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Real-time small signal stability analysis of the power electronic-based components in contemporary distribution systems

M. Amin Salmani*, Chris S. Edrington

Department of Electrical Engineering, Florida State University/The Center for Advanced Power Systems, Tallahassee, FL 32310, USA

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ABSTRACT

Power Electronic-based Components (PECs) can provide excellent features such as, load regulation, high power factor, and transient performance, especially in the large scale distribution systems. Accordingly, contemporary power distribution systems or Power Electronic-based Distribution Systems (PEDS) are highly penetrated with the Renewable Energy Resources (RERs) as well as innovative PECs such as, Solid State Transformers (SSTs) and inverters. Therefore, they are prone to exhibit negative impedance instability in consequence of high power factor and constant-power nature of the individual components in the system. Thus, small-signal as well as large-signal stability assessments of the PEDS play prominent role in operational (real-time) stage of the systems analyses. In this paper new small-signal stability analysis technique is developed based on $d-q$ impedance measurement and Nyquist criterion that is capable of investigating the systems' small-signal stability in real-time. Furthermore, small-signal stability of a sample PEDS comprised from a SST connected to the source and variable load is investigated through the proposed method and with utilizing Real-Time Digital Simulator (RTDS) platform.

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1. Introduction

1.1. Motivation and goal

Emerging new technologies in power electronics had a great influence in power distribution systems as well as other areas such as power delivery, storage, drives, and RERs utilization. Around the world, there has been a significant growth in utilizing PECs in power systems, due to the fact that they can considerably enhance power system characteristics such as power quality, voltage regulation, and power factor. Therefore, as the world moves toward a sustainable energy future, large scale integration of variable power generation as well as RERs and PECs into the grid is on rise. However, there are some issues with large integration of RERs, Distributed Generations (DGs), and PECs. For instance, there is energy security and reliability concern that was addressed with the idea of Virtual Power Plant (VPP) in previous studies [1–4]. Furthermore, PECs may have a significant effect on the stability of the large scale power systems, particularly, in a large scale power system that is highly penetrated with PECs. The downside of utilizing PECs is that they are prone to operate as Constant Power Loads (CPL), which have negative impedance effect (and as a results destabilizing effect) at input terminals. Therefore, compared to conventional power systems, the stability assessment of PEDS has considerably changed due to the capability of PECs to operate as negative impedances in the systems. In the small-signal viewpoint, negative impedance in the system intuitively has a destabilizing effect [5]. In other words, instability in PEDS is caused by the tendency of the power electronic-based components to behave as CPLs [6]. Therefore, to address stability of PEDS small-signal viewpoint has to be considered as steady-state and large-signal stability. Thus, stability assessment of PEDS that highly penetrated with PECs is a more critical task than in conventional power distribution systems.

1.2. Literature review

Several studies have been discussed and analyzed PEC's stability assessment to date. They mostly were dedicated for design purposes of single PEC. In other words, they address the small-signal stability of a PEC in order to identify acceptable source/load impedances for the system to remain in a stable region. Some of them are also addressed small-signal stability of a system with a PEC. However, no matter what methods have been used, the system's configuration is unchangeable. In other words, the topology of the understudy system is fixed that in reality and considering large power distribution systems, it changes all the time. On the

* Corresponding author. Tel.: +1 8505599870.
E-mail addresses: amin.salmani@gmail.com, ms11t@my.fsu.edu (M.A. Salmani), csedrington@gmail.com (C.S. Edrington).

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other hand, no technique/criterion has been developed so far to assess the small-signal stability of the PECs in real-time to investigate the absolute and relative stability of a system while it is operating. This achievement may be utilized in real-time applications and results to real-time small-signal stability analysis.

This paper describes a technique/criterion to address small-signal stability of the PECs in real-time. In order to achieve this concept, an impedance measurement-based technique is utilized to define the source impedance and load admittance. Subsequently, the small-signal stability of the system is investigated by Generalized Nyquist Criterion (GNC) and using obtained source/load impedances of the system. Furthermore, developed technique enables stability assessment of the PECs in real-time.

Stability study from the system's topology viewpoint may be divided into three different categories of steady-state, small-signal, and large-signal stability analyses [7]. Steady-state analysis is the initial step to study a system's stability and based on load flow calculations (algebraic equations). Steady-state stability study of the power systems provides significant understanding of the system behavior during normal operation. This form of stability study has been used in the conventional power system stability studies [8]. After ensuring steady-state stability of a system, small and large signal stabilities have to be addressed in the power systems. Small-signal stability is defined as: The capability to return to the identical stable operating point after the occurrence of a disturbance that leads to any changes in one or more of the state variables of a PEDS [9]. Generally, a system might operate in various equilibrium points of interest.

Large-scale displacement, also known as transient or large-signal stability, is defined as: The capability of a power system to return to any stable operating point after the large-scale disturbance that changes the system's topology [9]. The tripping of a generator or a line, the sudden change of a load (including a load trip) which is equivalent to the change of a load to zero, and the occurrence of a fault are some cases in point. If one of the above disturbances occurs, the system is no longer in steady state. Different quantities in the system, such as rotor speeds and node voltages, start to change and to deviate from their steady state values. If the fluctuations of the system's quantities damp out and the system settles at a stable operating point, it is considered stable. Conversely, when the deviation of the various quantities becomes greater, the system is unstable and will eventually collapse. The aforementioned definition of transient stability indicates that the electrical topology of the power systems will be change. This point is the main distinction between transient stability and small signal stability. An additional difference between transient stability and small-signal stability is that if a steady-state is reached after a disturbance leading to a transient phenomenon, such as a change in the system's topology, the new steady-state operating point can be different from the initial one. In contrast, if a system returns to a steady state after a gradual change in a state variable, the system remains at initial operating point, since there is not any change in the topology of the system [9]. Large-signal stability of the power systems have been investigated by direct methods (i.e., Lyapunov based techniques) or non-linear differential equations solutions.

Lyapunov techniques have been utilized for design purposes in large-scale stability assessment of specific types of PECs in [5] and [6] as well as small-signal in [10]. Since these methods addressed particular devices, they are not generic methods to be utilized for stability study of the PEDS. In [6], large-signal stability of the PEDS was investigated. In this regard, a new technique for estimating Regions of Asymptotic Stability (RAS) of the systems based on the Lyapunov stability theorem and genetic algorithm was developed. The RAS of an equilibrium state is the set of initial states which leads the system trajectories to the equilibrium state. In previous developed methods, the RAS was estimated based on sampling points in the region of the equilibrium state. Conversely, in the method proposed in [6], these sets are described by a quadratic Lyapunov function which is applicable to arbitrary Lyapunov functions as well. This feature reduces the complexity of computations in the procedure. Followed by finding the RAS estimation with Lyapunov function, optimizing the RAS function and solving the optimization problem with generic algorithm are well-developed via the aforementioned method.

In the small-signal viewpoint, stability of the systems is investigated around the desirable operating point. In many previously developed techniques, in order to ensure overall stability of a system, small-signal stability has to be addressed at each equilibrium point. Small-signal stability techniques are mainly developed based on average linearized models around the equilibrium points that allow different analytical tools such as Nyquist, Bode, and Root locus plots in the study. One well-known technique for small-signal stability assessment is using Middlebrook's criterion [11] to ensure stability of the systems by encircling the Nyquist contour of Z_s/Z_l (or $Z_s \cdot Y_l$) in unit circle in the s-plane. Therein, Z_s represents the impedance of a linearized source converter model, and Z_l represents impedance of the linearized load converter model. There are several criteria and techniques that were developed based on Middlebrook's criterion [11] in the associated research. Several methods for control design purposes were explained in [12] and [13]. Essentially, these methods are different in the degree of conservativeness.

Several methods for the purpose of control design were investigated in [12,13]. By and large, these methods ensure the system's stability by preventing encirclement of the $(-1 + j0)$ point by the Nyquist contour of $Z_s \cdot Y_l$. The first method is based on the Middlebrook criterion, which consists of a circle of radius 1/GM in the s-plane; where GM is Gain Margin (GM). For a given Z_s, this design criterion provides constraints for an allowable range of Y_l as

$$|Y_l| < \frac{1}{\left|Z_s\right| GM} \tag{1}$$

Obviously, with this constraint, the Nyquist plot of $Z_s \cdot Y_l$ is always within the circle. Therefore encirclements of the $(-1 + j0)$ point cannot occur, provided that GM is greater than 1. Due to an infinite Phase Margin (PM) demand, this method is likely to force artificially conservative designs. One alternative approach is the Opposing Component criterion [12]. In this method, the Nyquist diagram is required to fall to the right of a line at $s = 1/\mathrm{GM}$. Herein, the advantage over the Middlebrook criterion is that it can be less artificially conservative because it allows the Nyquist diagram to occupy a larger region of the s-plane. There are also several other approaches, which reduce the conservativeness of the design. The Gain Margin and Phase Margin (GMPM) criterion is a good case in point that considers PM in addition to GM and as a result decreases the degree of conservativeness [12].

In addition, some studies are allocated to small-signal stability analysis using numerical and computational methods. These methods are also called "model analysis-based methods" and may be utilized different numerical and computational techniques to address small-signal stability of the systems with analyzing their models. Model analysis-based methods are essentially divided into different two main categories of eigenvalue-based methods and the methods for defining a system's state transition matrix by numerical computation. Eigenvalue-based technique mainly has been utilized for the design of controller to improve small-signal stability of the PECs [14–17]. However, eigenvalue-based techniques, and more generally model analysis-based methods, are not the best solutions for investigating the stability of the large scale systems.

Basically model analysis-based methods separate systems into parts and pieces and define state-space equations, or optionally