Introduction to WAMS and Its Applications for Future Power System

Reza Zamani, Habib Panahi, Arash Abyaz, and Hassan Haes Alhelou

Abstract Nowadays, the increase in electrical energy consumption and power system restructuring have posed new challenges to the operation, control, and monitoring of power systems. In this situation, the supervisory control and data acquisition (SCADA) system is not enough to ensure power system security and stability. The SCADA is often unable to measure data of all buses simultaneously. In addition, the sampling rate in this system is not enough for some power system applications. Therefore, the information obtained from SCADA does not show power system dynamics properly. In order to improve the power system monitoring, wide area measurement system (WAMS) has been developed to overcome the problems of SCADA system. Phasor measurements units (PMUs) are the main part of WAMS system and it basically consists of three essential processes including collecting, transmitting, and analyzing data. WAMS receives obtained data via a high speed communication links. After data processing and extracting appropriate information, decisions are made to improve the power system performance. Efficient use of power system data to achieve a secure operation strategy is targeted using the WAMS system. Due to the effective role of WAMS and PMUs in the reliable operation of power system, it is necessary to study their concept and applications in this chapter. The history of PMU and its structure is presented in this chapter. In addition, the necessity of WAMS for future power system and its difference from SCADA system have been investigated

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in this chapter. Different algorithms and application of the WAMS are also introduced in this chapter which can be implemented to improve the performance of the future power system.

Keywords WAMS · SCADA · PMU · Power system monitoring

1 Introduction

The need to visibility, controllability, and send remote command power system has been felt, from the beginning of the creation it. In order to operate the network securely and with high reliability, it is necessary to have the information of different places of the network in a center and according to that information, the necessary decisions should be made. Telecommunication system with following specifications was necessary for this aim [1]:

- Fast: A fast telecommunication system is required to be able to send signals to the control center with minimum delay. Suppose that load increase in a substation in the south of the country and control center will find out five seconds later. In this case, there may not be enough time for preventive control.
- Bandwidth: It has a high bandwidth to be able to send a lot of information. This information includes buses voltage, current and power of lines, and keys status.

With the passage of time, bandwidth and speed of telecommunication systems increased. With this progress, system operators thought of creation of a control center for network observability. At first, supervisory control and data acquisition (SCADA) was created. This system received the information of different point of the network in control center. This development allows the operator to control and better operate the network in the control center.

Disadvantages of SCADA were found over the time. The lack of synchronization of data obtained from different substations is the most important disadvantage of SCADA. To extract the signal phase, a time reference is required, and for data reference time, data synchronization is required. For this reason signal phase was not calculated in SCADA. In first, state estimation (SE) was used to extract phase signal in SCADA. SE has a lot of errors due to bad data and error of measurement device. Sometimes, error of SE has so much such that many researchers believed that the blackout of US occurs because of it. For this reason, the need for a system that can measure synchronized data became very tangible.

With the help of a global positioning system (GPS), the synchronized data of different places can be measured. With deploying this technology, researchers focused on build a device that it could measure synchronized data. In the early 1980s, a device that could sample synchronized data from different point of the network was built in Virginia Tech. This device called phase measurement unit (PMU). An example of PMU is shown in Fig. 1.

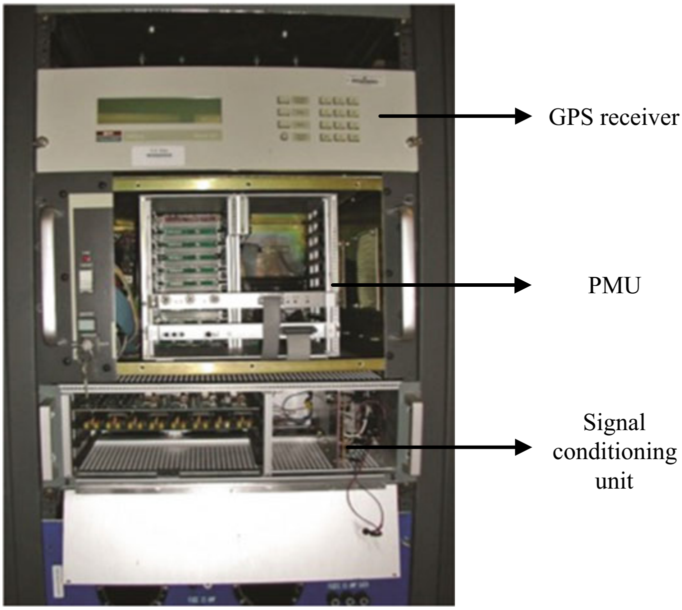

Fig. 1 An example of first PMU that was built at 1980s

The first built PMU was a huge improvement in power system because it could measure synchronized data from different Point. Therefore, IEEE published a standard for PMU [2–4]. PMU could extract signal phase because of synchronized measurements. Nevertheless, the first PMU had some disadvantages such as large scale and less input. Primary PMU was difficulty installed in panel because of large dimensions [5–9].

After this introduction, The SCADA has been described to make it clearer why PMU was built. Then structure of PMU and how to extract phase and frequency of signal are described. Finally, various WAMs and PMU applications have been discussed.

2 SCADA

As aforementioned in the introduction, the SCADA system has been used in the last decades for the visibility of the network purpose. The SCADA system consists of the following three parts [10–14]:

(1) Remote terminal unit (RTU)
(2) Concept and object modeling notation (COMN)
(3) Master terminal units (MTU)

2.1 RTU

RTUs are installed in substations and measure network parameters. The variables that RTUs can measure usually are listed as follows:

- Voltage magnitude
- Active and reactive power
- Tap changer position
- Circuit breaker status

The first three cases have continuous values, but the circuit breaker statuses are sent to the control center by binary variables. To increase the accuracy and security, status is sent with two bits instead of one bit, for example, 01 means that the circuit breaker is closed and 10 means that it is open. Also, these first three cases are transformed into DC currents using transducers in the range of 4–20 mA.

2.2 COMN

The telecommunication system is stablished between the substations and the control center. Power transmission lines have been used to send signals in some cases. In this method, the signal is added to the transmission line in the location of capacitor voltage transformer and the signal moves along the line to reach the upstream bus. Signals were sent on two different phases to ensure that transmission faults did not cause problems. The operation of this system would be disrupted if there was a fault on the transmission line (for example, a three-phase short circuit fault). For this reason, other methods of sending, for example, radio, etc., gradually replaced this method.

2.3 MTU

It is the control center to which signals are sent by a special protocol from RTUs. The most common protocol is IEC 60870-5-101 (or 104). There are several applications in MTU, the most common of which is SE, which is designed for two purposes:

- Signal phase extraction
- Reducing measuring signal error and sending data

In addition to performing these applications, the data is displayed on the diagram mimic and the operator sees information about different locations of the network on a large screen.

It should be noted that if only the time error for receiving signals assumed to be 1 ms, in the power network with a frequency of 50 Hz, this 1 ms error will caused to 18 degree error in measuring the signals phasor.

2.4 SCADA Problems

After explaining the different concepts of SCADA, its problems are described so that by knowing these problems, the requirements for constructing an efficient PMU system can be better understood. In general, the most shortages of SCADA system can be summarized as bellow:

(1) Measured data are not real-time and polling rate is about 2–10 s.
(2) Measurements do not exactly belong to a given time, i.e. time deviation exists.
(3) There is not any information on phase angle while this is a necessary tool for power system stability assessment.
(4) SE runs every few minutes, if any
(5) Dynamic of the system is not observable.

These problems were lead to several blackouts in the world such as:

- August 14, 2003 Northeast blackout due to lack of wide-area visibility of the system.
- A report prepared by U.S.-Canada investigation stated that if a phasor system was available at that time, this blackout can be prevented. Particularly, the voltage problem in Ohio could be identified and fixed earlier.
- In a few minutes before the cascade event, a divergence was occurred in phase angle between Cleveland and Michigan.

That's why researchers have developed a device that can simultaneously measure signals.

3 What Are PMU and WAMS?

Active power is closely related to the angle of the bus voltage. Many of the controllers of power plants depend on the active power of the system. For this reason, the need to measure the voltage and current angle of the buses has been considered to attract attentions. The main issue for this aim is existence of a reference for the angle and synchronization in the measurements. In 1980s, first PMU has been manufactured which was able to synchronize the measured angles. By developing the GPS, a huge change was made in synchronizing measurements. With the help of GPS, data can be synchronized with an accuracy of 1 μs that this accuracy is sufficient and appropriate for most of the power system applications. In the past, satellites were low enough to send signals to GPS, and the synchronization was keeping using a crystal for up

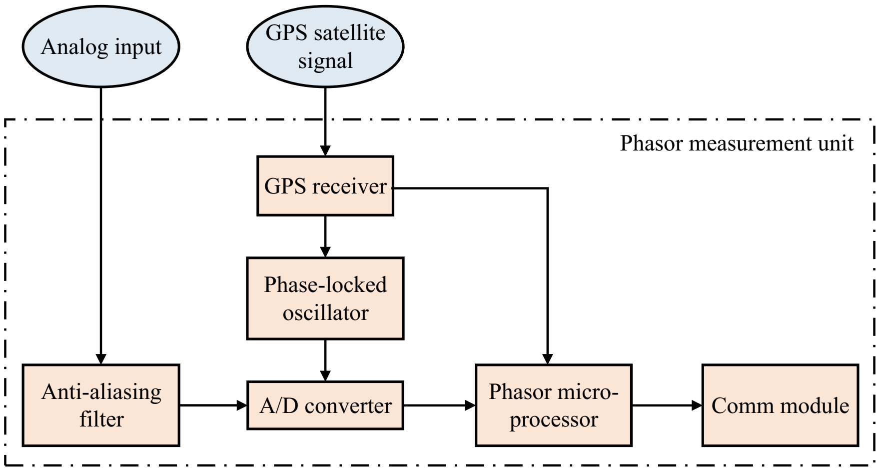

Fig. 2 Structure of the PMU

to 4 h. But today, the number of satellites has increased so that between 5 and 8 of these satellites are visible for GPS system.

The prototype PMU has been employed at some of substations of Bonneville power administration, American Electric Power Service Corporation, and New York power authority. The commercial version of the PMU was manufactured by Macrodyne in 1991. Nowadays, more than 50 vendors are offering PMU devices in the world. In addition, the related standards have been published by IEEE in 1991 and revised in 2005 and 2011.

The structure of the PMU is as shown in Fig. 2. As can be seen from the Fig. 2, A PMU consists of following essential elements:

(1) GPS receiver
(2) Phase-locked oscillator
(3) Anti-aliasing filter
(4) A/D converter
(5) Phasor microprocessor
(6) Communication module

The analog signals are imported into the PMU. First, the high frequency component of the signal will be removed by an anti-aliasing filter. The reason for this is that according to the sampling theorem, if the frequency of a signal is F and it is sampled with F_S frequency, this signal is similar to another signal with the frequency of

$$F \pm N \times F_S \tag{1}$$

where N can be an arbitrary natural number. Figure 3 shows interface between two signals.

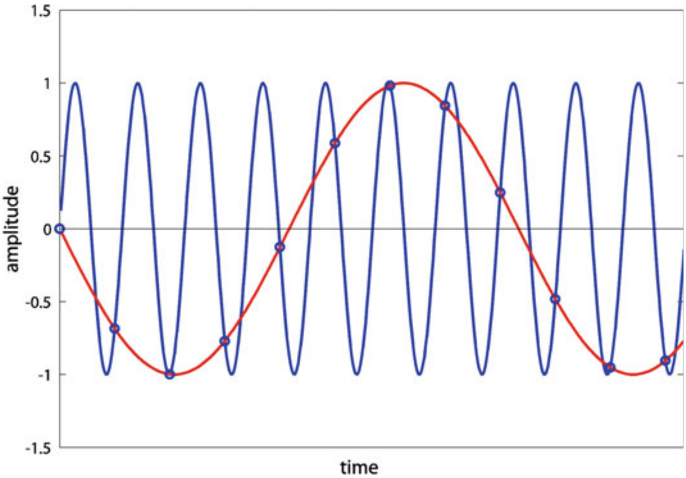

Fig. 3 Interfacing between two signals with low sampling rate

To prevent this phenomenon, a low-pass filter is considered at the beginning, which removes high frequencies components. The signals are then imported to the analog-to-digital (A/D) converters and converted to digital signals. In some PMUs, the anti-aliasing filter is also digitally located inside the A/D unit.

The task of the GPS is to be able to create synchronization with high accuracy, and the phase-locked unit is also designed to keep the clock in good accuracy until the next GPS signal is received.

The main idea of wide area monitoring systems (WAMS) is to create centralized data analysis capabilities that data are collected from different area of the power system simultaneously and in synchronized with each other. The purpose of analyzing this data is to evaluate the actual operating conditions of the system at any time and to compare the network parameters (voltage and current values and angles, temperature, active and reactive power) with the standard or predetermined limits. Also, with the help of certain algorithms, the security margin of stability or the distance of the system from the stability boundary is determined. Figure 4 shows the simple structure of the WAMS. In general, each WAMS is consist of the following processes:

- Data measuring and collecting
- Data delivering and communication
- Data analysis

The WAMS structure comprises following infrastructures:

(1) Phase measurement units (PMUs), which must be installed at key points in the network.
(2) Synchronizing system, which is the primary element to have a simultaneous image of the system variables, the effect of events, and the general nature of

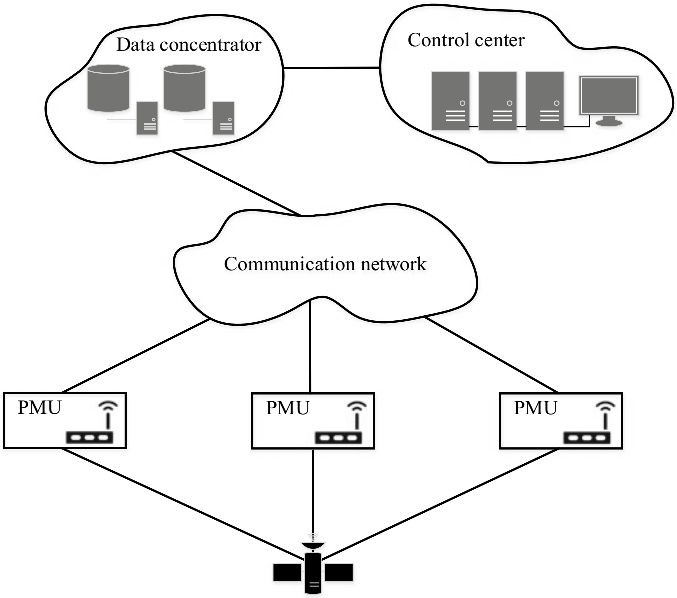

Fig. 4 Simple WAMS structure of power system

the system. This system synchronized the sampling frequency/time of PMUs to collect and send data.

(3) Data communication system, which must have the appropriate speed, reliability, and security for data transferring.
(4) Data collection and analysis center, which should be equipped with appropriate software for data analysis.

PMUs serve as the mainstay of the WAMS structure. The microprocessor is the brain of the PMU, which performs all the necessary actions on the signal, such as amplitude and phase extraction, as well as calculating the frequency and so on. After performing the calculations, the data is sent to the WAMS center by the communication module. At the WAMS center, data from all PMUs of the network is available, and because simultaneous data is available on all buses, dynamic and observable studies of the system can be performed at the same time, unlike SCADA. The WAMS center can be connected to different PMUs due to conduct following analysis by receiving data:

(1) Events analysis of power system using recorded event signals
(2) The behavior of the different bus phases at different times to predict future conditions
(3) Frequency behavior of different areas to predict generation shortages
(4) Different bus voltage behavior to improve operating conditions.

Also, due to the simultaneous data of different network buses, dynamic studies can be performed in the WAMS center and the network stability conditions can be evaluated and preventive actions can be executed if the network is going to be unstable. In addition, the protection system configuration can be considered and performed by using wide area data and remote buses that current transformers are not saturated and do not suffer from voltage fluctuations instead of local measurements.

4 Amplitude and Phase Angle Calculation Using PMU Data

The amplitude and phase angle of the signal can be calculated using different algorithms based on the PMUs measured data. In the following, three algorithms have been described for the purpose of amplitude and phase angle computation [7–9].

4.1 Man and Morison Algorithm

This algorithm is one of the short window algorithms that uses three samples to find the amplitude and phase of the signal. Suppose the input signal is represented as follows:

$$V = V_P \sin(\omega t + \varphi) \longrightarrow t = 0 V = V_P \sin \varphi \tag{2}$$

The derivative of the signal with respect to φ can be obtained as follows:

$$V^{'} = V_P \cos \varphi \tag{3}$$

Therefore, the amplitude and phase angle of the signal can be calculated as follows:

$$V_P = \sqrt{V^2 + V'^2} \tag{4}$$

$$\varphi = \tan^{-1}\left(\frac{V}{V'}\right) \tag{5}$$

The derivative of a signal in the adjacency of t = 0 can be achieved regarding to Fig. 5 and using (6).

$$V'(t = 0) = \frac{V^+ - V^-}{2\omega_0 \Delta t} \tag{6}$$

where

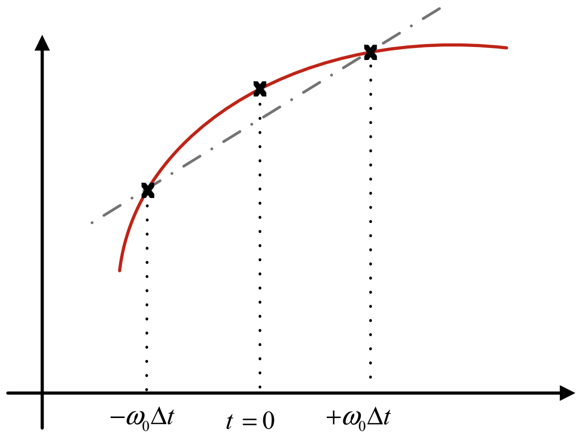

Fig. 5 Three samples for calculating derivative at t = 0

$$\omega_0 = 2\pi f_s \tag{7}$$

$$\Delta t = \frac{1}{f_s} \tag{8}$$

The f_s is the sampling frequency.

Therefore, using three samples of the signal, the V and V' can be obtained. If the V^-, V^0, and V^+ assumed to be three consecutive samples of the signal, the Man and Morison estimation algorithm can be implemented as shown in Fig. 6. Hence, the

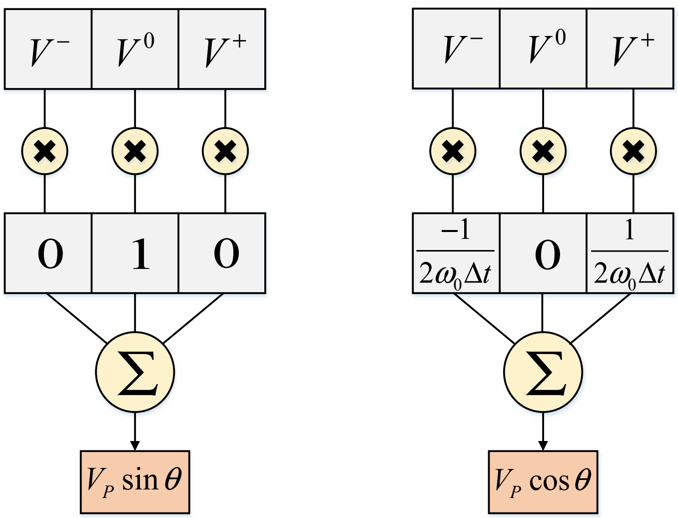

Fig. 6 Man and Morison estimation algorithm implementation

amplitude and phase angle of the input signal can be calculated as follows:

$$V_P = \sqrt{(V_P \sin\theta)^2 + (V_P \cos\theta)^2} \tag{9}$$

$$\theta = \tan^{-1}\left(\frac{V_P \sin\theta}{V_P \cos\theta}\right) \tag{10}$$

Despite the simplicity and ease implementation of this algorithm, following are the main drawbacks of this method:

(1) Has weak performance against noise.
(2) Due to the frequency response of this algorithm, in the presence of harmonics, the obtained result of this algorithm confronts with high error.
(3) The presence of a DC component in the input signal can cause error in this algorithm.
(4) The obtained amplitude for the main harmonic signal in this algorithm is 95% of the actual value of the signal and indicates error in the nature of this algorithm.

The Prodar 70 algorithm was developed to cope with the problem of having a smaller calculated amplitude by the Man and Morrison algorithm with a real signal amplitude.

4.2 Prodar 70 Algorithm

In this algorithm, the first and second derivatives of the input signal are used to extract the amplitude and phase angle of the signal. If the input signal and its derivative are assumed to be as shown in (2) and (3). Also, the second order derivative of the input signal can be obtained as follows:

$$V'' = -V_P \sin\varphi \tag{11}$$

Therefore, the amplitude and phase angle of the signal can be calculated as follows:

$$V_P = \sqrt{V'^2 + V''^2} \tag{12}$$

$$\varphi = \tan^{-1}\left(\frac{V''}{V'}\right) \tag{13}$$

In addition, the first and second order derivative of the signal can obtained regarding to Fig. 7. Accordingly, the first order derivative of the signal can be calculated as follows:

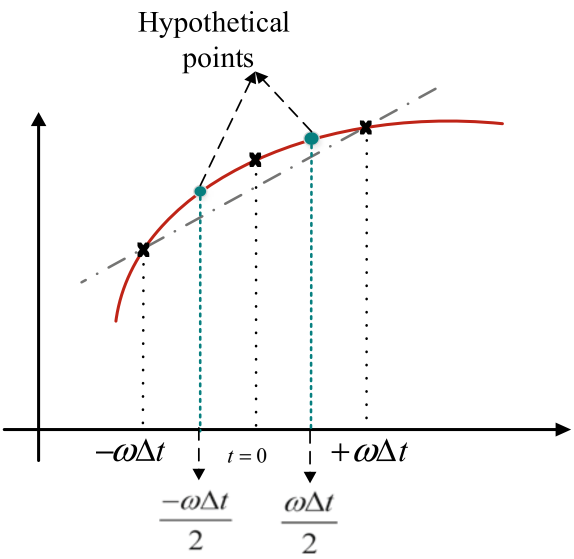

Fig. 7 First and second order derivative of the signal

$$V'(t = 0) = \frac{V^{+1} - V^{-1}}{2\omega\Delta t} \tag{14}$$

The derivative of the signal in two hypothetical points at times $\frac{\omega\Delta t}{2}$ and $\frac{\omega\Delta t}{2}$ can be obtained as follows:

$$V'\left(t = \frac{\omega\Delta t}{2}\right) = \frac{V^{+1} - V^{0}}{\omega\Delta t} \tag{15}$$

$$V'\left(t = \frac{-\omega\Delta t}{2}\right) = \frac{V^{0} - V^{-1}}{\omega\Delta t} \tag{16}$$

Therefore, the second order derivative of the input signal can be obtained at $t = 0$ as follows:

$$V''(t = 0) = \frac{V''\left(t = \frac{\omega\Delta t}{2}\right) - V'\left(t = \frac{-\omega\Delta t}{2}\right)}{\omega\Delta t} = \frac{V^{+1} + V^{-1} - 2V^{0}}{(\omega\Delta t)^2} \tag{17}$$

Likewise, the implementation of the Prodar 70 algorithm to calculate the amplitude and phase angle of the signal can be seen from the Fig. 8 similar to the Man and Morison algorithm. Although the problem of estimating the main harmonic amplitude error has been modified in this method, this algorithm is still susceptible to noise, harmonics, and DC component.

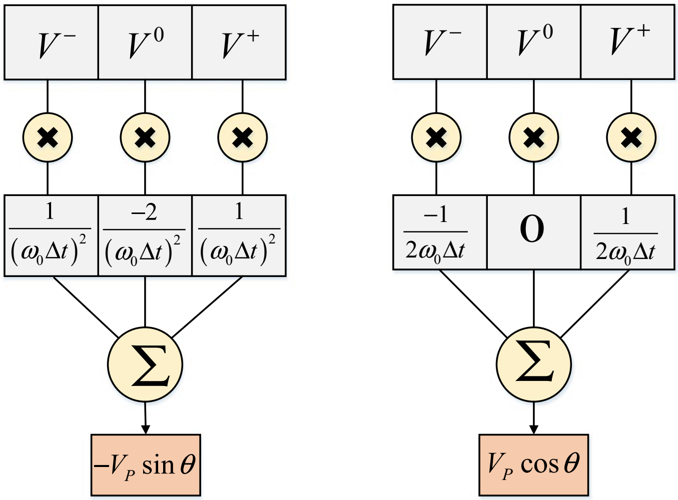

Fig. 8 Prodar 70 algorithm implementation

4.3 Fourier Algorithm

To improve the estimation of the phase angle and reduce the error caused by the presence of harmonics, DC component, and noise, the Fourier long window algorithm has been considered. If a periodic signal $V(t)$ with period T is assumed, then for all the values of $K = 0, 1, 2, \ldots$, $V(t) = V(t + kT)$. According to the Fourier algorithm, any periodic function can be written in the form of a Fourier series according to the following relationships [15–18]:

$$V(t) = \frac{a_0}{2} + \sum_{k=1}^{\infty} a_k \cos\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^{\infty} b_k \sin\left(\frac{2\pi kt}{T}\right) \quad (18)$$

where

$$a_0 = \frac{1}{T} \int_{t_0}^{t_0+T} V(t)dt \quad (19)$$

$$a_k = \frac{2}{T} \int_{t_0}^{t_0+T} V(t) \cos\left(\frac{2\pi kt}{T}\right)dt, \; k = 1, 2, 3, \ldots \quad (20)$$

$$b_k = \frac{2}{T} \int_{t_0}^{t_0+T} V(t) \sin\left(\frac{2\pi kt}{T}\right)dt, \; k = 1, 2, 3, \ldots \quad (21)$$

Discrete Fourier transformation is equivalent to Fourier transformation for digital signals that are specified at limited points in time. This algorithm transforms the input signal from the time domain to the frequency domain while retaining all the information in it. Therefore, by considering a signal in one of the domains, it is possible to obtain the signal in another domain. If the number of samples in a period of time is equal to M, the real and imaginary value of the signal in the frequency domain can be calculated using the time domain samples as follows:

$$\Re\{V\} = V_p \sin\varphi = \frac{2}{M}\sum_{n=0}^{M-1} V\left(\frac{n}{M}\right)\cos\left(\frac{2\pi n}{M}\right) \tag{22}$$

$$\Im\{V\} = V_P \cos\varphi = \frac{2}{M}\sum_{n=0}^{M-1} V\left(\frac{n}{M}\right)\sin\left(\frac{2\pi n}{M}\right) \tag{23}$$

Therefore, the amplitude and phase angle of the signal can be obtained using (24) and (25).

$$V_p = \sqrt{\left(\frac{2}{M}\sum_{n=0}^{M-1} V\left(\frac{n}{M}\right)\cos\left(\frac{2\pi n}{M}\right)\right)^2 + \left(\frac{2}{M}\sum_{n=0}^{M-1} V\left(\frac{n}{M}\right)\sin\left(\frac{2\pi n}{M}\right)\right)^2} \tag{24}$$

$$\varphi = \tan^{-1}\left(\frac{\frac{2}{M}\sum_{n=0}^{M-1} V\left(\frac{n}{M}\right)\cos\left(\frac{2\pi n}{M}\right)}{\frac{2}{M}\sum_{n=0}^{M-1} V\left(\frac{n}{M}\right)\sin\left(\frac{2\pi n}{M}\right)}\right) \tag{25}$$

For instance, if the system frequency is equal to 60 Hz and the sampling frequency is 720 Hz, the frequency response of sinusoidal and cosinusoidal filters (real and imaginary part of the Fourier algorithm) can be seen in Fig. 9.

It can be seen that, this algorithm unlike the previous two presented algorithms, can reduce the impact of the DC and other harmonics.

5 Frequency Calculation Using PMU

One of the important parameters of the system is frequency. PMUs measure the network frequency in a variety of ways. Some of these methods are listed as follows:

- Zero-crossing
- Least square
- Phase deviation

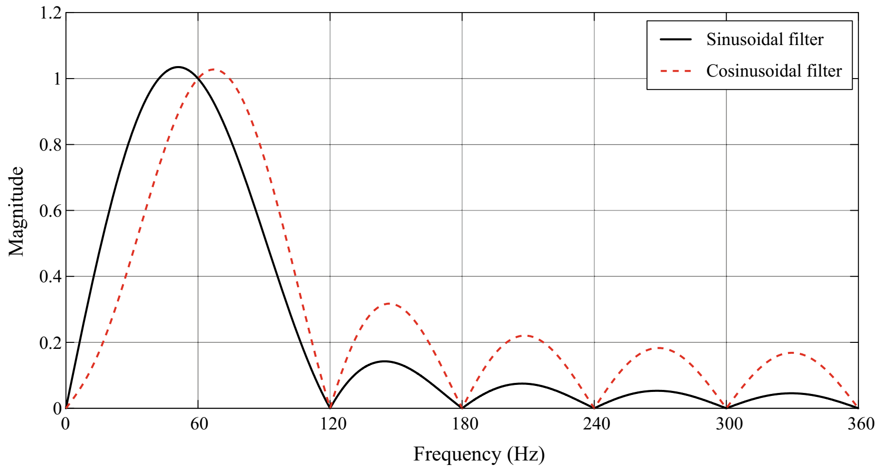

Fig. 9 Frequency response of the sine and cosine filters

5.1 Zero-crossing

This method takes the times that the signal passes to zero. For example, if the first pass occurs at time t_1 and the second time become t_2, half the period of the signal can be obtained as follows

$$\frac{T}{2} = t_2 - t_1 \tag{26}$$

Therefore the frequency of the system can be easily achieved as follows:

$$f = \frac{1}{2 \times (t_2 - t_1)} \tag{27}$$

The aforementioned frequency estimation method is considerably weak against harmonics and noise hence its accuracy is low.

5.2 Least Square

This approach is a statistical method that is used to solve the set of equations which the number of equations is greater than its unknown variables. In fact, this method is based on curve fitting of the data set. In this method, the best fit model where the sum of the squares of the difference between the data and the values obtained from the fitted curve is minimal.

Defining of the curve fitting problem:

$$e = ax - y \tag{28}$$

This definition of the error leads to the fact that if the error is positive and negative, the true value of the error is not shown correctly the accuracy of the fitted curve. Since, the positive and negative values may be removed together. Therefore, one way is to use absolute magnitude of the error as follows:

$$|e| = |ax - y| \tag{29}$$

Since it is difficult to apply absolute magnitude in mathematics, the other proposed solution is using the second power of the error, which is essentially the same as the second norm concept of the error or, more fully, the energy of error.

Now by minimizing the squares of error, we are actually looking for the ax vector to be as similar as possible to the y vector. If the input signal is assumed to be as follows:

$$V(t) = V_m \sin(\omega t + \theta) = V_m \cos\theta \sin\omega t + V_m \sin\theta \cos\omega t \tag{30}$$

If the three-terms of Taylor series are used instead of the $\sin\omega t$ and $\cos\omega t$, the above relation will be rewritten as follows:

$$\begin{aligned} V(t) &= \text{Sin}(\omega t)V_p\text{Cos}\theta + (\Delta\omega)t\text{Cos}(\omega t)V_p\text{Cos}\theta + \text{Cos}(\omega t)V_p\text{Sin}\theta - \\ &(\Delta\omega)t\text{Sin}(\omega t)V_p\text{Sin}\theta - \frac{t^2}{2}\text{Sin}(\omega t)(\Delta\omega)^2\text{Cos}\theta - \frac{t^2}{2}\text{Cos}(\omega t)(\Delta\omega)^2\text{Sin}\theta \end{aligned} \tag{31}$$

where $\Delta\omega$ is the change of angular speed. Six unknown variables can be found in (Eq. 31). Hence, seven equations are needed to obtain these variables using the least square error method. The measured voltage signal in (Eq. 31) can be rewritten as follows:

$$V(t) = S_{11}X_1 + S_{12}X_2 + S_{13}X_3 + S_{14}X_4 + S_{15}X_5 + S_{16}X_6 t \tag{32}$$

where

$$\begin{aligned} &S_{11} = V_p\text{Cos}\theta \; S_{12} = tV_p\text{Cos}\theta \; S_{13} = V_p\text{Sin}\theta \\ &S_{14} = -tV_p\text{Sin}\theta \; S_{15} = -\frac{t^2}{2}\text{Cos}\theta \; S_{16} = -\frac{t^2}{2}\text{Sin}\theta \end{aligned} \tag{33}$$

$$\begin{aligned} &X_{11} = \text{Sin}(\omega t) \; X_{12} = (\Delta\omega)\text{Cos}(\omega t) \; X_{13} = \text{Cos}(\omega t) \\ &X_{14} = (\Delta\omega)\text{Sin}(\omega t) \; X_{15} = \text{Sin}(\omega t)(\Delta\omega)^2 \; X_{16} = \text{Cos}(\omega t)(\Delta\omega)^2 \end{aligned} \tag{34}$$

Therefore, based on the least square theorem following relation can be developed:

$$\begin{aligned}&[S]_{N\times 6}[X]_{6\times 1}=[V]_{N\times 1}\\&[X]=[S]^{*}[V]\\&[S]^{*}=\left[[A]^{T}[A]\right]^{-1}[A]^{T}\end{aligned} \tag{35}$$

After calculating the unknown variables, using the following relationships, it is possible to calculate changes of frequency and frequency estimation:

$$\Delta\omega=\frac{X_2+X_4}{X_1+X_3} \tag{36}$$

$$f=f_{zero}+\frac{\Delta\omega}{2\pi f_0} \tag{37}$$

5.3 Phase Deviation

If the angular speed deviation from the nominal value, and the rate of change of angular speed at $t = 0$ are $\Delta\omega$ and ω', respectively, the angular speed at any time (t) is given by:

$$\omega(t)=\left(\omega_0+\Delta\omega+t\omega'\right) \tag{38}$$

The phase of signal can be obtained from the integral of angular speed as follows:

$$\phi(t)=\int\omega dt=\int\left(\omega_0+t\Delta\omega+t\omega'\right)dt=\phi_0+t\omega_0+t\Delta\omega+\frac{1}{2}t^2\omega' \tag{39}$$

It can be rewritten in the matrix form as follows:

$$\phi(t)=a_0+a_1t+a_2t^2 \tag{40}$$

The phase of the signal can be calculated from the algorithms in the previous section preferably by Fourier algorithm. Afterward, three unknown variables a_0, a_1, and a_2 can be achieved using the least square approach. If the phase of the signal at $t = 0$, $t = \Delta T$, $t = 2\Delta T$, $t = 3\Delta T$ are available, following relation can be derived based on the least square error algorithm:

$$\underbrace{\begin{bmatrix}\phi_0\\\phi_1\\\phi_2\\\phi_3\end{bmatrix}}_{\varphi}=\underbrace{\begin{bmatrix}1 0 0\\1\ \Delta\mathrm{t}\ \Delta t^2\\1 2\Delta\mathrm{t}\ 4\Delta t^2\\1 3\Delta\mathrm{t}\ 9\Delta t^2\end{bmatrix}}_{B}\underbrace{\begin{bmatrix}a_0\\a_1\\a_2\end{bmatrix}}_{A} \tag{41}$$

Therefore, the unknown vector A can be calculated using four samples. This matrix contains the frequency and rate of change of frequency according to (39). The unknown vector A can be obtained as follows:

$$[A] = \left[B^T B\right]^{-1} B^T [\phi] \tag{42}$$

6 Communication Infrastructure of WAMS

As mentioned, in order to implement WAMS, it is necessary to transfer the measured data provided by different PMUs to the control center using a high-speed communication infrastructure. This infrastructure must have the required reliability and capability. The various high-speed communication systems have been developed with an increasing need for data transferring. Therefore, there are different communication systems such as power line carrier (PLC), fiber optic, radio, microwave, and satellite to data transmission between PMUs and the control center [3].

The communication methods of WAMS that have different advantages and disadvantages are classified in two categories of wired and wireless communication. So, according to different capability of each method, the most suitable method for transferring data securely, reliably and economically is found according to network conditions. Transmission lines are used to data transferring in PLC method. The implement cost of this method is low because it does not require a separate structure for signal transmission. However the attenuation and distortion of signal while it propagate through the transmission line, noise caused by high voltage equipment around the transmission lines and limited band width are some of the problems of this method. In addition, data transferring is disrupted when a faults happens on the transmission line [19–23].

Fiber optic is another method used to data transmission in the WAMS. The high capability of data transmission along with the wide bandwidth attracts attentions to this method. A small portion of its bandwidth is used to data transmission and the rest of it can be used for other proposed. The transmission delay and attenuation are low in this method and it is not affected by noise and environmental factors. Thus, the security of this method is high. However, the high implementation time and initial cost are disadvantages of this method. Compare to fiber optic, the microwave and radio methods are low cost. The radio method has limited band width for data transmission. So, the data of PMUs may interfere with other data which may be sent in this frequency band. Due to the lack of need for wiring, the implementation time and cost of this method are low [24–28].

Due to the easy installation, relatively high security and lack of need for wiring, using microwave to data transferring between two points with a relatively large distance seems to be a good option. The microwave is a relatively low cost method

Table 1 Comparison of different communication methods in WAMS

Features	PLC	Fiber optic	Radio	Microwave	Satellite
Connection type	Wired	Wired	Wireless	Wireless	Wireless
Security	Low (bit error rate <10^{-2})	high (bit error rate 10^{-15})	Low (questionable)	Medium (bit error rate 10^{-7})	Medium (bit error rate 10^{-7})
Bandwidth	Limited	Not limited	Limited	Limited	Limited
Transmission delay	Low	Low	Low	Low	High
Attenuation	High	Almost zero	Medium	Medium	Medium (sometimes High)
Implementation time	Low	High	Low	Medium	High
Implementation cost	Low	High	Low	Low	Very High
Environmental condition	Low affected	Not affected	Affected	Affected	Affected

for data transmission. However, signal fading and multipath propagation are the challenges of using this technology. Also, weather condition may affect the performance of this method.

Satellite communication can be used to data transmission between PMUs and control center. The data transmission is not depend on the distance between two points. The high initial cost of a satellite communication structure is one of the limitation of this method. The transmission delay in this method is higher than others and weather conditions and electromagnetic interference may effect on this. Important data transferring method used in WAMS were introduced. The summery of these is presented in Table 1.

7 WAMS Applications Based on the PMU Measured Data

The PMUs were manufactured to measure the phase angle, but this ability, which could simultaneously measure the data of different locations and send it to a center, can create many capabilities and applications [29–32]. Nowadays, these capabilities are more and more developed so that there are several applications based on the WAMS which are briefly described in this section.

7.1 State Estimation

State estimation is assigning a value to an unknown variable of the system based on a special criterion that is obtained by measured data of the system. Measurements can be incomplete or over samples, and the state estimation of the system performed based on statistical methods, which the actual values of the state variables are estimated with maximum or minimum of specific criteria.

Monitoring of power systems is achieved by having information about different parts of the network. Therefore, estimating the state and knowing the information in all parts of the network is very important for the safe operation of the network. State estimation methods in the decade have been developed in 1970s. In these methods, active power and reactive power flows of transmission lines and bus voltage were obtained using measurements and the telecommunication system which is sent to a central unit for computational process. Many countries around the world still use the same method to estimate the state of the network. Due to the slowness of the telecommunications network, the frequency limitations, and the asynchronous data collection, the measured data from different parts of the network had time delay for several seconds to some minutes. Therefore, the estimated states had good accuracy only in the steady state condition. If a change is occurred in the system and leads to activation of dynamic modes, the result of the state estimation using these methods were only approximate to the actual state of the system, which in the most optimistic view was average vales of the actual state of the system and is therefore known and called as static state estimation [33].

Nowadays, with the expansion of telecommunication system and the implementation of PMUs, it is possible to have dynamic state estimation of the system. The important point of the system in using phase measurement for state estimate of the system is that it is not necessary to implement PMUs for measurement in all the points of the system and only its observability is sufficient. Having a limited number of PMUs at key points in the network, with the help of existing software, makes the entire system visible, so there is no chronic concern for installing new PMUs due to the implementation of network development projects.

7.2 Frequency Stability

As aforementioned before, PMUs are able to measure the frequency and rate of change of frequency and send them to the control center. The frequency is very important parameter in the network and its accurate measurement in different parts of the network is a very important and vital achievement. By measuring the frequency, we can get the loss of generation and the area where the generation is lost. It can be seen that there is a shortage of generation or surplus generation and by controlling it, the balance between generation and load is established. It is also possible to inform that if a part of the network becomes islanded. For example, if the frequency of a part of the network is 49 Hz and the other part is 51 Hz, and this command remains stable for a while, this indicates the separation of the two parts in the system [34–36].

7.3 Situational Awareness

Observability means having network information in different points of the system. This information can be the amplitude and phase angle of the bus voltage and line current. In addition, the frequency of different parts of the network is one of the parameters that help the observability of the network. By simultaneously measuring network data and sending it to the control center, PMUs have created the ability to access information from different locations. One of the special features of PMU and WAMS center is that it can draw information in illustrated form (different diagrams) to convey better vision and more accurate information to the reader (operator).

7.4 Power System Oscillation Detection

In the power grid, a group of generators may start to oscillate against another group. If these fluctuations do not stop, they will cause network instability and even global blackouts. For example, if 500 MW flows through two parallel transmission lines and one of these lines goes out of circuit due to a short circuit fault and its load responsibility falls on the other line, this will cause the power oscillation which will cause to cascade line outage and blackout if it does not damped. That's why it's very important to detect power oscillation. In SCADA system, it was impossible to detect power oscillation because the information was sent every few seconds, and this could be done in a suitable manner using WAMS structure. There are two ways to detect power oscillation in the WMAS system:

- Oscillation detection: When power oscillations are created and its amplitude increases, fluctuations are detected by processing the measured signals from the PMUs and this problem is solved by appropriate control measures or opening the lines.
- Mode meters: The various frequencies and harmonics of the signal are extracted before the occurrence of high amplitudes of the power oscillations is detected. And it can be prevented by taking preventive measures. In other hand, these methods detect the power oscillations before the fluctuations become severe when the system become closer to the critical situation.

7.5 Voltage Monitoring

Voltage instability can occur very quickly. After growing penetration of distributed generations, the issue of voltage stability has become much more important. Measurement of voltage and measurement of reactive power reserve value are among the vital issues in voltage stability that are measured and calculated by PMUs and sent to the WAMS center. To prevent voltage instability, there are under voltage load shedding (UVLS) relays that were operated locally in the past decades. In this approach, UVLS relays measure the voltage of a bus and according to it values; the necessary decisions have been made to disconnect the load. Nowadays, PMU data are deployed to improve the performance of the UVLS relays using wide area measured data.

7.6 Alarming

By having angles of different buses, several alarms can be implemented on the system. For example, the difference between the angles of the two ends of a line can be criterion of an alarm that if exceeds from a certain value, the alarm will be sent. It is also possible to record different buses voltage angles in different regions and then use them during the post event analysis.

7.7 Dynamic Line Ratings

Using phasor data of the system, the lines flow can be measured instantly and their loading status can be assessed. By implementing PMU and achieving instantaneous data, it is possible to determine the loading of the lines using the flow information of the lines and weather conditions to allow more power pass through the lines under certain conditions. There are two ways for dynamic line rating:

(1) The CAT method, which uses environmental information such as temperature and wind velocity and conductor information such as voltage and current measured data by a PMU, determines the dynamic loading limit of the lines.
(2) At both ends of the line PMUs are installed and simultaneously measure the voltage and current data to calculate the loading limit of the line.

7.8 Security and Stability Analysis

The security of the power system means that the system will be able to successfully pass through the disturbances without disruption in servicing to a customer group of customers. This is largely due to the system robustness during abrupt disturbances, and is dependent on operation conditions as well as the likelihood of disturbances. In other words, the security of the system means that the system is resistant to disturbances after the power system has been forced to change its status during the event of a disturbance.

Correct understanding of the disturbance, the place of its occurrence and the type of happened fault help to carry out these studies. Using WAMS features, the online snapshot is provided from the network structure, operation of protection elements, status of control devices, load and generation characteristics, condition of reactive power sources and etc. Then, it is examined at control center using the security analysis software. Also, the state estimation of power system is available at the pre-fault moment, which can be used as initial states for starting network analysis software. Finally, the results of power system dynamic security analysis are expressed as a set of necessary control proceedings. These proceedings are either to prevent faults and increase the security margin of the power system or to prevent instability and blackouts.

7.9 Event Analysis

Extensive events occur on power system every year. To find the source of these events and solve them, it is necessary to check the network status before and during the event. In the SCADA system, due to the lack of synchronization of data and the slowness of the telecommunication link, the network dynamics are not available. Therefore, it is not possible to check the network behavior during the disturbance. Due to the synchronization of data and large implementation of PMUs in the WAMS system, network dynamics can be observed and it is possible to investigate network events.

8 Conclusion

Over years, with the expansion of power system, its complexity has also increased. In this situation, monitoring of the dynamic behavior of power system is vital for secure operation. So, the focus of this chapter is on the concept and importance of WAMS in power systems. Before development of WAMS, the SCADA was used to monitor the power system condition. This chapter describes different features of SCADA. It shows that the SCADA system is not able to follow power system dynamics due to its features. Therefore, the advent of PMU along with increasing the data processing speed led to the development of WAMS. By collecting and processing the data, WAMS provides a set of results to the operators that facilitate system monitoring. Different application of WAMS which increase system performance, have been illustrated in this chapter. A part of this chapter is dedicated to a brief survey of the telecommunication systems used in WAMS because of the data transmission importance.

In this chapter, especially attention has been given to PMUs as the main components of WAMS. Thus, the developments, phasor calculation and frequency estimation methods used in PMUs are covered. Finally, the main purpose of this chapter is to show the importance of WAMS in modern power systems.

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