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A robust dynamic state estimation for droop controlled islanded microgrids

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ABSTRACT

This paper proposes a nonlinear particle filter (PF) method for dynamic state estimation in droop-controlled islanded microgrids (IMGs). The PFs are normally applied to systems that (1) have highly nonlinear system dynamics, and (2) do not require the additive process or observation noise to be Gaussian. This flexibility allows the PFs to handle noisy measurements from a range of varied distributions, thereby increasing its robustness. To that end, a nonlinear dynamic state model has been developed in this work for droop-controlled IMGs. Additive noise has been incorporated into the state model to account for the error in its accuracy. Monte Carlo simulations have been conducted to verify that the PF accurately tracks the IMG state variables in spite of using significantly corrupted state and observation values. A comparison between the PF and unscented Kalman filter (UKF) has been carried out to test the effectiveness and robustness of the proposed methodology.

1. Introduction

Smart power grids seek to decentralize active distribution systems with high penetration of distributed generation (DG) units into smaller and more manageable subsystems that are known as microgrids. True to their name, microgrids are miniature versions of the power grid consisting of a cluster of local loads and DG units [1]. Microgrids offer improvement in power system reliability and stability as well as assisting with renewable power integration, as they are capable of operating in two modes of operation: grid-connected and islanded. In the grid-connected mode, microgrids operate in parallel with the main distribution networks. While in the islanded mode of operation, microgrids are completely cut off from the main grid and the DG units become responsible for supporting their local load demand.

The majority of DG units in microgrids are interfaced via voltage-source inverters coupled with passive output filters. As converters lack physical inertia, primary local power controllers are usually implemented in the voltage-source inverters of the DG units during the islanded mode to mimic the droop characteristics of synchronous generators operating in parallel. The droop parameters of such controllers are conventionally designed so that the DG units forming the islanded microgrids (IMGs) share the load demand in proportion to their rated capacities [2]. However, conventional settings of the droop parameters: (1) do not ensure that the appropriate voltage frequency and magnitude regulations will be maintained in all loading conditions [3], (2) fail to take into consideration the system's stability and maximum loadability requirements, which are key considerations in the case of IMGs because the system is fed from a group of inverter-based DG units with small capacities [4,5], and (3) the IMG operation is not economically optimized, i.e., the cost of operation is not taken into account [6]. For these reasons, several researchers have proposed methods for optimal real-time adjustments of the droop control parameters of DG units in order to enhance the IMG operation [6–13]. These methods require a supervisory energy management system (EMS) to complement the primary local droop control of IMGs.

State estimation (SE) is a vital tool that is typically implemented in EMSs to monitor the stability of a power grid. It is also used to aid control and operation decisions such as: optimizing power flows, detecting and removing line faults, and providing forecasting for power failures [14–16]. The application of SE in power networks has been an active research topic since the 1970s and a variety of techniques have been proposed in this field [14]. Similar to conventional power grids, several SE algorithms have been recently proposed for microgrids. In [17], a belief propagation method is proposed to estimate the state of the microgrid. Both the microgrid modeling and its SE algorithm are implemented in a quasi-static fashion. However, modeling the dynamics of the

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microgrid as quasi-static is not an accurate assumption given that the static nature of the estimator: (1) does not capture the true system dynamics when a sudden disturbance occurs, (2) relies entirely on a fresh set of observations that might be severely corrupted or missed, i.e., discards any previous estimate made, and (3) is suboptimal compared to a dynamic SE that incorporates both past and present information systematically.

A dynamic model of microgrids is presented in [18], which uses the Weighted Least Squares (WLS) method to estimate the state. The WLS algorithm is easy to implement and is not computationally expensive. However, its solution is quite sensitive to the noise in the measurements [19]. In [20], an improved version of the Kalman Filter (KF) is used as the state estimator and it is applied to a linearized dynamic model of the microgrid. For linear models, the KF is the optimal SE algorithm of choice. However, the microgrid is a highly nonlinear system, and as such the KF is not an accurate solution [21]. When applied to nonlinear systems, the KF incurs significant linearization error and converges slowly. Though the method in [20] uses a linear quadratic regulation method to control state deviations, this method will not be able to support nonlinear system dynamics. Linearizing a highly nonlinear system is also an assumption that fails to capture the true dynamics of the system.

The extended Kalman filter (EKF) is often used to deal with nonlinear system identification. However, the EKF is not effective in the case of highly nonlinear problems [22,23]. In the EKF, the derivation of the Jacobian matrices i.e., the linear approximations to the nonlinear functions, are typically complex and cause implementation difficulties [22]. Further, these linearizations often lead to filter instability if the time step intervals are not sufficiently small [23]. To address these limitations, the unscented Kalman filter (UKF) was developed and proved its superiority in estimation performance for highly nonlinear systems [24]. A comparative study of the WLS, KF, and UKF has been performed in [25]. While the UKF preserves the nonlinearity of the system, it does not fare well when the process or observation noise distributions are non-Gaussian [26]. In real world systems, there are many different sources of noise, and as such, the robustness of the KF based approaches will falter when they are exposed to colored noise of various distributions.

Yet, the SE algorithms proposed in [17–21,25] addressed grid-connected microgrids. Although the general goal of SE in IMGs remains the same as grid-connected, the complications involved in the operation of IMGs ensures that the microgrid operator is in need of fast, reliable, and accurate system updates. These updates will aid in making crucial decisions related to the successful operation of IMGs. SE for IMGs is an emergent topic of research in which not much work has been done. In [27], SE is performed on microgrids operating in both grid-connected and islanded modes. However, a linear state model is used and a WLS estimation technique is employed which can be sensitive to outliers. In [28], the optimal KF is used; however the model is again linearized about an operating point. Given their special features and operation characteristics, the nonlinear modeling of IMGs in SE is essential in order to capture the very quick system dynamics. Further, nonlinear SE in microgrids is required to provide reliable, quick, and accurate state estimates in order to anticipate the IMG system disturbances. Hence, in order for microgrids to achieve a higher degree of efficiency and reliability, the role of an accurate and robust state estimator cannot be understated and thus careful consideration should be given for implementing appropriate SE approaches within the EMS of microgrids.

This paper explores the implementation of the particle filter (PF) as a dynamic state estimator for droop-controlled IMGs. Toward that end, a droop-controlled IMG dynamic state model is presented. The model has been discretized with a fixed time step to be implemented in the PF state estimation approach. Also a state noise vector has been defined as additive noise within the discretized state model to account for the error in the state model accuracy. The PF is a robust state estimator that can be applied to highly nonlinear dynamic systems such as IMGs. The PF is particularly robust because of its ability to filter noisy measurements that may be corrupted with probability distributions that are non-Gaussian. The same cannot be said for other popular SE techniques. The organization of the rest of the paper is as follows: Section 2 introduces the system modeling for IMGs, Section 3 introduces the proposed PF algorithm, Section 4 provides simulation results that test the robustness of the PF in a variety of scenarios compared with UKF, and Section 5 concludes the paper and summarizes its main contribution.

2. IMG dynamic state and observation model

Power electronic inverter-interfaced DG units dominate microgrid systems [1]. As such, the microgrid is critically susceptible to oscillations originating from system disturbances and improper choice of system parameters [2]. To study the dynamic behavior of IMGs, the nonlinear time domain model of the IMG is adopted [3]. This model consists of the individual models of the IMG components as described by their equivalent differential equations that are interconnected; namely the DG units, networks and loads.

2.1. Direct-quadrature (DQ) reference frame for IMG dynamic modeling

The voltages and currents in alternating current (AC) power networks have three phases in a stationary phase coordinate system (commonly referred to as the ABC frame). Since the network analysis in the ABC frame is complex, it is transformed to direct and quadrature (DQ) framework with two phases rotating about an axis symbolized as (d_n, q_n). Fig. 1 shows an explanation for the concept of DQ transformation in IMG systems. Fig. 1(a) shows an example of a small IMG system comprising two DG units and a single load. The system equivalent model in the DQ frame is shown in Fig. 1(b). In general, each DG unit supplies its output current $\{I_{oDn}, I_{oQn}\}$ to a node n that connects the DG to the IMG system. Also, the consumed

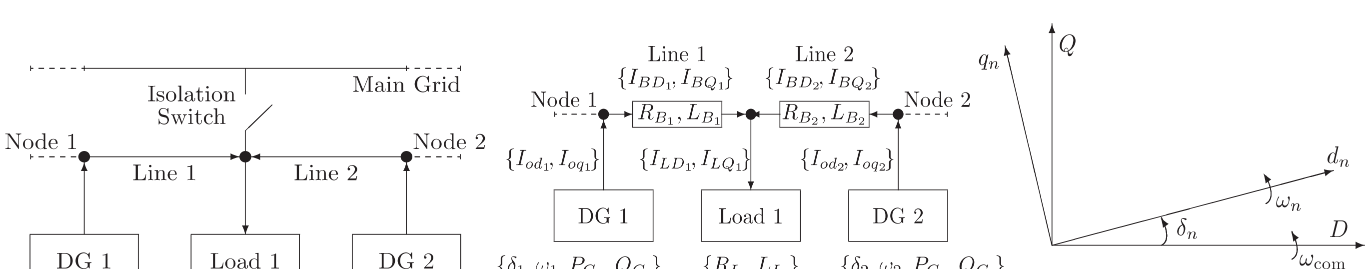

Fig. 1. From left to right (a) simple IMG network, (b) equivalent IMG network model in DQ frame, and (c) DQ reference frame.