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Robust sensor fault detection and isolation scheme for interconnected smart power systems in presence of RER and EVs using unknown input observer

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ABSTRACT

Correct measurement of variables used in frequency control of power system is crucial for power system operation, stability, and security. Once sensor fault is occurred in power system, the faulty sensor should be instantly isolated. To this end, a model-based fault detection and isolation (FDI) technique is adopted in this paper. The proposed sensor FDI scheme for complex power systems is built based on unknown input observer (UIO) which is robust for systems with unknown inputs. The load fluctuation and output power variation of renewable energy resources are modeled as unknown inputs of power systems. To show the effectiveness of the proposed schemes in case of future smart grids, the studied power system is developed to combine both electric vehicles (EVs) and high penetration level of renewable energy resources. The simulation scenarios are carried out for an eleven-order dynamical multi-area smart power system. The robustness of using UIO to detect and isolate sensor faults in power system is proved by several simulation scenarios. Likewise, the simulation results show that isolation of faulty sensors can be guaranteed by proper selection of the measured variables in the state space model of the studied system.

1. Introduction

Due to environment concerns, energy security risks, and fossil fuel problems, many countries around the world decided to increase the penetration level of renewable energy resources (RERs) in their energy networks. Beside this, many countries are moving toward implementation of smart grid concept in their power systems to achieve reliable and secure operation of their power systems with high penetration level of renewable energy resources. In such future smart grids, keeping the balance between electrical demand and the generated electric power would be the important issue due to the uncertainties of both demand and generated electrical powers from renewable resources [1,2]. The main result of imbalance between demand and generation of electrical power is the frequency deviation from its nominal value [3].

In power systems, to maintain the frequency in permissible range, two frequency control loops are usually used. Many control approaches such as, optimal control theory [4], model predictive control [5,6], evolutionary computing based control [7–9], different structures of PID including fractional order PID [10–12], observer-based control design [13,14], and sliding mode control theory [15,16] have been suggested for frequency control in literatures. However, due to its simplicity, PI/I controller are still the most used controller in industrial power systems. Likewise, many reserve sources such as, electric vehicles [17–21], flywheels [22,23], battery energy storage systems [10,24], different types of conventional generating units [10,22], distributed generating units [22,25], demand response [26,27] have been recently proposed for providing sufficient electric reserve for controlling the power system frequency.

In the control center of power systems, frequency control are usually divided into two control loops, in which, primary frequency control loop is a local control and the secondary frequency control loop is a central control [28]. Both control loops depend on the measured sets such as, frequency, power interchanges with other areas, and other measured sets to generate the frequency control signals. The correct measurement of frequency and other variable measurement sets are crucial for reliable and secure operation of power systems [29]. Therefore, the faulty sensors which are responsible for measuring the different variable sets such as frequency and tie-lines power, should be detected and isolated as soon as possible. In case of using robust fault diagnosis techniques, the operator of the power system can detect which sensor is faulty and replace it by the healthy one.

Nowadays, there is a great research activity in the development of new methodologies for fault diagnosis [30,31]. Fault detection and isolation (FDI) methods are mainly divided into three groups: signal-

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based, knowledge-based, and model-based methods. With the developments of system identification techniques, the model-based FDI methods have received considerable attention in recent years [32]. The model-based FDI methods can detect and isolate the faults in industrial systems by comparing the residuals with predefined thresholds [33]. The residuals are generated by comparing the computed outputs from mathematical model with the measured outputs via sensors. During the last decades, observer-based approach is the most adopted method in model-based FDI. Beard–Jones fault detection filter (BJFDF) was the first introduced observer-based approach for fault diagnosis in industrial systems [34]. Additionally, different robust observers-based FDI for systems with unknown inputs such as full order linear unknown input observer (UIO), reduced order linear UIO, and nonlinear UIO, have been developed [35–37]. Likewise, for detecting and isolating the faults in complex system, an adaptive observer -based fault diagnosis, a sliding-mode observer-based fault diagnosis, and an extended Kalman filter-based fault diagnosis have been proposed in [38–41].

Due to the great importance of power systems in modern life, robust fault diagnosis approaches are needed to keep reliably and securely operation of power systems. Among the studies associated with fault diagnosis methods applied to power systems, a sensor fault detection in dynamic system using model-based techniques has been introduced in [42,43]. A fault diagnosis technique using failure detection filter approach for detecting and isolating faults in frequency control loops of power systems has been proposed in [44]. FDI technique in frequency control system of linear power system using UIO has been introduced in [45]. Fault detection approach in electrical transmission network using UIO has been proposed in [46]. It is clear from the aforementioned literature survey that there is a knowledge gap in field of designing a robust fault diagnosis systems for future smart grid considering electric vehicles and renewable energy resources which needs to be widely investigated.

In this paper, a sensor fault detection and isolation scheme is developed for future smart grids. The proposed FDI scheme is built based on UIO method. The residuals are generated by comparing the computed variables from the mathematical model using UIO with the measured variables using frequency and power sensors. To design a robust sensor fault detector and isolator, the disturbances are considered as unknown inputs. Both load fluctuation and output power variation of renewable energy resources are considered as disturbances which are unknown to the operator of power systems. Moreover, a comprehensive dynamical state space model of *N*-area power system is developed. Likewise, to guarantee the existence of UIO-based FDI scheme, a new approach of assigning measured sets is proposed in this paper. Furthermore, the studied power system is developed to combine high penetration level of renewable energy resources i.e., solar power plants and wind farms. Likewise, it is assumed that the secondary reserve is provided to the studied power system from both conventional power plants and electric vehicles aggregator. Such system with high penetration level of renewable energy resources and integrated electric vehicles simulates the smart grids that would be a fact nearly. Then, the proposed sensor FDI scheme is applied to the developed power system to demonstrate the robustness of UIO in successfully detecting and isolating the sensor faults. Thus, the proposed sensor FDI scheme tells the power system operator which sensor is faulty to be replaced by healthy one as soon as possible.

The rest of this paper is organized as follows. The general concept of UIO used as a sensor fault detector is introduced in Section 2. The proposed sensor fault isolator using UIO is explained in Section 3. A general dynamical model of power system considering electric vehicles and renewable energy resources is proposed in Section 4. The studied power system is briefed in Section 5. The simulation results of various scenarios are discussed in Section 6. Conclusions of the proposed methods and results are given in Section 7.

2. General unknown input observer based fault detection scheme

It is difficult to design an observer with Luenberger structure for industrial systems modeled with disturbance terms such as electric power systems with high penetration level of renewable energy resources. Due to this fact, many observer methods for systems with known and unknown inputs have been developed in recent years. A robust observer for systems with disturbances modeled as unknown inputs called UIO is used in this study for designing a sensor fault detection and isolation scheme. To demonstrate this observer, let us consider an n-order dynamical system given in (1).

$$\begin{aligned}\dot{x}(t) &= Ax(t) + Bu(t) + Ed(t)\\ y(t) &= Cx(t)\end{aligned} \tag{1}$$

where $x \in \Re^{n\times1}$, $u \in \Re^{r\times1}$, $d \in \Re^{q\times1}$, $y \in \Re^{m\times1}$ and A,B,C are the state vector, the input vector, the disturbance vector, the output vector of the system, and the known state space matrices of the studied system with appropriate dimensions, respectively.

It should be noted that, in some dynamical systems, there is a term relating to the input vector in the output vector as shown in (2).

$$y(t) = Cx(t) + Du(t) \tag{2}$$

In such systems, a new output vector can be constructed as follows:

$$y^{new}(t) = y(t) - Du(t) = Cx(t) \tag{3}$$

The dynamical system given in (4) is an observer for the system with the unknown inputs, d, given in (1) if and only if the state estimation error, $e(t)$, given in (5) approaches zero asymptotically [33].

$$\begin{aligned}\dot{z}(t) &= Fz(t) + TBu(t) + Ky(t)\\ \hat{x}(t) &= z(t) + Hy(t)\end{aligned} \tag{4}$$

$$e(t) = x(t) - \hat{x}(t) \tag{5}$$

where $z \in \Re^{n\times1}$, $\hat{x} \in \Re^{n\times1}$, $e \in \Re^{n\times1}$, and F,T,K,H are the state vector of the UIO, the estimated state vector of original system, the state estimation error, and required matrices with appropriate dimensions, respectively.

It has been proved that the dynamics of the state estimation error will be $\dot{e}(t) = Fe(t)$ if the requirements given in (6) are satisfied [33].

$$\begin{aligned}(HC - I)E &= 0\\ T &= I - HC\\ F &= A_1 - K_1C\\ K_2 &= FH\\ K &= K_1 + K_2\\ A_1 &= A - HCA\end{aligned} \tag{6}$$

Notice that the required matrices in (6) should be met to design unknown input observer as long as all eigenvalues of F are stable in which K_1 should be assigned such that F is Hurwitz [32]. The sufficient conditions for (4) to be an UIO for (1) are:

(i) $rank(CE) = rank(E)$
(ii) The pair (C,A_1) is detectable.

It is clear from the above discussion that once the matrix K_1 is determined, all other matrices for designing UIO can be easily calculated. When the pair (C,A_1) is observable, K_1 will be easily determined by pole placement method in which F is stable. Otherwise, if the pair (C,A_1) is not observable, a transformation matrix P should be constructed by performing the method called observable canonical decomposition on the pair (C,A_1) as illustrated in (7) and (8) [47,48].

$$PA_1P^{-1} = \begin{bmatrix} A_{11} & 0\\ A_{12} & A_{22}\end{bmatrix} \quad where\ A_{11} \in \Re^{n_1\times n_1} \tag{7}$$

$$CP^{-1} = [C^*\ 0] \quad where\ C^* \in \Re^{m\times n_1} \tag{8}$$