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Optimum Placement of PMUs in the Power Transmission System of Afghanistan

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Abstract

Phasor Measurement Units (PMU) are essential parts of smart grids. There are several algorithms to determine the placement of these units for optimal observability of the system. In this paper two different hybrid methods and Integer Linear Programming method have been used for the placement of PMUs in the power system of Afghanistan. One of the hybrid approaches presented here is based on the combination of the Greedy and Breadth First Search algorithms. The other one is based on the Binary Search and Global Search algorithms. The power system of Afghanistan has been slightly modified to include the renewable energy sources. Results obtained have been compared between each other. The result of these algorithms are more proper than other algorithms like Depth First Search, Genetic Algorithm, Partial Swarm Algorithm and Binary Search algorithms that have been compared by other authors on IEEE test systems.

1. INTRODUCTION

Electric power consumers of the new century have demands such as high quality, continuous, secure, clean and stable power. Smart grid concept is seen as the solution to this problem. Smart grids must be digitalized and should allow the injection of energy from distributed renewable energy sources [1]. SMART transmission grid linked to the application of communication and digital technology in broad area, Observing and control of power transmission network [2]. Broad-area monitoring and control has been attracting worldwide interest. This include collecting data, controlling a wide region of the grid by using PMU [3].

Due to the technological development particularly in the field of sensing technologies, new parameter opened up in the field of PMU. In a result, there are many avenues come to the surface of research in term of PMU. Accurately measurement of power angles and voltage phasor of key buses are very crucial state variables for power network stability, synchronies PMU is a new type of measure unit with high accuracy and precision. Which is able to look after the whole network in real time to observe phasor voltage of the buses which has enabled the system in a broad manner [4]. However, it has become more important to note that distribution of power capacity, linkages and controlling are more crucial now.

The first step of digitalizing the smart grid is the placement of Phasor Measurement Units (PMU) on power grid. Compared to systems digitalized by SCADA systems, PMU equipped systems can perform between 10 and 60 (usually 30) measurements per second or more while SCADA has to spend several

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seconds per measurement. Also, synchronization of several local measurements via GPS in PMU gives a real-time portrait of all system.

There is no requirement to place a PMU in every individual bus. Typically, the number of PMU versus number of busses of the entire system should be around 20-30%. Therefore, an optimization is necessary for observation of the whole grid [5]. These issues led the researchers to conduct extensive researches for optimizing the numbers and locations of PMUs in grid.

In this paper, PMU placement problem of Afghanistan power system is studied. Three different algorithms; Hybrid Approach algorithms (Global Search based, Greedy Search based) and Integer Linear Program (ILP)are applied to this power system and results are compared. In the next section current situation and future expectations regarding Afghanistan power system are introduced. In Section 3, 4 and 5, PMU placement algorithms and their application results are given. In Section 6 results are evaluated.

2. AFGHANISTAN POWER SYSTEM

Most of the power generated in Afghanistan comes from hydro and thermal sources. The total installed capacity of hydro power is 253.71 MW [6], while the existing diesel-fired power plant is 221.2 MW. There is also a small amount of renewable energy utilization. According to the survey of the Ministry of Energy and Water of Afghanistan the total installed capacity of solar panels in 2013 is around 12.8 MW. 1.5 MW capacity is also under construction. The capacity of installed wind turbines is not significant [6].

Since the installed capacity is not enough, there is a need to import power from neighboring countries. Afghanistan imported 2246 GWh in 2011, amounting to 73% of its overall electrical energy demand. This ratio was only 34% in 2006. The imported power comes from different countries via 500, 220, 132 and 110 kV double-conductor systems. Table-1 summarizes the power capacity of Afghanistan over the years.

Table 1. *Electrical Energy in Recent Years in Afghanistan in GWh*

Year	2006	2007	2008	2009	2010	2011
Hydro	644	755	617	835	910	801
Thermal	213	211	197	93	101	39
Import	432	609	752	1155	1572	2246
Total	1289	1575	1566	2083	2583	3086

2.1. Grid Connectivity Rate

Householder connectivity to grid in Afghanistan was 28% in 2011. The situation is better in big cities such as Kabul (44%), Herat (82%) and Balkh (63%) [6].

According to master plan of energy sector; for an efficient accessibility of consumers and injection of distributed or centralized generation, electrical power grid will become ring system in near future. Currently there are another 53 substations under construction along to the existing transmission systems [6]. The planned ringed transmission system is shown in the Figure 1. A ringed transmission system has been assumed in this paper for PMU placement.

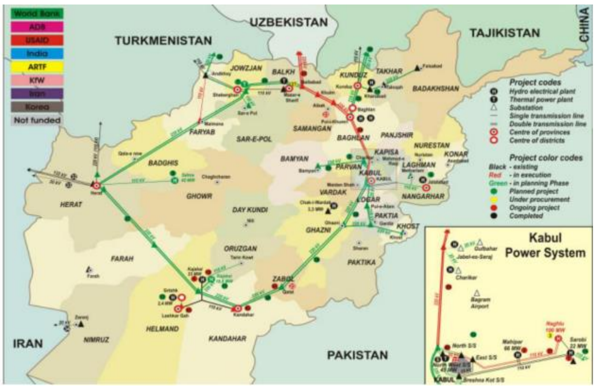

Figure 1. *Future planned power transmission system of Afghanistan [7]*

2.2. Electric Demand

Figure 2 shows the projection of net electricity demand till 2032 for three different scenarios: basic case, low scenario and high scenario [6].

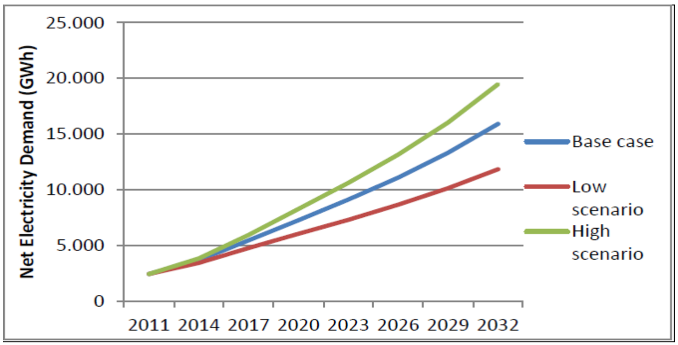

Figure 2. *Electrical energy demand projection up to 2032 [6]*

The net demand is expected to increase to 15,909 GWh in 2032 (in the low demand case). It means that the average annual growth rate is expected to be 9.8% during this period. Average of annual growth from 2012 to 2017 is supposed to be 14.1%, which decreases to 9.2% per annum in the second five-year from 2017 to 2022 and this rate will decrease to an average rate of 6.2% per year in the last five-year period.

2.3. Energy Potential

In this section the hydroelectric and renewable energy potential of Afghanistan is considered. Thermal energy is not evaluated.

2.3.1. Hydro power

A survey of the United Nations in 1972 and the recent survey of DABS show that the total hydrological potential of Afghanistan which can produce electricity is 20000 to 23000 MW, which includes all small, medium and large hydropower plants [6, 10].

2.3.2. Solar and Wind Power

NREL (National Renewable Energy Laboratory in US) research shows that Afghanistan solar energy potential differs from 4.5 kWh/m2 in the northern regions to 7 kWh/m2 in the western and south-western regions, and the average number of sunny days is 300 per year [8, 9].

Theoretical estimation of wind potential shows around 158 GW wind power capacity [6, 11]. This is summarized in Table 2.

Table 2. *Wind Power Estimation in Afghanistan*

Wind Status	Wind class	Wind Power w/m^2	Wind speed m/s^2	Land area km^2	Percent windy land	Installable capacity MW
Good	4	400-500	6.8-7.3	15,193	2.4	75,970
Excellent	5	500-600	7.3-7.7	6,633	1.0	33,160
Excellent	6	600-800	7.7-8.5	6,615	1.0	33,100
Excellent	7	>800	>8.5	3,169	0.5	15,800
Total				31611	4.9	158030

(*) Installable capacity per kilometer square is considered 5 MW. Below 6.5m/s speed is not considered suitable for turbine installation.

2.3.3. Hydroelectric Power

A list of hydroelectric power plants is given in Table 3.

Table 3. *List of hydroelectric power plants [22]*

Station	Town	Capacity	Commissioned
Asadabad	Kunar	0.7	1983
Gerishk	Helmand	2.4	1945
Istalif	Kabul	0.2	2006
Kajaki	Helmand	33	1975
Mahipur	Kabul	66	1967
Naghlu	Kabul	100	1967
Saraobi	Kabul	22	1957

2.3.4. Other Sources

Lists of gas turbines and solar energy resources are given in Table 4 and Table 5. There is no plan for the usage of biomass energy for electricity production in the near future. On the other hand, Afghanistan has a certain potential of geothermal energy along the Hindu Kush Mountain but there is no enough data available about depth, amount, temperature and else [6]. It should be investigated in the future.

Table 4. *List of gas turbines*

Stations	Town	Capacity	Commissioned
Northwest Kabul	Kabul	42	1983

Table 5. *List of solar energy resources*

No	Province	No of villages	Number of home lightening system	Nos. of SPV System of Mosque
1	Kapisa	20	913	20
2	Bulkh	20	671	20
3	Badakhshan	20	1157	20
4	Badghis	20	1068	20
5	Kandahar	20	1043	20
6	Kabul	20	348	Nil
Total			5200	100

For more efficient bulk generation south and south-west regions (Herat, Farah, Nimroz, Helmand and Kandahar) areas are suggested while for small amount generation everywhere in Afghanistan has the potential to install solar panels.

3. OPTIMUM PMU PLACEMENT BY HYBRID APPROACH BASED ON THE GLOBAL SEARCH ALGORITHM

Hybrid Approach based on Global Search Algorithm (HGSA) is a mathematical and numerical algorithm which deals with the optimization of a set of functions as it creates possible combinations, then studies the optimization conditions, afterward chose the best one(s) as optimum result.

Using this algorithm to find the optimal PMU placements, a large number of possible sets will be generated by Global Search Algorithm [13]. This causes consumption of extensive computational time and memory of the computer, especially for large and complex grids. To overcome this problem there are some critical procedures included in this algorithm which make it more reliable follows:

The optimal PMU placement will be achieved if one or more combinations are able to observe the entire power network [14].

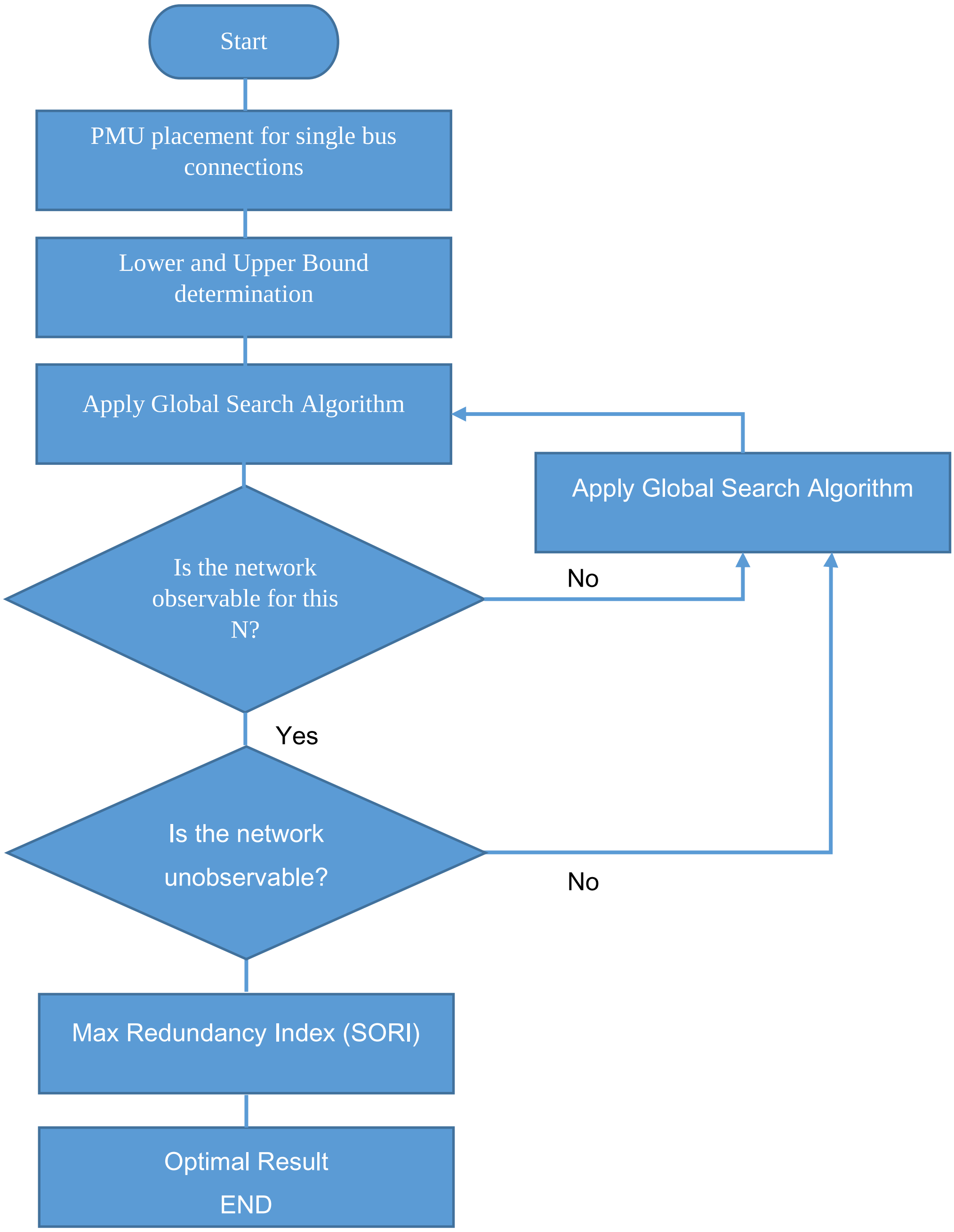

Figure 3. *Flowchart Hybrid Approach Based on the Global Search Algorithm (HGSA)*

3.1. Applying Binary Search Algorithm

Binary Search Algorithm search process starts from the midpoint of the array in an arranged set of elements the middle element will compared by a given value of *k* which intend to be the optimum result. It continues as follows [16]:

$$\left.\begin{array}{r}\text{If } A[m/2] > k, \text{search k in the midle of the lower half}\\ \text{If } A[m/2] < k, \text{search k in the midle of the upper half}\\ \text{If } A\left[\frac{m}{2}\right] = k, \text{the result is } m/2\end{array}\right\}$$

Initially GSA starts searching from the lower bound and tries to generate all possible combinations. If any combination could confirm the network full observability then stops searching at this step, if not, BSA will be applied to find element *k* with consideration of above conditions (3).

After finding the minimum number "*N*" of PMUs a sequential number of "*N-1*" is also needed to be check for the system observability, this will assure that the result is accurate.

3.2. PMU Placement to Cover Single Connection Buses

The algorithm initially determines the single connection buses in the system and installs a PMU in neighbor of them. After that, these single connection buses and their neighbors will be removed from the installation process and the rest are considered as PMU placement candidates.

3.3. Determine the Maximum and Minimum Number of PMUs

By using Domination Set (DS) rules [15]; algorithm will determine the probability of maximum and minimum number of PMUs. This will help to avoid unnecessary combinations to be generated.

Following equations represent the lower bound and upper bound of the PMUs in power system. The result of these equations should be integer.

$$B_{upper} = \frac{n}{3} \quad (1)$$

$$B_{Lower} = \frac{k+2}{3} \quad (2)$$

K shows the number of the bus which has at least 3 connections and *n* is the total number of buses in the system.

3.4. System Observability Redundancy Index (SORI)

For quality of system observability; evaluation of Bus Observability Index (BOI) is required. For every (i) number bus there is an index of (β) which shows that the bus can be observed by how many PMUs at the same time. So the BOI value shows the quality of observability in a system in case of PMU outage and it is equal to the buses links plus one. SORI are calculated with the following equation [17].

$$\text{SORI} = \sum_{i=1}^{n} \beta_i \quad (4)$$

What mentioned above is summarized in a system of6 buses. BIO value for figure 4(a) can be written as 1, 2, 1, 1, 2, 1 Consequently the total SORI can be written as $\gamma = 1 + 2 + 1 + 1 + 2 + 1 = 8$.Since for figure 4.b this value is 1, 1, 1, 1, 1, 1. and its SORI is $\gamma = 1 + 1 + 1 + 1 + 1 + 1 = 6$. Therefore Fig. 4.a is more reliable because of higher redundancy index.

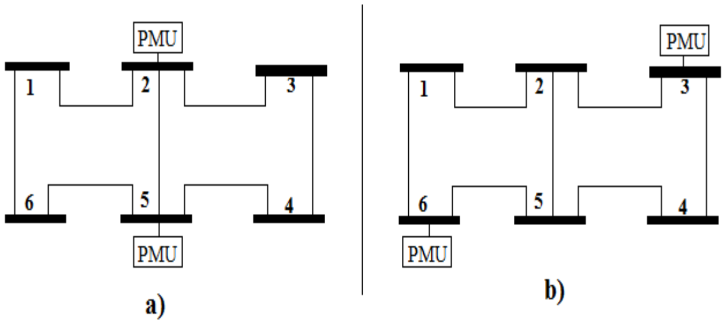

Figure 4. *Maximum SORI evaluations in a system*

4. APPLYING THE ALGORITHM IN AFGHANISTAN TRANSMISSION SYSTEM

According to the map of "Afghanistan the Power Generation and Import 2008 - 2012" this can describe the generation and transmission systems [7]. Totally there are 68 substations of 220 and 110 kV rated transmission system that is supposed to be equipped by PMU system, the optimum PMU placement by HGSA is done under MATLAB framework.

Because of complexity and large size of the system, HGSA cannot work on total system so the network system is divided into three parts and the algorithm is separately applied in each part, and finally the result is unified again.

By considering the condition which summarized in the following equation;

$$A_{k,m} = \begin{cases} 1 \ \ if k \ and \ m \ are \ connected \\ 1 \ if \ k \ is \ equal \ to \ m \\ 0 \ \ otherwise \end{cases} \qquad (5)$$

Above mentioned functions should be converted to binary *(0 & 1)* format which can be applicable on MATLAB framework.

$$A = \begin{bmatrix} 1 & 0 & 1 & \dots & 0 & 0 & 0 \\ 1 & 0 & 1 & \dots & 0 & 0 & 0 \\ & & & . & & & \\ & & & . & & & \\ & & & . & & & \\ 0 & 0 & 0 & \dots & 0 & 1 & 1 \end{bmatrix}$$

Using consequently Eq. 1. and 2. The minimum and maximum number of PMUs in the grid is 3 and 6. The upper and lower bound, as mentioned before, identify the range of PMUs. Here it is introduced as an array of [3 4 5 6]. At the first algorithm starts from the minimum number, it starts from 3. Then it discovers that 3 cannot cover all the network therefore it goes to midpoint of the array according to BSA. So 5 is selected and create all the possible combinations then checks if it is sufficient or not, and the answer is yes. Again for more assurance it goes for 4 PMUs (*N-1*) and check if it can cover the system, the combinations of 4 PMU sets cannot cover all network again goes to 5 PMUs set and place the PMUs in the network as Optimum Placements result.

Table 5. *Optimum PMU placement results*

No.	Bus numbers					SORI
I	3	5	8	10	16	20
II	**3**	**6**	**8**	**10**	**16**	20
III	3	6	8	12	16	20
IV	3	7	8	12	16	20

As seen in Table 5, the algorithm created 4 different combinations which have the same criteria's (number of PMUs and SORI values); therefore, we can select one of them due to real perspective of grid.

Above work procedure has been done on the other two parts of the system and finally the Optimum PMU placement on Afghanistan Transmission grid has been achieved as shown in Figure 5.

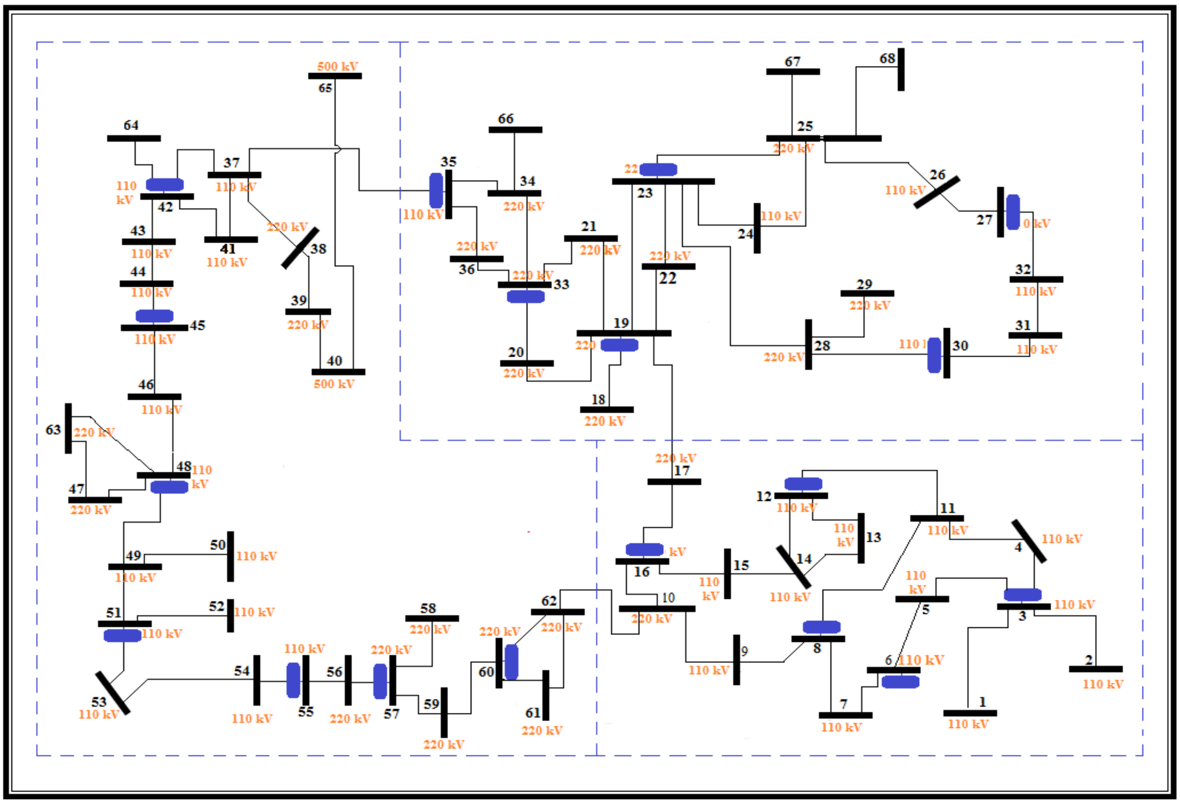

Figure 5. *Optimum of PMU placement in Afghanistan transmission grid*

5. HYBRID APPROACH BASED ON GREEDY ALGORITHM (HGA)

This algorithm works on the combined characteristics of Breath Frist Search (BFS) and Greedy Algorithms to optimize PMU placement in the system. The method organizes the buses in layers and finds the best solution in each stage which leads to all network optimum solutions. One of the main advantages of this method is that it requires less computational time and memory.

Considering the admittance matrix Greedy Algorithm looks for the most linked bus in each layer as triggering.

Existing of more than one high degree buses in each layer give the possibility to greedy algorithm to search multiple combinations and find more reliable one(s).

5.1. Applying BFS Algorithm

The Breadth-First Search Algorithm is a simple graphic searching algorithm [18]. In BFS a network can be illustrate by a graph of G= (V, E) which 'V' shows the buses and "E" is transmission line.

To build the hierarchical tree BFS select one node (bus) as root or start point after that it goes to organize the buses layer by layer, the BFS explores their undiscovered neighbor nodes layer by layer, until all the interconnection information has been ascertained.

5.2. Applying Greedy Algorithm

From a given set of S elements, the Greedy Algorithm will choose the best elements due to its greedy characteristic. At each stage, the element with the greatest value will be chosen and removed from the set of candidate elements. For this application, the greedy choice should be a clear that how many buses can be observed with the placement of a single PMU. After that the next PMU should be placed on the bus with the most unobservable buses.

Totally the general steps of Greedy Algorithm are [20]:
1. Create the "n x n" matrix A of grid Statues from the Eq5.
2. Find the bus with the greatest linked value. If there are multiple buses with the same value, then choose one of them randomly.
3. Update the PMU set and the set of observable buses. This can be achieved by equation $A = F \times X$, introduced in [19].
4.

$$x_i = \begin{cases} 1 & if a\ PMU\ is\ on\ bus\ i \\ 0 & otherwise \end{cases} \quad (6)$$

$$F_i = \begin{cases} 1 & if\ the\ bus\ i\ is\ observable \\ 0 & otherwise \end{cases} \quad (7)$$

5. Update F from the other observability rules.
6. Repeat steps 2-4 up to full network become observable ($F_i = 1$ for all buses i).

6. CASE STUDY: APPLYING THE GREEDY ALGORITHM IN AFGHANISTAN TRANSMISSION SYSTEM

As an example a part of Afghanistan grid is chosen and applied the above steps in the following, then it is applied for total power transmission system of Afghanistan in a unique system without partitions, the result of optimization became 19 buses, as it was tested by Hybrid Approach Based on Global Search Algorithm.

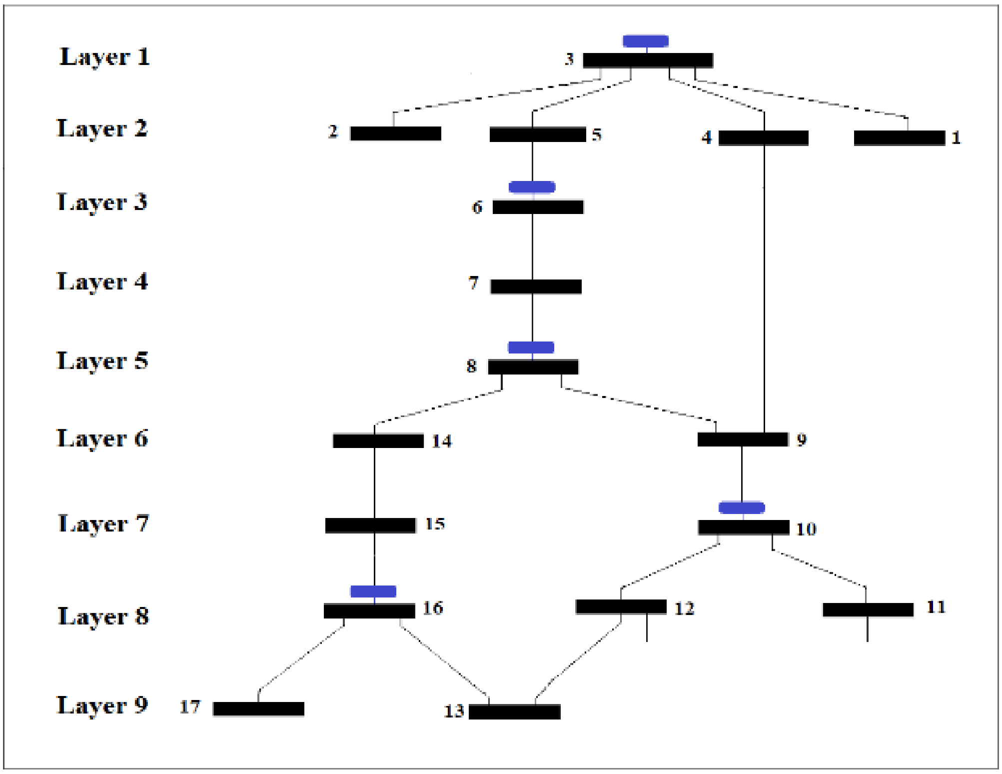

Figure 6. *Applying Greedy based search algorithm to Afghanistan grid*

First of all, a PMU will be placed in neighbor of single connection buses where the bus 3 and bus 16 are the neighbor of a single connection buses.

After that algorithm tries to determine the connection rate of each bus by incidence matrix has been created by Eq. 6. as seen; Bus 3 has the greatest value and it is linked to 4 other buses, The first PMU on

Bus 3 will be installed which make it directly observable, while the neighbor buses 1, 2, 4, and 5 can be pseudo-observable.

In 2nd placement algorithm sees that all the buses are observable in layer 2 and it is not necessary install any PMU at this stage, afterward it goes to another layer and looks for the most linked unobservable bus in this stage, therefore in this layer just one bus (number 6) is exist and PMU will be install to this bus as the 2nd placement, Then comes to another stage and sees if the bases are observable or not as the bus (number 7) in layer 4 is observable by PMU in previous layer the algorithm goes to layer 5 and put a PMU in bus number 8 (3rd placement). Finally, in the 4th PMU placement, the most linked bus is 10 in layer 7, by installing a PMU on this bus the system will be fully observable, the algorithm is stopped here.

Table 6. *Steps of the PMU placement procedure*

No	**Placement steps**	**PMU installed bus**
1	Initial Bus	3 [1 2 4 5], 16 [13 15 17]
2	2nd placement	6 [7 5]
3	3rd placement	8 [7 9 14]
4	4th placement	10 [9 11 12]

*Numbers in bracket shows the buses which can be covered by the same installed PMU.

The above illustrated works of this algorithm is coded in MATLAB and applied to total transmission grid of Afghanistan as one piece and it resulted the same number of PMUs resulted from Hybrid Approximation based on Global Search Algorithm as it is [3, 7, 10, 12, 14, 19, 25, 28, 32, 33, 37, 39, 44, 48, 49, 51, 54, 57 and 60] buses in Fig 5.

7. INTEGER LINEAR PROGRAMMING

Optimal PMU placement problem by integer linear programming method has a formulation of with and without conventional measurements [21], here we will use the without conventional method.

In this case, the flow measurement and the zero injection [12] are ignored. To finds a minimal set of PMUs by using ILP likely above mentioned algorithms, a bus must be observed at least once by one or more than one PMUs. This help us to define a matrix CPMU, by using Eq.5 the matrix can be created.

The optimal placement of PMUs for an N bus system is formulated as follows:

$$\mathrm{Min} \sum_{\mathrm{k=1}}^{\mathrm{N}} x_k \tag{8}$$

$$\mathrm{S.T.} \; = \mathrm{C_{PMU}}\, \mathrm{X} \geq \mathrm{b_{PMU}} \tag{9}$$

$$\mathrm{X} = [\mathrm{x_1}, \mathrm{x_2}, \mathrm{x_3}, \ldots, \mathrm{x_N}]^{\mathrm{T}} \tag{10}$$

$$\mathrm{x}_i \in \{0, 1\} \tag{11}$$

In the above equations x_i is the PMU placement variable, N is total number of system buses, X is a binary variable vector which entries are defined as Eq.7 and CPMU is a vector function corresponding bus voltage is observable using the given measurement set and according to observability rules mentioned above and it can be easily get from admittance matrix.

b is a vector whose entries are all ones as shown in Eq. (5). $\mathrm{b_{PMU}}$ can be written as follow:

$$b_{PMU} = \begin{bmatrix} 1 \\ 1 \\ . \\ . \\ . \\ 1 \end{bmatrix}_{N\times 1} \tag{12}$$

Here these formulations are applied for optimization of PMU placement in Afghanistan grid.

This is noticeable that this algorithm can be apply for more complex grids as for Afghanistan grid it doesn't need for partition of the grid as "Hybrid Approach Based On Greedy Algorithm" which is described above.

$$A = \begin{bmatrix} 1\ 1\ 1\ 0\ .\ .\ .\ 0\ 0\ 0 \\ 0\ 1\ 1\ 0\ .\ .\ .\ 0\ 0\ 0 \\ . \\ . \\ . \\ 0\ 0\ 0\ .\ .\ .\ 0\ 0\ 1 \end{bmatrix} \begin{cases} Bus\ 1 \\ Bus\ 2 \\ . \\ . \\ . \\ Bus\ 63 \end{cases}$$

The final integer linear programming for this example is

$$\text{Min} \sum_{k=1}^{63} x_k$$

$$S.T. \begin{bmatrix} 1\ 1\ 1\ .\ .\ .\ 0\ 0\ 0 \\ 0\ 1\ 1\ .\ .\ .\ 0\ 0\ 0 \\ . \\ . \\ . \\ 0\ 0\ 0\ .\ .\ .\ 0\ 0\ 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ . \\ . \\ . \\ x_{63} \end{bmatrix} \geq \begin{bmatrix} 1 \\ 1 \\ . \\ . \\ . \\ 1 \end{bmatrix}$$

The solution is

X = [0 0 1 0 0 0 1 0 1 0 0 1 0 0 1 0 0 0 1 0 0 0 0 0 1 0 0 1 0 0 0 1 1 0 0 0 1 0 0 1 0 0 0 1 0 0 0 1 0 0 1 0 0 0 1 0 0 1 0 1 0 0 0] or the [3, 7, 9, 12, 15, 19, 25, 28, 32, 33, 37, 40, 44, 48,51, 55, 58, and 60] number buses are dedicated to PMU placement with this algorithm. For this system, the total number of PMU placement is 18, therefore this method is more feasible as it can be applied in practice as well.

8. DISCUSSION

Optimization of PMU placement in different method shows that these three algorithms have different characteristics which are summarized in the Table 7 bellow

Table 7. *Comparison of optimization methods*

Algorithm Name	Number of PMUs	Discussion
HGSA	19	Grid partition
HGA	19	No partition
ILP	18	No Partition

9. CONCLUSION

The results which have been achieved from the hybrid algorithms are 19 PMUs for the total 68 buses (5 of them are located abroad) of 220 kV and 110 kV that cover all the system, for about every 4 buses are allocating one PMU, In Global Search Based the grid should be low-sized, while in Greedy based method can work without splitting. Therefore, the result can be achieved quickly. In ILP Algorithm the result is more optimum thus with 18 PMUs all the system is observable so we can say that the ILP is more reliable and it can be applied in practice, especially in complex grids.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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