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A new linear model for active loads in islanded inverter-based microgrids

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ABSTRACT

Active rectifier loads have major effects on the stability of microgrids, therefore the modeling and analysis of such loads become more popular, recently. In this paper, a new linear state-space model for inverter-based microgrids (IBMGs) as well as active loads is proposed and then the model is corrected using a time-step simulation. The proposed simulation drives the eigenvalues and transient response of such loads and systems directly and quickly which makes the stability analysis of active loads simple. Using these advantages, the load-flow analysis and, moreover, the linearization of equations around an operating point to study small-signal stability are no longer needed. The proposed method can also study large-signal stability analysis as simple and fast as the small one and the execution time of the simulation is much smaller than that of other simulations. The analysis and stability assessment of active loads in IBMGs are easy and fast using the proposed model due to linearity. The validation and comparison of different case studies show the performance of the proposed method.

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Introduction

The introduction of microgrid (MG) is started by the presence of distributed generations (DGs) in distribution networks [1]. The penetration of MGs into power systems has been accelerated by technological advances in small generators, power electronics, and energy storage devices for transient backup. Reliability, security, efficiency and power quality can be improved by these small autonomous regions of power systems and, moreover, such systems can help integrate renewable energy and other forms of DGs [1,2].

Although standards [3] prohibit active voltage regulation and islanded operation of MGs, the high penetration of DG units and power system outage necessitates control provisions for both grid-connected and autonomous operation mode of MG units [4,5]. The main network dictates system frequency and voltage regulation because of the relatively small size of MGs in grid-connected mode. However, such regulation in the autonomous operation mode is a critical control task and is dictated only by micro-sources. Several methods were presented to goal this objective in the literature using a communications link or a droop control method. When a master–slave link was involved in communication approaches, a dispatch signal was used to control DG outputs [6]. A master DG regulates the voltage and frequency of MG and if it is not functioning or does not have enough capacity, the regulation may be not satisfied.

In conventional power systems, frequency/real power and voltage/reactive power droop control has been extensively used. Several droop control methods in the literature have been suggested for islanded operation of MGs based on this concept [7–14]. The main advantage of droop control methods is that a communication link is no longer needed and MGs can be supported by any of DGs irrespective of which sources are available [15,16]. On the other hand, droop controlled MGs cannot directly incorporate load dynamics and present relatively complex properties in the case of inverter-based DGs [15]. Several strategies have been proposed to improve the performance of conventional droop control methods in the case of resistive lines and nonlinear loads using proportional, integral, and derivative controllers within the droop calculation [16–25].

Large and small disturbance studies are entitled 'the transient stability' and 'the small-signal stability' [26]. Small disturbances in MGs may be created by time-variant power outputs of DGs and can also be coupled with load fluctuations. These disturbances are studied frequently in the literature [26–28]. However, the large-signal stability of MGs has been studied rarely [12–30] due to nonlinearity. Analytical tools are particularly cumbersome to

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study large-signal stability and only a time-series simulation technique provides sufficient fidelity for examining this stability [31].

Use of machine drives, back-to-back converter configurations, and consumer electronics with unity power factor correction is the main reason which makes active loads more important challenge in recent distribution networks while more studies of MGs are conducted with passive loads (i.e. RL loads). Indeed, a few papers have studied MGs with active loads [15–36]. It may be due to the difficulty of active load modeling which is greatly simplified in this paper through using a linear model.

In this paper, a linear state-space model for islanded IBMGs as well as active loads is proposed. A time-step simulation is also suggested to correct the linear model and to drive the eigenvalues and transient response of such systems at each time directly and quickly. Using these advantages makes the stability analysis of active loads easy and fast. The proposed method investigates large-signal stability analysis as simple and fast as small-signal one, due to linearity. Therefore, the load flow solutions like Newton–Raphson methods and, moreover, required linearizations to assess small-signal stability are no longer needed. Another advantage of the proposed simulation is that it is much faster than other simulations such as MATLAB/Simulink and can easily handle large IBMGs with active loads of any size.

This paper will cover three main parts: First part describes the proposed linear model. A time-step simulation is developed to correct the linear model in the second part. The last part is the conclusion of the work.

Proposed linear state-space model

Linearization idea

The general state-space equations of a linear time-invariant (LTI) system can be given as:

$$\dot{x} = Ax + Bu \tag{1}$$

where x and u are the state and input vector and A and B are the system and input matrices. The state vector of this LTI system can be calculated directly as:

$$x(t) = e^{At}x(0) + \int_0^t e^{A(t-\tau)}Bu(\tau)d\tau \tag{2}$$

In addition to the simple calculation of the state vector, the eigenvalues of A can show the details of the stability of the system. These useful characteristics can be implemented for IBMGs as well as active loads if a linear model for such systems is developed. The general state-space equations of such systems can be written as:

$$\dot{x} = f(x) + Bu \tag{3}$$

In the literature [7,15,26–28], (3) is linearized around a given operating point, x_0, to study small-signal stability analysis using the first order term of the Taylor expansion as:

$$\Delta\dot{x} = D\Delta x \tag{4}$$

where D is the Jacobian of $f(x)$ evaluated at x_0. It should be noted that the input matrix, u, is constant for such systems ($\Delta u = 0$). As can be seen in the following section, $f(x)$ has restricted number of nonlinear terms and its linear terms tend to dominate the system behavior. The main and most general nonlinear term of $f(x)$ in (3) is $a_{ij}x_i^m(t)x_j^n(t)$. To linearize this term, it can be written using the Taylor expansion around $t_0 = t - \Delta t$ as:

$$a_{ij}x_i^m(t)x_j^n(t) = a_{ij}x_i^m(t_0)x_j^n(t_0) + ma_{ij}x_i^{m-1}(t_0)x_j^n(t_0)\Delta x_i(t) + na_{ij}x_i^m(t_0)x_j^{n-1}(t_0)\Delta x_j(t) + \cdots \tag{5}$$

where $\Delta x(t) = x(t) - x(t_0)$. Neglecting the higher order terms of the Taylor expansion and after some manipulation, (5) can be simplified as:

$$a_{ij}x_i^m(t)x_j^n(t) = ma_{ij}x_i^{m-1}(t_0)x_j^n(t_0)x_i(t) + na_{ij}x_i^m(t_0)x_j^{n-1}(t_0)x_j(t) + (a_{ij} - ma_{ij} - na_{ij})x_i^m(t_0)x_j^n(t_0) \tag{6}$$

If $\Delta x(t)$ is sufficiently small, (6) is true and higher order terms of the Taylor expansion can be neglected. A careful look at (6) shows that a linear form of the nonlinear term is obtained however, the coefficients of this linear form are variable and a function of time t_0. Using (6) to linearize nonlinear terms, the linear form of (3) at time t can be obtained as:

$$\dot{x}(t) = A(t_0)x(t) + Bu \tag{7}$$

As can be seen, the state matrix at time t is a function of the previous time i.e. t_0. Therefore, a time-step simulation can be developed where in the first iteration ($t = \Delta t$), starting from $t_0 = 0$, $A(0)$ is constructed using initial conditions, $x(0)$, and then $x(\Delta t)$ is calculated from (2). In the second iteration ($t = 2\Delta t$), first $A(\Delta t)$ is updated using $x(\Delta t)$ and then $x(2\Delta t)$ is calculated from (2). In a similar manner the state vector can be calculated for $t = 3\Delta t$ until time when the system steady-state is reached. In each time t, eigenvalues are derived from $A(t_0)$. Indeed, the proposed simulation can derive the transient response as well as eigenvalues of active loads in IBMGs at each time directly.

In the next section, the linear state-space equations of active loads is developed based on (6). The linear models of inverters, lines and passive loads of IBMGs are also developed in a similar way. It is worth mentioning that the complete nonlinear model of active loads and IBMGs suggested by Bottrell et al. [15] and Pogaku et al. [7], respectively, are used to derive the linear models.

Linear model of active loads

Active load subsystems include a LCL filter, DC voltage controller, AC current controller, switching bridge and DC load. A comprehensive diagram of an active load is shown in Fig. 1.

(1) *DC Voltage controller:* as shown in Fig. 2, the state variable of this section is the difference between the reference DC voltage and the feedback one and it is written as:

$$\dot{\varphi} = v_{dc}^* - v_{dc} \tag{8}$$

(2) *AC Current controller:* similarly, as shown in Fig. 3, the corresponding state equations of this section are:

$$\dot{\gamma}_d = i_{ld}^* - i_{ld} \quad \dot{\gamma}_q = i_{lq}^* - i_{lq} \tag{9}$$

Substituting the reference currents calculated in the DC voltage controller, (9) can be rewritten as:

$$\dot{\gamma}_d = K_{iv}\varphi - i_{ld} - K_{pv}v_{dc} + K_{pv}v_{dc}^* \qquad \dot{\gamma}_q = -i_{lq} \tag{10}$$

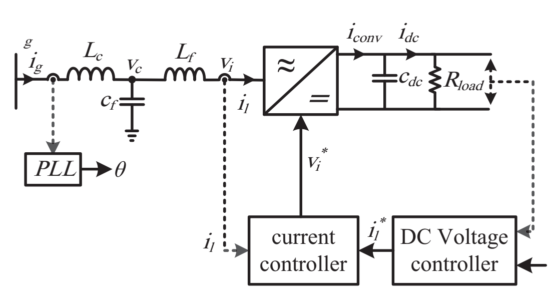

Fig. 1. Active load subsystems.

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