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Representation of a grid-tied microgrid as a reduced order entity for distribution system dynamics and stability studies

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ABSTRACT

Microgrids comprising multiple distributed resources are being increasingly considered for integration into electricity networks. Considering the multiplicity of the distributed resources in a single location and distributed nature of such single entities, it is impractical to represent them as detailed models in power system simulations. Hence, it will be attractive for electricity utilities to employ simplified models of microgrids in dynamic studies. This paper proposes a method for representing grid-tied microgrids as simplified generator or load units in such studies. For this purpose, the paper takes an approach in investigating the applicability of modal analysis as a tool for model equivalencing of grid-tied microgrids with inverter and non-inverter interfaced distributed generators. Validity of the reduced order dynamic equivalents is tested under different operating conditions: power export and import modes, with different load types and fault conditions. Scalability of the model equivalencing approach is demonstrated using a case study developed based on the IEEE 13-Bus test feeder. Furthermore, the model equivalencing is applied on microgrids in a multi-microgrid environment to validate the methodology. The dynamic model equivalent of the microgrid can be represented as a current source at the point of common coupling while retaining all imperative dynamic characteristics. The proposed methodology is also applicable to distribution network clusters comprising distributed generators.

Introduction

A microgrid can be considered as a part of a distribution network consisting generation and storage units, which can operate in grid connected and islanded modes [1,2]. Prior to the advancement of grid connected microgrids, dynamics of distribution networks were not required to be considered in stability studies as distribution networks were generally passive and remained stable when the transmission network was stable. However, with the increasing penetration of distributed generators (DGs), distribution networks have begun to feature active characteristics with bidirectional power flow.

For stability analysis, the common practice is to separate the power system into a study area of interest and external areas. In general, the study area is represented in a detailed manner while external areas are represented by dynamic equivalents [3,4]. These equivalent models will approximate the effects of the external systems on the study system.

Distribution network dynamics are imperative when investigating stability in power systems. Hence, such systems can no longer be represented merely by a static load at the point of common coupling (PCC). In particular, the dynamics of microgrids operating in grid connected mode must be taken into account in order to accurately characterise the stability of the network. Unlike traditional synchronous generators (SGs) and their auxiliary components, effects of grid connected microgrid dynamics on large power systems have yet to be completely characterised. Increasing size and complexity of power networks with renewable energy based DGs interfaced with power electronic systems have led to a need for new and accurate simplified models of grid connected microgrids. For distribution network operators, these models will simplify the representation of grid connected microgrids as single entities at the PCC.

Such equivalent models of complex grid connected microgrids must represent the aggregated load and generation at the PCC while retaining the important dynamics. For this purpose, three main model reduction approaches, namely: (i) coherency methods based on identifying coherent groups of generators [5–8], (ii)

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modal methods based on linearised models of the external systems [3,9,10], and (iii) system identification methods based on measurement and simulation responses [11–14] have been considered.

In coherency based methods, coherent groups of generators are identified from the generator rotor behaviour caused by a disturbance [15–17]. However, coherency based equivalencing cannot be applied to modern inverter interfaced sources due to decoupling of rotor dynamics from the network (e.g. doubly-fed induction generators, microturbines) or due to the absence of such rotor dynamics (e.g. in photovoltaic systems, battery energy storage systems). Generally, in modal methods, reduction of the linearised system is carried out by removing the eigenvalues located furthest from the origin and retaining the less damped modes. Thus, overall dynamic characteristics of the reduced system will be similar to the original system. However, care must be taken in applying modal methods for systems with inverter interfaced DGs, as their state variables are not well known as in the case of conventional SGs. In system identification, measured system data are used to fit the selected model parameters of the dynamic equivalents of power systems [18–21]. However, this requires iterative procedures to be carried out until model validation criterion is satisfied. Unlike system identification methods which involve parameter estimation, traditional model reduction methodologies are firmly based on mathematical concepts and have significant physical relevance to the system dynamic states.

This paper presents a novel approach in representing grid-tied hybrid microgrids as single generator/load units suitable for power system studies, by applying modal analysis as a tool for model order reduction. The basic modal method has not been applied to grid-tied microgrids as a means for deriving dynamic equivalent models. The enhanced modal analysis reduces the model order and represents the hybrid microgrid in terms of the states of the microgrid PCC, while preserving the important dynamics. The reduced order dynamic models of grid-tied microgrids are validated under different operating conditions: power import and export from the external grid, with different load types, fault conditions and in a multi-microgrid environment.

The paper is organised as follows; dynamic model reduction methodology on grid connected microgrids is described in Section 'Dynamic model reduction methodology'. Modelling of the microgrid is described in Section 'Modelling of the microgrid'. Section 'Model reduction and validation of microgrid model' presents model reduction and validation of the microgrid under different scenarios. Two case studies based on the IEEE 13-Bus system and multi-microgrid systems are presented in Section 'Model scalability and other practical aspects' followed by a discussion on providing a framework for an adaptive application of the methodology in simulation packages. Conclusions are given in Section 'Conclusions'.

Dynamic model reduction methodology

The dynamic model reduction process covered in this paper is illustrated in Fig. 1. As explained in the Introduction, modal analysis has been selected as the model reduction tool. Unlike for conventional systems, selective modal analysis [22,23] was considered not suitable for hybrid microgrids due to the difficulty of determining the significant states of inverter-interfaced DGs at the initial stages without carrying out a full eigenvalue analysis. From various modal methods available in the literature, the matrix transformation technique in [3,4] is based for this work, as it allows full eigenvalue analysis of the hybrid microgrid model. This basic modal method has not been applied to grid-tied microgrids as a means of deriving dynamic equivalent models. Furthermore, an additional step has been introduced in this paper for identifying and grouping dominant system modes which are to be retained in the reduced order microgrid model. The steps (Blocks A, B, C, and D in Fig. 1) associated with the enhanced model equivalencing process are described in the following sub-sections.

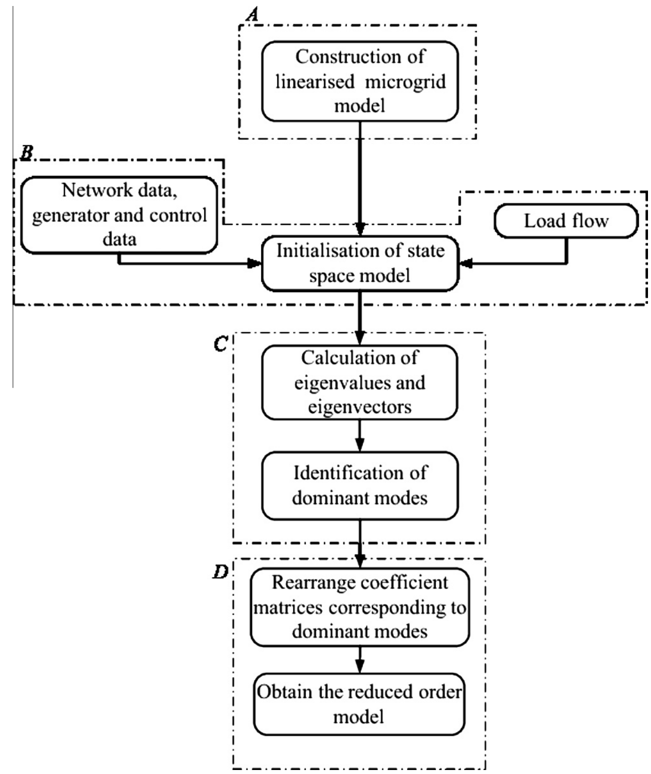

Fig. 1. Model reduction approach applied to grid-tied microgrids based on modal method.

Linearised microgrid model

For the purpose of stability analysis of large power systems, microgrids connected outside the study area of interest can be represented as linear systems. From the study system point of view, a microgrid can be seen as a single dynamic unit in a linearised state-space form in terms of the state variables at the microgrid PCC as follows:

$$\Delta\dot{x} = A_{sys}\Delta x + B_{sys}\Delta v_{pcc} \tag{1}$$

$$\Delta y_{pcc} = C_{sys}\Delta x_{o/p} + D_{sys}\Delta v_{pcc} \tag{2}$$

Vector Δx contains states of dynamic devices in the microgrid with coupling point Δv_{pcc} as input. Coupling point current Δi_{pcc} and microgrid reference d–q frame speed deviation $\Delta\omega_{ref}$ are taken as outputs in vector Δy_{pcc}. $\Delta x_{o/p}$ is a sub-vector of Δx containing states contributing to system output signals.

Initialisation of the state-space model

Once the linearised microgrid model is constructed, network, generator and control data are incorporated into the model, and the load flow results are used to initialise the state-space model.

Identification of dominant modes

As the first step of identifying dominant modes, matrix A_{sys} of (1) is transformed into a diagonal form using the following transformation [3,4]: