 s. Fig. 12 shows the frequency response of the system for this scenario.

2) Simultaneous and random changes of \( \Delta P_l, \Delta P_w, \) and \( \Delta P_s \) (shown in Fig. 13) is applied to the system, and results are shown in Fig. 14.

**Scenario II- Performance assessment in the presence of system uncertainties:**

Performance of the proposed control method under system uncertainty is examined in this study. The following scenarios are considered:
1) The $H$ and $D$ parameters are decreased up to 75%, while 0.1 pu step in $\Delta P_1$ is applied at 1 s (see Fig. 15).

2) The $H$ and $D$ parameters are decreased up to 90%, while 0.1 pu step in $\Delta P_1$ is applied at 1 s (see Fig. 16).

As seen, the results verify the effectiveness of the proposed method in presence of severe-disturbance and high-uncertainty situations. While the conventional-based EVSG is not able to provide a good performance, the $K_{\text{hint}}$ based-EVSG shows a great frequency response even in severe situations.

VII. CONCLUSION

This paper introduces a new concept called extended virtual synchronous generator, for frequency control of inverter-based systems, e.g., microgrids. Inspired by conventional SGs, the proposed extended VSG includes three virtual modules: rotor, primary control and secondary control. A $H\infty$ robust control method is then proposed to tune the EVSG parameters, optimally. A microgrid test system is used to validate the effectiveness of the proposed approach. The simulation results indicate that correlating the EVSG and robust controller is an effective and suitable approach to optimal and robust design of EVSG. The results report great performance of the proposed robust EVSG in the presence of high-uncertainty situation and large disturbances.

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