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Hopf bifurcation analysis in droop controlled islanded microgrids

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ABSTRACT

The stability analysis of the microgrid has been carried out by several researchers. However, these studies have been limited to small signal (or linear) stability analysis. Such systems usually lose their stability via Hopf bifurcations. These bifurcations are either subcritical or supercritical. In case of subcritical bifurcations the stable region defined by small signal stability analysis may have unstable limit cycles. In other words, the region identified as stable for (infinitesimally) small signal may be unstable for slightly larger (finite) signal. Therefore, small signal analysis is not sufficient and it is imperative to identify type of Hopf bifurcation for a given system. In order to carry out stability analysis of the system, a generalised model is developed. This model is used for studying stability characteristics of a two bus system, modified IEEE 13 bus system and IEEE 33 bus system. Five different droop techniques from literature are compared with each other for relative stability. A non-dimensional index is proposed, which is used for comparing stability margin for each of these techniques using small signal stability analysis.

1. Introduction

In recent years, there has been an increasing penetration of renewables in electricity grid. These renewable based generation units are smaller in capacity and hence have penetrated more into the distribution network. Renewable generators can be connected to the system directly or through power electronics interface (inverter based system). These inverter based systems respond faster to system dynamics compared to conventional generators. These generators along with loads and storage in the neighbouring network form microgrids. Microgrid is expected to operate in grid connected mode, islanded mode and during transition. Stability and load sharing are two main challenges in microgrid. While these two issues are taken care by the main grid in grid connected mode, the control logic of inverters/generators in microgrid is responsible for maintaining stability and proper load sharing in islanded mode. Power sharing in an islanded microgrid can be achieved either by using a communication based system or by using droop control [1–5]. The problem of load sharing using droop control is widely addressed in literature. The conventional droop control proposed in [6,7] is applicable for high voltage networks. For low voltage networks load sharing is achieved by using inverse droop control, virtual inductance and virtual resistance control techniques. These droop control techniques suffer from low inertia problems. Virtual inertia concept is proposed in [8] to handle problems related to unwanted overshoot of frequency during transition mode.

A droop based low voltage microgrid is vulnerable to load/generation change within the system. Stability analysis of such an islanded microgrid draws serious attention of the researcher. A detailed and generalised dynamic model of voltage source inverter has been presented in [9,10] to investigate the stability of islanded microgrid. Stability margin of the microgrid can be found by varying parameters of system. In this study stability margin of microgrid is studied by varying the droop gain. Higher droop is desirable for proper power sharing among sources in addition to improvement in transient response of the sources [11], and very high value of droop parameter causes small signal instability [9] of system. Hence for the effective operation of microgrid proper selection of droop is desirable.

Depending on the size and combination (mix) of loads, generator and storage, a microgrid is a replica of traditional power system both in terms of size and complexity. The intermittent nature and dynamic behaviour of sources, lack of inertia, response time of the sources contribute to the problems in microgrid in terms of power quality and stability [18].

The qualitative change in the system dynamics when the system parameters are changed is known as bifurcation. Bifurcation analysis has been extensively used to determine the stability margin of electric power system [12–17]. In a microgrid, the two common bifurcations are saddle node and Hopf bifurcation. Saddle

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node bifurcation is associated with voltage stability and this information is useful for operational planning [19]. When the load parameter is varied beyond a certain value, the operating point "vanishes" due to bifurcation leading to the phenomenon of voltage collapse. In [20], a continuation algorithm is developed to detect saddle node point in an islanded microgrid. Hopf bifurcation is observed when the droop parameter is varied in an islanded microgrid. The effect of allocating primary reserves by droop variation on stability due to Hopf bifurcation is presented in [21].

In the present study, linear (small signal) stability boundary is obtained by Hopf bifurcation analysis. However, Hopf bifurcation can be either subcritical or supercritical. Subcritical Hopf bifurcation leads to unstable limit cycle in the (linearly) stable region in the parameter space. Hence, it is considered as dangerous or hard. On the other hand, supercritical bifurcation has stable limit cycles in(linearly) unstable region. Therefore, linearly stable region is stable even for larger perturbation. Hence it considered safe or soft bifurcation. This also shows that linear stability analysis is sufficient if supercritical Hopf bifurcation is seen.

To perform stability studies, the differential equations of the system are obtained and then the operating point around which stability to be determined is found. After finding operating point, parameter variation is done to check the relative stability margin. For small signal stability analysis the system is linearised around the operating point before performing relative stability analysis. One of the major challenges to investigate stability in islanded microgrids is obtaining the operating points through load flow and this problem is severe when the system size increases. The conventional load flow techniques are inappropriate for microgrids with inverters slack bus and voltage controlled modes cannot be employed [22]. Alternatively, load points are obtained by time consuming and complex simulations.

In this paper, a generalised model/tool is proposed to calculate the load flow, operating point and finally determine stability margin based on parametric variation. The information required for this tool/model includes generator parameters, line parameters, load parameters and their interconnection pattern. In order to ensure stable operation of the system, it is important to study the stability boundary and the type of bifurcation associated with the boundary. Detailed numerical study of the dynamics near stability boundary is presented in this paper using the proposed model/tool.

Droop control in islanded microgrids is widely researched and reported in the literature. However, a comparison of these control techniques from stability point of view is important. To make such a comparison, a common metric is to be defined. In this paper a dimensionless index is proposed to compare stability margin of some selected droop control techniques proposed in the literature. The droop control techniques considered for the comparison include conventional [6,7], P-dP, Q-dQ control [3], Modified P-dP, Q-dQ control [23], Virtual reactance droop [24] and Adaptive droop control [4]. Also, the non-linear stability analysis (for relatively large signal) is also carried out to identify whether Hopf bifurcation is subcritical or supercritical for these cases.

In Section 2 generalised model is developed along with the dimensionless index for comparing stability margin. In Section 3, the proposed model is used to obtain tools required in stability analysis. Section 4 presents the study of dynamics near boundary along with stability index for five different droop controls. Section 5 concludes the paper.

2. System description and mathematical model

The mathematical model for microgrid can be represented by a set of differential and algebraic equations of the form

$$\frac{dX}{dt} = f(X, Y, \mu) \tag{1}$$

$$0 = g(X, Y, \mu) \tag{2}$$

where X is the state vector, Y is the algebraic vector and μ is the parameter vector. Generators (inverters, synchronous, asynchronous), loads and interconnecting lines are main constituents of a microgrid. The detailed modelling of each component is given in [9,25,26]. In this study, focus is on microgrids in which power is transferred to the grid from source via a power electronic interface. The inverter control circuit consist of conventional voltage, current and droop controllers. Droop equation implemented in the droop controller gives reference values for the cascaded controllers. For each inverter, model is written in its own reference frame and is then translated onto a common reference frame, which is arbitrarily chosen as the reference frame of first inverter. Model for interconnecting lines and loads are written in the common reference frame. Complete model of microgrid in the form (1) and (2) is obtained by combining the model of each element.

2.1. Block diagram approach

The generalised model of microgrid with proposed block diagram approach is shown in Fig. 1. This system assumes I inverters, B buses, N lines and L loads, represented as separate blocks. It is possible to extend this approach to any number of inverters, line and loads. The parameter vector μ as defined in (3) consists all the data related to inverters, lines and loads (Refer (4)–(6)). The entire microgrid can be modelled using the matrices μ, P_L, P_I and P_N.

$$\mu = [P_{inv} \quad P_{load} \quad P_{line}]^T \tag{3}$$

where

$$P_{inv} = [P_{inv1} \quad P_{inv2} \quad \ldots \quad P_{invI}]^T_{(15I\times1)} \tag{4}$$

$$P_{invk} = [m_{pk} \; n_{qk} \; \omega_n \; V_n \; r_c \; L_c \; r_f \; L_f \; C_f \; F \; K_{pv} \; K_{iv} \; K_{pc} \; K_{ic} \; \omega_c]^T_{(15\times1)} \tag{5}$$

where m_{pk} = Real power droop coefficient of inverter (rad/W-s); n_{qk} = Reactive power droop coefficient of inverter (V/VAR); V_n = Nominal voltage (V); r_c = Coupling inductor resistance (Ω); L_c = Coupling inductor reactance (H); r_f = Filter resistance (Ω); L_f = Filter reactance (H); C_f = Filter capacitance (F); K_{pv}/K_{iv} = Proportional/Integral gain of voltage controller; K_{pc}/K_{ic} = Proportional/Integral gain of current controller; ω_c = common angular speed; subscript k is used for k^{th} inverter.

$$P_{load} = [P_{load1} \quad P_{load2} \quad \ldots \quad P_{loadL}]^T_{(3L\times1)} \tag{6}$$

$$P_{loadk} = [R_{loadk} \quad L_{loadk} \quad TYPE_k]^T_{(3\times1)} \tag{7}$$

In 7, $TYPE_k$ = 1 for constant power loads and $TYPE_k$ = 0 for RL loads.

$$P_{line} = [P_{line1} \quad P_{line2} \quad \ldots \quad P_{lineN}]^T_{(2N\times1)} \tag{8}$$

$$P_{linek} = [R_{linek} \quad L_{linek}]^T_{(2\times1)} \tag{9}$$