Application of MCDM - AHP Technique for PMU Placement in Power System

J. S. Bhonsle[1]
Department of Electrical Engineering
Priyadarshini Institute of Engineering and Technology,
Nagpur, India
jsbhonsle.piet@gmail.com

A.S. Junghare[2]
Department of Electrical and Electronics Engineering
Visvesvaraya National Institute of Technology,
Nagpur, India
asjunghare@eee.vnit.ac.in

***Abstract*— The analytical hierarchy process (AHP) , one of the multi-criteria decision making (MCDM) technique has been widely employed in making complex decisions in various applications. This paper presents the grid topology based phasor measurement unit (PMU) placement scheme utilizing AHP technique in a power system assistive / helpful for fetching the important functionality of modern energy management system (EMS). Paper addresses the aspects of complete topology based network observability of wide area grid system with both conventional meters and featured PMUs. PMU located at appropriate bus improves network observability and increases the measurement redundancy essential for situational awareness of wide area monitoring system.. In this paper, priority for PMU inclusion in the existing measurement set of power system is modeled using MCDM – AHP technique. Proposed final grid monitoring system design using decision making technique is tested and validated on standard IEEE 14 bus and IEEE 30 bus system.**

Keywords—Analytical Hierarchy Process; Grid Monitoring; Multi Criteria Decision Making technique; Phasor Measurement Units.

I. INTRODUCTION

Presently PMUs are the most classic time synchronized, fast and accurate device available to power engineers. PMU placed at a bus measures the voltage phasor at that bus and the current phasors in branches of the adjacent buses. Data provided by PMUs are time tagged and precise. Integration of synchronized PMUs into a power system enhances the aspect of grid monitoring from local to wide area. This provides the critical aspects of the transmission grid useful for power system analysis. PMU located at appropriate bus improves network observability and increases the measurement redundancy essential for situational awareness of wide area monitoring system and beneficial for fetching the important functionality of modern energy management system.

Though PMU's may be placed at all buses, limitations are posed due to the heavy cost of reliable communication facilities. Hence, optimal PMU placement with regard to cost of PMU, cost of communication infrastructure, network observability, measurement redundancy, application of synchronised data to power system and so on becomes an impending issue in recent years and focused area for researchers. It would not be feasible and economical to replace the existing conventional measurements which are still contributing. The more realistic solution is to incorporate PMUs with conventional measurements for the purpose of wide area grid monitoring and measurement. Further an incremental placement of PMUs would be a better strategy in the current power systems scenario. In [1] author presented summary of experts from several countries stating their wide area measurement system (WAMS) –related experience and activities in detail. In [2] author provides a brief introduction to the PMU and WAMS technology and discusses the uses of these measurements for improved monitoring, protection, and control of power networks.

Power system network observability is a primary and important step in EMS functionality. It determines whether the entire power system state vector is observable or not with the available measurement system design. Observability analysis algorithms can be broadly classified as topological and numerical. In [3] author presents an algebraic method that uses the triangular factors of gain matrix to determine the observable islands of a measured power system, whereas in [4] author make direct use of the measurement Jacobian matrix. The network observability and hence the state observability depends upon the number of measurements and the location of their deployment in network. With more available measurements, redundancy increases and the system states can be estimated more accurately. In [5] author uses sequential elimination technique for obtaining the essential measurements required for complete numerical observability. In [6] author uses integer quadratic programming approach for placing PMU considering complete observability of a power system. In [7] unified approach is proposed to determine the optimal PMUs placement for power system state estimation. A comprehensive literature review on optimum PMU placement algorithm is presented in [8], whereas state of art of optimization method for solving optimal PMU placement problem is discussed in [9]. Diverse factors influencing the PMU placement decision-making processes including specific application area are derived based on sound practical solutions by experienced industry practitioners in [10].

In this paper, author proposed topology based grid monitoring system design with both conventional meters and featured PMU using MCDM-AHP theory. PMUs are added sequentially in the measurement set until a final target of measurement system design is achieved. Priority-wise placed

978-1-4799-6023-1/15 $31.00 © 2015 IEEE
DOI 10.1109/CICT.2015.127

PMUs at appropriate bus in an incremental way along with existing conventional measurements eliminates critical measurement set. Proposed grid monitoring system design is tested and validated on standard IEEE 14 bus and IEEE 30 bus system.

The paper is organized as follows. Section II explains the MCDM- AHP theory in detail. Section III presents application of AHP for priority-wise PMU placement along with conventional meters in a measurement set. Section IV deals with the case studies and analysis of results and section V concludes the paper.

II. MCDM-AHP TECHNIQUE

In order to obtain the best alternative out of a large number of available options and problem involving a number of objectives which have to be addressed simultaneously, decision can be obtained employing MCDM technique.

MCDM involves a systematic way of selecting the best available alternatives based on different opinions and conflicting priorities. AHP is one of the MCDM method that was originally developed by Prof. T. L. Saaty [11]. It is a very robust problem solving technique based on pair-wise comparisons in which problems are decomposed into a hierarchy of factors and criteria.

The MCDM – AHP approach in general can be summarized in the following steps:

Step 1: Decision hierarchy model building. It involves breaking the problem into interconnected decision elements by defining goal.

Step 2: Pair wise comparisons of the decision elements. Scale for same is as shown in table I.

Step 3: Relative weight estimation of decision elements using matrix-oriented methods.

Step 4: Alternative ranking which involves relative weights aggregation of the decision elements yielding a final score for each option.

TABLE I. SCALE FOR PAIR-WISE COMPARISON

Intensity of Importance	Definition / Explanation
1	Equally Important
3	Slightly Important
5	Strongly Important
7	Very Strongly Important
9	Extreme Important
2, 4, 6 and 8	Intermediate points of Importance

AHP can be briefly illustrated / explained as follows:

Let A, B and C are influencing criteria for set objective / goal. Pair wise comparison matrix will be:

$$\begin{pmatrix} \frac{A}{A} & \frac{A}{B} & \frac{A}{C} \\ \frac{B}{A} & \frac{B}{B} & \frac{B}{C} \\ \frac{C}{A} & \frac{C}{B} & \frac{C}{C} \end{pmatrix} \quad (1)$$

Let $\frac{A}{A}=C11$, $\frac{A}{B}=C12$ and $\frac{A}{C}=C13$ (2)

and so on. Thus, pair wise element matrix obtained using Equation (2) is as follow:

$$\begin{pmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{pmatrix} \quad (3)$$

The element of normalized pair wise matrix can be formed using Equation (4) as follow :

$$Xij=\frac{Cij}{\sum_{j=1}^{n} Cjj} \quad (4)$$

where n is number of selected criteria.

Thus, normalized pair wise element matrix obtained is as follow :

$$\begin{pmatrix} X_{11} & X_{12} & X_{13} \\ X_{21} & X_{22} & X_{23} \\ X_{31} & X_{32} & X_{33} \end{pmatrix} \quad (5)$$

The element of weight matrix can be formed using Equation (6) as follow :

$$Wjj=\frac{\sum_{j=1}^{n} Xij}{n} \quad (6)$$

Thus, element of weight matrix also known as priority matrix obtained is as follow :

$$\begin{bmatrix} W11 \\ W12 \\ W13 \end{bmatrix} \quad (7)$$

Consistency of decision can be checked by evaluating consistency ratio CR using Equation (8) as follow:

$$CR=\frac{CI}{RI} \quad (8)$$

where CI is consistency index. It is given as follow :

$$CI=\frac{\lambda \max - n}{n-1} \quad (9)$$

and RI is random consistency index. It is the consistency index for a randomly-filled matrix as shown in table II.

TABLE II. RANDOM CONSISTENCY INDEX VERSUS COMPARISON MATRIX ORDER

n	2	3	4	5	6	7	8	9	10
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

$\lambda_{\max}$ is eigen vector corresponding to the maximum eigen value and can be found using Equation (10) as :

$$\lambda= \sum_{j=1}^{n} Cvjj \quad (10)$$

where Cv_{ij} is consistency vector and element Cv_{11} is as given by Equation (11) as :

$$Cv11=\frac{1}{W11}[C11W11+C12W12+C13W13] \quad (11)$$

Other element can be calculated in similar manner.
Final normalized principle eigen vector which is also known as priority vector as seen in equation (7) is obtained as equation (12).

$$\begin{bmatrix} Cv11 \\ Cv12 \\ Cv13 \end{bmatrix} \quad (12)$$

If the value of CR $\leq$ 0.1, the inconsistency is acceptable whereas if the value of CR $>$ 0.1, it needs revision of subjective judgment.
Decision makers are free to allocate relative weights to various decision element under consideration.

III. PMU PLACEMENT USING MCDM-AHP

The decision of selecting a suitable subset of optimal PMU locations, in stage, for improving the accuracy and functionality of EMS involves addressing important factors such as network observability, measurement redundancy, network topology and so on. An MCDM – AHP model discussed above is adopted for placing PMU at selected buses along with available conventional measuring meters to form new redundant measurement set. AHP modeling is quite simple, effective and an intuitive approach of decision making.

Following are the steps of implementation of proposed AHP modeling for priority wise PMU placement :

1. State the Objective (PMU placement)
2. Define the Criteria (three criteria are chosen).
   i. Criteria A - maximum no. of electrical quantity that can be measured at bus.
   ii. Criteria B - no. of times electrical quantity is observed. (redundancy, reliability)
   iii. Criteria C - actual no. of electrical quantity measured at the bus.
3. Form the pair-wise criteria matrix.
4. Normalize the pair-wise criteria matrix.
5. Form the weight matrix / Priority matrix for criteria.

Once the weight matrix for criteria is formed, weight matrix for available alternatives for each criteria needs to be obtained in same manner.

6. For each criteria,
   i. Form pair-wise alternative matrix.
   ii. Normalize the pair-wise alternative matrix.
   iii. Form the alternative weight matrix
7. Form the criteria alternative weight matrix.
8. Form the ranking matrix from criteria alternative weight matrix and criteria weight matrix.
9. Finalize the PMU location by following the mentioned condition :
   a. Place the PMU on bus with highest ranking calculated in step (8) using MCDM-AHP technique.
   b. For next placement, skip the buses adjoining to the PMU placed bus.
   c. Continued placing the PMU according to ranking and above mentioned condition till set redundancy target is achieved.

Normalized pair wise matrix (NPM) for considered three criteria mentioned as step (4) of proposed implementation of this section and shown by equation (5) of above section is as follows :

$$\text{NPM} = \begin{pmatrix} 0.2381 & 0.7894 & 0.0769 \\ 0.0476 & 0.1579 & 0.6923 \\ 0.7143 & 0.0526 & 0.2307 \end{pmatrix}$$

Weight matrix (WM) or Priority matrix (PM) for considered three criteria mentioned as step (5) of proposed implementation of this section and shown by equation (7) of above section is as follows:

$$\text{WM} = \begin{pmatrix} 0.3682 \\ 0.2992 \\ 0.3326 \end{pmatrix}$$

IV. CASE STUDY AND RESULT ANALYSIS

Proposed grid monitoring system design using MCDM-AHP technique is tested and validated on standard IEEE 14 bus and IEEE 30 bus system. Fig. 1 shows IEEE 14 Bus test system employed for analysis.

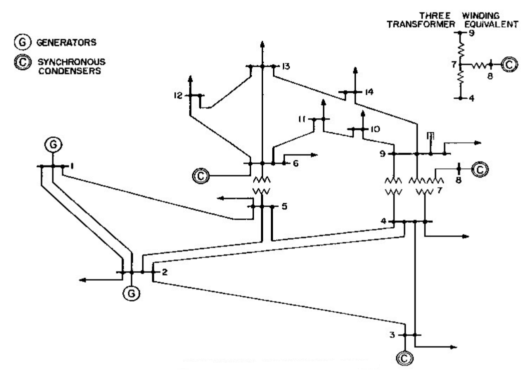

Fig. 1. IEEE 14 Bus test system

Using multi criteria decision making problem solving technique, weightage for decision criteria i.e. Criteria A, Criteria B and Criteria C for both the test system are found to be 36.82%, 29.92% and 33.26% respectively.

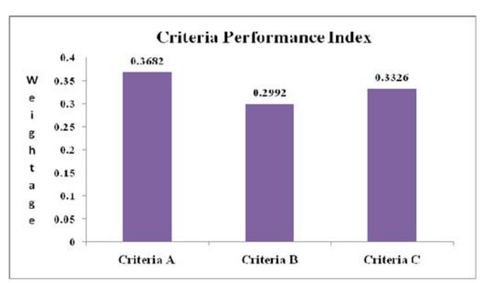

Fig. 2. Performance Index of selected Criteria

Fig. 2 shows the performance index of selected criteria. Criteria A is the most important criteria followed by criteria C and criteria B with a relative weightage ratio of 1.23 and 1.11 respectively.

Following step (6) of proposed implementation using AHP technique for PMU placement, weight matrix for Criteria A for IEEE 14 bus system is given as follows:

$WM_{\_CA\_IEEE14}$ = [0.025 0.121 0.025 0.234 0.121 0.121 0.060 0.012 0.121 0.025 0.025 0.025 0.060 0.025]

Similarly weight matrix for Criteria B and Criteria C for IEEE 14 bus system are calculated and criteria alternative weight matrix is formed as mentioned in step (7) of proposed algorithm. Then Ranking matrix is obtained by using criteria alternative weight matrix and criteria weight matrix as mentioned in step (8) of algorithm.

Ranking matrix for IEEE 14 bus system is given as follows:

RM_{IEEE14} = [0.039 0.058 0.039 0.145 0.115 0.077 0.121 0.062 0.115 0.081 0.039 0.021 0.040 0.039]

From Ranking matrix, it is clear that alternative which is representing bus no. 4 have highest ranking value of 0.145 and hence bus no. 4 is chosen / selected for PMU placement first with the existing / available measurement design for IEEE 14 bus system. Latter by implementing step (9) b and c, PMU placement at buses 7, 5 and 9 are skipped for IEEE 14 bus system (referring Fig. 1) and placed at other buses in sequence till redundancy index of 2.5 is achieved in measurement set design.

Thus, PMUs are finalized to be placed at bus no. 4, 10, 6 and 8 in sequence stage wise for IEEE 14 bus system with a priority weightage of 0.145, 0.081, 0.077 and 0.062 respectively whereas for IEEE 30 bus system, they are finalized to be placed at bus no. 6, 12, 27, 22, 11, 13 and 26 with a priority weightage of 0.107, 0.073, 0.051, 0.034, 0.030, 0.029 and 0.014 respectively.

Fig. 3 and 5 shows the overall performance index of available alternatives for IEEE 14 bus and IEEE 30 bus system respectively according to ranking matrix thus obtained. Fig. 4 and 6 shows the performance index of three chosen criteria for available alternatives for IEEE 14 bus and IEEE 30 bus system respectively.

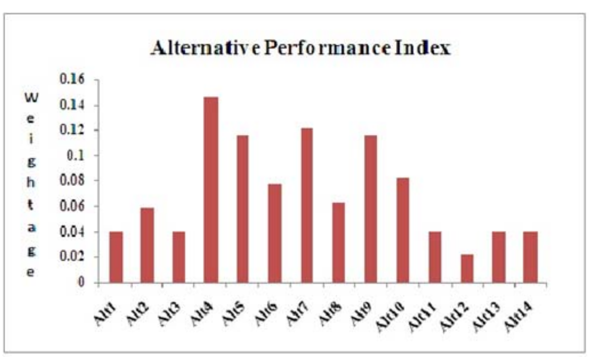

Fig. 3. Overall Performance Index of Alternatives for IEEE 14 bus system

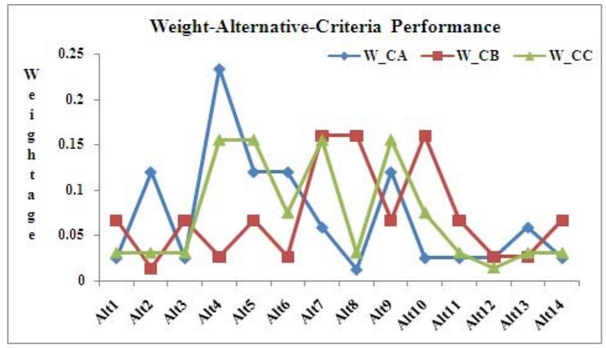

Fig. 4. Performance Index of Weight - Alternatives – Criteria for IEEE 14 bus system

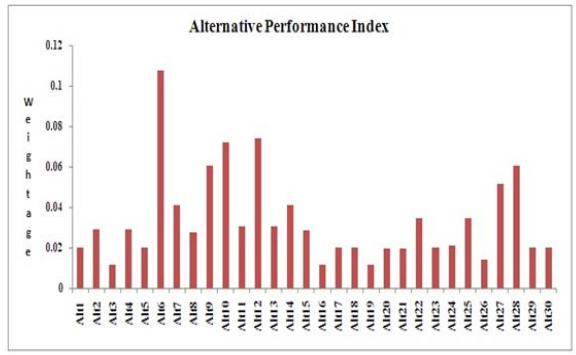

Fig. 5. Overall Performance Index of Alternatives for IEEE 30 bus system

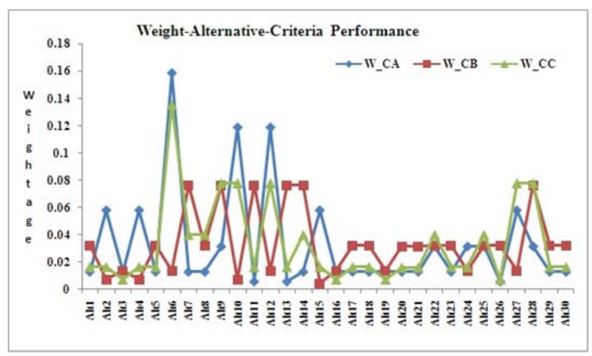

Fig. 6. Performance Index of Weight - Alternatives – Criteria for IEEE 30 bus system

From figure 3 and 5, it is seen that performance index of alternative 4 which represent bus no. 4 for IEEE 14 bus system and alternative 6 which represent bus no. 6 for IEEE 30 bus system are highest respectively and hence those buses with PMU are integrated in system on priority basis according to decision criteria for achieving the set goal.

From figure 4 and 6, it is concluded that criteria A is having highest weightage index and accordingly alternative which is having highest performance index is priority wise finalized for PMU placement in IEEE 14 bus and IEEE 30 bus system respectively.

Table III provides the details of conventional measurement configuration and priority wise final PMU Placement considering measurement redundancy index which is given as the ratio of no. of measurements to the no. of states for the test system.

TABLE III. TEST SCENARIO WITH MEASUREMENT CONFIGURATION

System	Conventional Measurement Configuration	Prioritized final PMU Placement
IEEE 14 bus	Voltage magnitude and angle at bus 1 Power injections at buses 3, 4, 8, 10, 11,12 and 14 Power flows at branches 1–2, 2–3, 4–2, 4–7, 5–2, 6–11, 6–13 and 12–13	Bus no. 4 , 10, 6 and 8
IEEE 30 bus	Voltage magnitude and angle at bus 1 Power injections at buses 2, 3, 4, 6, 8, 9, 10, 11,12, 13, 15, 16,19, 21, 24, 26, 27 and 30 Power flows at branches 1–3, 2–4, 3-4, 2-5, 2-6, 4–6, 5–7, 12-15, 12-16, 14-15, 16-17, 15-18, 18-19, 19-20, 10-20,10-17,10-22,21-22, 5-23, 23-24, 24-25, 25-26, 27-29, 27-30, 29-30 and 8-28	Bus no. 6, 12, 27, 22, 11, 13 and 26

V. CONCLUSION

This paper present grid topology based scheme for priority wise PMU placement using MCDM-AHP technique which is quite simple, effective, practical and adaptive approach. Wide area grid monitoring and measurement system is designed with four PMUs placed at 4, 10 ,6 and 8 for IEEE 14 bus system and with seven PMUs placed at 6, 12, 27, 22, 11, 13 and 26 for IEEE 30 bus system for situational awareness and necessary corrective steps to be taken henceforth. With the change in conventional meter placement design, PMU placement design will be easily modified using the proposed decision making approach.

REFERENCES

[1] A.G. Phadke, "The Wide World of Wide Area Measurement", IEEE Power and Energy Magazine 2008, Vol. 6, No. 5, pp. 52-65.

[2] J. Ree, V. Centeno, J. S. Thorp and A. G. Phadke, "Synchronized Phasor Measurement Applications in Power Systems", IEEE Transactions On Smart Grid, Vol. 1, No. 1, June 2010, pp. 20-27.

[3] B. Gou and A. Abur, "A Direct Numerical Method for Observability Analysis", IEEE Transactions On Power Systems, Vol. 15, No. 2, May 2000, pp. 625-630.

[4] B. Gou, "Jacobian Matrix-Based Observability Analysis for State Estimation", IEEE Transactions On Power Systems, Vol. 21, No. 1, February 2006, pp. 348-356.

[5] C Rakpenthai, S Premrudeepreechacharn, S Uatrongjit and N. Watson. "An Optimal PMU Placement Method Against Measurement Loss and Branch Outage", IEEE Transactions On Power Delivery, Vol. 22, No. 1, January 2007, pp. 101-107.

[6] S. Chakrabarti, E. Kyriakides, and D. G. Eliades, "Placement of Synchronized Measurements for Power System Observability", IEEE Transactions On Power Delivery, Vol. 24, No. 1, January 2009, pp. 12-19.

[7] N. H. Abbasy and H. M. Ismail, "A Unified Approach for the Optimal PMU Location for Power System State Estimation", IEEE Transactions On Power Systems, Vol. 24, No. 2, May 2009, pp. 806-813.

[8] W. Yuill, A. Edwards and S. Chowdhury, "Optimal PMU placement: A comprehensive literature review", *Published in Power and Energy Society General Meeting* 2011, pp. 1-8.

[9] N. M. Manousakis, G. N. Korres and P. S. Georgilakis, "Taxonomy of PMU Placement Methodologies", IEEE Transactions On Power Systems 2012, Vol. 27, No. 2, pp. 1070 – 1077.

[10] V. Madani, M. Parashar, J. Giri, S. Durbha , F. Rahmatian , D. Day , M. Adamiak and G. Sheble, "PMU Placement Considerations – A Roadmap for Optimal PMU Placement ", Published in Power system Conference and Exposition 2011, pp. 1-7.

[11] T. L. Saaty, "How to make a decision : The Analytic Hierarchy Process", European Journal of Operational Research 48 (1990), pp. 9-26.