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Modeling and analysis methods for assessing stability of microgrids

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Abstract: It is proposed in this paper that all components comprising microgrids with highly heterogeneous technologies can be modeled as interconnected dynamic modules. The resulting standard state space component models and the interconnected microgrid model have structure that lends them to highly distributed analysis, necessary stability conditions and local control design. A real world microgrid is used to illustrate modeling and analysis approach.

Keywords: Modeling and simulation of power systems, Smart grids, Power systems stability, Dynamic interaction of power plants

1. INTRODUCTION

Microgrids can be interpreted as small blocks of today's energy grid capable of functioning by themselves, even when they are disconnected from the large utility grid. They are fundamentally based on utilizing intermittent energy sources such as solar PV, and wind power. Nonlinear dynamics of microgrids might have multiple equilibria. Some of these equilibria are stable and others unstable. Their sensitivity w.r.t model uncertainties vary as well. The reducing cost of solar PVs is resulting in increased power generated by consumers. These and other renewable sources are integrated into the grid through fast power electronics control and could lead to fast interactions destabilizing the entire grid unstable. It is not straightforward to determine the allowable maximum solar PV injection such that the grid has a stable and robust equilibrium. Present practices assume the existence of such an equilibrium and are primarily concerned with droop-based voltage and frequency regulation.

In this paper, we approach the operating problem of microgrid from a systems point of view. Without loss of generality, we make use of a test system representing real world microgrids. This is described in Section 2 and is used to illustrate our modeling and analysis approach. We view microgrid as a system comprising heterogeneous components. Each of these heterogeneous components is modeled starting from first principles and using a common modeling framework described in Section 3. Then, the automated method is used to obtain the interconnected system dynamics, which is described in Section 4. It is further described in Section 5 that there is a structure inherently present in microgrid models which are elaborated. This system can have multiple equilibria based on control logic implemented in one or more of these components, as illustrated in Section 6. The stability of these equilibria is assessed through linearized analysis of the system. Necessary conditions for stability on limits of solar PV injection are then derived in Section 7. It is further seen in Section 8 that the common practices of making use of droop-based control of microgrids are not appropriate when there are very fast interactions between the components. Finally, Section 9 concludes the paper by leaving some open questions for further analysis.

2. SYSTEM UNDER STUDY

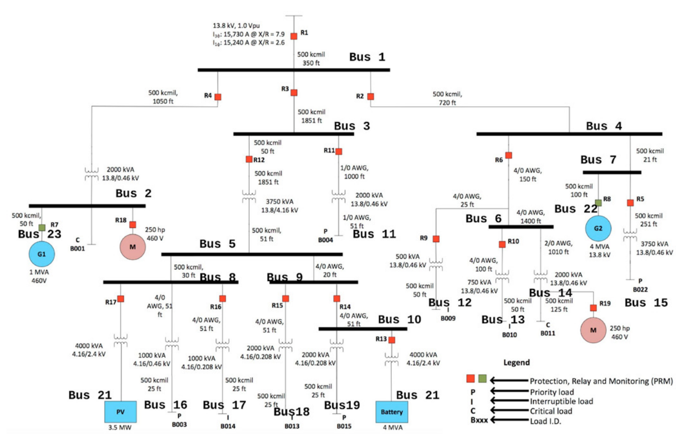

Fig. 1. Typical future microgrid

Shown in Fig.1 is a one-line diagram of a real-world microgrid serving a typical commercial complex Salcedo et al. (2016). The microgrid has two generator sets for purposes of self-providing electricity when utility-generated power may be too expensive or is not available. These are rated 1 MVA and 4 MVA operating at a nominal voltage of 460 V and 13.8 kV, respectively. There is also a solar PV source, having a maximum rated capacity of 3.5 MW operating at a nominal voltage of 2.4 kV. The distributed generation and loads are interconnected through a distribution network consisting of 13 distribution transformers and different kinds of relays and circuit breakers to ensure the protection of the components. Loads are quite diverse and are classified accordingly as priority, critical and interruptible loads. There is a total of 3.5 MW and 1.6 MVAR of priority loads which must be continuously

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supplied energy, but may be disconnected in the event of a contingency. There is a total of 2.1 MW and 1.3 MVAR of critical loads which require a continuous supply of energy. The remaining loads are interruptible and can be cut out in the event of an insufficient generation. In this microgrid, there is a total real power demand of 6.2 MW and a reactive power demand of 3.2 MVAR. There are also two large induction motors rated 250hp each.

Depending on how the components are controlled, the existing microgrid may have operating problems or not. The problem gets amplified when it is attempted to integrate intermittent renewable sources into the grid. In this paper, we will utilize this microgrid to illustrate modeling, simulation, and analysis needed to assess potential problems and their root causes.

3. GENERAL DYNAMIC MODEL OF MICROGRID COMPONENTS

Microgrids are generally operated over a very broad range of conditions of solar irradiance, loading levels, and grid connection status. It is expected of these microgrids to sustain large disturbances that might occur in its states when microgrid gets suddenly disconnected from the utility (isolated mode or grid forming mode) and/or it is reconnected to utility (interconnected mode or grid feeding mode). These phenomena are not studied extensively and are consequently not well understood. While the microgrids are expected to operate in qualitatively different operating modes and also to respond to often significant disturbances in outputs of intermittent resources, common practice control designs are made under often strong assumptions which do not hold in such situations. Meeting these assumptions is currently done through careful equipment sizing and topology design Alatrash et al. (2011). Microgrid modeling and control represent altogether a new challenge because methods used in large electric power grids can not be directly applied to them. In particular, dynamics of individual microgrid components are more likely to interact with the dynamics of the system to which they are connected than it has typically been the case in EHV and HV bulk power systems (BPS) and conventional distribution power systems (DPS). Because of this, and also because of relatively little experience with operating them over broad ranges of inputs and modes, it is necessary to establish a systematic approach to modeling their dynamics in the form which lends itself to utilizing well-established analyses and control methods. Analyses methods are needed to predict possible dynamic problems, and control is required to ensure that for the ranges and types of disturbances seen by the microgrids, they continue to operate according to pre-specified performance Ilic and Zaborszky (2000). In order to get started, we introduce first the general model of any dynamic component. Both open-loop and closed-loop models are conceptualized.

Some power system models neglect the dynamics of electric variables, which greatly simplifies the model. However, while designing power system control for a very fast time performance, such as for frequency or voltage stabilization, the dynamics of electrical variables are necessary to include. Hence, this paper considers physics-based dynamics of all power system components.

3.1 Open-loop dynamic model of microgrid components

A microgrid is essentially a network comprising interconnected dynamic components. These dynamic components can be single port (eg: synchronous machine, induction machine) or two port (eg: distribution lines, Thyristor Controlled Series Reactor (TCSR)) devices as shown in Fig.2. Assuming that all components (distribution wires and transformers) have dynamics modeled using lumped parameters, any microgrid component $\mathbf{i}$ can be expressed in a common standard state space form Ilic and Zaborszky (2000):

$$\frac{d\mathbf{x_i}}{dt} = \mathbf{f_i}(\mathbf{x_i}, \mathbf{p_i}, \mathbf{u_i}, \mathbf{m_i}), \qquad \mathbf{x_i}(0) = \mathbf{x_{i0}} \tag{1}$$

$$\mathbf{u_i} = \mathbf{g_i}(\mathbf{z_i}, \mathbf{z_i^{ref}}, \mathbf{m_i}) \tag{2}$$

where $\mathbf{x_i}$ is the vector of state variables of component $\mathbf{i}$, $\mathbf{u_i}$ is the vector of controllable inputs to component $\mathbf{i}$, $\mathbf{m_i}$ is the vector of exogenous inputs to component $\mathbf{i}$, and $\mathbf{p_i}$ is the vector of port inputs to component $\mathbf{i}$ that will be determined by its connection to the rest of the system. The exogenous input can be any form of unanticipated disturbance given by one or more of the following elements of the vector:

$$\mathbf{m_i} = \begin{bmatrix} \Delta\mathbf{z_i^{ref}} & w_i & \Delta\mathbf{u_i} \end{bmatrix}^T \tag{3}$$

where $\triangle\mathbf{z_i^{ref}}$ denotes the sudden change in reference points given by the higher layer, w_i denotes any kind of white noise appearing in the form of delays, and measurement error, and $\mathbf{\Delta u_i}$ denotes the sudden change in control input owing to saturation or failure of available local controllers.

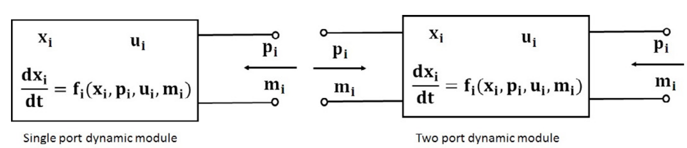

Fig. 2. Single-port and two-port dynamic components

3.2 Closed-loop dynamic model of microgrid components

In order to ensure that a dynamic component meets certain specifications, its feedback control needs to be designed at the component level. The local controllable input is designed to respond to deviations of local output variable $\mathbf{y_i}$ from its reference value $\mathbf{y_i^{ref}}$. Typically output variables to which local controllers respond are frequency, voltage, and/or current. However, these physical variables need to be controlled so that, at the same time the interconnected grid is operated according to certain microgrid level criteria. For example, typically microgrid shown in Fig. 1 has a system level controller which for predictable conditions schedules generation produced by conventional generators and PVs so that total fuel cost is minimized. The result of this scheduling gives desired power $\mathbf{z_i^{ref}}$ to be produced by these generators and PVs. The power $\mathbf{z_i}$ is a non-linear function of the state variables and port inputs of component $\mathbf{i}$, given by

$$\mathbf{z_i} = \mathbf{h_i}(\mathbf{x_i}, \mathbf{p_i}) \tag{4}$$

The component in closed-loop after the application of primary control is as shown in Fig.3. It has to be noted