Chapter 25
PMU Deployment in Power System Oscillation Monitoring

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Abstract Oscillatory events at low frequencies are commonly witnessed in interconnected power systems. Phasor Measurement Units (PMU) can provide time-synchronized measurements; it can communicate the synchronized local and inter-area information to remote station. In this paper, we have modeled a PMU, and we have tested it in the 14-bus power system. It proposes a real-time monitoring tool that exploits synchronized phasor measurements from PMUs, which allow real-time analysis of higher-frequency events, filling the lack of such monitoring application in the power systems area.

25.1 Introduction

Power system operation and control have for decades been performed with systems built in a centralized architecture, with a SCADA and Energy Management System (EMS) located in a control center. In the control center, operators have been provided with analog measurements and digital indications from the power system via the SCADA system. This has allowed them to monitor and control the power system on a near real-time basis (Phadke 2008; Bentarzi 2010).

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With the advent of new communication and computing technologies, numerous visions for future power system operation and control have been created (Karlsson et al. 2004; Phadke and Thorp 2008; Bakken et al. 2007).[1] Synchronized phasor measurements have started to become available at selected substations in the system. Phasor measurement units (PMU) are devices, which use synchronization signals from the global positioning system (GPS) satellites and provide the positive sequence phasor voltages and currents measured at a given substation (Ouadi et al. 2009). These types of measurements will in turn improve the performance of the state estimators. In these future architectures, the functionality needed for control and protection of the power system can be located at any computing platform within a distributed control system.

There is global interest in the prospects of PMU-based monitoring and control technology (Marinez et al. 2005; Chenine et al. 2009; Zima et al. 2005). These systems promise to offer more accurate and timely data on the state of the power system increasing the possibilities to manage the system at a more efficient and responsive level and apply wide area control and protection schemes. Of the pioneering works in PMU development and utilization, one would state the works done by Phadke et al. (1986), Phadke (1993). Most of the efforts worldwide; e.g., (Chenine et al. 2009; Zima et al. 2005; Phasor Application Classification 2007; Chenine and Zhu 2008),[2] has been on developing monitoring and assessment applications based on PMU measurements in addition to platforms that would support these applications. Monitoring and assessment applications are known as Wide Area Monitoring Systems (WAMS); these new applications were previously impossible with SCADA measurements due to its generally low data sampling rate quality, and lack of exact time synchronization. There has been generally less work on developing protection systems for PMU-based monitoring and assessment application, and even less so for wide area control applications. The latter group of systems which not only monitors the power system states is referred to as Wide Area Monitoring and Control Systems (WAMC).

With the increase of the interconnected power network scale and complexity, the problem of various potential power oscillations has caused a lot of damage to the system stability operation security. The increasing amount of renewable power, which constitutes one kind among different intermittent generation sources, involves numerous new challenges for its integration into existing power systems. Transient, stability issues have already been studied (Wiik et al. 2000). However, it has been only recently that some Transmission System Operators (TSOs) have measured, with PMUs (White and Chisholm 2011), sub-synchronous oscillatory events resulting from interactions between wind farms at frequencies around 13–15 Hz. The oscillations were observed at the consumer level in the form of flickering (White et al. 2012).

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[1] North American Synchrophasor Initiative, www.naspi.org.

[2] OPNET Modeler, OPNET Inc., www.opnet.com.

This paper is concerned with any oscillatory behaviors occurring at a frequency of the frequency of the power system different from inter-area, or local oscillations will be referred to as sub-synchronous oscillations.

25.2 PMU Modeling

PMU technology provides phasor information (both magnitude and phase angle) in real time. Phasor measurement units (PMUs) are the most accurate and advanced synchronized phasor measurement equipment. Figure 25.1 gives a functional block diagram of a typical PMU. The GPS receiver provides the one pulse-per-second (pps) signal, and a time tag consisting of the year, day, hour, minute, and second.

Effective utilization of this technology is very useful in mitigating blackouts and learning the real-time behavior of the power system. With the advancement in technology, the microprocessor-based instrumentation such as protection Relays and Disturbance Fault Recorders (DFRs) incorporate the PMU module along with other existing functionalities as an extended feature.

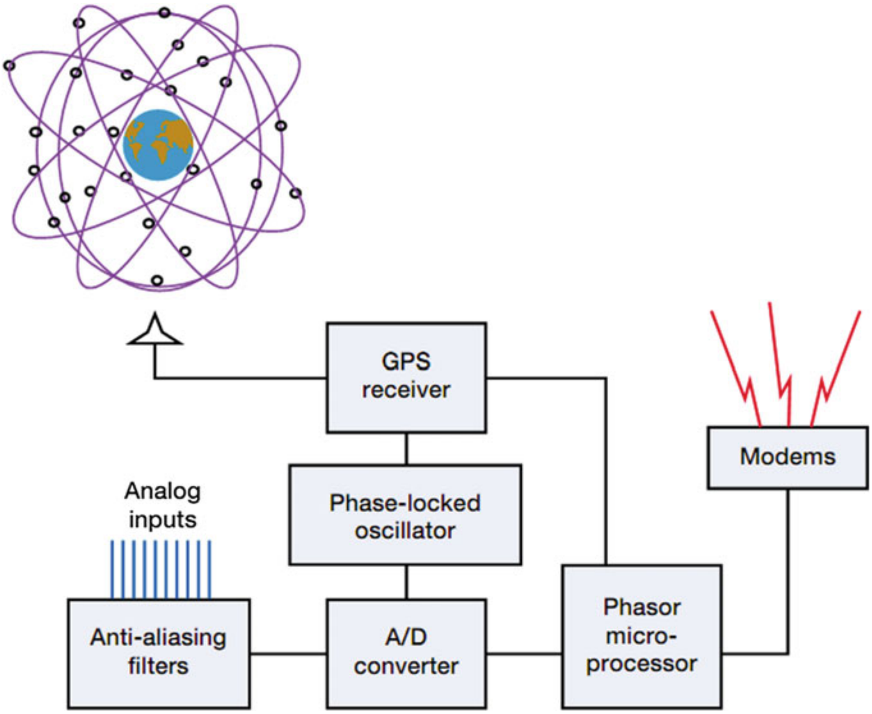

Fig. 25.1 Functional block diagram of a typical PMU

The synchronized phasor measurement technology is relatively new, and consequently, several research groups around the world are actively developing applications of this technology. It seems clear that many of these applications can be conveniently grouped as follows:

- Power System Real-Time Monitoring
- Advanced network protection
- Advanced control schemes

25.2.1 PMU Principle

A pure sinusoidal waveform can be represented by a unique complex number known as a phasor.

Consider a sinusoidal signal

$$X(t) = X_m \cos(\omega t + \Phi) \tag{25.1}$$

X_m the peak value of the sinusoidal voltage,
$\omega = 2\pi f$ the frequency of the voltage in radians per second,
f the frequency in Hz,
Φ the phase angle in radians with respect to the reference value.

The phasor representation of this sinusoidal is given by

$$X(t) = \frac{X_m}{\sqrt{2}} e^{j\Phi} = \frac{X_m}{\sqrt{2}} (\cos\,\Phi + j\,\sin\,\Phi) \tag{25.2}$$

Note that the signal frequency 'ω' is not explicitly stated in the phasor representation. The magnitude of the phasor is the rms value of the sinusoid, and its phase angle is Φ, the phase angle of the signal in Eq. (25.1). The sinusoidal signal and its phasor representation are given by Eqs. (25.1) and (25.2).

25.2.2 Phasor-Data Applications

Although PMU data collected at a few points on the grid can reveal conditions across a wide area and inform a variety of grid applications, PMU placement should support the needs and functionalities of the intended applications and system characteristics. As a result, the discussion on PMU siting is organized according to real-time and off-line applications with sub-categories as shown in Table 25.1.

Table 25.1 PMU real-time and off-line applications

Real-time applications	Off-line applications
Visualization and situational awareness • Situational awareness • Generating stations • Flow gates and regional transmission interfaces • Separation islands	*Analysis and assessment* • Base lining and correlation analysis • Disturbance analysis • Model validation • Frequency response analysis • Renewable generation
Monitoring and alarming • Phasor-data augmented state estimation • Phasor-data only state estimation • Small-signal stability monitoring • Voltage stability • Thermal monitoring and congestion monitoring	*System planning* • Load characteristics • Primary frequency response
Protection and control • Out-of-step protection • Small-signal stability protection • Long-term stability control	

25.3 PMU and Power Systems

Inter-area oscillations result from system events coupled with a poorly damped electric power system. The oscillations are observed in the large system with groups of generators, or generating plants connected by relatively weak tie lines. The low frequency modes (0.1–0.8 Hz) are found to involve groups of generators, or generating plants, on one side of the tie oscillating against groups of generators on the other side of the tie. These oscillations are undesirable as they result in sub-optimal power flows and inefficient operation of the grid. The stability of these oscillations is of vital concern.

To overcome the inter-area oscillation, equipment such as Static Var Compensator (SVC) and various Flexible AC Transmission System (FACTS) devices are being increasingly used. These techniques have become possible due to the recent advancement in power electronic technology. The involvement of SVC and FACTS in a transmission network is through the so-called Variable Series Compensation (VSC). Besides the FACTS devices, the application of Super-Conducting Magnetic Storage (SMES) to enhance the inter-area oscillation damping is also reported.

Although Power System Stabilizers exist on many generators, their effect is only on the local area and does not effectively damp out inter-area oscillations. It can be shown that the inter-area oscillations can be detected through the analysis of PMU located within the system. Oscillations in power systems are classified by the system components that they effect

- Intra plant mode oscillations: Machines on the same power generation site oscillate against each other at 2.0–3.0 Hz.
- Local plant mode oscillations: In local mode, one generator swings against the rest of the system at 1.0–2.0 Hz.
- Inter-area mode oscillations: This phenomenon is observed over a large part of the network. It involves two coherent group groups of generators swinging against each other at 1 Hz or less.

Instability in a power system may be manifested in many different ways. Generally, the stability problem has been one of the maintaining synchronous operations. Instability may also be encountered without loss of synchronism. Since power systems rely on synchronous machines for generation of electrical power, a necessary condition for satisfactory system operation is that all synchronous machines remain in synchronism.

In this paper, we discuss this advanced technology (PMUs) with the help of MATLAB simulation. We design this PMU model in MATLAB SIMULINK, and then we installed this model in the 14-bus power system. Such application is made for the protection, monitoring, and control of a wide power system.

25.4 Simulation of the 14-Bus Power System

We simulated the 14-bus power system associated with the PMUs, and provoked a fault in the line 4 between the time 4 and 5 s as shown in Fig. 25.2. Figures 25.2, 25.3, 25.4, 25.5, 25.6 and 25.7 show the simulation results. Where Fig. 25.4 shows

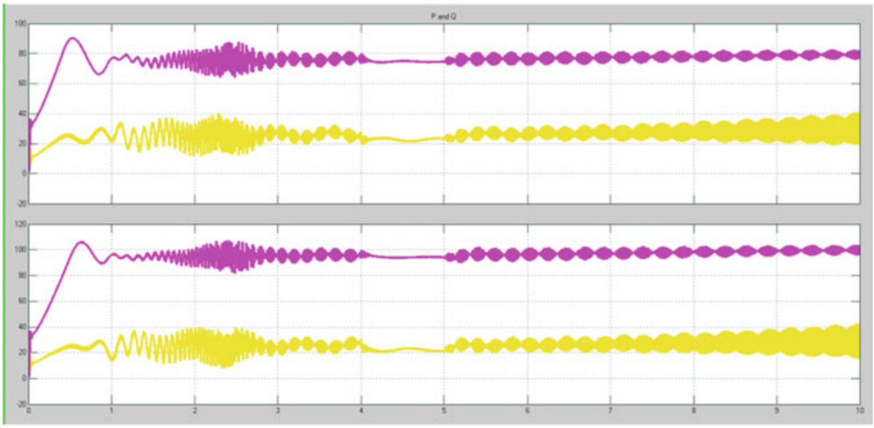

Fig. 25.2 Active power (*pink*) and reactive power (*yellow*) noted by two PMU (G1 and G2)

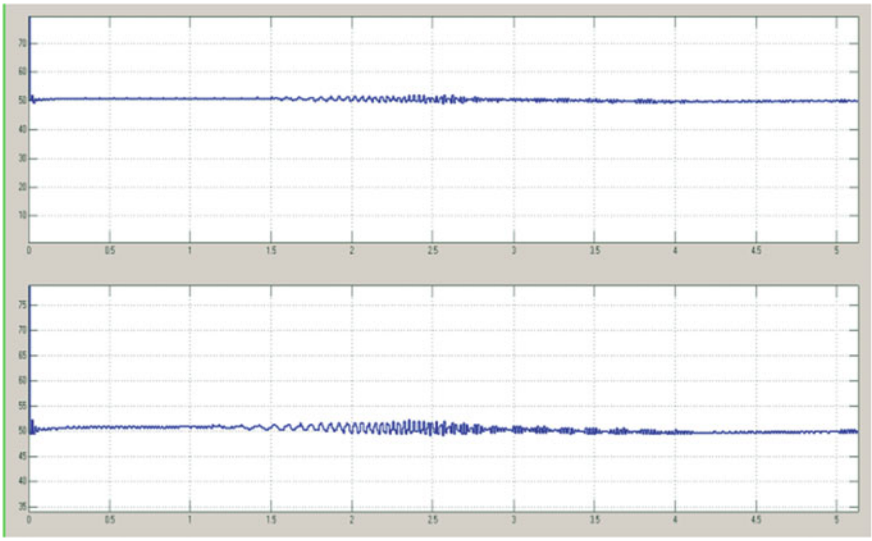

Fig. 25.3 Frequency variations (G1 and G2)

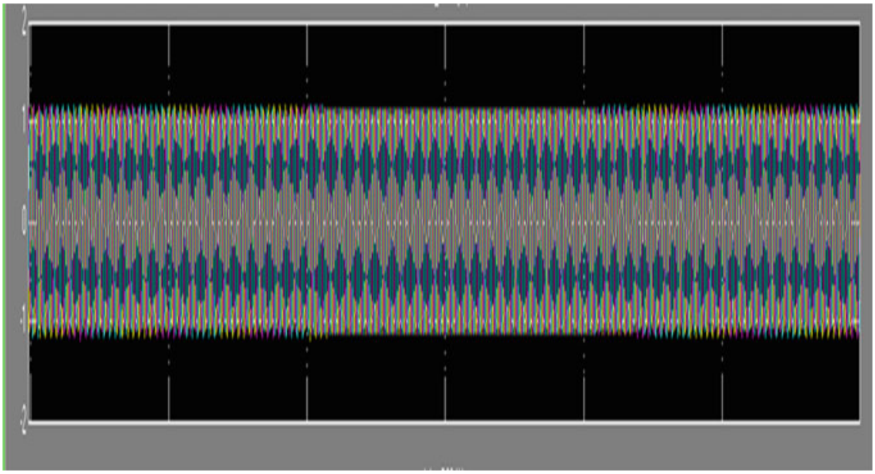

Fig. 25.4 The voltage at the bus 01

the active and reactive power at different generators such as G1 and G2 measured by PMUs. However other curves show frequencies and voltages that can be used for monitoring oscillations in the whole power system and mitigating them by proper switching actions of FACTS. The fault effects may appear at the bus which is near to it. Frequency can significantly be varied at G2 rather than G1 as illustrated in Fig. 25.3.

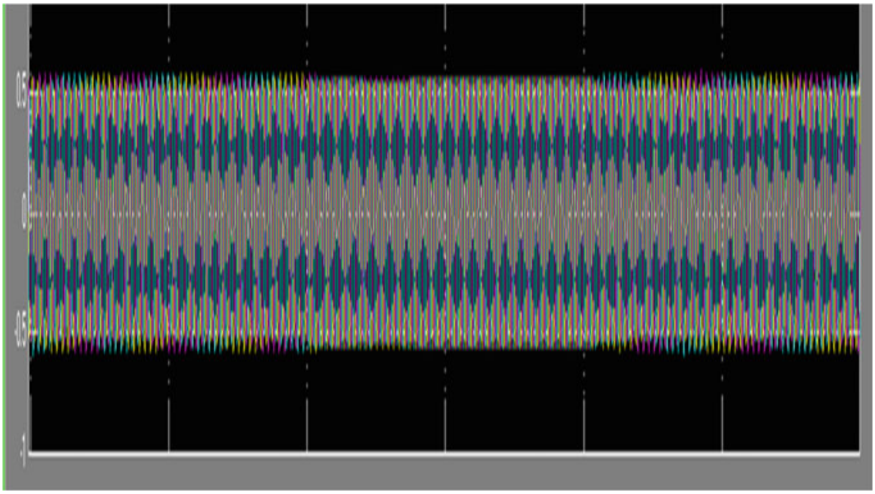

Fig. 25.5 The voltage at the bus 02

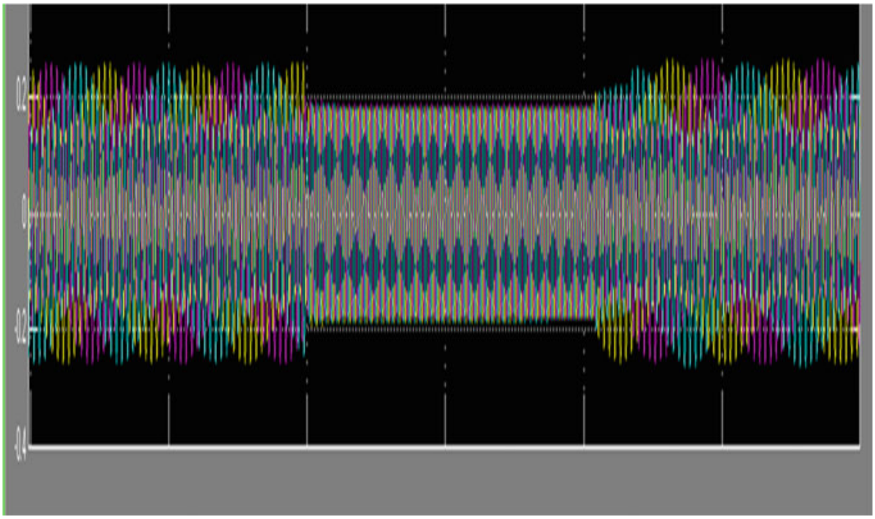

Fig. 25.6 The voltage at the bus 03

The voltages at the bus 4 totally collapse because this bus is too close to the fault (see Fig. 25.7), however, the voltages at the other buses are partially affected or not affected as shown in Figs. 25.4, 25.5, 25.6 and 25.7.

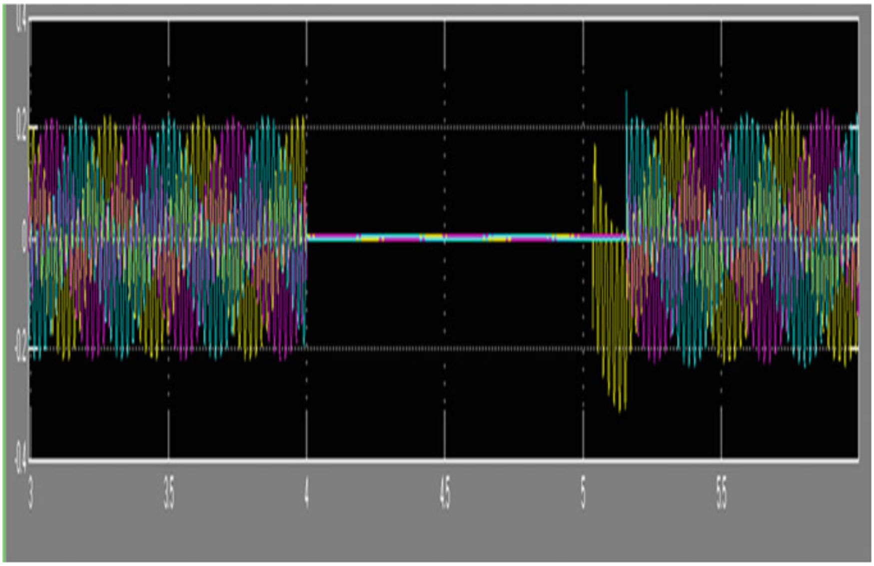

Fig. 25.7 The voltage at the bus 04

25.5 Conclusion

The use of PMU in the electrical network provides good results for monitoring all power system parameters. With the use of GPS for data synchronization, the power system states like voltage magnitude, voltage phase angle, current magnitude, current phase angle, frequency and rate of change of frequency are provided by PMU. All given states are real times. The information supplied by PMU can be used to protect the electric grid. Simulation results show the operation of the PMU for monitoring the power grid.

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