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Improvement of small signal stability margin and transient response in inverter-dominated microgrids

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ABSTRACT

Inverter-based distributed generators (DGs) based on renewable sources are widely used in microgrids. Most of these sources operate in droop control mode for effective load sharing. Higher droop is desired in these systems to improve dynamic power sharing, however, such systems suffer from stability issues. Stability margin of a system having different combinations of inverter and synchronous generator-based sources is compared in this work. A microgrid is modeled here with three DGs on a modified IEEE 13-bus system using state space approach. The study showed that lack of stability of inverters restricts the use of higher droop gains, resulting in poor power-sharing dynamics. A modified droop control is proposed to improve transient response and stability margin in such cases. The results are validated with time domain simulations using Simulink/MATLAB.

1. Introduction

With distributed generators (DGs), loads and storage, a microgrid system is capable of operating in grid-connected mode, islanded mode and during transition [1–3]. These DGs can be AC, DC or hybrid and can be converter-interfaced or directly connected. Predictably, inverter-based microgrids will become a trend. Droop control is employed in these inverters for effective power sharing in island mode [4]. These inverters operate in plug-and-play model and hence no additional communication is required. The droop control can be conventional droop (active power vs frequency) or inverse droop (active power vs voltage) depending on the ratio of impedance to resistance of the network. For highly resistive networks, angle droop control is suggested, while for microgrids with inverter-based sources, arctan power–frequency droop can be effective [5–7]. Droop control of a microgrid containing unbalanced and non-linear load has been proposed [8]. A novel droop control based on maintenance cost, fuel cost and emission penalty has been reported [9]. Transient response and power sharing in a microgrid can be improved by dynamically changing (increasing) the droop [10,11].

Recent trends suggest an increase in the use of inverters in microgrids. Due to the intermittent nature of source and loads, a microgrid may be subjected to small signal stability. Research is abundant on small signal stability analysis for conventional power systems with standard models [12–29]. However, such an analysis in microgrids is challenging given the nature of sources, controls, loads and associated models [12]. Issues related to small signal stability, transient stability and voltage stability of utility connected and facility microgrid with scope of improvement are well reviewed in [13–17].

Mathematical models for small signal stability for microgrids with conventional and electronically interfaced sources have been presented in [18–20]. It is known that the stability of a system can be improved by increasing storage but requires additional investment [21]. A dynamic model of an inverter for small signal stability studies has been investigated [22–24] and the significance of system configuration, source variability, operation status and energy storage reported in [12]. Eigenvalue analysis and root locus plot have been extensively used to determine the small signal stability of microgrids [18–32]. It has also been proved that droop could improve the frequency stability and compensate for lack of inertia in weak microgrids [25]. Modeling and analysis of inverter-based microgrids is an area of growing research interest.

Although small signal stability of a microgrid having inertial and non inertial sources has been presented in the literature but the effect of penetration of inverter based sources in a microgrid with synchronous generators on small signal stability is not investigated so far. This paper investigates the effect of inverter based sources on small signal stability of microgrid containing synchronous generator(s). This paper also investigates the enhancement in stability margin of an inverter based microgrid with modified

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droop control. The remainder of the paper is organized as follows: Section 2 presents the state space model of the microgrid and its components. Eigenvalue analysis of the microgrid is presented in Section 3. Section 4 presents the simulation results for various case studies, and conclusions are presented in Section 5.

2. Microgrid modeling for small signal stability analysis

For eigenvalue analysis, state space equation of the complete microgrid is required. These state space equations consist of individual components such as generators, inverters, loads and lines of microgrid.

2.1. Synchronous generator and its associate component modeling

The synchronous generator dynamic modeling in droop control mode is considered for the stability analysis. This divided into three sub-modules: (a) Generator, (b) Excitation system and (c) Prime mover with governing system.

Generator modeling

The stator voltage equations for synchronous generator are given by:

$$V_d = E'_d - R_a I_d - X'_q I_q \tag{1}$$

$$V_q = E'_q - R_a I_q + X'_d I_d. \tag{2}$$

Prime mover and the rotor of the machine are considered to be a single mass unit. The rotor motion equations are given in (3) and (4), while rotor electromagnetic equations are given by (5) and (6).

$$\frac{d\delta}{dt} = \omega_0(\omega - 1) \tag{3}$$

$$\frac{d\omega}{dt} = \frac{1}{M}(P_m - P_e - D\omega) \tag{4}$$

$$\frac{dE'_d}{dt} = \frac{1}{T'_{q0}}[-E'_d - (X'_q - X_q)I_q] \tag{5}$$

$$\frac{dE'_q}{dt} = \frac{1}{T'_{d0}}[-E'_q + (X'_d - X_d)I_d + E_{fd}]. \tag{6}$$

Real power, reactive power, frequency droop and voltage droop equations are given in (7)–(10) respectively.

$$P = E'_d I_d + E'_q I_q \tag{7}$$

$$Q = E'_d I_q - E'_q I_d. \tag{8}$$

Frequency droop equation:

$$\omega_{ref} = \omega_n - m_p P. \tag{9}$$

Voltage droop equation:

$$V_{ref} = V_n - n_q Q. \tag{10}$$

Excitation system modeling

The role of excitation system is to regulate generator terminal voltage through change in current supplied to the generator field winding. Regulator, exciter and damping feedback are basic elements of excitation system (as shown in Fig. 1 and the differential equations governing them are given in (11)–(13) respectively.

$$\frac{dE_f}{dt} = -\frac{1}{T_a}E_f + \frac{K_a}{T_a}(V_{ref} - V_d - V_S). \tag{11}$$

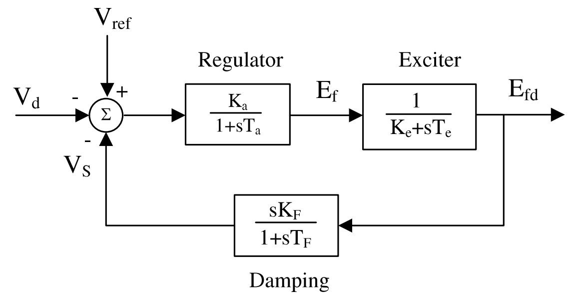

Fig. 1. Excitation system.

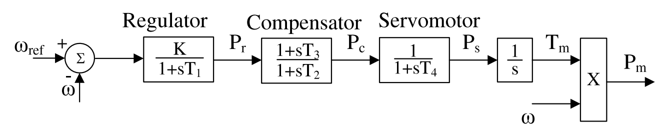

Fig. 2. Prime mover and governing system.

In this study the terminal voltage $V_t = (V_d^2 + V_q^2)^{\frac{1}{2}} = V_d$. q-axis voltage V_q has been made equal to zero through the control.

$$\frac{dE_{fd}}{dt} = -\frac{K_e}{T_e}E_{fd} + \frac{1}{T_e}E_f \tag{12}$$

$$\frac{dV_S}{dt} = -\frac{1}{T_F}V_S - \frac{K_e K_F}{T_e T_F}E_{fd} + \frac{K_F}{T_e T_F}E_f. \tag{13}$$

Prime mover and governing system (PMGS) modeling

Block diagram of prime mover and governing system (PMGS) is shown in Fig. 2. The role of governor is to regulate frequency to its reference value by providing required mechanical power input to the turbine. The output frequency is sensed and compared with reference frequency and the error is fed to the compensator block which in turn adjusts the output of the valve which controls the input of the turbine. Dynamic equations corresponding to PMGS are given in (14), (15), (16), and (17) respectively.

$$\frac{dP_r}{dt} = -\frac{1}{T_1}P_r + \frac{K}{T_1}\omega_{ref} - \frac{K}{T_1}\omega \tag{14}$$

$$\frac{dP_c}{dt} = -\frac{1}{T_2}P_c + \frac{T_1 - T_3}{T_1 T_2}P_r + \frac{KT_3}{T_1 T_2}\omega_{ref} - \frac{KT_3}{T_1 T_2}\omega \tag{15}$$

$$\frac{dP_S}{dt} = -\frac{1}{T_6}P_S + \frac{1}{T_6}P_c \tag{16}$$

$$\frac{dP_m}{dt} = \omega P_S. \tag{17}$$

The complete state space equation of synchronous generator can be obtained by linearizing and combining Eqs. (1)–(17) which can be written as:

$$[\Delta \dot{X}_G] = \bar{A}_g[\Delta X_G] + \bar{B}_{I_g}[\Delta I_{dqg}] + \bar{B}_{V_g}[\Delta V_{dqg}] \tag{18}$$

$$[\Delta V_{dqg}] = \bar{P}_g[\Delta X_G] + \bar{Z}_g[\Delta I_{dqg}] \tag{19}$$

where,
$[\Delta X_G]$, $[\Delta I_{dqg}]$ and $[\Delta V_{dqg}]$ are:

$$[\Delta X_G] = [\Delta\delta\ \Delta\omega\ \Delta E'_d\ \Delta E'_q\ \Delta E_f\ \Delta E_{fd}\ \Delta V_S\ \Delta P_r\ \Delta P_c\ \Delta P_S\ \Delta P_m]' \tag{20}$$

$$[\Delta V_{dqg}] = \begin{bmatrix} \Delta V_d \\ \Delta V_q \end{bmatrix} \tag{21}$$

$$[\Delta I_{dqg}] = \begin{bmatrix} \Delta I_d \\ \Delta I_q \end{bmatrix}. \tag{22}$$