APPLICATION OF PHASOR MEASUREMENT UNIT IN SMART GRID

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Abstract-A smart Grid uses two way digital communication with advanced sensors to collect and analyze data for transforming the existing electric grid into intelligent, dynamic self-healing, self optimizing transmission and distribution grid. As critical grid events often require real-time recognition and real time response. A smart grid uses IP-based, open standard, intelligent communication to measure real-time events such as congestion, system stability, equipment performance, outages and demand response events. Synchrophasor measurement technology is accurate and real-time monitoring with high resolution of actual system conditions in wide area. The proposed methods has been verified, compared and studied using PSAT Software which incorporated elapsed time, speed, observability of buses in whole system for optimal placement of Phasor Measurement unit.

Keywords: Smart grid control center, Wide area measurement and control and synchronized phasor measurement unit, optimal placement of Phasor measurement unit.

I. INTRODUCTION

From the time that Thomas Edison commissioned the world’s first power system in 1882 the electric power industry has continually moved forward working to improve the functionality, efficiency and availability of electricity. Through evolutionary advancements in technology the electrical power industry has transformed the way we generate, deliver and consume power today. Smart grid is the term generally used to describe the integration of the elements connected to the electrical grid with an information infrastructure to offer numerous benefits for both the providers and consumers of electricity. It is an intelligent future electricity system that connects all supply, grid, and demand elements through an intelligent communication system. The backbone of a successful smart grid operation is a reliable, resilient, secure, and manageable standards-based open communication infrastructure that provides for intelligent linkages between the elements of the grid while participating in the decision making that delivers value to the utility and supply and demand entities connected to it.

II. ADVANTAGES OF SMART GRID

i) Enables active participation by consumers by providing choices and incentives to modify electricity purchasing patterns and behavior.
ii) Autonomous control actions to enhance reliability by increasing resiliency against component failures and natural disasters actions.
iii) Efficiency enhancement by maximizing asset utilization.
iv) Resiliency against malicious attacks by virtue of better physical and IT security protocols.
v) Integration of renewable resources including solar, wind, and various types of energy storage.
vi) Real-time communication between the consumer and utility.
vii) Improved market efficiency. It enables new products, services, and markets through a flexible market providing cost benefit tradeoffs to consumers and market participants.
viii) Higher quality of service – free of voltage sags and spikes as well as other disturbances and interruptions – to power an increasingly digital economy. ix) Consumers have more control over the source of their power and the price they pay for it [2],[3].

![Fig 1. Control center in smart grid](image)
III. APPLICATION DOMAINS

A. Wide-area monitoring and control

Wide-area monitoring and control has been gaining worldwide interest. This involves gathering data from and controlling a large region of the grid through the use of time synchronized phasor measurement units—analyzing the ability of the Smart Grid to withstand outages of a critical infrastructure element and simulating the effects of various contingency events [4].

B. Inter-Area Oscillation Damping:

Identifying inter-area oscillations and modulating voltage to damp out those oscillations to ensure maximum power transfer and optimal power flow.

IV. WIDE AREA CONTROL SYSTEM FOR SELF HEALING GRID APPLICATION:

i) Monitoring Distribution Operations:
ii) Transmission and Distribution Grid Management
iii) Grid monitoring and control.
Evaluating power system behavior to prepare for combinations of contingency events, prevent wide-area blackouts and fast recovery from an emergency state.

Voltage Security:
Detecting low voltage conditions and initiating corrective action (e.g., load shed). Voltage, VAR and Watt Control: Adjusting loads with respect to voltage tolerances, eliminating overload.

The key application areas include
Phase angle monitoring
Slow extended oscillation monitoring
Voltage stability enhancement
Line thermal monitoring dynamic rating
PMU augmented state estimation

V. SYNCHRONISED PHASOR MEASUREMENT UNITS:

Synchronized phasor measurements have become the measurement technique of choice for electric power systems. The phasor measurement units provide synchronized positive sequence voltage and current measurements within a microsecond. This has been made possible by the availability of Global Positioning System (GPS) and the sampled data processing techniques developed for computer relaying applications. In addition to positive sequence voltages and currents these systems also measure local frequency and rate of change of frequency and may be customized to measure harmonics, negative and zero sequence quantities as well as individual phase voltages and currents. At present there are about 24 commercial manufacturers of phasor measurement units (PMUs) and industry standards developed in the Power System Relaying Committee of IEEE has made possible the interoperability of units from different manufacturers. Synchrophasor technology can help deliver better real time tools that enhance system operators’ situational awareness. A synchronized phasor measurement unit with high speed communication network to collect and deliver synchronized high speed grid condition data along with analysis. Other advanced on line dynamic security assessment and control applications will improve real time situational awareness and decision support tools to enhance system reliability.

Real time operations applications
Wide area situational awareness
Frequency stability monitoring and trending
Power oscillation monitoring
Voltage monitoring and trending
Alarming and setting system operating limits and event detection
Resource integration
State estimation
Dynamic line ratings, congestion management
Outage restoration
Operations planning
Wide area controls

In contrast to SCADA system synchrophasor technology allow the collection and sharing of high speed, real time, time synchronized grid condition data across an entire system or interconnection. This data can be used to create wide area visibility across the bulk power system in ways that let grid operators understand real time conditions evidence of emerging grid problems and better diagnose, implement and evaluate remedial actions to protect system reliability [9].

VI. SYNCHROPHASOR TECHNOLOGY:

An AC waveform can be mathematically represented by the equation:

\[ x(t) = x_m \cos(\phi + \int_0^t \omega(\tau) \, d\tau) \]  

where: \( x_m \) = magnitude of the sinusoidal waveform \( \omega = 2 \pi f \) where \( f \) is the instantaneous frequency \( \phi \) = angular starting point for the waveform
Note that the synchrophasor is referenced to the cosine function. In a phasor notation this waveform is typically represented as:

\[ \vec{x} = x_m \leq \phi \]

Since in the synchrophasor definition correlation with the equivalent RMS quantity is desired. A scale factor of \( \frac{1}{\sqrt{2}} \) must be applied to the magnitude which results in the phasor representation.

\[ \vec{x} = \frac{x_m}{\sqrt{2}} < \phi \]

Adding in the absolute time mark a synchrophasor is defined as the magnitude and angle of a cosine signal as referenced to an absolute point in time as shown in figure 2.

The time strobes are shown as UTC Time Reference 1 and UTC Time Reference 2. At the instant that UTC Time Reference 1 occurs, \( \vec{T} \) there is an angle that is shown as \( \Theta \) and assuming a steady state sinusoidal (i.e. constant frequency) there is a magnitude of the waveform of \( X_1 \). Similarly at UTC Time Reference 2 an angle with respect to the cosine wave of \( \Theta \) is measured along with a magnitude or \( X_2 \). The range of the measured angle is required to be reported in the range of \( \pm \pi \). It should be emphasized that the synchrophasor standard focuses on steady-state signals that is a signal where the frequency of the waveform is constant over the period of measurement.

In the real world the power system seldom operates at exactly the nominal frequency. As such the calculation of the phase angle \( \Theta \) needs to take into account the frequency of the system at the time of measurement. For example if the nominal frequency of operating at 59.5Hz on a 60Hz system (or 50 Hz) the period of the waveform is 16.694ms instead of 16.666ms a difference of 0.167%. [9].

The captured phasor are to be time tagged based on the time of the UTC Time Reference. The Time Stamp is an 8-byte message consisting a 4-byte Second Of Century (S.O.C) a 3-byte Fraction of Second and a 1-byte Time Quality indicator. The SOC time tag counts the number of seconds that have occurred as an unsigned 32-bit integer. With 32 bits the SOC is good for 136 years or until the year 2106. With 3-bytes for the Fraction of Second one second can be broken down into 16,777,216 counts or about 59.6 nsec/count. If such resolution is not desired the proposed standard (C37.118) allows for a user definable base over which the count will wrap (e.g. a base of 1,000,000 would tag a phasor to the nearest microsecond). Finally the Time Quality byte contains information about the status and relative accuracy of the source clock as well as indication of pending leap seconds and the direction (plus or minus). Note that leap seconds (plus or minus) are not included in the 4-byte Second of Century count. Synchronized Phasor Reporting standards the IEEE C37.118 pending 2 proposes to standardize several reporting rates and reporting intervals of synchrophasor reporting. Specifically the proposed required reporting rates are shown in Table 2 below[9].

**TABLE NO.1 SYNCHROPHASOR REPORTING RATES**

<table>
<thead>
<tr>
<th>System frequency</th>
<th>50Hz</th>
<th>60Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reporting rates</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>

A given reporting rate must evenly divide a one second interval into the specified number of sub-intervals. This is illustrated in figure 3.2 where the reporting rate is selected at 60 phasor per second (beyond the maximum required value which is allowed by the proposed new standard). The first reporting interval is to be at the Top of Second that is noted as reporting interval 0 in the figure. The Fraction of Second for this reporting interval must be equal to zero. The next reporting interval as in Figure 2 reported 1/60 of a second after Top of Second with the Fraction of Second reporting 279,620 counts on a base of 16,777,216.

**VII. MAJOR ELEMENTS OF THE MODERN PMU**

Figure 3. based upon the configuration of the first PMUs built at Virginia Tech. The PMUs are...
evolved out of the development of the symmetrical component distance relay. Consequently the structure shown in figure 3 parallels that of a computer relay. The analog inputs are currents and voltages obtained from the secondary windings of the current and voltage transformers. All three phase currents and voltages are used so that positive sequence measurement can be carried out. In contrast to a relay a PMU may have currents in several feeders originating in the substation and voltages belonging to various buses in the substation.

The current and voltage signals are converted to voltages with appropriate shunts or instrument transformers (typically within the range of ±10 volts) so that they are matched with the requirements of the analog to digital converters. The sampling rate chosen for the sampling process dictates the frequency response of the anti-aliasing filters. In most cases these are analog type filters with a cut-off frequency less than half the sampling frequency in order to satisfy the Nyquest criterion.

VIII. PMU IMPLEMENTATION:

Phasor measurement units are predicted to become a very vital part of power systems state estimation. As such the measurements from PMUs are proven to increase the observability of power systems by strategic placement of a minimal number of phasor

As in many relay designs one may use a high sampling rate called oversampling with corresponding high cut-off frequency of the analog anti-aliasing filters. This step is then followed by a digital decimation filter which converts the sampled data to a lower sampling rate thus providing a digital anti-aliasing filter concatenated with the analog anti-aliasing filters. The advantage of such a scheme is that the effective anti-aliasing filters made up of an analog front end and a digital decimation filter are far more stable as far as aging and temperature variations are concerned. This ensures that all the analog signals have the same phase shift and attenuation thus assuring that the phase angle differences and relative magnitudes of the different signals are unchanged. As an added benefit of the oversampling technique if there is a possibility of storing raw data from samples of the analog signals they can be of great utility as high bandwidth digital fault recorders.

The sampling clock is phase locked with the GPS clock pulse. Even higher sampling rates are certainly likely in the future leading to more accurate phasor estimates since higher sampling rates do lead to improved estimation accuracy.

IX. CASE STUDY:

Optimal placement of PMU

Another approach for PMU placement using spanning trees of power systems graphs has been proposed by Nuqui and Phadke [8,9]. Here, in this paper a simulated method has been used to add constraints on the PMU placement algorithm. Performance of IEEE 14 Bus model for optimal placement using PSAT is used as a simulation tool for analyzing PMU implementing methods. Results are carried out for placement of one PMU, three PMU randomly on any buses and optimal PMU placement. The Static report provides power flow through different methods and state variables, total P,Q and plots of theta, frequency, voltage magnitude are calculated for IEEE 14 bus.
This has been discussed by Authors Xu and Abur [8]. In this work the cost of installation of PMUs is taken as the objective function to be minimized with the constraint being the observability of the power systems. The observability can be defined using a matrix containing ones and zeros. If there is a PMU present on a bus or on an adjacent bus then it is given a value of one otherwise a zero. If there are other measurements available then these can be incorporated in the matrix which ultimately reduces the number of PMUs by reducing the cost. Another approach for PMU placement using spanning trees of power systems graphs has been proposed by Nuqui and Phadke [8,9]. Here a simulated annealing procedure has been used to add constraints on the PMU placement algorithm [11].

**Table 3: Comparison of different methods for three set optimal placement PMU**

<table>
<thead>
<tr>
<th>Method</th>
<th>Elapsed time</th>
<th>Number of PMUs</th>
<th>Placement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth First</td>
<td>0.031 s</td>
<td>6</td>
<td>1,4,6,8,10,14</td>
</tr>
<tr>
<td>Graph theory</td>
<td>0.046 s</td>
<td>5</td>
<td>1,4,6,10,14</td>
</tr>
<tr>
<td>Simulated Annealing</td>
<td>0.531 s</td>
<td>4</td>
<td>1,4,6,9</td>
</tr>
<tr>
<td>Re-spanning tree</td>
<td>0.719 s</td>
<td>3</td>
<td>2,6,9</td>
</tr>
<tr>
<td>Direct spanning tree</td>
<td>0.109 s</td>
<td>4</td>
<td>2,7,11,13</td>
</tr>
<tr>
<td>Mini(N-1)spanning Tree</td>
<td>0.187 s</td>
<td>8</td>
<td>2,5,6,7,9,10,13,14</td>
</tr>
<tr>
<td>Direct (N1)spanning tree</td>
<td>0.0465 s</td>
<td>9</td>
<td>2,3,4,5,6,7,10,13,14</td>
</tr>
</tbody>
</table>

The several methods of optimal placement of PMU is compared using simulation of IEEE fourteen bus system with help of Power System analysis tools (PSAT) and the analysis of their merits and demerits is carried out. On the basis of optimal principle of DFS method, we can obtain Re-spanning tree method by improving its optimization criterion.

This approach overcomes the shortcomings of the poor optimization of DFS method and less elapsed time, high speed of Simulating Annealing method, keeps good balance of quality and efficiency of the optimal placement as well as improves the multi-formity of the results.

Reactive Power [P.U.] 1.698
Real Power [P.U.] 3.4216
Reactive Power [P.U.] 0.9772
*Total Losses*
Real Power [p.u.] 0.257382
Reactive Power [p.u.] :0.720781

In this research paper, cost of PMU placement is taken as objective function. Objective function is minimized as per constraints observability of system.

**X. Copyright forms and reprint orders**

I here by declare that, this research paper has been neither published nor submitted for publication, in whole or in part, either in a serial, professional journal or as a part in a book which is formally published and made available to the public.

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It is my privilege to express sincere gratitude and whole hearted thanks to all which gave me continuous inspiration and guidance for this research work.
CONCLUSIONS

i) Rising fuel costs, under investment in an aging infrastructure, and climate change are all converging to create a turbulent period for the electrical power-generation industry. As utility companies prepare to meet growing demand, greenhouse gas emissions from electricity generation with committed generation capacity may soon surpass those from all distributed energy sources with micro grids.

ii) Smart grid benefits for Advanced smart metering, high power quality, accommodates generation options, load adjustment, wide area measurement and control with PMUs and SCADA system, consumer participation, Demand response support, cyber security and many more for fulfilling consumers demand.

iii) Synchrophasor technology has the potential to greatly improve operator’s ability to conduct real time grid operations and detect and respond to potential disturbances. Phasor systems and data will help operators and planners to improve accuracy.

iv) The Static report provides power flow through different methods and state variables, total P,Q and plots of angles ,frequency, voltage magnitude are calculated for IEEE 14 bus system. The optimal PMU Placement decreases number of PMUs that reduces cost of system. Using PMU in smart grid increases reliability of power system stability. Therefore it is possible to monitor the power system observability by using PMU.

References
[3] Internet based phasor measurement system for phase control of synchronous islands David M Laverty IEEE