PMU Placement in IEEE 14-bus System and an Aspect on Transmission Line Fault Detection

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ABSTRACT

In this paper, improvements in power system control and protection by utilizing real time synchronized phasor measurements is suggested. Various methods like Depth First, Recursive Security, Recursive N-1 spanning suggesting optimal placement of Phasor Measurement Units (PMUs) for complete observability of a power system are reviewed. Steady state and single branch outages for PMU placement algorithms are analyzed on IEEE-14 bus test system. Also a possible strategy for the transmission system fault location using the concept of Synchro phasor and PMU is explored.

KEYWORDS:*fault analysis, optimal PMU placement, phasor measurement unit (PMU), synchronized phasor measurement (SPM), sequence component.*

INTRODUCTION

Secure operation of power systems requires close monitoring of the system operating conditions. The measurements received from numerous substations are used in control centers to provide an estimate for all metered and un-metered electrical quantities e.g. bus voltage (V),frequency (f), current (I), active power flow (P) reactive power (Q), load angle (δ) and network parameters of the power system. Until recently, the available measurements were provided by SCADA, including active and reactive power flows and injections and bus voltage magnitudes. The utilization of global positioning system (GPS), in addition to sampled data processing techniques, for computer relaying applications has led to the development of PMUs. Phasor measurement units are monitoring devices that provide extremely accurate positive sequence time tagged measurements (Phadake and Thorp, 2008). A PMU installed at a bus can make synchronized measurements of the voltage phasor of the bus and the current phasors of some or all the branches incident to the bus, assuming that the PMU has sufficient number of channels. With the increasing use of PMUs in recent years, improved monitoring, protection, and control of power networks can be achieved (Reynaldo-2005).The complete observability of the power system, while using phasor measurements, implies that each bus of the network must have one voltage phasor measurement or a voltage phasor pseudo-measurement. These phasor measurements are obtained from the PMUs directly at the locations, where these have been installed. Then applying Kirchhoff's and Ohm's laws, the remaining variables can easily be calculated as pseudo measurements. The problem of network observability has been studied by various researchers in the past. Two different approaches used for solving this problem (Manousakis-2011) are based on numerical observability and topological observability, which have their own advantages and disadvantages. A wide range of such strategies can be cited from the Optimum PMU

Placement(OPP) literature, like depth first search (DFS),minimum spanning tree (MST), simulated annealing(SA), tabu search (TS), genetic algorithms (GA),differential evolution (DE), immune algorithms (IA), Recursive N Security, particle swarm optimization (PSO) or ant colony optimization (ACO) etc. In recent years, PMUs synchronized measurements are used for fault detection/location (Chun-2007). These techniques make use of local fault messages (synchronized voltages and currents at two terminals of a transmission line) to estimate fault location. In this paper, analysis of three different OPP methods, a) Depth First Search, b) Recursive N Security, c) Recursive N-1 spinning's carried out and PMU nos. and placement suggested. Also, the PMU measured data is applied for the purpose of determining the exact fault location on transmission line. The sequence components of fault current for the later are extracted using MATLAB/Simulink. This will be employed as an input to alternative transient program for determination of fault.

PHASOR MEASUREMENT UNIT (PMU)

Phasor measurement units (PMUs) are power system devices that provide synchronized measurements of real-time phasors of voltages and currents. Synchronization is achieved by same-time sampling of voltage and current waveforms using timing signals from the Global Positioning System (GPS) Satellite. Synchronized phasor measurements elevate the standards of power system monitoring, control, and protection to a new level. They are located in substations. The GPS receiver provides the 1 pulse-per-second (pps) signal and a time tag to every information, which consists of the year, day, hour, minute, and second. The time could be the local time, or the UTC (Universal Time Coordinated).

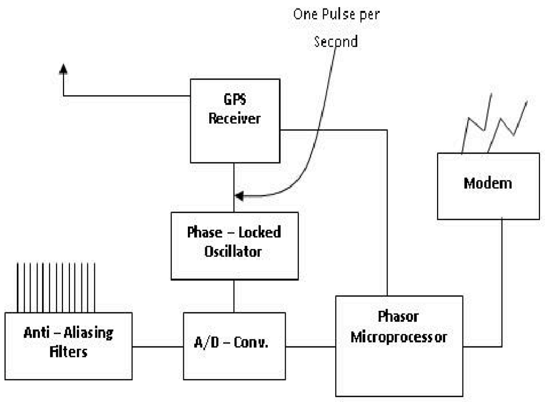

Fig.1. Basic Structure of PMU

The l-pulse per second (pps) signal is usually divided by a phase-locked oscillator into the required number of pulses per second for sampling of the analog signals. In most systems being used at present, this is 12 times per cycle of the fundamental frequency. A basic structure of PMU is shown in Fig. 1.The analog signals are derived from the voltage and current transformer secondary, with appropriate anti-aliasing and surge filtering. The microprocessor determines the positive sequence phasors according to the recursive algorithm and the timing message from the GPS, along with the sample number at the beginning of a window, is assigned to the phasor as its identifying tag. The computed string of phasors, one for each of the positive sequence measurements, is assembled in a message stream to be communicated to a remote site. The messages are transmitted over a dedicated communication line (IEEE Std C37.118-2005).

PHASOR MEASUREMENT UNIT (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 (Baldwin-1993).

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 another 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).This rule applies when the current balance at a node is known.

The observability conditions that have to be met for selecting the placement of PMU sets are (Baldwin-1993).

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.

The measurements obtained from Condition 1 are called direct measurements. The measurements obtained from Conditions 2-3 are also called pseudo-measurement. The measurements obtained from Conditions 4-6 are called extension-measurements. Various types of optimization techniques like Heuristic methods-depth first and Metaheuristic methods Recursive Security, Recursive N-1 Spanning,-are discussed as per review paper. (Meliopoulos - 2011)

Depth First Algorithm (Milosevic B 2003).

This method uses rules from 1 to 3 (it does not consider pure transit nodes) only. The first PMU is placed at the bus with the largest number of connected branches. If there are more than one bus with such characteristic, one is randomly chosen. PMUs are placed with the same criterion, until the complete network visibility is obtained, as depicted in Fig-2.

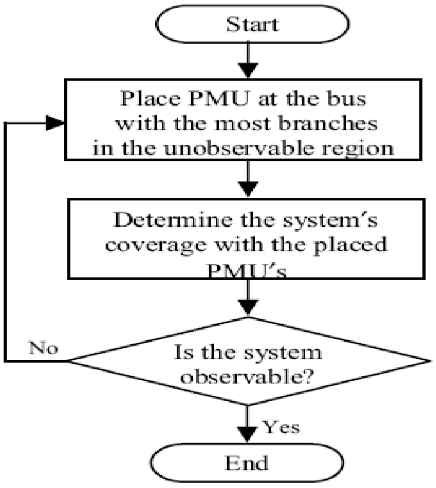

Fig.2. Flow Chart of Depth First Algorithm.

RECURSIVE N SECURITY ALGORITHM (Reynaldo F. 2005)

This method is a modified depth first approach. The procedure can be subdivided into three main steps as per Fig.3.

Generation of N minimum spanning trees

Fig.3 depicts the flowchart of the minimum spanning tree generation algorithm. The algorithm is performed N times (N being the number of buses), using each bus of the network as starting bus.

1.Search of alternative patterns

The PMU sets obtained with the step (1) are reprocessed as follows: one at a time, each PMU of each set is replaced at the buses connected with the node where a PMU was originally set, as depicted in Fig. 3. PMU placements which lead to a complete visibility are retained.

2.Reducing PMU number in case of pure transit nodes

In this step, it is verified if the network remains observable taking out one PMU at a time from each set, as depicted in Fig. If the network does not present pure transit nodes, the procedure end sat step (2).The placement sets which present the minimum numbers of PMUs are finally selected.

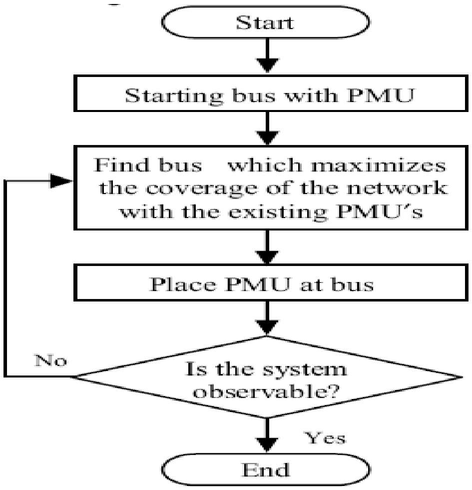

Fig.3. Flow Chart of Recursive Security N Algorithm

RECURSIVE N-1 SPANNING ALGORITHM (Denegri-2002)

The rules for minimal PMU placement assume a fixed network topology and a complete reliability of measurement devices. Simple criteria which yield a complete visibility in case of one line outage at a time (N-1 spanning) is based on the following

A bus is said to be observable if at least one of the two following conditions applies:

Rule 1. A PMU is placed at the node.
Rule 2: The node is connected at least to two nodes equipped with a PMU. Rule 2 is ignored , if the bus is connected to single-end line.Fig.4 depicts the algorithms for obtaining the N-1 Spanning placement.

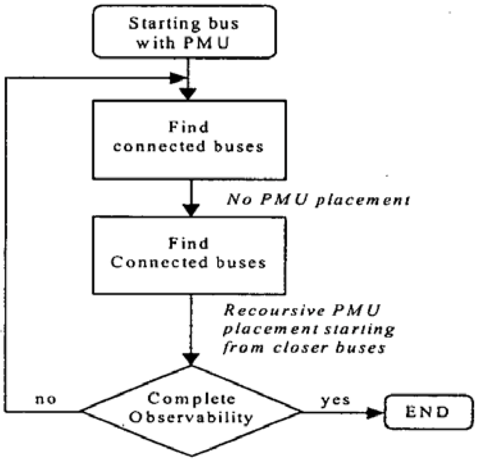

Fig.4. Flow Chart of Recursive N-1 Spanning Algorithms

ALGORITHM ANALYSIS AND RESULT SUMMARY

The above discussed algorithms are applied to IEEE 14 bus test system. Fig. 5 represents its graph model. Results of all methods are gained with help of Power System Analysis Toolbox (PSAT) (Milano-2010) and described as per Table - I. The PMU heading in table – I indicates minimum PMU hardware required for complete system observability, and the heading-Set, indicates various PMU placement combinations possible for complete observability with the no. of PMUs remained same. The heading 'Bus location' points out the bus numbers for PMU position. Following a line outage, N-1 method result PMU set list and network would remain still observable. For complete system observability the Recursive N Security algorithm suggests minimum three PMUs instead of six from Depth First algorithm, hence it would be beneficial in cost comparison. However Recursive N-1 Spanning algorithm would be more preferable as it includes single outage of system component.

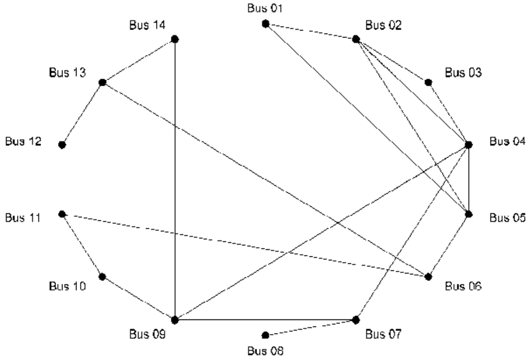

Fig.5. Graph Representation of IEEE 14 Bus System

Table 1. PMU placement results through distinct algorithms

IEEE-14 BUS TEST SYSTEM			
Method	**No. of PMUs**	**Set**	**Bus Location**
Depth First	06	01	1,4,6,8,10,14
Recursive N Security	03	01	2,6,9
Recursive N-1 Spanning	08	10	2,5,6,7,9,10,13,14
			1,3,5,7,9,11,12,13
			1,2,4,6,7,10,13,14
			2,3,5,7,9,11,12,13
			2,3,5,7,9,10,11,12
			1,2,4,6,7,10,13,14
			2,3,5,7,9,11,12,13
			2,3,5,7,9,11,12,14
			2,3,5,6,7,9,11,13
			1,2,4,6,7,10,12,14

FAULTS ON TRANSMISSION LINES

As very well known, transmission line faults can be grouped in symmetrical and asymmetrical components. Summarizing, symmetrical components are involved in three phase line fault (L-L-L),three phase line to ground fault (L-L-L-G) and whereas asymmetrical components in line to ground fault (L-G), line to line fault (L-L) and double line to ground fault (L-L-G).The identification of type of fault is achieved with the help of symmetrical components of fault currents. In the case of a symmetrical three-phase fault, a single-phase representation is widely accepted for the short-circuit and transient analysis. However, for the majority of the fault situations, the power system appears unsymmetrical. Symmetrical components and, especially, the sequence networks are an elegant way to analyze faults in unsymmetrical three-phase power systems because in many cases the unbalanced portion of the physical system can be isolated for a study, the rest of the system being considered to be in balance. Fig. 6 shows disunion of an unbalanced current phasor into positive, negative, and zero sequence components. This is, for instance, the case for an unbalanced load or fault. In such cases, we attempt to find the symmetrical components of the voltages and the currents at the point of unbalance and connect the sequence networks, which are; in fact, copies of the balanced system at the point of unbalance (the fault point) (Anderson-1995).

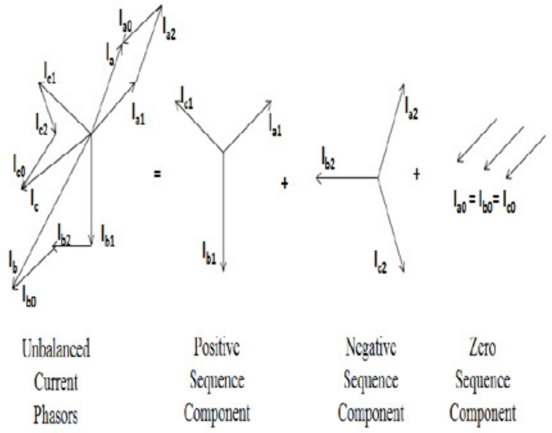

Fig.6. Sequence Components representation

$$I_a=I_{a1}+I_{a2}+I_{a0}$$
$$I_b=I_{b1}+I_{b2}+I_{b0} \qquad \text{Eq. (1)}$$
$$I_c=I_{c1}+I_{c2}+I_{c0}$$

Unbalanced current phasor can be mathematically as per eqn. (1) where I_a, I_b, I_c are three phasors that are not in balance and I_{a1}, I_{b1}, I_{c1} andI_{a2}, I_{b2}, I_{c2} are two sets of three balanced phasors with an angle of 120^0 between the components a, b, and c. The components of the phasor set I_{a0}, I_{b0}, and I_{c0} are identical in amplitude and angle Equations can be simplified by making use of the α-operator, where $\alpha = e^{j2\pi/3}$(Fortescue-1918) The relation between the set of phasors (I_a, I_b, I_c) and the positive phasors, negative phasors, and zero phasors is in matrix form as per eqn. (2).

$$\begin{pmatrix} I_a \\ I_b \\ I_c \end{pmatrix} = \frac{1}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{pmatrix}\begin{pmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{pmatrix} \qquad \text{Eq. (2)}$$

Or I_{abc}=[A] I_{012}

TRANSMISSION LINE FAULT SIMULATIONS AND RESULTS ANALYSIS

A single machine infinite bus system (Fig. 7) is modeled in MATLAB/Simulink, where two transmission line sections of equal length i.e. 200kms each are used. The mechanical input and excitation to synchronous generator kept at constant level. The transformer secondary and load at bus are grounded. Different faults, viz. symmetrical and unsymmetrical, are simulated at mid-point of transmission line on computer software for the duration of one cycle of 50Hz system frequency (i.e. 20ms).In case of grounded fault, value of fault resistance taken as 0.001Ω. The Discrete Fourier Transform block in Simulink computes the fundamental value of the input phase current signal over a running window of one cycle of the specified fundamental frequency. Its output provides the magnitude and phase angle. The sequence components (positive, negative and zero) of the fault current have been obtained using the sequence filter circuit created in the MALTAB/Simulink software. The inputs to above circuit are fault currents I_a,I_b ,I_c and the outputs obtained are plots of magnitude and phase of all three components of currents from bus 1.In the figures of simulation results the colour codes used are - Positive Sequence– Red, Negative Sequence – Black, Zero Sequence – Green.

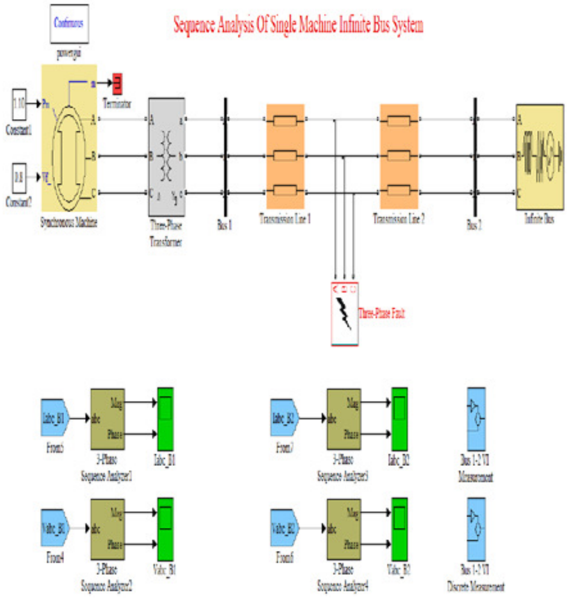

Fig.7. Single Machine Infinite Bus System

In case of a single line to ground fault, it is observed from Fig. 8 that zero seq. component is greater in magnitude than both the other two sequence component during the period of fault. However, the system regains and positive sequence current of reasonable magnitude is restored. The phase angle oscillations are significant for zero sequence component, as expected.

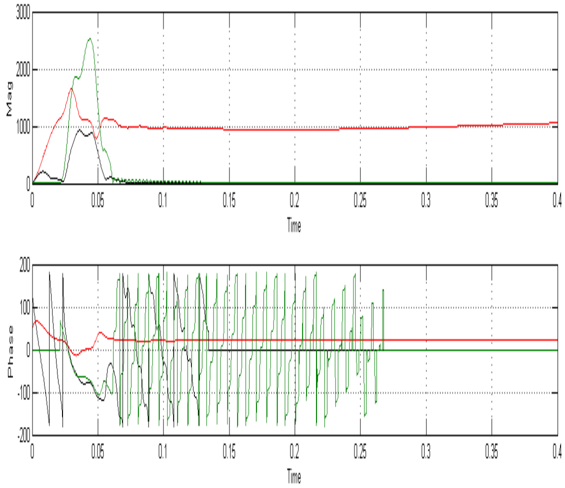

Fig.8. Line to Ground Fault (R-G)

From the Fig. 9, it is observable that the zero sequence component of current is absent, indicating the line - to -line fault.

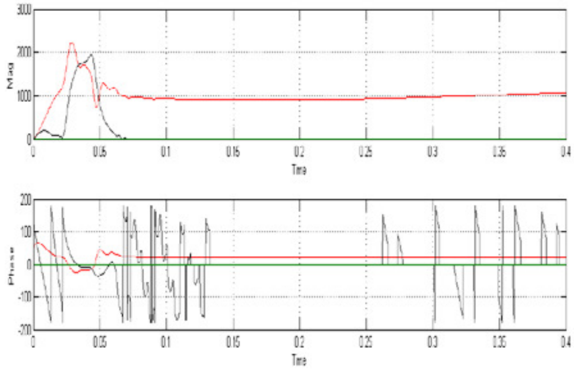

Fig.9. Line to Line Fault(R-Y)

From Fig. 10 it is noticeable that in line line to ground fault Negative sequence and Zero sequence components are nearly equal in magnitude and duration.

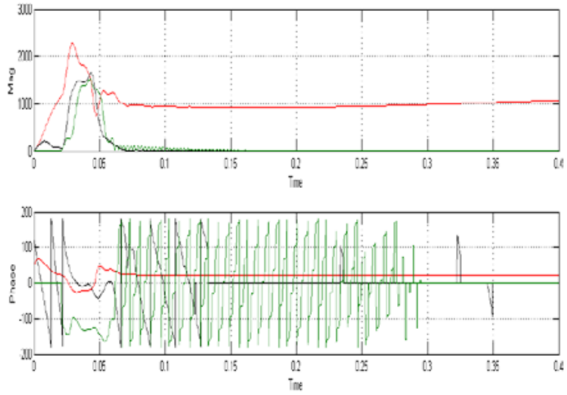

Fig.10. Line-Line-to ground Fault(R-Y-G)

In three phase faults, are balanced in nature. From Fig. 11 it is observed that negative sequence present only during transient time and zero sequence components is always zero.

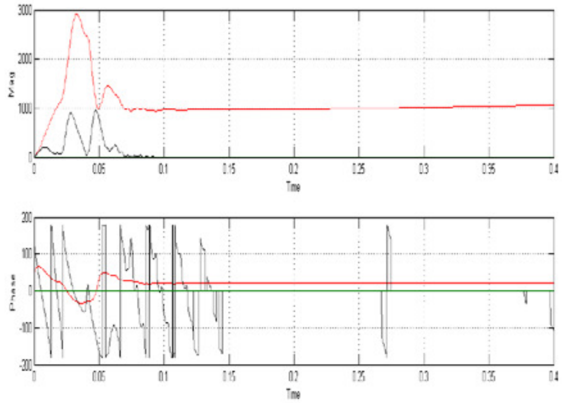

Fig.11. Line-Line-Line Fault(R-Y-B)

In three phase to ground fault, fault current is highest among all cases. Noted from Fig. 12 Negative sequence and Zero sequence present only during transient time.

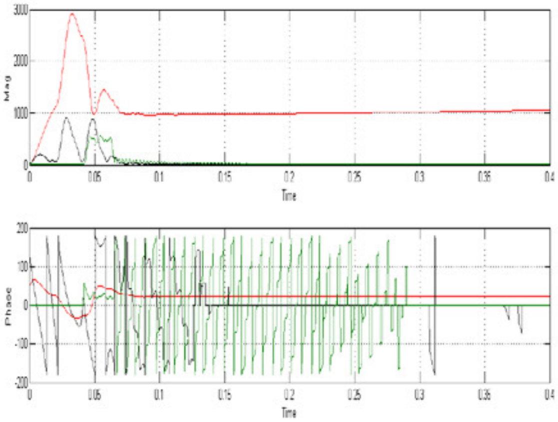

Fig.12. Line-Line-Line to ground Fault(R-Y-B-G)

The above information, if fed into the transient analyser programme, it might lead to the identification of the faults. Although, this fact is suggested in literature, it is yet to be comprehended.

CONCLUSION

In this paper three distinct PMU placement algorithms 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 results are discussed.

The sequences components of fault current acquired from described MATLAB/Simulink model. The literature provides proposal that with the help of these data, transmission line parameters, PMU and WAMS fault location can be determined.

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