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Impact assessment of reliability of phasor measurement unit on situational awareness using generalized stochastic Petri nets

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ABSTRACT

Situational awareness (SA) in power systems enables timely and right decisions by the system operators to prevent a blackout. Real-time monitoring of the grid provides adequate SA for successful grid operations. Phasor measurement units (PMUs) are instrumental in providing with a comprehensive real-time view of the grid. They provide with time-aligned phasor measurements (synchrophasors) from different locations of the network. Therefore, PMUs are instrumental in SA. In this paper, effect of reliability of PMU modules on SA of the power system has been analysed. Reliability modelling of PMU and its modules has been done using generalized stochastic Petri nets (GSPNs). They provide a strong graphical representation and model minute details of a system accurately. The results of reliability analysis of modules obtained are employed to investigate their effect on SA through event tree analysis (ETA).

1. Introduction

The power grids are complex entities with continuously changing dynamics [1,2]. A fault, if unheeded might be transmitted and cause system blackout. It can be prevented by being aware of real-time status of all the important grid components [3–7]. The unfaltering monitoring of grid to record, measure and process continually varying grid vitals for better understanding of grid operations is called situational awareness (SA) [8,9]. Any event can be split into two phases: pre-cascading period and cascading period. During the former, operators have sufficient time to act and save the system from blackout. While during cascading period, there is no time to react resulting in total blackout [8,9]. Thereby, SA enables timely right decisions and their implementation to avert an undesired incident. Synchrophasors of analog quantities (like, voltage and current) at different buses are highly capable of providing an accurate and comprehensive view of the grid at operating room [3,4]. PMUs are recent devices that provide synchrophasors, and which in turn aid the critical need of SA. Therefore, PMUs have carved a niche for themselves as new era sensors of power grids [3–7].

1.1. Basic concepts of SA

SA in power systems can be formally defined as perception and comprehension of information related to constituting elements for projection of their future status using this data [8,9]. The necessity of SA has been proved in various domains such as military, aviation, air traffic control, automotive, etc. Basic definition of SA is split into three parts [8,9], and explained in Fig. 1.

- Perception: To be aware of the status of key power system components through measurements of corresponding analog quantities.
- Comprehension: To understand the acquired data related to components for better system awareness.
- Projection: To predict the future state of power system through comprehension of acquired data.

PMUs are instrumental in enhancement of SA in power systems. They provide real-time synchrophasors which are processed and relayed to control rooms [4,5]. Then, the most critical information (such as weakest bus voltage of the network) is segregated and prioritized according to goals and objectives (security levels, stability levels, and voltage levels) of the system [8]. This data is used for prediction of future behaviour of the system as well as to develop an action plan (set of strategies and responses) to events. Therefore, adequate SA aids prevention of undesirable events in power systems [8,9].

1.1.1. SA for complete network using optimally placed PMUs

A power network is completely observable when all its states can be determined, i.e., voltage and current phasors at all buses should be measured [5]. However, it is expensive to place PMUs

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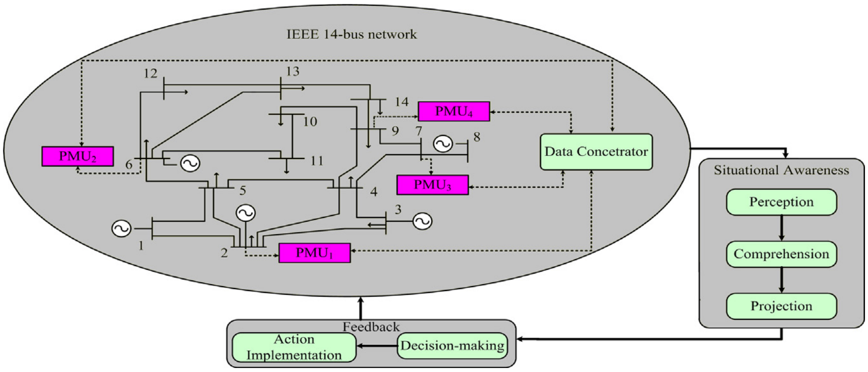

Fig. 1. Situational awareness in power systems.

on every bus of a network [10]. Therefore, optimal PMU placement to make the system observable has been of research interest since its advent. Fig. 1 illustrates optimal placement of PMUs at bus 2, 6, 7 and 9 for complete network observability for IEEE 14-bus network. The observability rule states that a PMU installed at a given bus makes the bus and all incident buses to it observable [5,10]. In Fig. 1, bus 2 is directly observable by PMU$_1$. Incident buses 1, 3, 4 and 5 are also observable by PMU$_1$. Similarly, PMU$_2$ at bus 6 makes bus 6 as well as buses 5, 11, 12 and 13 observable. PMU$_3$ at bus 7 makes buses 7, 4, 8 and 9 observable. PMU$_4$ at bus 9 makes buses 9, 4, 7, 10 and 14 observable. Thus, complete system with 14 buses is observable with PMUs placed at 4 buses.

1.1.2. Impact of measurement error of PMUs on SA

IEEE Standard C37.118.1-2011 describes error calculations for signal frequency (f), voltage magnitude ($|V|$), current magnitude ($|I|$) and phase angle (ϕ) [11]. The errors for two class of PMUs i.e., P (for protection applications) and M (for measurement applications) are described as follows and limits are specified in Table 1.

- Total Vector Error: It is the error between ideal phasor and phasor estimate of signal provided by PMU. Mathematical representation is as follows:

$$TVE \text{ in } \% = \left| \frac{V_{\text{measured}} - V_{\text{ideal}}}{V_{\text{ideal}}} \right| \times 100 \qquad (1)$$

- Frequency error: It is the difference between measured and actual signal frequency. The mathematical representation is as follows:

$$FE = |f_{\text{true}} - f_{\text{measured}}| = |\Delta f_{\text{true}} - \Delta f_{\text{measured}}| \qquad (2)$$

  where f is frequency and Δf represents change in frequency in Hz.

- Rate of Change of Frequency Error: It is defined as the difference between measured and theoretical rate of change of frequency of signal. The mathematical representation is as follows:

$$RFE = |ROCOF_{\text{true}} - ROCOF_{\text{measured}}| \qquad (3)$$

Since PMUs are manufactured in compliance with IEEE standards C37.118.1-2011, therefore, the errors will be less than 1% and they will not affect SA of the system.

1.2. Motivation

Post-event analyses of major blackouts worldwide have identified inadequate SA as one of the main causes [9]. Insufficient SA leads to poor coordination among operators. Therefore, SA enhancement as well as improvement is mandatory for successful grid operations [8,9]. PMUs play a critical role in SA by enabling engineers to perceive real-time grid operating conditions. The vast PMU data acquired is converted into operator-friendly information that includes angular separation, oscillatory stability, resynchronization, fault location identification, and islanding [3,4]. Thus, failure of PMUs would result in loss of SA, which in turn would cripple the system from avoiding cascading failures.

1.3. Related works

Reliability investigation of PMU has been extensively done by researchers through different reliability models ranging from Markov models, reliability graphs to fault-trees [12–16]. Markov models efficiently represent the logical relationship among functional components of PMU. However, they suffer from state explosion problem and do not take into account multiple fault patterns [12–14]. Therefore, in [17] authors have proposed a Monte

Table 1
IEEE standards for steady state measurements [11].

	P Class		M Class	
Signal	Range	Max *TVE* (%)	Range	Max *TVE* (%)
	Steady state synchrophasor measurement requirements			
f range	±2.0 Hz	1	±2.0 Hz for $F_s < 10$ $\pm\frac{F_s}{5}$ for $10 \leqslant F_s < 25$ ±5.0 Hz for $F_s \geqslant 25$	1
$\lvert V\rvert$	80–120% rated	1	10–120% rated	1
$\lvert I\rvert$	10–200% rated	1	10–200% rated	1
ϕ	$\pm\pi$ radians	1	$\pm\pi$ radians	1
	Steady state frequency and ROCOF measurement requirements			
f	Max *FE* 0.005 Hz	Max *RFE* 0.01 Hz/s	Max *FE* 0.005 Hz	Max *RFE* 0.01 Hz/s