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Optimal placement of phasor measurement units considering islanding contingency, communication infrastructure, and quality of service

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ABSTRACT

In this study, the PMUs are placed to operate in normal and islanded cases taking into account power system observability, reliability, Communication Infrastructure (CI), and latency time associated with this CI. Moreover, the economic study for additional new data transmission paths is considered as well as the preexisting Communication Devices (CDs) and the availability of predefined locations of some PMUs in some buses. The PMUs placement and their communication network topology and link channel capacity are co-optimized simultaneously. Two different approaches are applied to optimize the objective function; the first approach is combined from Binary Teaching Learning Based Optimization Algorithm (BTLBOA) and the Minimum Spanning Tree (MST) algorithm, while the second approach is based on BTLBOA. The proposed approaches are examined using IEEE 118-bus systems.

1. Introduction

In recent years, the security of the power system is carefully related to the measurement and monitoring conditions of the system operating. The Phasor measurement units (PMUs) give real-time phasors of the bus branch currents and voltages in a wide-area network. The phasors from different buses, which are coordinated to the same time–space, can improve performance of control and monitoring systems by enhancing transient stability analysis, frequency stability analysis, power flow calculation, and state estimation [1]. PMUs have become the best choice of the measurement techniques in the power systems. They offer positive sequence current and voltage measurements which are synchronized with accuracy of a microsecond. The output sample rate of the PMUs is high and vary from 1 to 120 samples per second with synchronization accuracy less than one microsecond and maximum total vector error of about 1% [2]. Because of this high sampling rate, the PMUs provide large amounts of data; and therefore, they need modern communication systems with high bandwidth in order to transmit their data. The topological design of the communication networks is becoming important. The transmission medium should satisfy the purpose of high bandwidth data. Also a number of limitations while designing a communication system gives rise to need for an optimal solution that takes into account the Quality of Service (QoS) requirements such as reliability, data loads, latency time, and congestion of the communication network [3]. However, high per unit cost and challenges related to its communication system have made its judicial placement in an electric grid significant [4]. The data produced by PMUs needs a reliable and stable communication network. The Optical Power Ground wire (OPGW) is selected to be the media of the case study based on the high channel capacity, low latency time, and immunity to electromagnetic interference [5, 6, 7, 8]. With restricted annual investments, it'd be desirable to add a restricted variety of PMUs till a final

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goal is achieved. Initially, there will not be enough PMUs to execute a linear estimator. The try is to place the PMUs so that at every stage the PMUs placement selection satisfies design criteria [9]. In order to obtain an adequate amount of observability of a power system, PMUs sites are spread over a wide area. In recent years, many investigators presented different methods to find the minimum number and optimal placement of PMUs [10, 11]. The actual problem is the issue of sequentially adding PMUs to a system starting with a low degree of observability and ending with Complete Observability (CO) with redundancy. Generally, observability analysis can be done using either a numerical approach or a topological approach. The problem is the issue of consecutive adding PMUs to a system beginning with a low degree of observability and ending with CO and redundancy. Generally, there are two type of the observability analysis, numerical and topological approaches [12]. In the numerical approach, the network is observable if its measurement gain matrix is full column rank [13]. In this approach the observability is estimated from Energy Management System applications [14, 15]. On the opposite, the topological observability approach determines network observability based on the type and site of measurements within the entire system. The topological observability analysis uses graph ideas. The network is observable topologically if a spanning tree can be found within the graph. For more details concerning topological observability analysis readers could refer to [16, 17, 18]. Furthermore, PMU placement problems while considering branch outages and measurement losses were studied in [19, 20, 21]. A new problem formulation and its associated solution based on mixed integer linear programming method for obtaining the best locations of PMUs and taking account of the available number of PMU channels has presented in [22]. The authors in [23] consider the so-called branch PMUs which monitor a single branch by measuring the associated current and terminal voltage phasors. The study also takes into account PMU failures and network contingencies that involve topology changes. The authors in [24] discusses optimally placing of the PMUs using deterministic approach for ensuring system observability. Also, in this work, the contingency with N-1 and N-2 are considered. The authors in [25] proposed a new method of the PMUs optimal placement to monitor the status of the boundary buses during Power System Restoration. Since, measure and its application lie inside the power system studies, power system engineers primarily concentrate on these observability issues in their researches. On the opposite, in some researches, telecommunication engineers concentrate on the communication systems. As a result, few researches have thought-about the full domains of the observability and CI comprehensively [26]. Many researchers thought-about the PMUs optimization problem as a minimization of the PMUs number. The primarily used optimization techniques are conventional such as integer linear programming [27, 28, 29, 30, 31, 32], semi-definite programming [33], Convex Relaxation [34], and equivalent integer linear programming method [35]. Despite they have better execution time, the major drawback of these methods is their considering Optimal PMU placement (OPP) as a finding the minimum number and locations of PMUs and not consider CI (i.e. OPGW length - link capacity- number of switches, etc.) and quality of service. Several meta-heuristic optimisation methods were used to solve OPP such as Genetic Algorithms [36, 37], simulated annealing [4, 12, 38], tabu search [39], and binary particle swarm optimization [40]. In [15], the author assumed a pre-known installed CI for the system and assigned a penalty for the case when a PMU is placed at a bus lacking CI. In other words, in this approach, CI is additionally considered as a constraint. In [26], the measurement devices and CI were designed using the GA. They optimized this problem using GA in both independent and simultaneous approaches. The results indicate that while the total number of measurement devices for system observability could increase (and therefore, the observability is improved), the total cost is reduced. However, they did not introduce any method to evaluate the location of the Control Center (CC). In addition, the meter optimal placement has been carried out only for PMUs as measurement devices. Also, the authors considered that the cost of the network depends on the accumulative length of the OPGW only, and did not consider the allocation of the link capacity. Moreover, the authors did not take into account the QoS.

Therefore, in the proposed approaches, the power system observability, CI requirements, system reliability, and the latency time are considered in the objective functions. In addition, the predesign requirements such as predefined locations of some PMUs and any existing CDs in some buses are taken into account. Also, the PMUs placement serves in the normal case (considering the whole network as a single area) and after a large disturbance islanding case (considering the network composed of interconnected subareas). Two different approaches are used. The first approach uses BTLBOA to search the best location of the PMUs and the channel capacity of the Communication Links (CLs) while the connection topology is done using MST algorithm. The second approach uses BTLBOA to search the best location of the PMUs, the channel capacity of CLs, and the connection topology.

The rest of the paper is organized as follows: Section 2 describes the methodology developed to build the used approaches. Section 3 presents the methods of the problem formulation and implementation. Section 4 presents the simulation results & discussion. Finally, conclusions are extracted in Section 5.

2. Methodology

2.1. Power system islanding

The power system islanding is an effective tool for avoiding system wide cascading outages and complete blackouts. In the case of the power system integrity cannot be avoided, splitting strategies are executed to split the system into small subsystems (islands). This is generally performed in order to create more stable islands with minimum possible mismatch of the load generation, coherent generators with static and dynamic constraints [41]. The slow coherency concept is based on that following a disturbance the groups of generators have a tendency to swing together. Slow coherency is used to solve the problem of identifying the weakest connections between the subareas in the power system network. The weakest connections are function of the system admittance, initial rotor angles and machine inertias of the interconnected generators. In addition, these islands must be splitted considering the existence of Black-start units within each island. Based on the same splitting strategy in [25] the test IEEE 118-bus system is splitted into four subsystems. The weak connections for this system are showed in Table 1 and dashed line in Fig. 1.

2.2. Observability constraint

In general, given a PMU at a bus with unlimited number of channels, bus voltage phasor and all current phasors along lines connected to that bus will be available. Eq. (1) presents observability constraint in general form (i.e. no conventional measurements with or without zero injection bus – contains conventional measurements with or without zero injection bus) as introduced in [16, 17].

$$\text{Observability constraint}: \quad AX \geq B \tag{1}$$

Where

- For normal case:

Table 1
Weak connections cut-set for the IEEE 118 bus.

Cut-set	Lines
1	(24-70), (71-72), (38-65), (43-44), (40-41), (40-42)
2	(75-77), (76-77), (69-77), (68-81)
3	(83-84), (83-85), (85-88), (85-89)

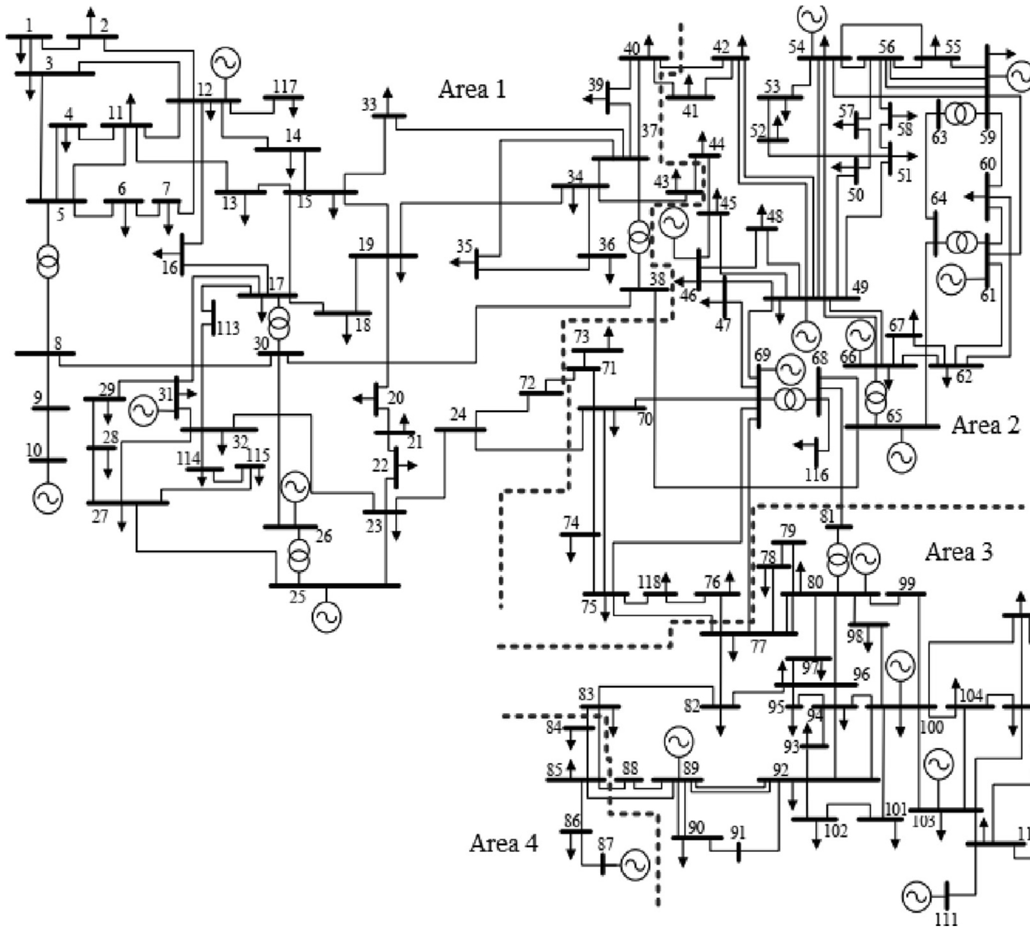

Fig. 1. IEEE 118-bus test system representing the weak connections.

X is the PMUs placement variables $X = [x_1 \;\; x_2 \ldots x_N]$,

$$x_i = \begin{cases} 1 & \textit{if PMU at bus i} \\ 0 & \textit{if No PMU at bus i} \end{cases},$$

N is the number of buses

$$B = \begin{bmatrix} r_{ed} \\ r_{ed} \\ . \\ . \\ r_{ed} \end{bmatrix}_{N \times 1}$$

$r_{ed} \geq 1$ (depend on the required redundancy [16])

A is the power system connectivity matrix,

$$a_{ij} = \begin{cases} 1 & \textit{if i and j are connected} \\ 0 & \textit{if i and j are not connected} \end{cases}$$

- For islanded case

$X = [X_{area\ 1} \;\; X_{area\ 2} \ldots X_{area\ M}]$

$$A = \begin{bmatrix} A_{area\ 1} \ldots 0 & & \ldots 0 \\ 0 & \ldots A_{area\ 2} & \ldots 0 \\ \ldots & \ldots & \ddots \;\; \ldots \\ 0 & \ldots 0 \;\; \ldots & A_{area\ M} \end{bmatrix}, B = \begin{bmatrix} B_1 \\ B_2 \\ . \\ . \\ .B_M \end{bmatrix},$$

M is the number of area

$A_{area\ i}$ and B_i are power system connectivity matrix and redundancy vector for each area

The minimum number of PMUs (PMU_{Smin}) can be formulated as a problem of Integer Linear Programming [42] as shown in the following equation.

$$PMU_{Smin} = \begin{cases} min \sum_{k=1}^{N} X_k \\ \textit{Subject to : Observability constraint } (1) \end{cases} \tag{2}$$

2.3. TLBO algorithm

Teaching-Learning-based optimization (TLBO) is one of the recently proposed population based algorithm [43] This algorithm has the nature of meta-heuristic optimization algorithms. One of the main advantage of these Algorithms is that they do not need a function formulation, but rather need a fitness function only or any other way for distinguishing the results. As a result, the black box problem can be solved using these algorithms. For the above-mentioned reasons, this version will be used in this study. The algorithm simulates two phases of learning: (i) "teacher phase" and (ii) "learner phase. In the teacher phase, the teacher ($X_{teacher}$ = best solution in each population) tries to enhance the result of the other students by moving the mean of the classroom (Xmean) towards his position according to the following equation [43].:

$$X_{i\_new} = X_i + r\left(X_{teacher} - T_f \;\; X_{mean}\right) \tag{3}$$

where X_{i_new} and X_i are the new and existing solution of the student i, r is random value in the range of 0 and 1, and Tf is a teaching factor which can be either 1 or 2 [43]. In the learner phase. The students gain knowledge by interacting with other students. During learner phase, the student X_i interact randomly with another student X_j to develop his knowledge according to the following equation:

$$X_{i\_new} = \begin{cases} X_i + r(X_i - X_j) & if \;\; f(X_i) < f(X_j) \\ X_i + r(X_j - X_i) & if \;\; f(X_i) > f(X_j) \end{cases} \tag{4}$$

If X_{i_new} is better, it is accepted in the population. The algorithm will continue until the termination condition is met. The velocity in teacher and learner phases of each student can be calculated as follows:

$$V_i = r(X_{teacher} - T_f \;\; X_{mean}) \tag{5}$$

$$V_i = \begin{matrix} r(X_i - X_j) & if \;\; f(X_i) < f(X_j) \\ r(X_j - X_i) & if \;\; f(X_i) > f(X_j) \end{matrix} \tag{6}$$

Then the Binary TLBO Algorithm (BTLBOA) can be done by applying “tanh” transformation to the component of the velocity as follows [44]:

$$\tanh(|V_i|) = \frac{\exp(|2V_i|) - 1}{\exp(|2V_i|) + 1} \tag{7}$$

The equation for updating the positions is then replaced with:

$$X_{i\_new} = \begin{cases} 1 & \text{if} \quad rand < \tanh(|V_i|) \\ 0 & \text{otherwise.} \end{cases} \tag{8}$$

2.4. Minimum spanning tree

The nodes (vertices) of the CI in a power grid correspond to PMUs, CDs, and CC, while the edges correspond to high-voltage lines [45] or a new data transmission paths. Dijkstra's algorithm [46], is a graph search algorithm that solves the shortest path problem for a graph with nonnegative edge [47]. The Dijkstra's algorithm is used to search the short path in the MST algorithm. The complete pseudocode for MST algorithm is shown in Fig. 2. Step 3 in this algorithm could be modified to start with a highest short path and end with the lowest short path. This modification is preferable when small propagation time delay is required, where this modification shrinks the network and reduces the maximum propagation time delay of the farthest site. In step 4, the node is connected with tree through switch.

2.5. Quality of service

The Wide Area Measurement System (WAMS) is a distributed communication network (CN). The QoS in the WAMS depends on the latency time and reliability of the system. The latency time performance is extremely important especially in dynamic control and protection applications [48]. The tree network is a common methodology in order to design the communication networks [49, 50]. In the power system, CN consists of many PMUs, CDs, and Phasor Data Concentrators (PDCs). PDC gathers the data generated by these PMUs over a communication network. In addition, it achieves quality checks on phasor data and interprets, and it inserts the missing data at their position [51, 52]. Typically, several PMUs are located at various substations to collect data and send it in real time to a PDC. Several PDCs can be connected to a main central PDC, in order to provide a wide snapshot of the power system measurements. In large systems, they contain more than one PDC, where one PDC is placed in each subarea. For simplicity in this work, one PDC is used in the control center.

Step 1: Assign all nodes to tentative

Step 2: Choose the CC node as root node

Step 3: Select the node (PMU or CD) from tentative, which has *the lowest* short path to CC, and include it in the tree

Step 4: Select new node (PMU or CD) from tentative, which has *the lowest* short path to any node in the tree (including intermediate nodes (any included buses)), and include it in the tree.

Step 5: Repeat from step 3 until including all PMUs and CDs in the tree

Fig. 2. MST pseudocode.

2.5.1. Latency time

The measurements are made at specific time and physical distant locations. Then they are transmitted to a CC for use by wide area applications. The latency time between PMU and the CC is a combination of PMU reporting delay, the network propagation delays, routing delays, queuing and transitions delay, and PDCs delay [53]. The latency time of the communication network is shown in Fig. 3.

The PMU reporting delay (t_{pmu}) is defined as the time interval between the data input time, and the time when the data becomes available at the output of the PMU. This delay includes several factors, such as the window over which data is collected to make a measurement, filtering, and the PMU processing time.

The PDC delay (t_{pdc}) is defined as the time interval between the data input time and the time when the data becomes available at the PDC output. This delay includes several factors such as processing and alignment received data from PMUs and PDCs. The PDC aligns received data and places this data in a packet. Additionally, the PDC data processing may include reporting rate conversion, phase and magnitude adjustment, interpolation, and filtering.

The Queuing and transitions delays (T_{qu}) are caused by the data rate of the medium and the amount of data that has to be transported through the medium. Using M/M/1 model, T_{qu} can be presented as in the following equation [54]:

$$T_{qu} = \frac{\mu}{C_l - f_l} \tag{9}$$

$$C_l > f_l$$

Where

μ is the average packet length in bits,
C_l is the capacity in bps,
f_l is the flow of the link l in bps.

The propagation delay (t_p) is a function of both the medium and the physical distance separating the individual components of WAMS. In the OPGW, the propagation delay can be expressed as in the following equation [55].

$$t_p = \frac{NL}{S} \tag{10}$$

where

S is the speed of the light in a vacuum.
L is the length of the communication link
N is the group index of the material ≈ 1.5

Considering the network is connected using backbone switches. The above mentioned facts can be summarized and concluded in the following equation:

$$T = t_{pmu} + \sum_{i=1}^{l_n} t_{p_i} + \sum_{i=1}^{SW_n} t_{qu_i} + t_{pdc} \tag{11}$$

where

T is the total latency,
l_n is the number of links between PMU and CC
SW_n is the number of switches between PMU and CC
t_{pdc} is PDC delay

Based on the typical values, which is introduced in Table C.2 in [56],

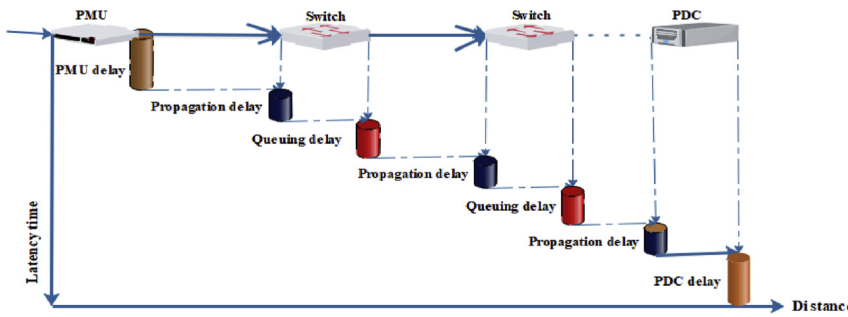

Fig. 3. Latency time.

and with assuming PDC uses direct forward mode $t_{pmu} \approx 25ms$ and $t_{pdc} \approx 2ms$. The (11) will be as follows:

$$T \approx 25 + \sum_{i=1}^{l_n} t_{p_i} + \sum_{i=1}^{SW_n} t_{qu} + 2 \tag{12}$$

2.5.2. *WAMS reliability*

The reliability of the WAMS depend on the reliability of media channel and communication components. Based on the same concept in [57]. The relation, which assess the reliability of connection between any Required-node (Rnode = PMU at any bus) and PDC, can be described as follows:

$$RS = \prod_{s} R_i \tag{13}$$

$$Rp = 1 - \prod_{p} [1 - R_i] \tag{14}$$

Where

R_i = the reliability of the component i
R_s = the total reliability of the series components
R_p = the total reliability of the parallel components
s = Number of series components
p = Number of parallel components.

There are two cases for bus observation reliability:

- CO without redundancy.

In this case, there is only exist one path between Rnode and PDC. If the PMU is located at Rnode the series components are only communication components such as Communication Links (CL), switches, and PDC as shown in Fig. 4a. If the PMU is located at Neighbor-node (Nnode), the series components are communication components plus the transmission line (TL) as shown in Fig. 4b.

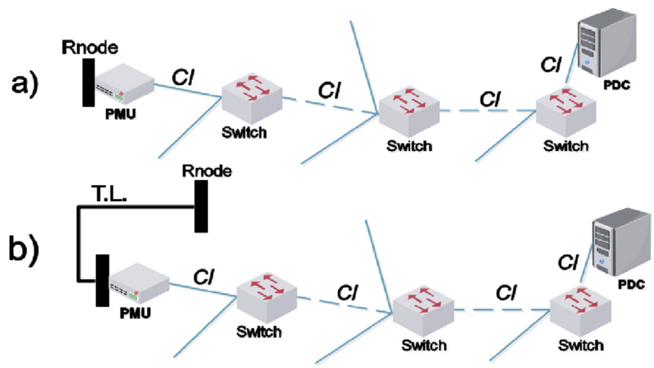

Fig. 4. CO without redundancy.

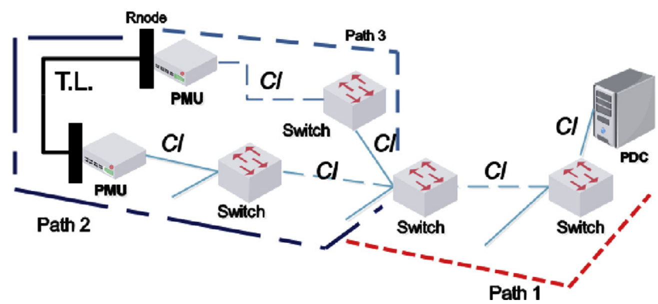

Fig. 5. Redundancy with PMU at Rnode and Nnode.

- CO with redundancy.

In this case, there are parallel and series paths between Rnode and PDC as shown in Figs. 5 and 6 (for two degree of redundancy example). If the PMUs are located at Nnodes and Rnode, the path contain Rnode has only communication components and the other paths have communication components and T.Ls. If the PMUs are located at Nnodes, all paths contain communication components and T.Ls.

The reliability of each switch is assumed 0.99 and the reliability of transmission lines and OPGW is calculated as follows:

$$Reliability_{cl\ or\ T.L.} = R^{L/BL} \tag{15}$$

Where

L is the length per km of the transmission line or OPGW link
R is the reliability of the base length (is assumed 0.99)
BL is the base length (is assumed 20 km)

2.5.3. *Cost calculation*

The WAMS cost depends on PMUs cost, CC cost, and CI cost. The cost of a CI is composed of two components including the cost of passive components and active devices. In the fiber optic networks, the price of passive components depends on OPGW capacity and length. On the opposite, the cost of active devices depends on the switches number, which are installed at connection nodes [58]. As a result, the cost of CI correspond to the number of switches, data transmission medium (i.e.

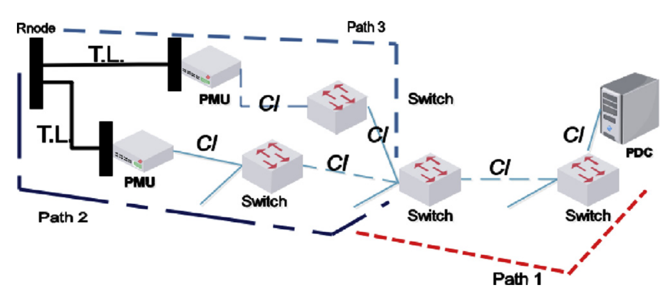

Fig. 6. Redundancy with PMUs only at Nnodes.

OPGW) price, and installation cost as in the following equation

$$Cost_{CI} = \sum_{i=1}^{l} L_i d_i + \sum_{i=1}^{SW_n} SWc_i \tag{16}$$

where

l = number of the links
$L_i = L_{crp_i} + L_{in\,i}$
L_{crp} = link capacity price factor (Depend on the link capacity)
L_{in} = link installation cost factor
d_i = length of the link
$SWc_i \approx switch_{crp_i} + switch_{in_i}$
$switch_{crp}$ = switch capacity price factor
$switch_{in}$ = switch installation cost
Subscript i indicate link or node i

However, the channel capacity can take only discrete values. In addition, there are the cost of PMUs, which equal to the total price of the PMUs and its installation cost

$$Cost_{PMUs} = \sum_{i=1}^{pmu} pmuc_i \tag{17}$$

where

pmu = number of the PMUs
$pmuc_i = PMU_{pchi} + PMU_{in_i}$
$PMU_{pch\,i}$ = PMU price factor(depend on the PMU channal number)
PMU_{in_i} = PMU installation cost (depend on site location)

In the case of adding new data transmission paths, the economic study has considered the establishment of new towers; the cost of the towers will depend on the direct link length. The total link cost can be calculated as follows:

$$cd_i = (Lavcrp + L_{ini})d_i + tc = L_{avi}\, d_i + \alpha_i d_i = L_{avi} d_{vi} \tag{18}$$

$$d_{vi} = \frac{d_i(L_{avi} + \alpha)}{L_{avi}} = d_i\left(1 + \frac{\alpha_i}{L_{avi}}\right) = d_i(1+\beta) \tag{19}$$

where

cd_i = cost for new direct link i
$Lavcrp$ = Capacity price factor of the new link
L_{in} = link installation cost factor
α = tower cost factor
$L_{avi} = Lavcrp + L_{in\,i}$
d_i = actual distance for link i
$d_{v\,i}$ = virtual direct distance for link i
β = direct connection factor

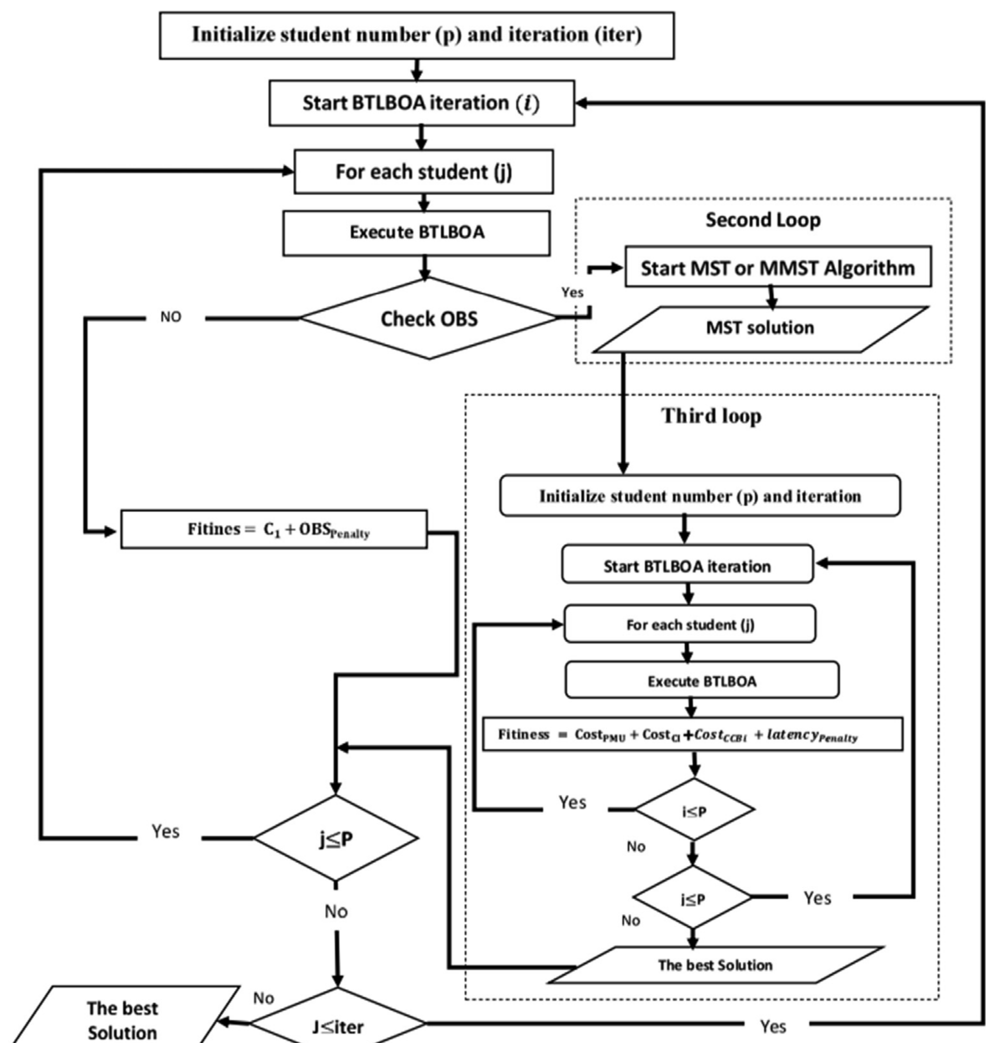

Fig. 7. Flow chart of BTLBOA and MST.

The minimum number of the PMUs required could be calculated using (2). In addition, the number of CDs (Ncds) are known, Therefore the capacity of the new data transmission line (C_{av}) could be approximated as follows:

$$C_{av} \approx \left(\frac{PMU_{Smin}}{2}\right) PMU_{data\ flow} + \left(\frac{Ncds}{2}\right) CD_{data\ flow} \tag{20}$$

Where

$PMU_{dataflow}$ is the pmu data flow (kbps)
$CD_{data\ flow}$ is the CD data flow (kbps)

For each new data transmission paths, calculate virtual distance from (19) and (20). After calculating virtual distance there are two distance matrices: distance matrix corresponding to power system transmission lines distance matrix (D_{power}) and distance matrix from virtual calculating ($D_{virtual}$). Merge the two matrixes in one matrix D_{merged} as follows:

-For direct connected buses, compare the link distance in D_{power} with $D_{virtual}$ and take the d_{vi} as link distance if it is less than d_i in D_{power}.
-For not direct connected buses, take the virtual length as link distance.
-Then modify (16) as follows:

$$Cost_{CI} = \sum_{i=1}^{lp} L_i d_i + \sum_{i=lp+1}^{l} (L_i d_i + \alpha \ d_i) + \sum_{i=1}^{SW_n} SWc_i \tag{21}$$

where

from 1 to lp are the links from power system network
from $l_p + 1$ to l are the links from new added paths

Finally, the total cost will be as following

$$Total\ \ Cost = Cost_{CI} + Cost_{PMUs} + Cost_{CCBi} \tag{22}$$

where

$Cost_{CCBi}$ is the cost of control center base station (Include CC site and PDC cost) at location i

3. Methods

3.1. Problem formulation and implementation

For N buses system, the search space for PMUs locations is 2^N without considering CI topology and capacity, the rate of the channel capacity, and number of PMU channels. Therefore, the PMUs optimal problem is considered as a combinatorial optimization problem [59]. Meta heuristic algorithm based methods, such as BTLBOA, are candidate for solving such problems. In the following, two approaches based on BTLBOA are presented to minimize the total cost with considering the observability and CI. In these approaches, the optimization problem is defined as follows:

$$Prob.\ : \begin{cases} Min: \ (Total\ \ Cost = Cost_{CI} + Cost_{PMUs} + Cost_{CCBi}) \\ \quad vvariable: PMUs\ locations;\ the\ network \\ \quad topolgy;\ link\ capcity;\ and\ buffer\ memory \\ \quad\quad i)\ Observability\ constraint \\ \quad\quad ii)\ Connection\ constraint \\ Subject\ to: \left\{ \begin{pmatrix} All\ PMUs;\ CDs;\ and \\ CC\ are\ connected \end{pmatrix} \right. \\ \quad\quad iii)\ Latency\ time\ constraint \\ \quad\quad V)\ Reliability\ constraint \end{cases} \tag{23}$$

The following considerations are made in these approaches:

- CC location is not predefined.
- Some PMUs locations are predefined.
- PMU and CD dataflow are assumed 128 kbps.
- Some CDs are existed, and will be connected to the CN.
- Two cases are considered for the power system: normal and islanded.
- The required degree of observability and required redundancy are considered in the observability constraint such as in Section 2.2.
- Based on fairness grade of service, the link capacity is allocated to minimize the maximum latency time. The maximum Latency time for any PMU($\mathbf{t_{req}}$) < 0.04 Sec.
- The reliability for any node (r_{req}) > 0.8

3.1.1. Using BTLBOA combined with MST

The optimization in this approach is based on three loops as shown in Fig. 7. The first loop, the BTLBOA in IV is used to search the best location of the CC and PMUs that minimize the cost and achieve the observability constraint as shown in Section 2.2. If the observability condition is not met, the inner loops are not required. Therefore, the cost function of the outer loop is as follows:

$$Total\ \ Cost = \ C_1 + OBS\_Penalty \tag{24}$$

Where

$OBS_{Penalty} = C_2 * ineqdsum$
C_1, C_2 are constants with large values as shown in the supplementary data.
ineqdsum = summation of all postive elements in OBS_d vector

Initialize students (Each student contains zeros and ones; zeros lead to drop this links from D_{merge})
Construct the Connectivity Matrix $= \sum_{r=1}^{N-1} A^r$
where

$A_{(n,n)}$ is pi direction adjacency matrix,

$$a_{ij} = \begin{cases} 1 & \text{if node i and j is connected} \\ 0 & \text{if node i and j is unconnected} \end{cases}$$

If connectivity index (C_{indx}) > 0
Where

$C_{indx} = (PMUs\_CDs_n - con)$

$PMUs\_CDs_n$ = number of PMUs, and CDs

$$con = \sum_{j=1}^{PMUs\_CDs_n} j \begin{cases} 1 \text{ if Connection Matrix}(_{CC,j}) > 0 \\ 0 \text{ if Connection Matrix}(_{CC,j}) = 0 \end{cases}$$

$$\boldsymbol{Cost\ CI = \ c3 * C_{indx}} \tag{27}$$

c3 = large number but less than c1 and c2 in (24) as shown in the supplementary data

Else,
Use short path Dijkstra's algorithm to select the shortest distances between PMUs and CDs and CC from the remaining links in D_{merged} and go to third loop
End

Fig. 8. Connectivity algorithm.

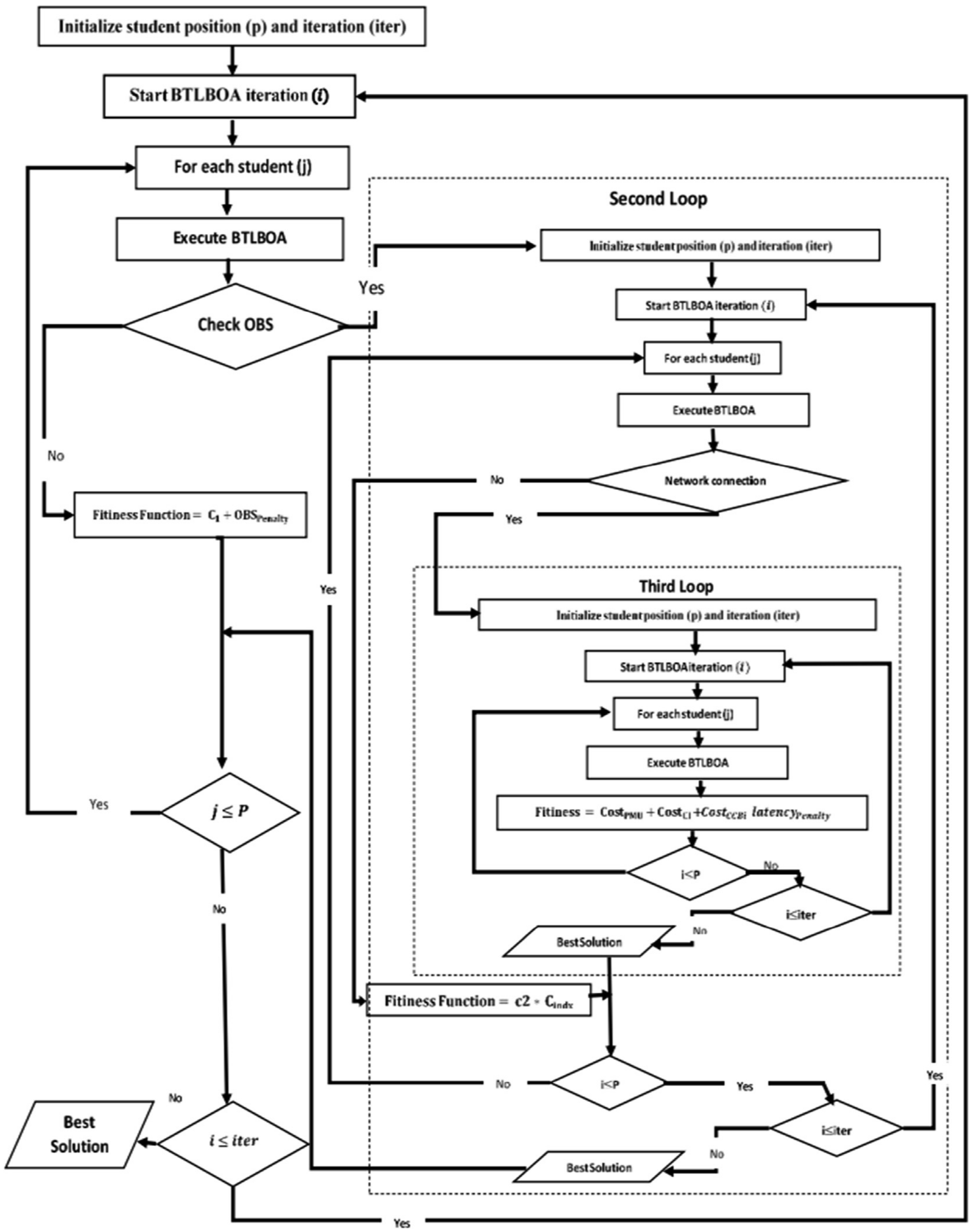

Fig. 9. Flow chart of BTLBOA.

OBS_d = right hand side of (1) − left hand side of (1)

- In the second loop. Based on D_{merged}, the MST or MMST in Section 2.4 is used to connect all PMUs, CDs, and CC.

- The third loop, BTLBOA is used to allocate links capacity of the connected network. This loop return the total cost of the connected network according to (22) with considering the (25) and (26) as a weighted penalty (the weights of each penalty is shown in the supplementary data).

$$\max\ (T_{pmu}) < t_{req} \tag{25}$$

$$\min\ (R_{Node}) < r_{req} \tag{26}$$

where

T_{pmu} is a vector of latency time for all PMUs according to (12).
R_{node} is a vector of latency time for all nodes according to (14), (15).

3.1.2. *Using BTLBOA*

In this approach, the optimization is based on three loops.

- The first loop is treated as explained in the Section 3.1.1.

Table 2
Predefined locations.

Predefined locations	
PMUs locations	2,5,10,12,14,21,32,34,37,41,94
CDs locations	91, 92, 96, 100, 105

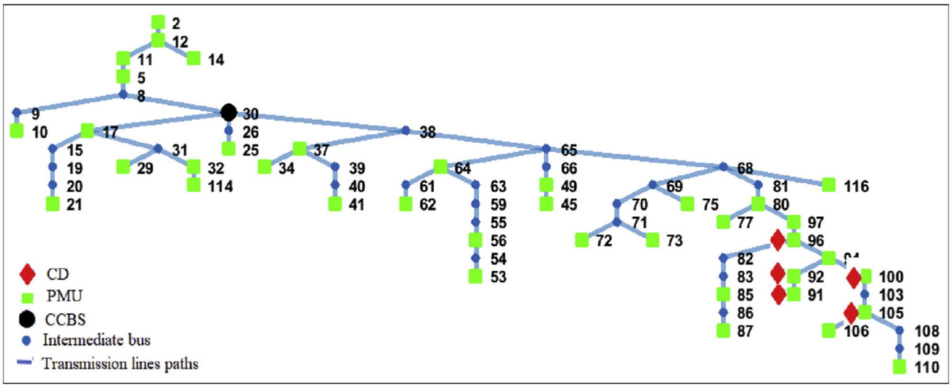

Fig. 10. Normal case network topology USING BTLBOA Combined with MST.

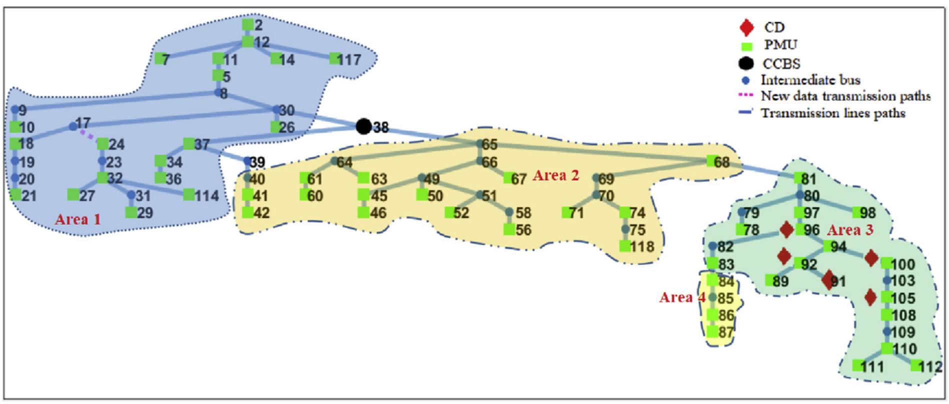

Fig. 11. Islanded case network topology USING BTLBOA Combined with MST.

- The second loop, the BTLBOA with students dimension equal length of D_{merged} is used to search the low cost network connection topology, which connect all CC, PMUs, and CDs. The value of the fitness function for this loop is estimated using the connectivity algorithm, which is shown in Fig. 8.
- The third loop is treated as explained in the Section 3.1.1. Fig. 9 shows the complete flowchart of this approach.

The difference between this approach and the Section 3.1.1 approach is that the connection topology is not depend on the length of the network, but it is depend on the CI cost.

3.2. Implementation considerations to reduce the run time

In the first approach and second approach, If the observability constraint in the outer loop is not achieved the inner loops are excluded. This excluding reduces the run time. The global student value is used for each student, which equals to the global student without recalculating this value from inner loops. This reduces the run time especially near the end of the iterations. To reduce the run time of the second approach, the MST algorithm with fixed channel allocation (channel capacity = 10*data flow) is used for network topology if the student has a number of PMUs larger than $1.6*PMUs_{min}$. Then the BTLBOA is used for network topology with fixed channel for the student which has a number of PMUs larger than $1.3*PMUs_{min}$. Finally, the accurate inner loops with channel capacity allocation are used for the student which has a number of PMUs less than $1.3*PMUs_{min}$.

4. Results & discussion

Considering the predefined locations of the PMUs and CDs, as shown in Table 2 the IEEE 118-bus systems with given data in the supplementary data is investigated using the two approaches for full observability condition in normal case and islanded case (with cut set as explained in Section 2). PC with Intel Core i5-430M @ 2.27 GHz and Matlab 2016 are used to simulate the test system. The results of the method in [18] at normal case, without adding new paths, without islanding, and with fixed channel capacity (ten times actual data flow) gives cost equal 58 per unit, maximum latency

Table 3
Results of the USING BTLBOA combined with MST.

i) Normal case		
CC location		30
All PMUs locations		2,5,10,11,12,14,17,21, 25, 29,32,34,37,41,45,49, 53,56 .62.64,72, 73, 75,77, 80,85,87,91,92,94,96,97, 100,105,106,110,114, 116
Total cost		49 (Per unit) + penalty of the reliability constraint
Maximum latency time (Sec)		0.031341
Minimum reliability		0.79868 < 0.8
Runtime (minute)		180
ii) Islanded case		
CC location		38
All PMUs locations	Area 1	2,5, 7,10, 11, 12,14, 18, 21, 24, 26, 27,29, 32,34, 36, 37,114,117
	Area 2	41, 42,45,46,50,52,56, 60,61,63,67,68,71,74, 118
	Area 3	78,81,83,89,92,94,96,97,98,100,105,108,110,111,112
	Area 4	84,86,87
Total cost		66.473
Maximum latency time (Sec)		0.028945
Minimum reliability		0.80162
Runtime (minute)		190

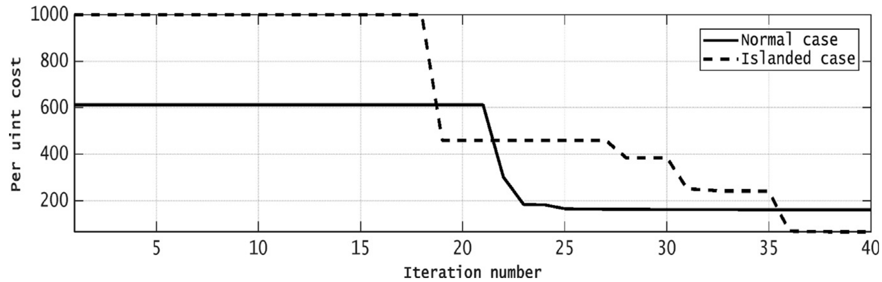

Fig. 12. Total cost converge curve USING BTLBOA Combined with MST.

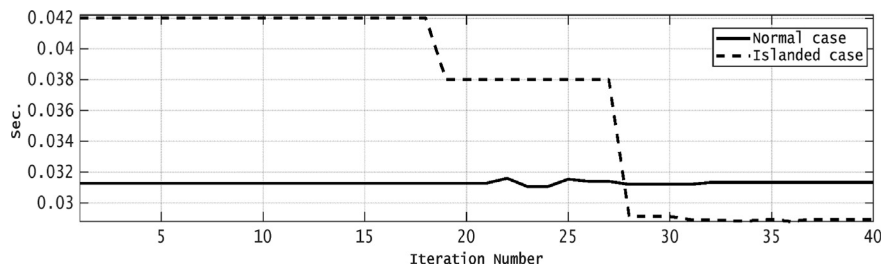

Fig. 13. Maximum latency time converge curve USING BTLBOA Combined with MST.

equal 0.029074 Sec., and minimum reliability equal 0.76225. While the results of the proposed approaches are shown in the following sections.

4.1. USING BTLBOA combined with MST

The results of the proposed approach are listed in Table 3. In addition, the network topology for normal and islanded cases are shown in Figs. 10 and 11. The total cost and latency time converge curves of the main loop for the two cases are shown in Figs. 12 and 13.

4.2. Using BTLBOA

Table 4 shows the results of the proposed approach in normal and

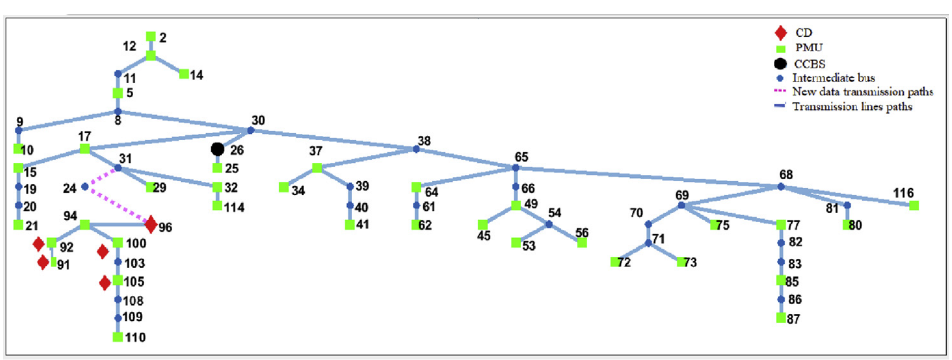

Fig. 14. Normal case network topology USING BTLBOA.

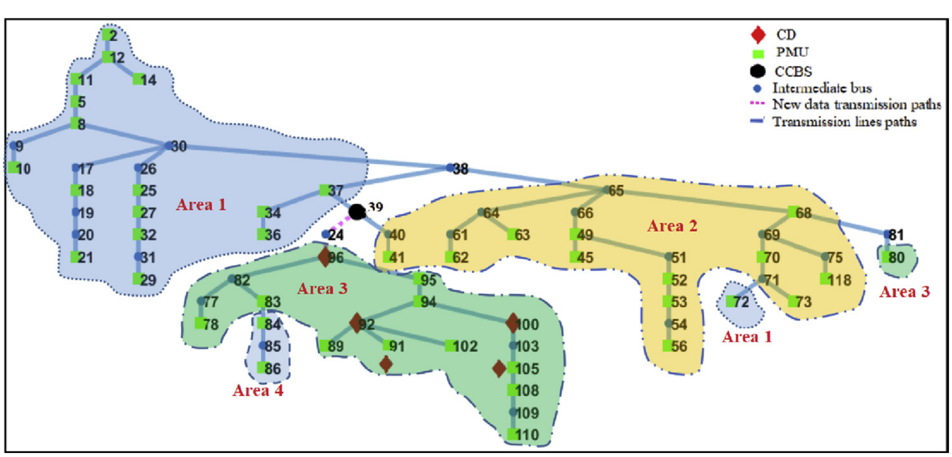

Fig. 15. Islanded case network topology USING BTLBOA.

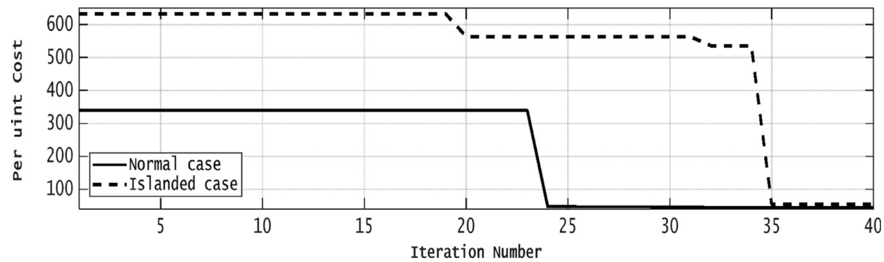

Fig. 16. Total cost converge curve USING BTLBOA.

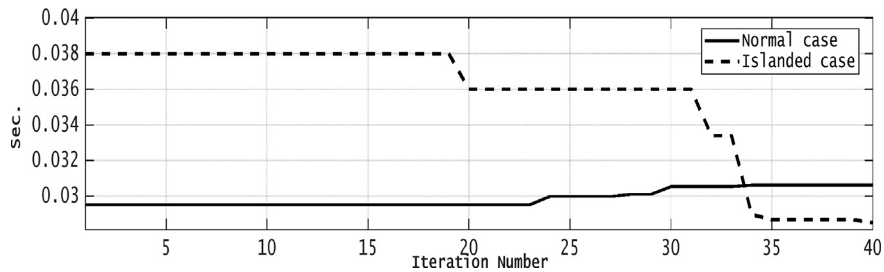

Fig. 17. Maximum latency time converge curve USING BTLBOA.

islanded cases. The network topology for normal and islanded cases are shown in Figs. 14 and 15. The total cost and latency time converge curves of the main loop for the two cases are shown in Figs. 16 and 17.

From the simulation results it is possible to extract the following notes:

- The run time of second approach is longer than the first approach
- As shown in Tables 3 and 4, the second approach is more cost efficient than the first approach, especially if the difference in price resulting from channel capacity change is significant.
- As shown in Tables 3 and 4, generally more PMUs are required in islanded case. Therefore the reliability and cost of the islanded case is higher than normal case

Table 4
Results of USING BTLBOA.

i) Normal case		
CC location		26
All PMUs locations		2,5,10, 12,14, 15,17, 21, 25, 29,32,34, 37,41,45, 49,53,56, 62,64,72,73, 75,77, 80,85,87, 91,92, 94, 100,105,110,114, 116
Total cost (Per unit)		45.267
Maximum latency time (Sec)		0.030619
Minimum reliability		0.80655
Runtime (minute)		1200
ii) Islanded case		
CC location		39
All PMUs locations	Area 1	2,5,8,10,11,12,14,18,21,25,27,29,32,34,36,37, 72
	Area 2	41,45,49,52,53,56,62,63,68,70,73, 118
	Area 3	78,80,83, 89,91,94, 95,102, 105,108, 110
	Area 4	84, 86
Total cost		54.167
Maximum latency time (Sec)		0.028494
Minimum reliability		0.82874
Runtime (minute)		1220

- It is noted that the tow approached try find the best cost that achieve latency time within required range as shown in Figs. 13 and 17.
- Indeed, the methods presented in [18] was unsuccessful to achieve the global solution. Since it used MST algorithm to find the network topology and did not take into account the channel capacity allocation. Also due to, the multi-loop is not used in this method, the runtime is large.

5. Conclusion

In this study, optimal placement of PMUs and their required CI for power systems are co-optimally designed in normal and islanded cases. Two approaches have been presented. The first approach (i.e. BTLBOA Combined with MST) and the second approach (i.e. BTLBOA) to find the optimum placement of PMUs and their CI are investigated using IEEE 118 buses. The simulation results indicate that the second approach is cost effective. Moreover, the second approach, due to using BTLBOA in all loops, may converge to the global solution. In contrast, the first approach due to using MST for network topology can take less run time but it may not converge to the global solution. However, using multi loop search as shown in Fig. 9 to achieve observability constraints and considering the recommendations as introduced in Section 3.2 can reduce the run time of the second approach. The cost of the CI in this study is not depend on the accumulative length of the OPGW only. However, it considered the switches and the link capacity in the objective function. In addition, the quality of service such as latency time and the reliability of the communication network and the degree of the observability are considered. Also, the partially optimization problem (predefined locations of some PMUs and CDs), and the economic study for additional new data paths are considered in the proposed approaches.

Declarations

Author contribution statement

M. M. H. Elroby: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

S. F. Mekhamer & H. E. A. Talaat: Analyzed and interpreted the data; Wrote the paper.

M. A. M. Hassan: Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

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