Electrical Power and Energy Systems 95 (2018) 327–340

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Fault tolerant control of electronically coupled distributed energy resources in microgrid systems

Sasan Gholami [a,*], Sajeeb Saha [b], Mohammad Aldeen [a]

[a] Department of Electrical and Electronic Engineering, University of Melbourne, Australia
[b] School of Engineering, Deakin University, Australia

ARTICLE INFO

Article history:
Received 21 November 2016
Received in revised form 5 July 2017
Accepted 21 August 2017

ABSTRACT

This paper proposes a sensor fault tolerant control (FTC) strategy for electronically-coupled distributed energy resource (DER) units in grid-connected microgrid systems. First, a fault dependent dynamical model of the DER unit incorporating sensor faults is proposed. The FTC strategy is then developed using a sliding mode observer (SMO) which has an inherent robustness property. The rational for using a SMO is the need to detect and reconstruct any fault that may occur in output measurements of the system as a result of sensor failure. The fault signals are reconstructed by using a robust approach that encompasses uncertainties in the system, such as frequency variation. This paper also represents the cyber attack as an unknown sensor fault, and consequently the DER current sensor measurements manipulated by a data integrity attack can be detected and reconstructed. The reconstructed fault signals are then used to modify the faulty sensor measurements, which are fed to the voltage source converter (VSC) controller. This ensures accurate generation of pulse width modulation (PWM) signals and consequently accurate tracking of real and reactive power references. Different case studies are tested on a detailed nonlinear model of the DER system. The impact of faults on the DER performance and the effectiveness of the proposed FTC scheme are evaluated through extensive simulation studies. Experimental verification of the method is provided to further validate the proposed approach.

1. Introduction

The smart grid vision has encouraged a move towards seamless integration of the distributed and renewable energy resources into microgrids. A microgrid can be defined as a group of distributed energy resources (DERs), energy storage systems and interconnected loads that can act as a single controllable entity and is able to connect and disconnect from the grid [1]. Due to the substantial benefits of microgrids, extensive efforts have gone into expanding their penetration in electric power systems. However, reliable operation and efficient control design of microgrids still remain central issues both in the grid-connected and islanded operation modes. A comprehensive literature review on microgrid system research, including microgrid operation, control and communications issues is presented in [2].

In the grid-connected mode, the microgrid trades real and reactive powers with the grid. Because of such two-way power transfer protocols, deployment of proper control strategy remains imperative to efficient operation of microgrids. The commonly featured DER units in microgrid system (such as wind generators, PV panels, fuel cells etc.) are electronically interfaced with the electrical network through power electronic converters such as voltage source converters (VSC), current source inverters (CSI) and etc. The controllers of converters are specifically designed to facilitate the aforementioned two-way power transfer in the fastest possible manner. In this paper, we focus on the DER connected to grid through three-phase VSCs.

Control of VSC-based DER units in microgrids has been widely discussed in the literature [2–7]. An extensive review of control strategies, and the main trends and challenges in microgrid control are discussed in [3]. A thorough evaluation of grid-connected inverter controllers is presented in [4], in which controllers are classified based on their reference frame. It has been well studied in literature (for example [5]) that in *dq* reference frame the VSC-based DER units in a grid-connected microgrid system can be represented by linear time invariant systems, and therefore, simple proportional-integral (PI) controllers can be utilized to achieve required control objectives. A detailed dynamical modeling, and current-mode approach for real and reactive powers control in *dq* frame for grid-connected VSC-based DER unit is reported in [6]. This control approach is based on the PCC voltage and current measurements obtained from the secondary terminals of current transformer (CT) and potential transformer (PT), respectively.

* Corresponding author.
E-mail address: gholami.sasan@gmail.com (S. Gholami).

http://dx.doi.org/10.1016/j.ijepes.2017.08.024
0142-0615/© 2017 Elsevier Ltd. All rights reserved.

The CT and PT secondary terminal current and voltage are sensed by appropriate current and voltage sensors. These measurements are then processed by data acquisition (DAC) devices before being transferred to the controller to generate appropriate pulse width modulation (PWM) signals required by the VSC to accomplish the control objective. It is obvious that the accuracy of the sensed and processed PCC voltages and currents plays a pivotal role in the performance of the microgrid system controller. In the case of malfunction or fault in the sensor or data acquisition devices, or inaccuracies in CT and/or PT measurements, the amounts of real and reactive powers delivered to the main grid may considerably deviate from their reference values. Another reason for such deviation might be attributed to the manipulation or tinkering of the sensed PCC voltage and/or current by cyber attacks [8]. If faulty measurements and/or cyber attacks are not detected, and a timely remedial action is not initiated, then power imbalance will exist. This will result in an uncontrolled operation of the microgrid, which may then adversely impact the operation of the main grid. Thus, detection and mitigation of faults or cyber attacks in the sensor and DAC devices are of crucial importance for reliable operation of grid-connected microgrid systems.

Although a lot of research has been carried out on microgrid network fault detection and protection, reported research on sensor fault tolerant control of microgrids is very limited. Among a very few available sensor fault detection approaches in power systems, in [9,10], unknown input observer based sensor fault detection approaches for load frequency control (LFC) loops of interconnected power systems are presented. In references [11–14], sensor fault detection and isolation schemes for electric motor drives are presented. Kalman filter and chi-squared test have been used in [15] to detect faults or cyber attacks in phasor measurement unit (PMU). It is evident from the above literature review that even though faults or cyber attacks in the sensors of electronically-coupled DER units can have adverse impact on the reliable operation of systems, there is a paucity of research on fault tolerant control of electronically-coupled DER units in microgrids.

Various approaches have been discussed in the literature for fault detection in control systems, for example [16,17]. Some approaches generate residual signals which act as indicators of faults, see for example [18]. When the system under consideration is subject to unknown disturbance or unknown inputs, a robust fault detection scheme is used to avoid generating false residual or ' false alarms'[19,20]. On the other hand, a particular class of sliding mode observers is proposed in [21] to *reconstruct* the fault rather than to just detect the presence of faults through residual signals. Therefore, *fault estimation* or *reconstruction*, using a sliding mode observer, is a more effective alternative to just fault detection using residual signals [22]. As shown (and implemented in real-time on real systems) in [23], the information from reconstructed fault(s) can be used to provide a fault tolerant control scheme. Furthermore, from the point of view of robustness, sliding mode observers are insensitive to system/plant matched uncertainty because of the discontinuous (switching) action of observer [21].

In this paper, an observer based sensor fault tolerant control (FTC) strategy for electronically-coupled DER units in a grid-connected microgrid system is proposed. The proposed FTC scheme is based on a derived fault dependent dynamical model of DER unit in *dq* coordinate. The scheme employs a sliding mode observer (SMO) to reconstruct sensor faults, which impact the accuracy of the *dq* components of the output current of the DER unit under consideration. The reconstructed fault signals are then used to compensate for the sensor faults to ensure accurate generation of PWM signals, and in turn reliable operation of the DER unit in the microgrid system. Although the design of controller and observer is based on a derived linear model, the performance of the proposed FTC schemes is investigated on the original nonlinear model. Scenarios where the DER unit output current sensor data become erroneous due to (i) CT ratio and phase angle error, (ii) sensor loss, and (iii) malicious attack on the sensor data are investigated in detail. In summary, the main contributions of this paper are:

- A fault dependent dynamical model of DER unit in *dq* coordinate is proposed in this paper.
- SMO theory is applied to the proposed fault dependent dynamical model of DER, to detect attack and estimate sensor fault(s).
- This paper also represents the cyber attack as an unknown sensor fault, and consequently the DER current sensor measurements manipulated by a data integrity attack can be detected and reconstructed.
- The estimated fault(s) are used in a mitigation approach to provide a fault (attack) tolerant control of DER unit.

The rest of this paper is organized as follows. The electronically-coupled DER system dynamical model and controller design under normal operating condition for a grid-connected migrogrid are presented in Section 2. Section 3 focuses on detailed description of sensor faults and malicious attacks in a DER unit and the proposed sensor fault dependent DER model. The fault tolerant control strategy is presented in Section 4. Designed parameters are given in Section 5. Simulation results are provided in Section 6 to study the impact of faults and attacks on the system and evaluate the effectiveness of the proposed FTC scheme. Experimental research results are provided in Section 7 to verify the presented concept. Finally, conclusions are drawn in Section 8.

2. Modelling and control of electronically-coupled DER

This section presents a detailed model, as well as a real and reactive power control, of an electronically-coupled DER unit in a grid-connected microgrid system operating under nominal operation. Fig. 1 shows a DER unit in a grid-connected microgrid. The DC side of the DER is assumed to be a constant DC voltage source, which may be supplied by controlled energy source, such as solar PV panels, wind generator, fuel cell, micro turbine etc. The DC output power of the energy source is converted into AC power through the converter. The DER is connected to a three-phase grid supply at point of common coupling (PCC), the converter used is an IGBT (insulated-gate bipolar transistor) based, six-pulse bridge, three-phase voltage source converter (VSC). The output AC power of the converter is supplied to the grid through connecting lines and *LCL* filter, where *R* represents the ohmic loss of the filter and converter loss, L_1 and L_2 are the total inductances of the connecting lines and filter, and C_f is the filter capacitance. In Fig. 1 the voltages at the VSC, capacitor and PCC are denoted by v_{tabc}, v_{cfabc} and v_{sabc}, respectively. Notations i_{1abc} and i_{2abc} denote currents flowing out of the VSC and at the PCC respectively.

2.1. State space modelling of a DER in a grid connected microgrid system

In *dq* coordinate, the following set of differential equations describes the dynamics of a DER unit in a grid-connected microgrid system.

$$\dot{i}_{1d} = -\frac{R}{L_1} i_{1d} + \omega i_{1q} - \frac{v_{cfd}}{L_1} + \frac{v_{dc}}{2L_1} m_d$$
$$\dot{i}_{1q} = -\omega i_{1d} - \frac{R}{L_1} i_{1q} - \frac{v_{cfq}}{L_1} + \frac{v_{dc}}{2L_1} m_q$$
$$\dot{i}_{2d} = \frac{1}{L_2}(v_{cfd} - v_{sd}) + \omega i_{2q}$$
$$\dot{i}_{2q} = \frac{1}{L_2}(v_{cfq} - v_{sq}) - \omega i_{2d}$$