A New Technique for Designing Restoration Based Reliable WAMS Structure

N V Phanendra Babu[1], Dr. P Suresh Babu[2], Mrs. P Rohini Krishna Chaitanya[3]

[1,] Assistant Professor, Electrical & Electronics Engineering, Chaitanya Bharathi Institute of Technology, Hyd-500075

[2] Assistant Professor, Dept. of Electrical Engineering, National Institute of Technology Warangal-506004

[3] Assistant Professor, EEE department, Dr. Samuel George Institute of Engineering & Technology, Markapur, Andhra pradesh

Abstract— **Wide-Area Measurement System (WAMS) plays a significant role in recovering the historical data for power system post-mortem analysis. For this purpose, the paper presents a new methodology for partitioning a WAM network into number of WAMS regions. It enables restoration process easier. Later, it also suggests a reliable placement of Phasor Data Concentrators (PDCs). For this, transformer equivalent bus constraint, generation-load balance and observability constraints are considered. An IEEE-30 bus system is used for demonstrating the proposed scheme.**

Keywords— Power system Restoration, PMU, Reliability, PDC, WAMS.

Nomenclature:

S_p: observability function for bus p, $S_p>1$.
c_{pq} : Binary connectivity parameter.
r: the total number of regions.
n_r: the number of buses in each island,
P_{Gi}: The maximum generation at i^{th} bus
P_{Li}: the load at i^{th} bus
A_p : system connectivity matrix of p^{th} region.
x_p: PMU placement vector of p^{th} region
k :number of buses in p^{th} island.
A: system connectivity matrix.

INTRODUCTION

In general, power system is highly prone to interruptions in power supply even though many attempts were made to reduce the chances for the occurrence of failures. Sometimes, the power to a complete network will be lost and causes complete outage of network elements like generators, transformers and loads. This phenomenon is called Blackout, which is the most dangerous outage than any normal outage [1]. So, the power system elements need to be restored after blackout. The Build-up strategy achieves this restoration. This power system restoration should be effective as the latency in restoration leads damage to loads, and incurs economic and political costs. The build-up strategy proposed in [2] is followed in this work as it interconnects the islands after being restored separately.

The planning and importance of Build-up strategy are clearly explained in [2-5], but they failed in introducing ideas to sectionalize a network into separate islands. Reference [6] has suggested a method for sectionalizing the power system into islands but as it doesn't consider Generation-Load constraint during initial partitioning, it was failed in producing stable islands in initial partitioning and more number of islands for larger systems. The proposed technique has partitioned without disturbing the observability of every bus in every island.

A model based algorithm for partitioning the WAMS into different regions is proposed in this paper. Unlike [6], it considers generation-load constraint initially, and applies the observability constraint in the final stage of partitioning. Interestingly, this will improve the stability and the number of all the feasible islands. Hence, by separating the faulty islands, it protects the power system from the most dangerous events such as blackouts. Later, it suggests a new placement technique for placing Phasor Data Concentrators (PDCs). The proposed methodology is explained with the help of an IEEE-30 system.

This paper is organized as follows: the optimal PMU placement for the completed network is presented in section I. Section II discusses the constraints of restoration. Sections III and IV describe network partition and final modification. PDC placement is presented in section VI. Section VII concludes the paper.

I. OPTIMAL PMU PLACEMENT

The PMU uses Kirchhoff's laws to calculate different electrical quantities of all the buses connected to the bus where it is located. This section identifies the number of PMUs required for observing the system completely. Initially, the optimization problem was introduced in [7]. After, many heuristic method based approaches were presented to solve the optimization problem.

The proposed Optimal PMU Placement problem uses Binary Cuckoo Search (BCS) method for identifying the minimal PMU locations for complete observability. The locations of PMUs obtained using BCS are listed in Table 1. The problem can be formulated as:

Minimize

$$\sum_{q\in N} x_q \quad (1)$$

Subjected to $$s_p(X) \geq 1, \quad \forall p \in N \quad (2)$$

Where $$s_p = \sum_{q\in N} c_{pq}\, x_q \,, \quad \forall p \in N \quad (3)$$

Here, equation (1) gives the objective function. The variable c_{pq} is given by:

$$c_{pq} = \begin{cases} 1, if\ p = q \\ 1, if\ p\ and\ q\ are\ connected \\ 0, else \end{cases} \quad (4)$$

Table 1. Locations of PMU

Test system	PMU Locations
IEEE-30	2, 3, 6, 9, 10, 12, 15, 19, 25, 27
IEEE-39	2,6,9,10,12,14, 17, 20, 22, 23, 25, 29, 33
IEEE-118	2,5,9,12,13,17,21,23,26,29,34,37,42,45,49,53,56,62,64, 71,75,77,80,85,86,90,94,101,105,110,115,116

II. CONSTRAINTS FOR WAMS POWER SYSTEM RESTORATION

After partitioning, each region in the power system must be independent and observable. For this, three constraints such as transformer equivalent bus, generation-load balance and observability of island are introduced here. They can be described as below.

A. Generation-Load balance

This is a mandatory constraint. As this constraint ensures surplus power, it should be fulfilled in each-iteration of partitioning. This constraint ensures that there should be enough amount of surplus power in each region. It is given by,

$$\sum_{i=1}^{n_r} P_{Gi} > \sum_{i=1}^{n_r} P_{Li}\ , \quad i = 1, 2, 3.....r. \quad (5)$$

B. Joining the islands on either sides of transformer

For the independent islands, there should not be any transformer that connects two or more regions. This can be avoided by joining the regions that are being connected on either sides of the transformer. It will be applied at the end of initial partitioning.

C. Observability of islands

This constraint will be checked by

$$A_p \times x_p \geq \begin{bmatrix} 1 \\ 1 \\ . \\ . \\ 1 \end{bmatrix}_{k \times k} \quad (6)$$

Equation (7) helps in determining A_p. For the regions to be observable, this must be satisfied. The bus whose entry is zero (0) would be treated as unobserved bus. The elements of connectivity matrix A are,

$$a_{ij} = \begin{cases} 1, if\ i = j\ or\ if\ buses\ i\ and\ j\ are\ connected \\ 0, otherwise \end{cases} \quad (7)$$

III. PROPOSED NETWORK SECTIONALIZING

This partition will be processed in two phases such as initial partition and final partition. Initial partition gives stable islands which may or may not be observable. Final partition assures observable islands by moving the unobserved bus to suitable islands. After initial partition, it is to be noted that the transformers must be allocated to particular regions to which the transformer buses are incident. This enables each region to run independently.

The proposed partitioning technique is explained using an IEEE-30 bus system shown in Fig. 1. During initial partition, the first step starts with identifying the number of islands which is equal to the minimum of number of generator buses, load buses and PMU installed buses.

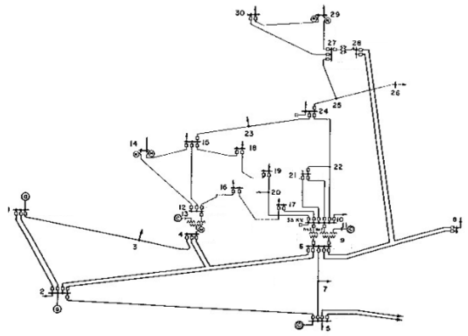

Fig. 1: IEEE-30 bus system.

The number of islands is calculated from,

$$r = \min \left\{ \sum_{i=1}^{n} G_i, \sum_{i=1}^{n} L_i, \sum_{i=1}^{n} M \right\} \quad (8)$$

Where,

$$G_i = \begin{cases} 1, if\ there\ is\ a\ generator\ at\ bus\ i\ connected \\ \quad with\ an\ affordable\ load \\ 0, otherwise \end{cases} \quad (9)$$

$$L_i = \begin{cases} 1, if\ there\ is\ a\ load\ bus\ at\ bus\ i \\ 0, otherwise \end{cases} \quad (10)$$

$$M = \begin{cases} 1, if\ bus\ i\ has\ PMU \\ 0, otherwise \end{cases} \quad (11)$$

Then formulate a regional matrix R whose rows represent regions. In the beginning, set all the elements of a row to zero (0) except for two buses i.e. generator bus and load bus that could be afforded by the generator. After, calculate the higher order regional matrix using the system connectivity matrix as:

$$R_k = R'_{k-1} \times A, k > 1 \quad (12)$$

Here, R'_{k-1} is the regional matrix, R_{k-1} after corrections. This equation has to be executed iteratively until all the buses are considered. The following instructions are needed to be followed while constructing the higher order regional:

$$R_1 = \begin{bmatrix} 1&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&1&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&1&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&1&0&0\to&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&1 \end{bmatrix} \quad (13)$$

$$R_2^{'} = \begin{bmatrix} 1&1&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 2&1&1&2&1&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&1&0&0&0&0&0&0&0&2&2&1&1&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&2&0&0&0&0&0&0&0&0&0&0&2&2&0&1\to&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&1&0&1&2&0&0&1&0&0&0&0&2&1&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&2&1&2&2 \end{bmatrix} \quad (14)$$

$$R_2 = \begin{bmatrix} 1&1&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&1&0&1&1&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&1&1&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&1&1&0&1\to&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&1&1&0&0&1&0&0&0&0&1&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&1&1&1&1 \end{bmatrix} \quad (15)$$

$$R_4 = \begin{bmatrix} 1&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&1&0&1&1&1&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&1&1&1&1&1&1&1&1&1&0&0&1&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&1&1&1&0&0&0&0&0&0&0&0&0&1&1&0&1\to&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&1&1&1&1&1&1&1&1&1&0&0&1&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&1&1&1&1&1 \end{bmatrix} \quad (16)$$

IV. FINAL PARTITION OF NETWORK

Once the network is sectionalized, all the regions (islands) need to be modified in order to accommodate the restoration constraints. Interestingly, the network obtained after initial partitioning, Fig. 2, exhibits generation-load balance since the initial network partition has come across verifying the constraint in each-iteration. In final partitioning, after verifying the second constraint, the regions r2, r3 (or r5) were joined. Finally, for the islands to be observable, the observability constraint must hold good. If it doesn't do, the unobserved buses should be made observable using the following rules.

1. If Unobservable bus is Load/Generator bus:

If a Load/Generator bus is unobserved, move it to an island which could make it observable without disturbing the generation-load balance.

2. Unobservable bus is ZIB:

If, a ZIB bus is unobserved, move to an island that would make it observed.

Applying the above modifications to IEEE-30 bus system, the regions r3 (or r5) and r6, r2 and r6 were joined via boundary lines as initially after sectionalizing the network the buses 24 and 8 were not observable. Moreover, their target islands are not affordable to supply the respective loads independently. And so, they have been combined. After all

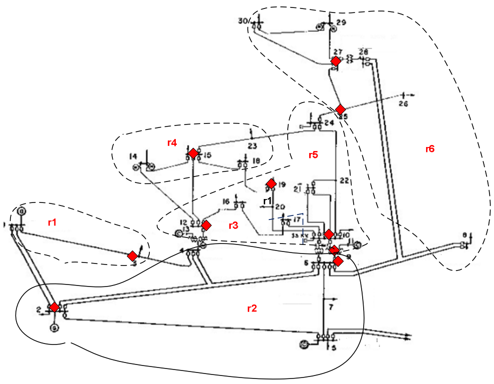

Fig. 2: Initial Partition of the IEEE-30 bus system

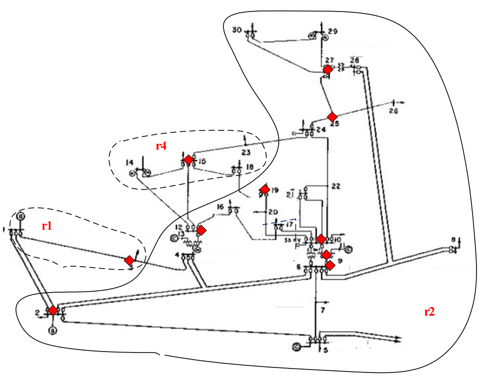

Fig. 3: Final Partition of the IEEE-30 bus system

these modifications, the final sectionalized network is as shown in Fig. 3. Since the generation in the region r3 is accumulated and the load is distributed it covers larger portion of the network.

V. PDC PLACEMENT

The archival of synchronized phasor data will be handled by the Phasor Data Concentrator (PDC) and enable it time-tagged. Now, as all commercial communication channels are deployed to minimize the phasor measurement system costs, the present problem is to design a reliable topology for communication that links all the substations with control centers. Previously, in [8], a PDC placement methodology is suggested considering the future expansion of the system. Then, in [9], authors have designed a communication structure by placing PDCs first, based reducing communication link distance, and then by placing PMUs. Later, [10] proposed an ILP based PDCs placement by minimizing the total WAMS traffic. Recently, an optimization model was proposed on a WAMS integrated with a heterogeneous communication network in [11]. This section, in this paper presents a reliable PDC placement technique for restorable WAMS regions. This initially requires WAMS network that is being partitioned into multiple regions which are restorable. This partition has already been carried out in sections 4 and 5. The reliability based PDC partition in this section is presented as below.

A. Reliability Evaluation

For the WAMS to be more reliable, it should have one back-up path for every primary path to communicate data from PMU. Because, whenever there is any contingency/failure in primary path, the back-up will be switched-in to transfer data from PMU. Considering the assumption that all communication links in a regional network are independent, the availability and unavailability rates [12] of each communication link can be computed as below:

$$A_l = \frac{\mu_l}{\lambda_l + \mu_l} \tag{17}$$

$$U_l = \frac{\lambda_l}{\lambda_l + \mu_l} \tag{18}$$

Where λ_l and μ_l are failure and repair rates of the communication link l in a regional network. As the communication network in region is multi-input and single-output network, to communicate the measured data, there must be at least two disjoint paths from each PMU to its associated PDC. The dijikstra algorithm was used here to find two disjoint paths for each PMU. Under normal operating state, when PMU communicates PDC through primary path, the state of the regional network (R) is given by

$$R = \bigcap_{i=1}^{n} R_i \tag{19}$$

Here R and R_i are the states of the network and i^{th} path under normal conditions. The i^{th} path is the path through which the measured data from ith PMU will be transferred to PDC. As each PMU has two disjoint paths, the state of the i^{th} path (R_i) can be calculated as below.

$$R_i = R_i^p \cap R_i^b \tag{20}$$

$$= \left(\bigcap_{x_{i,p} \in R_i^p} x_{i,p} \right) \cup \left(\bigcap_{x_{i,b} \in R_i^b} x_{i,b} \right) \tag{21}$$

Here R_i^p and R_i^b are the links of primary and backup paths of i^{th} PMU under normal condition. And, $x_{i,p}$ and $x_{i,b}$ gives the availability of respective links in primary and backup paths respectively. The equation--can be rewritten as

$$\overline{R} = \bigcup_{i=1}^{n} \overline{R}_i \tag{22}$$

Now, the unavailability of a regional network is nothing but the probability of the state (R) defined above. So,

$$P(\overline{R}) = \sum_{i=1}^{n} P(\overline{R}_i) - \sum_{i<j=2}^{n} P(\overline{R}_i \cap \overline{R}_j) \tag{23}$$

As the primary and backup paths of i^{th} PMU are disjoint, using (21) and (23), the first order term becomes,

$$P(\overline{R}_i) = 1 - P(R_i) \tag{24}$$

$$\begin{aligned} &= 1 - P(R_i^p \cup R_i^b) \\ &= 1 - \left[P(R_i^p) + P(R_i^b) - P(R_i^p)P(R_i^b) \right] \\ &= 1 - \prod_{x_{i,p} \in R_i^p} P(x_{i,p}) - \prod_{x_{i,b} \in R_i^b} P(x_{i,b}) + \\ &\quad \prod_{x_{i,p} \in R_i^p} P(x_{i,p}) \prod_{x_{i,b} \in R_i^b} P(x_{i,b}) \end{aligned} \tag{25}$$

And, the second order term becomes

$$\begin{aligned} P(\overline{R}_i \cap \overline{R}_j) &= 1 - P(R_i \cup R_j) \\ &= 1 - P(R_i^p \cup R_i^b \cup R_j^p \cup R_j^b) \end{aligned} \tag{26}$$

Using the covering aw of set theory, equation (26) becomes

$$P(\overline{R}_i \cap \overline{R}_j) = 1 - P\begin{pmatrix} R_i^p + \overline{R}_i^p \cdot R_i^b + \overline{R}_i^p \cdot \overline{R}_i^b \cdot R_j^p + \\ \overline{R}_i^p \cdot \overline{R}_i^b \cdot \overline{R}_j^p \cdot R_j^b \end{pmatrix} \tag{27}$$

In the above equation, R_i^b , R_j^b are the disjoint backup paths of the primary paths R_i^p , R_j^p respectively.

B. Reliability based PDC placement

Let P_{ij} is the reliability of the i^{th} regional network assuming a PDC on j^{th} bus. The P_{ij} value can be obtained from section 6.1. Assuming $P_{i,\max}$ as maximum reliability of i^{th} regional network by replacing PDC on all of the buses in the network,

$$P_{i,\max} = \max_{a=1}^{n_i} P_{ij} \tag{28}$$

Where, n_i is the number of buses in i^{th} regional network. Now, the objective function(S) becomes,

$$S = \sum_{i=1}^{m} P_{i,\max} \tag{29}$$

The output vector that maximizes the objective function most will be the PDC placement vector. To apply this method to large systems, it is convenient to divide the network into a number of regional networks and by conserving each regional as a separate network.

VI. RESULTS AND DISCUSSIONS

To find the PDCs locations of in all regions, this algorithm will be applied only after partitioning the network into islands, as shown in Fig. 3. The PDC locations obtained on applying this algorithm are shown in the Table 2 given below. The primary and back-up paths of a finally partitioned IEEE-30 system are presented in the Table 3. Since the amount of generation in region 2 is very large, it supplies larger portion of the network. The proposed methodology has been clearly explained with the help of the flowchart shown in Fig. 4.

Table 2 PMU and PDC locations for IEEE-30 system, after final partitioning

Region	Buses	PMU locations	PDC locations
r1	1, 3	3	3
r4	14, 15, 18, 23	15	15
r2	2, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 16, 17, 19, 20, 21, 22, 24, 25, 26, 27, 28, 29, 30	2, 6, 9, 10, 12, 19, 25, 27	6

Table 3 Primary and backup paths in various regions of IEEE-30 bus system

Region	Primary and backup paths	Relia-bility	PMUs with disjoint paths
r1	$R_{3\to3}$: (3→3), (✓)	1.000	90 %
r2	$R_{15\to15}$: (15→15), (✓)	1.000	
r3	$R_{2\to6}$:(2→4→12→16→17→6), (2→6), (2→5→7→6) $R_{6\to6}$: (6→6), (✓) $R_{9\to6}$: (9→6), (9→10→6) $R_{10\to6}$: (10→6), (10→9→6), (10→17→16→12→4→6), (10→22→24→25→27→28→6) $R_{12\to6}$:(12→4→6), (12→16→17→10→6) $R_{19\to6}$: (19→20→10→6), (×) $R_{25\to6}$:(25→24→22→10→6), (25→27→28→8→6) $R_{27\to6}$:(27→25→24→22→10→6) , (27→28→8→6)	0.982	

VII. CONCLUSION

This paper sectionalizes a practical and complex network into small islands. These islands are very easy to restore during build-up strategy. Since the number regions are more, the restoration gets easier and faster, and the isolation of faulty region becomes easier. And, this WAMS partition approach on a PMU-installed power system also provided a reliable PDC placement which not only provides complete observability but also the highest reliability in all the regions. After applying the first restoration constraint to sectionalize the network initially, the remaining two constraints were used to finalize the network partitioning. Finally, it has designed a reliable communication network between PMUs and their corresponding PDCs.

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