Matlab based Simulink Model of Phasor Measurement Unit and Optimal Placement Strategy for PMU Placement

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Abstract—For the secure and reliable operation of the interconnected power system, it is required to measure and monitor the system in real time. Conventional Supervisory Control and Data Acquisition/Energy Management System (SCADA/EMS) obtain the data at interval of 2-10 sec. This paper gives an idea about Synchronized Phasor Measurement (SPM) based Wide Area Monitoring System (WAMS) using Phasor Measurement Unit (PMU) placed at various locations in electrical power network. They are synchronized by the Global Positioning System (GPS) satellites. A Matlab based simulink model of the Phasor Measurement Unit and Phasor Data Concentrator for Data storage and a common reference time data is also developed in Matlab. Optimal PMU Placement in power system network is an important task. A PMU placement strategy is developed and analyzed on IEEE – 14 bus test system.

Keywords: Phasor Measurement Unit (PMU), Phasor Data Concentrator (PDC), Global Positioning System (GPS), Synchrophasor, Synchronized Phasor Measurement, Optimal Placement Strategy.

I. INTRODUCTION

SYNCHRONIZED phasor measurement units (PMUs) were first introduced in early 1980s, and since then have become a mature technology with many applications which are currently under development around the world. The occurrence of major blackouts in many major power systems around the world have given a new impetus for large-scale implementation of wide-area measurement systems (WAMS) using PMUs and phasor data concentrators (PDCs) in a hierarchical structure.

Data provided by the PMUs are very accurate and enable system analysts to determine the exact sequence of events which have led to the blackouts, and help analyze the sequence of events which helps pinpoint the exact causes and malfunctions that may have contributed to the catastrophic failure of the power system. As experience with WAMS is gained, it is natural that other uses of phasor measurements will be found. In particular, significant literature already exists which deals with application of phasor measurements to system monitoring, protection, and control.

This paper is organized as follows. Section II reviews the basic concepts of phasor representation of power system voltages and currents. Section III discusses optimal PMU Placement Strategies and Algorithm. Section IV provides concluding remarks with Simulation and Result obtained from this work.

II. PHASOR MEASUREMENT UNIT

A. Classical Definition of a Phasor

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

\[ x(t) = X_m \cos(\omega t + \phi) \] (1)

The phasor representation of this sinusoid is given by

\[ x(t) \leftrightarrow X = (X_m / \sqrt{2}) e^{j\phi} = (X_m / \sqrt{2}) [\cos \phi + j \sin \phi] \] (3)

Fig. 1: Phasor representation of a sinusoidal signal. (a) Sinusoidal signal. (b) Phasor representation.

Note that the signal frequency 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 the phase angle of the signal in (1). The sinusoidal signal and its phasor representation given by (1) and (2) are illustrated in Fig. 1.

Note that positive phase angles are measured in a counterclockwise direction from the real axis. Since the frequency of the sinusoid is implicit in the phasor definition, it is clear that all phasor which are included in a single phasor diagram must have the same frequency. Phasor representation of the sinusoid implies that the signal remains stationary at all times, leading to a constant phasor representation. These concepts must be modified when practical phasor measurements are to be carried out when the input signals are not constant, and their frequency may be a variable. This will be discussed in the next section.

B. Phasor Measurement Concepts

Applications related to processing actual power system signals, either in real-time (protection, control, visualization) or for off-line analysis, call for synchronized phasor measurements.

The latter developed into a mature field of engineering in the last few decades. Fig. 1 presents two possible architectures used for real-time phasor measurements. As shown in Fig. 1, the input signal is sampled...
at a variable sampling frequency equal to the actual frequency of the power system, or at a constant frequency depending upon the nominal power system frequency.

Introduction to the Discrete Fourier Transform (DFT) Discrete Fourier Transform

Digital computers are usually used to analysis the phasor data of a power system. First, a discrete-time signal is obtained by sampling the original analog waveform. A mathematic method which is called Discrete Fourier Transform is then applied to this sampled data to obtain a sampled frequency waveform.

Consider periodic discrete-time finite signal, taking N samples from 0 to 2\pi, so that the sampling time interval is 2\pi/N. The Fourier Transform can be expressed as

$$
X = \frac{\sqrt{2}}{N} \sum_{k=1}^{N} x_k e^{-j2\pi k/N}
$$

X is the complex number to express phasor (usually expressed in rectangular form as a + bj)

- N is the number of samples (usually is 12, 24, 36,...)
- A factor 2 usually appears in front of the sum as the signal with frequency \( f \) in the DFT has components at +\( f \) and -\( f \). These components can be combined and divided by the square root of 2 to get the RMS value.
- In the Matlab simulation process, the k range from 1 to N, rather than 0 to N-1.

An analog anti-aliasing filter is used to limit the bandwidth of the input signal to be compatible with the sampling frequency chosen. A digital filter may be used to provide band-pass filtering and removing frequency components that may create problems for a specific application. The phasor estimator calculates the phasor representation of the input signal complying with the definition given in (2). The discrete Fourier transform (DFT) is a simple widely used method for phasor estimation

Sampled data \( x_k \) used to calculate the phasor as,

$$
X = \frac{\sqrt{2}}{N} \sum_{k=1}^{N} x_k e^{-j2\pi k/N} = \frac{\sqrt{2}}{N} (X_c - jX_s)
$$

Where, \( X_c = \sum_{k=1}^{N} x_k \cos(k\theta) \)

\( X_s = \sum_{k=1}^{N} x_k \sin(k\theta) \)

N = number of Samples in 1-cycle of nominal frequency

Sampling angle \( \theta = \frac{2\pi}{N} = 2\pi f_o \tau \)

The above block diagram represents the basic Architecture of the PMU. A prototype PMU Simulink model is developed in Matlab.

III. Concept Of PMU Placement

A PMU is able to measure the voltage phasor of the installed bus and the current phasors of some or all the lines connected to that bus. The following generalized rules can be used for PMU placement.

- **Rule 1:** Assign one voltage measurement to a bus where a PMU is placed, including one current measurement to each branch connected to the bus itself.
- **Rule 2:** Assign one voltage pseudo-measurement to each node reached by an other equipped with a PMU.
- **Rule 3:** Assign one current pseudo-measurement to each branch connecting two buses where voltages are known. This allows interconnecting observed zones.
- **Rule 4:** Assign one current pseudo-measurement to each branch where current can be indirectly calculated by the Kirchhoff current law (KCL). The observability conditions that have to be met for selecting the placement of PMU set are

  - **Condition 1:** For PMU installed at a bus, the bus voltage phasor and the current phasors of all incident branches are known.
  - **Condition 2:** If one end voltage phasor and the current phasor of a branch are known, then the voltage phasor at the other end of the branch can be calculated.
  - **Condition 3:** If voltage phasors of both ends of a branch are known, then the current phasor of this branch can be directly obtained.
  - **Condition 4:** If there is a zero-injection bus without PMU and the current phasors of the incident branches are all known but one, then the current phasor of the unknown branch can be calculated using KCL.
  - **Condition 5:** If the voltage phasor of a zero-injection bus is unknown and the voltage phasors of all adjacent buses are known, then the voltage phasor of the zero-injection bus can be obtained through node voltage equations.
  - **Condition 6:** If the voltage phasors of a set of adjacent zero injection buses are unknown, but the voltage phasors of all the adjacent buses to that set are known, then the voltage phasors of
zero injection buses can be computed by node voltage equations.

Based on above rules and conditions, an algorithm for PMU Placement is developed and implemented in IEEE – 14 bus test data system.

IV. SIMULATION AND RESULTS

Fig. 3: Algorithm for PMU Placement

Fig. 4: Matlab Simulink Model of PMU

Sampling of Input signal is very important task. For our case study we have taken 10 Samples/Cycle following the Nyquist criteria for Sampling frequency.
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Fig. 9: Voltage and Currents in Discrete Form
Case Study of IEEE-14 bus test system

Fig. 10: Result for Optimal PMU Placement

<table>
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<th>Method</th>
<th>No. of PMUs</th>
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A. A result from developed Method is as under:
Total No. of Possible Solutions for 14 bus Network = \(2^{14}=16384\)
Solutions with Complete Observability = 6181
Solutions with Minimum PMUs = {2, 6, 7, 9}{2, 6, 8, 9}{2, 7, 10, 13}{2, 8, 10, 13}{2, 7, 11, 13}

V. CONCLUSION
From above work we can conclude that a Prototype Simulink modeling of PMU is carried out in Matlab. From this work we are able to achieve the Voltage and Currents measurements in Phasor form with accurate Time stamping. So Limitation of SCADA measurement of accurate time stamped measurements is rectified. By developing Optimal PMU Placement strategy we have reviewed three distinct PMU Placement algorithms with developed algorithm. Three strategies are compared with the aim of achieving complete observability of the power system in steady state conditions. The outage of one of the line or equipment also analysed and the results of IEEE 14 bus test system are discussed.

REFERENCES