# APPENDIX A :

# PHASOR MEASUREMENTS

Computer relaying is a well-established field by now, and it has furnished a new insight into the technique of measuring power system quantities in real-time from sampled data. Voltage and current phases in a three phase power system can be measured from waveform samples, and the measurements process can be made to be responsive to dynamically changing system conditions. In relaying applications, response times of the order of a fraction of the fundamental frequency period are common. In other measurement applications, such high speeds of response are not desirable since, in the presence of measurements noise, the errors of the measurement process increase in inverse proportion to the square-root of the measurement response time [20].

For many new applications of Phasor measurements now under consideration, measurement response times of 1-5 periods of the power frequency seem desirable. Based upon the measurement performed in the substation, it becomes possible to think of real-time communication of these measurements to a central location, where many improved system-wide protection and control functions can be performed.

## A.1 Phasors from sampled data

A Phasor is a complex number that represents the fundamental frequency component of a waveform [21].

Consider the sample $x_k$ obtained from a signal x(t). The Phasor representation of the signal x(t) is related to the fundamental frequency component calculated by the Discrete Fourier Transform (DFT) [21]. If the Phasor is X, and the fundamental frequency component calculated by the DFT is $X_1$, then

$$X = \frac{1}{\sqrt{2}} X_1 = \frac{1}{\sqrt{2}} \frac{2}{K} \sum_{k=1}^{K} x_k e^{-jkw\Delta t}$$

where K is the total number of samples (usually a multiple of the fundamental frequency period), and $\Delta t$ is the sampling interval.

For all practical frequency deviations, the magnitude error in the Phasor calculation is negligible. Even the phase angle error is generally small, but even this small error can be eliminated if one uses the phases of the three phase signals (voltages or currents) to compute the positive sequence quantity. The positive sequence quantity $X_1$ (not to be confused with the fundamental frequency component computed by the DFT) is given by: $X_1=X_a+aX_b+a^2X_c$ where a and $a^2$ are the usual phase shift operators of $120^{.0}$ and $240^0$ .

An important use of the positive sequence voltage is the measurement of the power system frequency [20]. If we write the positive sequence Phasor in its polar form, the phase angle of the positive sequence Phasor can be differentiated to obtain the incremental frequency of the input waveform over the nominal frequency. If $\varphi$ is the phase angle of $X_1$ , and $\omega_0$ is the nominal frequency, then the actual frequency of the input signal is given by $\omega = \omega_0 + \frac{d\varphi}{dt}$. It is one of the most sensitive methods of measuring power system frequency. It has been noted that when the frequency is calculated from the positive sequence voltage errors introduced by off-nominal frequencies are completely eliminated.

## A.2 Synchronization of the sampling process

The state vector of a power system, i.e., the collection of all positive sequence bus voltages- is meaningful only if the sampling instants at all measurement sites are synchronized. The necessary accuracy of synchronization may be specified in terms of the prevailing phase angle differences between buses of a power network. Typically, these angular differences may vary between a few degrees to $60^0$ under extreme loading conditions. Under these circumstances , a precision corresponding to $0.1^0$ seems to be desirable measure angular differences. On a 50 or 60 Hz power system, this corresponds to about 5 microseconds. Allowing for other sources of error in the measurement system, a synchronizing accuracy of about 1 microseconds would meet the needs of this measurements technique [21].

Synchronization accuracy of this order can be achieved in a few ways. One could use fiber optics communication links, but this remains a very expensive option and, at best, the fiber optic links are available at only a few substations. Technically, a much superior and satisfying solution to the synchronizing problem is to use the 1 pulse-per-second (pps) transmission provided by the global Positioning System (GPS) satellites. The GPS receivers are designed with a high accuracy internal oscillator that continues to provide the 1 pps signal even when no satellite is in view, and locks onto the satellite transmission when the satellites become available.

## A.3 Implementation for field trials

The most convenient sampling rate for Phasor and symmetrical component computation is 12 times the fundamental power system frequency. The three signals from the GPS receiver are connected to a microprocessor, which acquires the power system current and voltage input signals through the Analog-to-Digital converter.

The A/D converters are typically 12-bit converters, and provide measurements with very good precision. As we look to the future, 16-bit A/D converters and 32-bit computers are likely to be the choice for the next generation of Phasor measurement systems [21]. The measured Phasor, its associated time-stamp, and other message codes of interest are communicated to the next hierarchical level over a communication channel. The synchronization is achieved locally, and is recovered at the central site by matching the time-stamps of measurements obtained from different substations.