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Cost Effective Wide Area Measurement Systems for Smart Power Network

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ABSTRACT Due to the large number of applications of wide area monitoring systems (WAMSs), many power utilities are implementing phasor measurement units (PMUs)-based WAMS replacing the conventional supervisory control and data acquisition system. The biggest challenge in implementing the technology is the cost of WAMS. Many researchers are trying to minimize the cost of WAMS by making the system observable with optimal placement of PMU. Along with the cost of PMU, the cost of communication infrastructure (CI) is dominating the cost of WAMS. Hence, it is necessary to optimize the communication path link and also to find out the optimal location of phasor data concentrator (PDC). In this paper, an optimization model to find the optimal placement of PMU, optimal location of PDC, and their CI is developed. For this, both independent and simultaneous optimization carried out by using differential evolution algorithm. The multi-objective differential evolution is used for simultaneous optimization. The presence of conventional flow measurement device and its effect on overall cost of WAMS with and without considering presence of optical fiber is presented. The method is implemented with different $(N - 1)$ contingency considerations. Also, the results with the presence of pre-existing PMUs and optical fiber paths are provided.

INDEX TERMS Wide area monitoring systems (WAMS), communication infrastructure (CI), phasor measurement units (PMUs), differential evolution (DE).

I. INTRODUCTION

Wide area monitoring systems is a new technology introduced into smart grids to upgrade the conventional grid [1]. WAMS includes the implementation of PMU along with advanced communication network for rapid control in smart transmission grid. The research, development and applications of WAMS in power systems includes various areas such as real time monitoring and control, state estimation, congestion management, post-mortem analysis, power system restoration, oscillation damping, adaptive protection and power system planning [2], [3].WAMS basically performs three types of operations : 1) data collection, 2) data transmission and, 3) data monitoring & control. The first operation is performed by metering devices which includes PMU. The real time synchronized data collected by widely distributed measuring devices need to be send to control center through high speed communication infrastructure. High speed, low latency advanced communication network is required for performing the second operation. The last operation refers to energy management system (EMS) which performs various power system operations [4]. Fast growing adaption of WAMS led researcher to investigate challenges and applications in PMU installation. There are many articles reported to find the minimum number of PMU's so that the system remains observable and also the cost will be minimized. Various techniques are used to find the optimal placement of PMU satisfying the complete network observability under normal as well as different contingency condition [5], [6].

Optimal PMU placement problem is an optimization problem. For solving the optimal placement of PMU, different deterministic methods such as binary integer linear programming and equivalent integer linear programming are used. Likewise, a number of meta-heuristic optimization algorithm genetic algorithm, binary particle swarm optimization, and binary imperialistic competition algorithm (BICA) and differential evolution (DE) are employed to solve the problem [7]–[10]. Presence of existing conventional measurement devices such as flow measurement devices and power injection devices are also considered to determine the observability of the system [8]. Due to the large number of applications of WAMS,many power utilities are implementing PMU based WAMS replacing the conventional SCADA system. The biggest hurdle in the implementation of WAMS is that it requires huge investment. The most dominating part is the cost of PMU. Many methods are proposed for optimal PMU placement in the recent years so as to reduce the cost of WAMS. However, in addition to the cost of PMU, cost of CI is also dominating when optical fiber is used as a transmission media. The optimal design of communication link and PDC location can help further in reducing the cost of WAMS [9], [10]. In [9], multi-objective BICA is used for simultaneous optimization of PMU and their related communication infrastructure so as to minimize cost under normal as well as (N-1) line and PMU contingency. Genetic algorithm is used to solve the above mentioned problem and Shahraeini *et al.* [10] have reported that simultaneous optimization of PMU and CI reduces cost compared to the optimization of PMU and CI separately. Classical optimization cannot give a global optimization solution. Evolutionary multi-objective algorithm such as genetic algorithm, particle swarm optimization, differential evolution (DE) which uses population based approach for its search space are used. It does not give a single solution but a trade-off of multiple solutions called pareto-optimal solution [11], [12]. Convergence and speed of DE depends upon various parameters such as scaling factor, cross-over probability, population size [13]–[16]. In order to minimize the cost of WAMS, there are two main objectives; first one is optimal placement of PMU and second one is optimal communication path.

In this paper, both independent and simultaneous optimization is done for optimal placement of PMU and optical fiber links under normal operating condition. Therefore for solving simultaneous optimization, multi-objective differential evolution is used. The optimal placement of PMU is evaluated using differential evolution. The rest of the paper is organized as follows: In section II, design consideration for different parts of WAMS is explained. In section III, optimization formulation for PMU placement for different cases is formulated. In this paper, in addition to PMU, existence of pre-installed conventional devices is also considered and its effect on overall cost of WAMS with and without considering availability of optical fiber path is calculated. In section IV, optimization model for CI is explained and, simultaneous optimization model for co-optimal placement is elucidated. Finally section V the results are included with conclusion in section VI.

II. DESIGN AND OPTIMIZATION OF DIFFERENT PARTS OF WAMS

A. PMU PLACEMENT DESIGN

PMU provides huge amount of data with very small time difference and all the data is synchronized with the help of global positioning system. PMU is different from conventional SCADA system in the sense that sampling rate of PMU is very high about 30 to 50 samples/second compared to 1 sample for 2-3 second of SCADA.The PMU placement design is an optimization problem for finding the minimum number and optimal location of PMU so that network is topologically observable. Once PMU is installed at the bus it makes that bus observable by measuring the voltage phasor of that bus and also all the adjacent buses connected to the PMU bus are made observable by measuring the current phasor. In general the optimization problem of PMU placement can be described as:

Minimize: Number of PMUs

Subject to: Network is completely observable

This will give the least number of PMUs need to be installed along with their position.

B. DESIGN OF COMMUNICATION INFRASTRUCTURE

The practical feasibility of WAMS depends upon the characteristics of communication system. Optical fiber communication is recently used as transmission media in power system. Medium to high bandwidth, low communication delay, light in weight, high security, high data rates are the important features of optical fiber and satisfies the requirement of communication media in WAMS. Communication infrastructure consists of two parts; 1) Active devices and, 2) Passive device [10]. Active devices consist of switches and routes installed at each bus. Communication links are connected to each other with the help of active devices and passive devices consist of optical fiber. The total cost of CI is cost of switches, routers and optical fiber length. It is given by,

$$COST_{CI} = COST_{Active} + COST_{Passive} \tag{1}$$

As cost of CI depends upon the length of optical fiber, the cost of CI can be reduced by reducing the cost of optical fiber. Hence it is required to find out the minimum length path for optical fiber.

C. DIJKSTRA's SINGLE SOURCE SHORTEST PATH ALGORITHM

Optimal structure of CI means, we have to find the optimal location of PDC so that all the PMUs are connected to PDC via shortest path. For solving this shortest path algorithm is used which finds the shortest path from one vertex to other. There are three types of algorithm basically used for shortest path calculation namely, Bellman–Ford algorithm, Dijkstra's algorithm, Floyd–Warshall algorithm. The computational burden for Dijkstra algorithm is less and also it is more efficient [17]. It is called as greedy algorithm because it chooses closest node at every step. Hence Dijkstra's algorithm is used for calculating the shortest optical fiber length in WAMS.We have to find the path from source s to all other nodes a,b,c,d. The weight of the path is mentioned above the edges. Initially it is assumed that the weight of all the nodes is infinity. The method start with source s, its adjacent

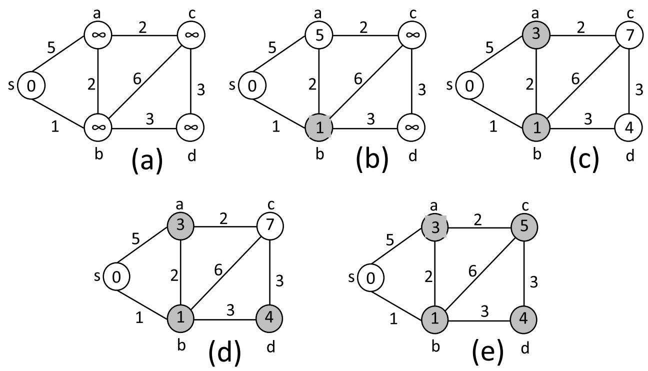

FIGURE 1. **Dijkstra algorithm implimenatation procedure.**

nodes are ***a*** and ***b*** with weigh of 5 and 1 respectively. Hence closest node to ***s*** is node ***b***. The next closest node is ***b*** with weight 3 following path ***s-a-b***. Now length of ***c*** following ***s-a-c, s-b-c,*** and ***s-b-a-c*** are respectively 7, 7, and 5. Similarly of ***d*** following ***s-b-d*** are respectively 4. Hence closest node is ***d***. In the similar manner, the process is carried out. Thus it is iterative procedure and find out the shortest path from source to all nodes considering all paths. The complete procedure is depicted in Fig.1 (a)-to-(e).

While calculating the optimal path for communication infrastructure, we run the Dijkstra's algorithm for N number of times where ***n*** is the size of the system. Here we assumed that PDC is installed at a particular bus and then Dijkstra's algorithm for calculating the shortest path from node under consideration to all PMU nodes (PMU location is found out from optimal placement of PMU algorithm). The process is repeated for all nodes. The node giving shortest path from all PMU buses will be considered as optimal location of PDC and the path for optical fiber can be find out. Also the number of switches required can also be determined from the algorithm.

D. OPTIMIZATION ALGORITHM FOR DIFFERENTIAL EVOLUTION

DE is proven to be more efficient compared to other evolutionary algorithms as discussed in introduction section . The biggest advantage of DE is that it maintains its initial best population. The steps involved in the DE are as follows:

Initialization**:** *Depending upon the dimension of problem, the population size is decided and it remains constant through the process. In this step, based on the lower and upper bound of the variables, random values of variables are generated and the size of initial population vector is equal to* ***Nv***×***Np***. Where, ***Nv*** *is the number of variables and* ***Np*** *is the size of population. The initial population is generated such that*

$$x_i^L \leq x_{i,j,1} \geq x_i^U \tag{2}$$

The initial vector is given by,

$$x_{i,G} = \left[X_{1,i,G}, X_{2,i,G} \cdots X_{N_p,i,G}\right] \; for \; i = 1, 2, \ldots, N \tag{3}$$

Initial vector so generated is called parent vector. To move towards the global solution, the vector passes through number of process such as mutation, recombination and selection.

Mutation: *The initial vector so generated is called parent vector. Now to expand the search space of algorithm, new vector called mutant vector is formed through mutation and is given as*

$$v_{i,G+1} = X_{r1,G} + F \times \left(X_{r2,G} - X_{r3,G}\right) \tag{4}$$

where,

F- is a scaling factor whose value varies between [0, 1]

r1, r2, r3 – random number generated.

This is a general called as DE/rand/1/bin mutation strategy. There are many mutation strategies such as DE/best/1/bin, DE/rand/2/bin, DE/best/2/bin, etc. the choice of it varies according to the problem. $v_{i,G+1}$ *is called as donor vector.*

Recombination: In this parent vector and donor vector combines with crossover probability CR which takes value between [0, 1]. Some random number is generated between 0 to 1.

$$u_{i,j,G+1} = v_{i,j,G} \quad if \; j \leq CR \tag{5}$$

$$u_{i,j,G+1} = x_{i,j,G} \quad if \; j \succ CR \tag{6}$$

u *is called as trial vector.*

Selection: *In this trial vector is compared with the parent vector to select best member for next generation. The fitness function value is calculated for both vector and one with the minimum value is selected.*

$$x_{i,G+1} = u_{i,G+1} \; if \; f\left(u_{i,G+1}\right) \prec f\left(x_{i,G}\right) \tag{7}$$

$$x_{i,G+1} = x_{i,G} \; Otherwise \tag{8}$$

The process from step 2 repeated till the convergence criteria is reached. It can be either maximum number of generations of function evaluation. In a single objective algorithm, the function with the best fitness value is selected. However in multi-objective optimization, we can get multiple best solutions. To form the Pareto optimal solution, dominance filter is used. If any population has either of the fitness function better than the other populations, then it will enter into Pareto-optimal solution set. The constraints are satisfied with penalty based approach. For a population not satisfying the constraints, huge penalty is imposed hence, it will never be selected.

III. OPTIMIZATION FORMULATION FOR PMU PLACEMENT

The problem is formulated for base case, single line contingency, single PMU loss. Zero injection bus effect is also added.

A. PMU FORMULATION AT BASE CASE

The objective and observability function at base case condition is given by following equation,

$$Min \; C_{PMU} \sum_{i-1 \in N} P_i \tag{9}$$

Subject to observability function $O_i \geq 1$

where,

Pi - Binary variable which is equal to 1 if PMU is placed at i^{th} bus otherwise 0.

N- Total number of buses in the network.

$\boldsymbol{O_i}$- Observability function of i^{th} bus.

$$O_i = \sum_{j \in N} a_{ij} P_j \; for \; i \in N \tag{10}$$

where,

$\boldsymbol{a_{ij}}$ – Binary connectivity parameter between bus i and bus j and is defined as,

$$a_{ij} = \begin{cases} 1, & if \; i = j \\ 1, & if \; bus \; i \; and \; j \; are \; connected \\ 0, & Otherwise \end{cases} \tag{11}$$

The observability of ***a*** bus depends on the installation of PMU at that bus or one of its incident buses. When all buses are observable, the value of observability function is equal to or greater than 1. In order to minimize the number of PMUs, effect of zero injection bus is incorporated in the model.

B. EFFECT OF ZERO-INJECTION BUSES

Zero-injection bus means no load or generator is connected to it. If zero injection bus and all the buses connected to it are observable except one, the unobservable bus can be made observable by applying KCL.After considering the effect of zero injection bus, observability function for $i \in N$ becomes;

$$\left.\begin{aligned} O_i &= \sum_{j \in N} a_{ij} P_j + \sum_{j \in N} a_{ij} e_j w_{ij} \\ \sum_{j \in N} a_{ij} w_{ij} &= e_j \end{aligned}\right\} \tag{12}$$

where,

$\boldsymbol{W_{ij}}$ - auxiliary binary variable of buses ***i*** and ***j***, which models the effect of zero injection buses.

$\boldsymbol{e_j}$ – zero injection parameter is equal to 1, if $\boldsymbol{j^{th}}$ bus is zero injection otherwise 0.

C. EFFECT OF LINE CONTINGENCY

Different types of contingencies may occur in power system. One of them is line contingency. The optimal PMU placement problem (OPPP) should be able to maintain the observability of the system even if single line outage occurs. The effect of a single line outage is added to the proposed model using the following set of constraints;

$$\begin{aligned} O_i &\geq 1 \\ O_i^k &= \sum_{j \in N} a_{ij}^k P_j + \sum_{j \in N} a_{ij}^k e_j w_{ij}^k \\ i, j &\in N, k \in K \end{aligned} \tag{13}$$

$$\sum_{j \in N} a_{ij} w_{ij} = e_j \tag{14}$$

where, ***K*** is set of line contingency

$$a_{ij}^k = \begin{cases} 1, & if \; k \; line \; is \; between \; bus \; i \; and \; j \\ a_{ij}, & Otherwise \end{cases} \tag{15}$$

D. EFFECT OF PMU LOSS

Another type of contingency is a measurement contingency which includes loss of PMU. In a network, if it is desired that even during single PMU outage the network would remain observable, each bus should be observed by means of at least two PMUs. If we are considering the effect of zero injection bus, corresponding constraint should be consider while forming the model. Thus, related constraint is as eqs. (13)-(15) where,

O_i^k is the observability of bus '***i***' when PMU at bus ***k*** is outages. ***K*** is a set of PMU outage.

$$a_{ij}^k = \begin{cases} 1, & if \; k = j \; i.e. \; PMU \; loss \; at \; bus \; j \\ 0, & Otherwise \end{cases} \tag{16}$$

w_{ij}^k represents that bus '***i***' is made observable through zero injection effect on bus ***j*** when $\boldsymbol{PMU^k}$ is out. The combined effect of either line contingency or PMU contingency can be considered by combining all the equation defined above.

E. OBSERVABILITY WITH RESPECT TO CONVENTIONAL DEVICES

Conventional devices include flow measurement devices and power injection measurement devices. Here the observability with respect to only flow measurement devices is added. If flow measurement device is installed for measurement of power flowing through branch (***i-j***) at ***i*** side, then active and reactive power flow is given by,

$$P_{1,j} - jQ_{i,j} = V_i I_{i,j} = V_i \left(V_i - V_j \right) y_{i,j} \tag{17}$$

Thus, if the voltage phasor of the either side at which device is installed is known we can calculate the voltage phasor of the other side. Hence installation of flow measurement device makes that bus observable. The observability function with respect to flow measurement device at base case is given by,

$$O_i = \sum_{j \in N} a_{ij} P_j + \sum_{j \in N} a_{ij} f_j r_{ij} \tag{18}$$

where,

$\boldsymbol{f_j}$- binary parameter is equal to 1 if flow measurement device is installed at $\boldsymbol{j^{th}}$ bus, otherwise 0.

$\boldsymbol{r_{ij}}$- auxiliary binary variable of buses ***i*** and ***j***, which decides which bus is to be made observable by flow measurement device. Other parameters will remain as defined as above.

Likewise line and PMU, we can consider flow measurement device contingency. The observability function considering flow measurement device is given by,

$$O_i = \sum_{j \in N} a_{ij} P_j + \sum_{j \in N} a_{ij} f_j^{FM_t} r_{ij}^{FM_t} \tag{19}$$

where, $f_j^{FM_t}$, $r_{ij}^{FM_t}$ - parameters refers to contingency of flow measurement device.

IV. SIMULTANEOUS OPTIMIZATION

A. OPTIMIZATION FORMULATION OF CI

The objective of this is to minimize the cost of optical fiber length which connects all PMU buses to PDC bus. The problem formulation is given as,

$$Min: \ C_{fb} \sum_{i-1\in m} OPGW\_length_i + C_{sw} \sum_{i\in N} SW_i \quad (20)$$

Subject to: (OPGW links, PMU) is connected graph

$$OPGW_{ij} = 1 \ldots i \in N, \ j \in N$$

If bus i is connected to bus j via OPGW link.

where,

C_{fb} – cost of optical fiber per Km

$OPGW\_length_i$ - length of optical fiber from PDC determined bus to all PMU buses

m- number of OPGW link path

The connectivity matrix for OPGW is same as connectivity matrix of transmission line. For calculating the OPGW link path, transmission line length needs to be known. The Dijkstra's algorithm is used for solving this problem as mentioned in section. The computational burden of multi-objective increases with respect to single objective hence population size needs to be increased. The steps carried out in the optimization algorithm are explained in the section. Again the objective function is considered for all the cases; base case, zero-injection effect, line contingency, PMU contingency and flow measurement device contingency. The two objective functions which are to be minimized are 1) total cost of PMUs and, 2) total length of communication links. From the second objective function, we also get to know the number of switches. In simultaneous optimization at the end, we get the Pareto-optimal solution. As the cost of optical fiber and switches varies, the power utility can calculate its cost of total CI by calculating the total cost of investment on optical fiber length and number of switches as per calculated in Pareto-solution. Hence the final total cost can be calculated. The solution with minimum cost can be implemented. Figure 2 presents algorithm for simultaneous optimization by differential evolution.

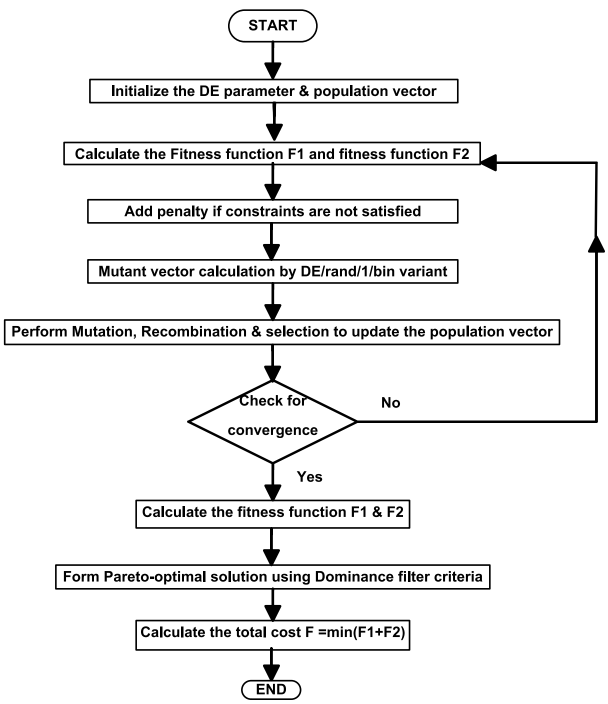

FIGURE 2. Algorithm for simultaneous optimization by Differential Evolution.

B. SIMULTANEOUS OPTIMIZATION OF PMU AND CI

The objective function for the simultaneous optimization is combination of OPP model and optimal CI design. It is given by,

$$Min: \ C_{PMU} \sum_{i-1\in N} P_i + \sum_{i-1\in m} OPGW\_length_i \quad (21)$$

Subject to: $O_i \geq 1 \ldots i \in N$
(OPGW links, PMU) is connected graph.

V. RESULTS AND DISCUSSION

The Simulation is carried out by two approaches. In the first method, two objective functions are optimized separately with single objective DE. In the next method, two objective functions are simultaneously optimized with multi-objective DE. For both the optimization, all the cases (base case, zero-injection effect, line contingency, PMU contingency and flow measurement device contingency) have been considered. The algorithm is tested for IEEE 30 bus system. The data for the simulation is taken as mentioned in [18] and [19]. The population size of problem varies with the dimension and complexity of problem. Generally it should be 5D to 10D, where D is dimensional size. The parameters taken for solving DE is mentioned in the Table I. Initial population can be specified based on some specific conditions such as degree one buses which are not zero-injection buses as well as higher degree buses will have maximum probability for placement of PMU. Hence we can specify the initial population with [$x_i = 1$], where i=degree one buses or higher degree bus. This helps in reducing the computational time of the problem. In the cost estimation, cost of each PMU is considered as ($40,000), cost of optical fiber per Km is considered as ($4000) and Cost of each switch is considered as ($4000) as in [11]. Also presence of zero injection has considered in all the cases.

TABLE 1. Parameter specification for DE.

Sl.no	Specifications	Value
1	Number of variable (N_v)	Size of the test system
2	Population Size	6* N_v
3	Scaling factor	0.6
4	Crossover Probability	0.4
5	Maximum number of generations	200

A. BASE CASE OPTIMIZATION

Here optimization is performed for a base case without considering observability with respect to conventional device. The results by both independent optimization (IO) and simultaneous optimization (SO) are depicted in the Table II. From the results it can be observed that, SO approach has considerable impact on the OPGW length as compared to IO approach. Even though in SO the number of PMU increases, the OPGW length is comparatively low. Also, the number of switches required also decreases. Hence there is reduction in the cost of CI and hence the overall cost of WAMS decreases. Here the final cost is calculated by assuming cost of switches and OPGW as mentioned above. The cost may vary with respect to variation in cost of CI. As compared to IO, the saving in the OPGW length is 312.64 Km, with respect to first solution in Pareto in SO and it is 325.48 Km with respect to second solution. Similarly the overall cost saving is $12, 74,560 with respect to first solution and it is $12,81,920 with respect to second solution. The Fig.3 shows

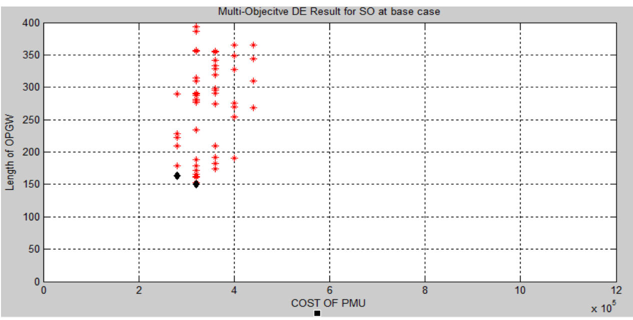

FIGURE 3. **Multiobjective DE result for SO at base case.**

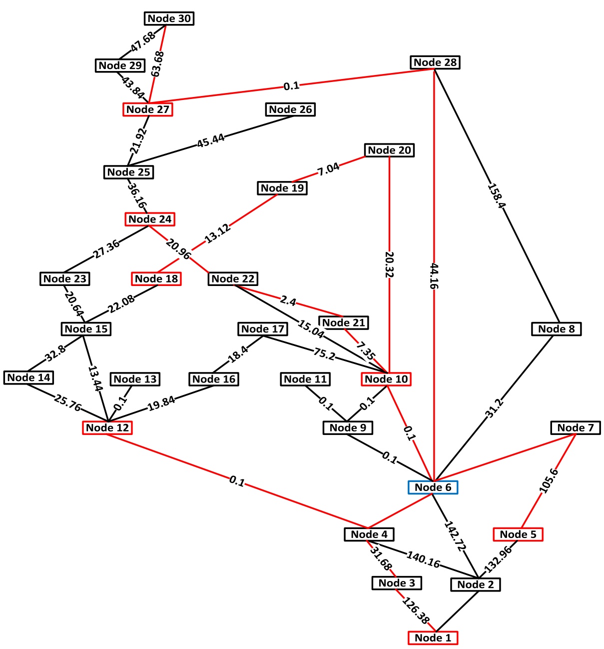

FIGURE 4. **Dijkstra algorithm result for shortest path calculation.**

the final result for multi-objective DE with black astericks indicating position of Pareto solution and red astericks indicating other population position. The Fig.4 shows how the Dijkstra algorithm determines the PDC location and optimal communication path. The blue box is indicating the PDC location, where as the red box and red path is indicating the PMU location and OPGW path.

B. OPTIMIZATION CONSIDERING LINE OR PMU CONTINGENCY

In this case, optimization is performed considering (N-1) line/PMU contingency. The overall process remains same as in base case and the observability function will be as per explained in previous section. In this case, only single solution is obtained in Pareto. Due to all types of contingency, the number of PMUs required to maintain the observability of the system increases compared to base case. Hence overall cost also increases [Table III].

C. BASE CASE IN THE PRESENCE OF FM

In this case, the observability of the system takes into consideration the effect of conventional devices (flow measurement (FM)) as shown in equation (11). It is assumed that conventional devices are present at bus no [1, 3, 21, 26,30] (Table IV). In this case, no Line/PMU/FM contingency is considered. In this case, optimal PDC location and optimal communication path is calculated with respect to conventional devices. The effect of varying the position of conventional devices is also depicted in Table V. Thus with the variation in the position of FM, the number of PMU almost remains same, but communication length varies slightly. This can vary with the practical system condition. Also if we compare this case with base case without FM, it is observed that there is huge increment in cost due to increase in the optical path length as pre-existing PDC location and pre-existing optical fiber from FM is not considered. The presence of FM affect the cost adversely and there is no meaning to presence of FM along with PMU compared to only presence of PMU. If we consider that the flow measurement devices are already placed and connected to control center with optical fiber, then we can consider the availability of that path while calculating the OPGW length. The results are as shown below. Here the optimal location of PDC and Communication path with respect to only conventional devices is calculated first. It is then assumed communication path is also available for PMU. Then the algorithm is run to optimize the problem.

From the Table VI it is observed that, the length of OPGW in this case is very less compared to both the cases discussed above. If we compared with base case, the number of PMU decreases by one only but the length of OPGW has significant decrement. The first solution in Pareto in base case gives 163.28 Km OPGW lengths. Thus saving in OPGW in this case is 112.46 Km and 129.42 Km with the first and second solution in Pareto, respectively. Hence the overall saving in cost of WAMS is $5,09,840 and $5,41,680 respectively. Similarly, with respect to second solution in Pareto in base case,

TABLE 2. PMU and CI placement at base case.

Test system		Optimal PMU Placement			Optimal Communication Infrastructure				
		No. of PMU	PMU Location	Cost of PMU's (in $)	PDC Location	OPGW Length(Km)	No of SW	Cost (in $)	Total Cost (in $)
30 bus	IO	7	1,5,10,12,18,24,27	7*40000=2,80,000	6	475.92	16	19,67,680	22,47,680
	SO	7	3,6,10,12,1823,27	7*40000=2,80,000	12	163.28	10	6,93,120	9,73,120
		8	3,6,10,12,15,20,22,27	8*40000=3,20,000	27	150.44	11	6,45,760	9,65,760

TABLE 3. PMU and CI placement at Line or PMU.

Test system		Optimal PMU Placement			Optimal Communication Infrastructure				
		No. of PMU	PMU Location	Cost of PMU's (in $)	PDC Location	OPGW Length(Km)	No of SW	Cost (in $)	Total Cost (in $)
30 bus	IO	17	1,3,6,7,10,11,12,13,15,16,18,19,22,23,26,27,29	17*40000=6,80,000	19	505.98	23	21, 15,920	27, 95,920
	SO	17	1,3,6,7,10,11,12,13,15,16,19,20,24,26,27,29	17*40000=6,80,000	6	501.98	22	20, 95,920	27, 75,920

TABLE 4. PMU and CI placement at Line or PMU in the presence of FM (Presence of FM at bus no. [1, 3, 21, 26, 30]).

Test system		Optimal PMU Placement			Optimal Communication Infrastructure				
		No. of PMU	PMU Location	Cost of PMU's (in $)	PDC Location	OPGW Length (Km)	No of SW	Cost (in $)	Total Cost (in $)
30 bus	IO	6	6,10,12,19,24,27	6*40000=2,40,000	6	422.32	16	17,53,280	19,93,280
	SO	6	6,10,12,19,24,27	6*400000=2,40,000	6	422.32	16	17,53,280	19,93,280
		7	6,10,12,15,20,25,27	7*400002,80,000	27	405.16	14	16,76,640	19,56,640

TABLE 5. PMU and CI placement at Line or PMU in the presence of FM at different location (In the presence of FM at [1,2,21,22,29]).

Test system		Optimal PMU Placement			Optimal Communication Infrastructure				
		No. of PMU	PMU Location	Cost of PMU's (in $)	PDC Location	OPGW Length (Km)	No of SW	Cost (in $)	Total Cost (in $)
30 bus	SO	7	3,6,10,12,1823,27	2,80,000	1	389.84	15	15,59,360	16,19,360
		8	1,6,10,12,1520,22,27	3,20,000	1	367.440	14	14,69,760	15,25,760

TABLE 6. PMU and CI placement at base case in the presence of FM considering OPGW availability

Test system		Optimal PMU Placement			Optimal Communication Infrastructure				
		No. of PMU	PMU Location	Cost of PMU's (in $)	PDC Location	OPGW Length (Km)	No of SW	Cost (in $)	Total Cost (in $)
30 bus	SO	6	6,10,12,19,24,27	2,40,000	27	50.82	5	223280	4,63,280
		7	6,10,12,15,20,25,27	2,80,000	25	33.86	4	1,51,440	4,31,440

TABLE 7. PMU and CI placement at line or PMU or FM contingency in the presence of FM.

Test system		Optimal PMU Placement			Optimal Communication Infrastructure				
		No. of PMU	PMU Location	Cost of PMU's (in $)	PDC Location	OPGW Length (Km)	No of SW	Cost (in $)	Total Cost (in $)
30 bus	IO	16	3,5,6,10,11,12,13,15,17,19,20,22,23,26,27,29	16*40,000=6,40,000	19	693.66	26	28,78,640	35,18,640
	SO	17	3,5,6,10,11,12,13,15,16,19,20,22,23,26,27,29	17*40,000=6,80,000	6	627.42	23	26,01,680	32,81,680
		18	1,3,6,7,10,11,12,13,15,16,18,19,21,23,25,26,27,29	18*40000=7,20,000	6	521.82	22	21,75,280	28,95,280

TABLE 8. PMU and CI placement at Line or PMU or FM contingency in the presence of FM with pre-existing optical fiber.

Test system		Optimal PMU Placement			Optimal Communication Infrastructure				
		No. of PMU	PMU Location	Cost of PMU's (in $)	PDC Location	OPGW Length(Km)	No of SW	Cost (in $)	Total Cost (in $)
30 bus	SO	16	3,5,6,10,11,12,13,15,16,19,20,22,24,26,27,30	16*4000=640000	25	255.94	10	10,63,760	17,03,760
		17	3,4,6,7,10,11,12,13,15,16,19,20,22,24,26,27,30	17*4000=680000	25	150.35	10	6,41,400	13,21,400
		18	3,4,6,7,10,11,12,13,15,16,19,20,21,23,25,26,27,30	18*4000=720000	25	147.62	9	6,26,480	13,46,480

the saving is 99.62 Km and 116. 58 Km. the overall saving in cost of WAMS is $5,02,480 and $5,34, 320 respectively. Thus the presence of FM is advantageous only with the availability of optical fiber. It has a considerable an impact on cost of WAMS. The results may vary slightly with the position and number of FM depending on practical condition of system.

TABLE 9. PMU and CI placement in the presence pre-installed PMU at bus no. [2 12].

Test system		Optimal PMU Placement			Optimal Communication Infrastructure				
		No. of PMU	PMU Location	Cost of PMU's (in $)	PDC Location	OPGW Length(Km)	No of SW	Cost (in $)	Total Cost (in $)
30 bus	SO	8	2,4,6,10,12,18,23,27	320000	4	271.56	10	11,26,240	14,46,240
		9	2,4,6,10,12,15,20,22,27	360000	4	259.12	11	10,80,480	14,40,480
Contingency		17	2,4,6,7,10,11,12,13,15,16,18,19,22,24,26,27,30	680000	1	603.58	24	25,10,320	31,90,320

TABLE 10. PMU and CI placement in the presence pre-installed PMU at bus no. [2 15].

Test system		Optimal PMU Placement			Optimal Communication Infrastructure				
		No. of PMU	PMU Location	Cost of PMU's (in $)	PDC Location	OPGW Length(Km)	No of SW	Cost (in $)	Total Cost (in $)
30 bus	SO	9	2,4,6,10,12,15,18,22,27	9*40000=3,60,000	4	260.88	11	10,87,520	14,47,520
		10	2,4,6,10,11,12,15,20,22,27	10*40000=4,00,000	4	259.32	13	10,89,280	14,89,280
Contingency	SO	18	2,3,6,7,10,11,12,13,15,16,18,19,21,23,25,26,27 ,30	18*40000=7,20,000	1	573.82	22	23,83,280	31,03,280

TABLE 11. PMU and CI placement in the presence pre-installed optical fiber.

Test system		Optimal PMU Placement			Optimal Communication Infrastructure				
		No. of PMU	PMU Location	Cost Of PMU's (in $)	PDC Location	OPGW Length(Km)	No of SW	Cost (in $)	Total Cost (in $)
30 bus	SO	7	3,6,10,12,1924,27	280000	3	88.54	6	3,78,160	6,58,160

TABLE 12. Comparison with other method.

Method		No of PMU	PMU location	PDC location	OPGW length (Km)	No of switches	Total cost ($)
Base case	GA	10	3,6,7,10,12,19,24,26,27	7	298.58	15	16,54,320
	BICA	7	3,7,10,12,15,20,27	3	205.88	10	11,43,520
	Proposed DE	7	3,6,10,12,18,23,27	12	163.28	10	9,73,120
		8	3,6,10,12,15,20,22,27	27	150.44	11	9,65,760
Line / PMU Contingency	BICA	16	1,2,3,5,8,10,11,1215,16,19,20,23,26,27	1	621.34	22	32,13,360
	Proposed DE	17	1,3,6,7,10,11,12,13,15,16,18,19,2223,26,27,29	6	501.98	22	27,75,920

D. LINE, PMU, FM CONTINGENCY WITH FM AT [1, 3, 21, 26, 30]

In this case all three contingency; line, PMU and FM are considered.Optimal PDC location and optimal communication path is calculated with respect to conventional devices also. Pre-existing PDC location and optical fiber from FM is not considered. If we consider it, the required communication length has decreased and corresponding cost also decrease. The results for the same are depicted in Table VIII. Likewise base case, the similar impact observed in the contingency case also. The length of OPGW decreases drastically. The saving in OPGW in this case is 371.48 Km, 477.07 Km and 479.8 Km with the first, second and third solution in Pareto, respectively compared to first solution in Table VII (FM without optical fiber availability). Hence the overall saving in cost of WAMS is $18,14,880, $21,97,240 and $21,72,160 respectively. Similarly, with respect to second solution in Pareto Table VII, the saving is 265.88 Km, 371.47 Km and 374.2 Km. The overall saving in cost of WAMS is $11,91,520, $15,73,880 and $15,48,800 respectively.

E. PRACTICAL CONDITIONS CONSIDERATION

Further as cost of PMU is very high and it is new technology, all the PMUs may not deploy at a time. Hence it may possible that there is availability of pre-installed PMUs which cannot be replaced. Hence optimization should be carried out considering the presence of pre-installed PMUs. The pre-installed PMUs may not be already at an optimal location. Hence result will vary with the position of PMU. Here two cases are considered for pre-installed PMU. Here both the location is not optimal with respect to base case. In Table IX, one location is optimal with respect to base case condition. In Table X, both the location is not optimal with respect to base case. Thus it is observed that the presence of pre-installed PMU affects the Cost of PMU, communication length and overall cost of WAMS. If it will be already at optimal location it will not affect but if it is not so, it will affect the cost. Likewise PMU, there may be pre-installed optical fiber path. If optical fiber is already available in some path then the optimization result varies. In Table XI, it is assumed that, optical fiber is available in the path (10-17-16-12) and (21-22-24-25) as taken in [9].

F. COMPARISON WITH THE OTHER METHOD

From the Table XII it is observed that in the base case as well as contingency criteria, DE is found to be more efficient than Genetic algorithm used in [10] and BICA used in [9]. In base case, the overall saving with respect to first solution is \$6,81,200 by GA and \$1,70,400 by BICA and with respect to second BICA.

VI. CONCLUSIONS

Huge investment cost is the biggest hurdle in implementing the WAMS technology. Along with the cost of PMU, cost of CI is also dominating the cost. Simultaneous optimization has given better result compared to independent approach. Effect of already present conventional measurement device is added on to the observability of the system and its effect on optimization result is also shown. If we consider availability of optical fiber with FM devices, then it requires low investment on CI. Effect of all possible (N-1) contingency is also modeled for increasing robustness of the system. The number of PMUs required and hence the length of optical fiber increases for contingency compared to base case and hence overall cost of WAMS. Some more practical consideration such as preinstalled PMU and optical fiber is also tested and the result varies depending upon its location. In this multi-objective DE is used for performing the optimization and results are compared with the other method. Results showed that the method implemented has given better result and significant reduction in the cost. Further study can be continued considering communication channel redundancy and contingency. Also the cost of energy management system can also be optimized to further reduce the cost.

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