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Contingency Constrained Optimal PMU Placement in Power System using Binary Sine Cosine Algorithm

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ABSTRACT: In recent electrical power systems, phasor measurement units (PMUs) are playing a crucial role with regard to power system monitoring, control and protection. This presented work mainly aims to attain entire network observability with the incorporation of lesser number of PMUs. In this regard, the binary sine cosine algorithm (BSCA) has been employed to decide on optimal PMU number and their feasible location such that the entire power network is observable. Impacts of consideration of network contingencies (single line/PMU outage) with and without zero injection buses (ZIBs) have also been considered while solving the considered optimization problem. The viability of the considered method has been investigated by implementing it onto the various standard (IEEE-14 and IEEE-30 bus) systems. In order to confirm the efficacy of the employed algorithm the obtained results have been compared with other approaches employed in the literature. Obtained results indicate that BSCA offers similar or improved results.

Keywords: Optimal PMU Placement, Binary Sine Cosine Algorithm, Zero Injection Bus, Contingency.

Abbreviations: SCA, Sine Cosine Algorithm**;** BSCA, Binary Sine Cosine Algorithm; PMU, Phasor Measurement Unit, ZIB, Zero Injection Bus.

I. INTRODUCTION

In the past few decades, the electrical network has undergone a paradigm shift. The rapid rise in electricity demand, grid integration of intermittent renewable energy sources and deregulated market environment are the key reasons behind this shifting regime. These changes have been offering opportunities to market players but also the operation and control of the electric power system are becoming challenging with reference to stability and security. Therefore, the instant monitoring and determination of power network states are required to assure reliable and secure operation of the electric power system [1].

PMU placement offers favorable solutions in this regard as they enhance monitoring and measurement aspects of the system. PMU offers highly precise and time-synchronized measurement of system parameters (voltage as well as current phasor) [2-4]. Since the cost of PMU and its related circuitry requires a large investment, it would not be viable to place PMUs at every single bus. Thus, it is very much required to place PMUs at only feasible locations [5].

So as to resolve the optimal PMU placement problem, various approaches have been utilized in the literature that can be grouped under two main categories of conventional approaches and heuristic algorithms. Conventional approaches provide a single solution whereas multiple optimal solutions may exist this is the main drawback with conventional approaches. On the other hand, heuristic algorithms inspect the different permutations of solutions before providing the globally best solution [6-7].

The effect of ZIBs has been considered in their proposed formulation of the PMU placement problem [8, 9]. Taking into consideration of ZIBs can minimize PMUs requirement while ensuring entire network observability. However, proper modeling of ZIBs is also one of the challenging tasks. In practical scenarios, contingencies can take place and the occurrence of contingency can make the system unobservable. Therefore, consideration of contingency while formulating PMU placement problems would offer more reliable results thereby would enhance network reliability. However, this incorporation would enhance PMUs requirements to solve the problem.

The model determined observable solutions while taking into account single line contingencies [10]. The effect of single PMU outage was considered; although, the effect of line outage contingencies was not incorporated [11]. Emami & Abur explain in their formulation the outage of single PMU [12]. Simultaneous outages of a single branch and PMU were presented [13]. Moreover, very few reported literature have ensured the entire network observability taking into account the presence of ZIBs under various contingency cases [14, 15].

A review of available literature discloses that several techniques have been applied by researchers to solve the PMU placement problem. The main focus behind this work is to apply a novel technique to solve the mentioned problem. To realize this undertaking, SCA algorithm has been applied in this paper. The feature of applied algorithm is that it is capable of exploring various search space regions, does not stuck in local optima, converges in the direction of the global optimum and efficiently exploits possible search space regions.

In this paper, an optimization problem is formulated with an objective to attain full observability of the electrical power network with a reduced count of PMUs.

Primarily, the general formulation is presented. Subsequently, the impact of consideration of network contingencies (with and without ZIBs) has also been added to the general formulation. The formulated problem is solved by employing a binary sine-cosine algorithm. It has been presented that the considered approach effectively resolves the optimal PMU placement concern.

The key contributions of the presented work are as follows:

– BSCA as an optimizing tool has been employed so as to resolve the optimal PMU placement concern.

– The viability of the considered method has been investigated by implementing it on the various standard test systems.

– To exhibit the efficacy of employed algorithm obtained results are compared with those available in the literature.

This paper has been structured as follows: The mathematical formulation of the considered problem has been discussed in Section II. The description regarding the solution method has been presented in Section III and IV. Section V includes the results obtained with the implementation of the considered approach on standard systems followed by the conclusion in Section VI.

II. MATHEMATICAL FORMULATION

In this section, the mathematical formulation related to the PMU placement problem has been presented. The considered problem aims to make observable entire power network with a lesser number of PMUs. The problem is formulated as follows:

Minimize NOP

$$\mathrm{NOP} = \sum_{m=1}^{NB} Z_m \quad (1)$$

Subject to

$$F = YZ \geq 1 \quad (2)$$

where

$$Y = [y_{mn}]_{NB\times NB}$$
$$Z = [z_1, z_2, \dots\dots\dots z_{NB}]^T_{NB\times 1}$$
$$F = [f_1, f_2, \dots\dots\dots f_{NB}]^T_{NB\times 1}$$

Where,

NOP: Number of PMUs

NB: total number of buses in the electric network

Z_m: binary variable indicates the PMU presence at bus m. The value being '1' refers to the presence of PMU and '0' indicates the absence of PMU at bus m.

F: represents a vector wherein non-zero entries signify that related bus is observable and zero entries signify that related bus is not observable.

Y: represents the connectivity matrix in which element 'y_{mn}' indicates the connection of buses as follows:

$$y_{mn} = \begin{cases} 1 & \text{if } m = n \text{ or bus 'm' and bus 'n' are connected} \\ 0 & \text{otherwise} \end{cases}$$

In case, if PMUs are pre-installed at certain buses then Eqn. 2 will be updated as follows:

$$F = YZ \geq 1 \quad (3a)$$
$$Z_{\mathrm{pre-installed}} = 1 \quad (3b)$$

Eqn. (3b) will ensure that entries of binary variable 'Z_m' corresponding to buses where PMUs are pre-installed remain as defined.

A. Optimizing problem with the inclusion of ZIBs

Buses at which there is no presence of generator or load are referred to as ZIBs. At ZIBs the summation of current flowing is zero. Therefore, in case ZIB or any one of its associated bus is not observable then Kirchoff's current law (KCL) can be utilized to determine the observability of that bus provided all other buses linked with ZIB are observable. To include the effect of ZIBs, the constraints in (2) are replaced with constraints of (4) as follows:

$$F_{\mathrm{new}} = Y_{\mathrm{new}} Z \geq 1 \quad (4)$$

To obtain the Y_{new}, the method as proposed by [16] is adopted. In which, it is presented that summation of observability functions of the buses associated to ZIBs are carried out to obtain F_{new}.

B. Effect of Single Line Outage Contingencies

This sub-section aims to ensure full observability of the power network even in the event of a single line outage. Since the outage of line affects the network observability due to loss of observability path. For example, if a line connected with ZIB is out then it would not be possible to ensure the observability of the connected bus by making use of ZIB property. Therefore, it is important to take into consideration this abnormal situation while optimizing the problem.

To ensure observability, under line outage of the network without considering ZIBs every single bus should have either a PMU or it should have observability through two different lines.

$$Y_x Z \geq 2 \quad (5)$$

Where, x represents a set of buses where PMUs are not present.

In order to optimize the problem in case of line outage with consideration of ZIBs following steps are considered. First, i^{th} line is opened and corresponding entries are updated in Y matrix. To include the ZIBs presence Y_{new}, is determined as discussed in the previous sub-section and observability constraints for the i^{th} line outage are set as follows:

$$Y_{\mathrm{new},\,i} Z \geq 1 \quad (6)$$

C. Effect of Single PMU Outage Contingencies

This sub-section aims to ensure full observability of the power network even in the event of a single PMU outage. PMU being a device may stop functioning owing to the failure of any associated devices. In such cases, extra PMUs are installed to ensure network observability and to enhance reliability. These extra PMUs should be placed into the network in such a manner that every single bus is being observed by no less than two PMUs. To include the PMU loss effect the constraint in (2) is updated as follows:

$$YZ \geq 2 \quad (7)$$

III. SINE COSINE ALGORITHM

The Sine Cosine Algorithm (SCA) is a population-based technique driven by means of creating the initial population of arbitrary solutions that are made to oscillate inward or outward the optimal solution by incorporating a mathematical model based on sine and cosine functions [17]. In the case of population-based techniques, it is reasonably difficult to find an optimal solution in a single trial. Yet, the possibility of achieving a global optimal solution becomes high with a large population size and numerous iterations.

In this technique, the positions are updated by means of the following equation:

$$X_i^{t+1} = \begin{cases} X_i^t + c_1 \times sin(c_2) \times |c_3 P_i^t - X_i^t|, c_4 < 0.5 \\ X_i^t + c_1 \times cos(c_2) \times |c_3 P_i^t - X_i^t|, c_4 \geq 0.5 \end{cases} \quad (8)$$

Where X_i^{t+1} is the updated position of solution at t^{th} iteration, c_1, c_2, c_3 and c_4 represents the random numbers, P_i is the position of the destination point.

In SCA the exploration and exploitation are controlled by parameters c_1, c_2, and c_3. The parameter c_1 denotes the movement direction of the next position's region that can be lying within or outside the search space. The distance of movement towards or away from the destination is governed by parameter c_2. The parameter c_3 produces the weight to show the impact of the destination solution in defining the distance. The parameter c_4 oscillates within the sine and cosine component is represented in Eqn. 8.

IV. BINARY SINE COSINE ALGORITHM

SCA in its original form offers a means to solve continuous optimization problems. Optimization under binary search space is not similar to continuous search space. Therefore, modifications in the original SCA are required to make it suitable for binary optimization. In many literature, authors have employed transfer functions to make continuous soft computing suitable for solving binary optimization problems. In this work, to solve binary optimization problems with SCA algorithm, the S-shaped transfer function has been utilized.

Transfer function exploits the floating-point position values for each individual to find out a bounded probability in the interval [0, 1]. These probabilities then are exercised to produce a bit-string position vector from a floating-point vector. The following equations are then employed to update the position of search agents in binary search spaces*:*

$$S\left(y_i^d(t+1)\right) = \frac{1}{1+e^{-y_i^d(t)}} \quad (9)$$

The probability of ith is individual in d^{th} dimension is as per below:

$$y_i^d(t+1) = \begin{cases} 1, \text{if value} \leq S(y_i^d(t+1)) \\ 0, \text{if value} > S(y_i^d(t+1)) \end{cases} \quad (10)$$

The flowchart pertaining to binary sine cosine algorithm is shown in Fig. 1.

A. BSCA Algorithm applied to base case PMU placement problem

Step 1: Initialize the population of search agents, the maximum number of iteration, the dimension of search agents (Number of buses), constant 'a'.

Step 2: Evaluate the objective function which is the minimum number of PMUs (Eqn. 1) with consideration of penalty for constraint violation (Eqn. 2) for each search agent.

Step 3: Find out the search agent having the minimum count of PMUs with full power system observability.

Step 4: Calculate $c_1$and generate c_2, c_3 and c_4.

Step 5: Calculate the ∆X which is the change required in the position of member of the search agent.

Step 6: Apply sigmoid function on ∆X to calculate the probability of changing position (Eqn. 9) and depending upon the value of sigmoid function change the position of the member (Eqn. 10).

Step 7: Repeat Step 5 and 6 for each member of the search agents.

Step 8: Update the iteration count and repeat Step-2 to 7 up to the maximum number of iterations.

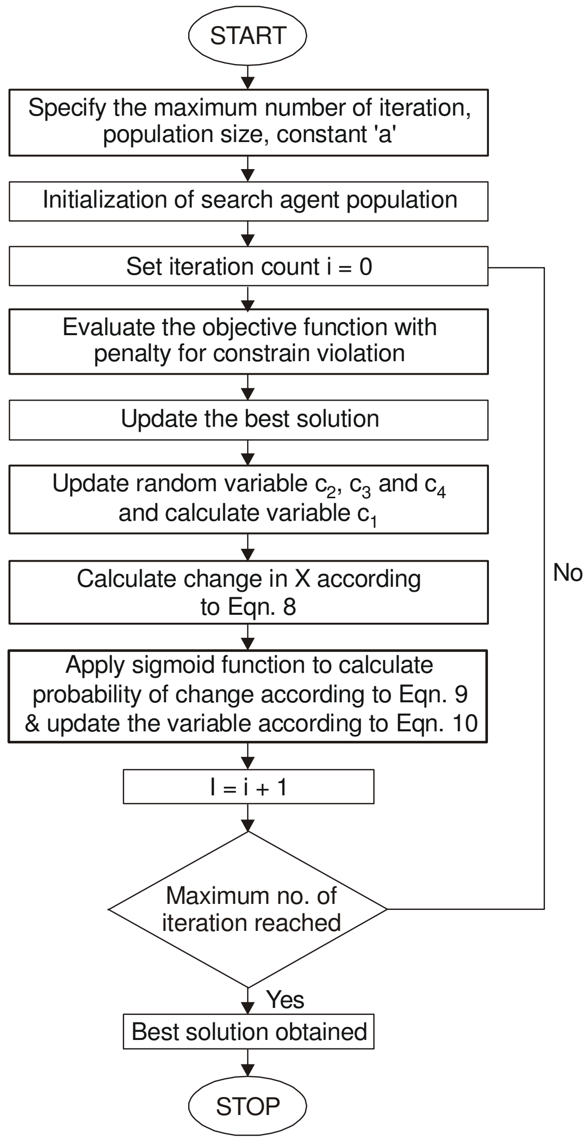

Fig. 1.

V. CASE STUDIES

In order to investigate the usefulness of the BSCA method, the optimization problem discussed in section-II has been executed on the WSCC-9 bus, IEEE-14 bus and IEEE-30 bus test system. Various data for these test systems have been taken from [18]. Additional information with reference to ZIBs (number and their respective location) have been accessed from [1]. To perform the required computation, a computer with Intel Core i3 processor, 2.4 GHz, 4 GB RAM has been utilized. Optimal PMU placement result for different test systems for the base case without and with consideration of ZIB effect is shown in Table 1(a) and (b).

Table 1(a): Optimal number and placement of PMUs without Incorporation of ZIBs.

Test System Considered	PMU required	Placement of PMUs at buses
WSCC 9 Bus	3	3,4,7
IEEE 14 Bus	4	2,7,10,13
IEEE 30 Bus	10	1,5,8,9,10,12,19,24,26,29

Table 1(b): Optimal number and placement of PMUs with Incorporation of ZIBs.

Test System Considered	PMU required	Placement of PMUs at buses
WSCC 9 Bus	2	4,8
IEEE 14 Bus	3	2,6,9
IEEE 30 Bus	7	2,4,10,12,19,24,29

From the study of Table 1(a) (b), it is evident that consideration of ZIB has a significant impact on optimal PMU numbers and their placement locations. For example, for the IEEE-30 bus test system, it can be viewed that the number of PMUs required without consideration of ZIBs are 10 whereas with consideration of ZIBs only 7 number of PMUs are necessary to achieve full observability. It is worth mentioning that there are 6 ZIBs available but 5 ZIBs have been utilized. Therefore it can be concluded that with consideration of ZIBs significant reduction in total installation cost can be achieved.

Results obtained by the BSCA method are compared with various methods explored in available literature and comparison is provided in Table 2. A comparison is carried out on the basis of the optimal number of PMUs while ensuring total network observability. From the study of Table 2, it can be viewed that BSCA also provides optimized results.

Table 2: Comparison of results obtained with various methods considering ZIBs.

IEEE- 14 bus system	IEEE-30 bus system	Methods
3	7	[5]
3	7	[19]
3	7	[20]
3	7	[21]
3	7	[22]
3	7	BSCA

Table 3 demonstrates the results pertaining to the optimal placement of PMUs for the condition where it is considered that PMUs are pre-installed at some of the buses. Optimized results obtained taking into consideration pre-installed PMUs should possess those locations where already PMUs have been installed.

It can be observed from Table 3 that in the IEEE-30 bus system under pre-installed PMUs condition, the obtained results include Location of Pre -Install PMUs and corresponding buses have been highlighted.

Table 3: Optimal number and placement of PMUs with consideration of pre-installed PMUs.

Test System	Location of Pre -Install PMUs	PMU required	Placement of PMUs at buses
WSCC 9 Bus	8	4	4,7,8,9
IEEE 14 Bus	5	5	3,**5**,6,8,9
IEEE 30 Bus	5,6,8,10	11	3,5,6,8,10,11,12,15,19,25,27

Table 4: Optimal number and placement of PMUs for Line Outage Case.

Test System Considered	Without Incorporation of ZIBs		With Incorporation of ZIBs	
	PMU required	Placement of PMUs at buses	PMU required	Placement of PMUs at buses
WSCC 9 Bus	6	1,2,3,4,7,9	4	1,2,3,9
IEEE 14 Bus	7	1,3,6,8,9,11,13	7	1,3,6,8,9,10,13
IEEE 30 Bus	16	2,3,7,8,10,11,13,14,15,16,19,22,23,26,27,29	13	2,3,7,10,11,12,13,15,16,19,24,26,29

Table 5: Optimal number and placement of PMUs for PMU Outage Case.

Test System Considered	Without Incorporation of ZIBs		With Incorporation of ZIBs	
	PMU required	Placement of PMUs at buses	PMU required	Placement of PMUs at buses
WSCC 9 Bus	6	1,2,3,4,7,9	4	3,4,5,8
IEEE 14 Bus	9	1,2,4,6,7,8,9,10,13	7	2,4,5,6,9,10,13
IEEE 30 Bus	21	1,2,3,6,7,8,9,10,11,12,13,15,16,18,20,22,23,25,26,29,30	14	1,2,4,5,10,12,13,15,17,18,19,24,27,29

Table 6: Comparison for number of PMUs required under line outage and bus outage contingency (IEEE 30 bus).

Single Line Outage	Single PMU Outage	Method
13	15	[5]
13	14	[16]
NA	16	[23]
NA	15	[24]
17	NA	[25]
13	14	BSCA

This study also considers different contingencies like single line-outage/PMU-outage. Taking into the consideration of contingencies results in more number of PMUs requirements in comparison to the base case condition. Results obtained under mentioned abnormal situations without and with consideration of ZIBs have been presented in Table 4 and 5.

In Table 4, the optimal number and placement of PMUs for different test systems pertaining to single line outage conditions have been listed. As the outage of the line leads to decrement in the observable path, therefore, more PMUs as compared to base case conditions are required in this situation. For example, the IEEE 30-bus test case, which is observed by 7 PMUs in base case condition, requires 13 PMUs in the single line outage with ZIBs condition.

In Table 5, the optimal number and placement of PMUs for different test systems pertaining to single PMU outage conditions have been listed. As the outage of PMU leads to a decrement in observable sources, therefore, more PMUs as compared to base case conditions are required in this situation. For example, IEEE 30-bus test case, which is observed by 7 PMUs in base case condition, requires 14 PMUs in the single PMU outage with ZIBs condition.

Results obtained by the BSCA method are compared with those available in literature and comparison is provided in Table 6 comparison is carried out on the basis of the optimal number of PMUs while ensuring total network observability for the IEEE-30 bus test case. The study of Table 6 reveals that BSCA offers improved optimized results in comparison to other methods.

Convergence curves for base case, single line outage and single PMU outage condition for IEEE 30 bus test system have been illustrated in Figs. 2, 3 and 4 respectively.

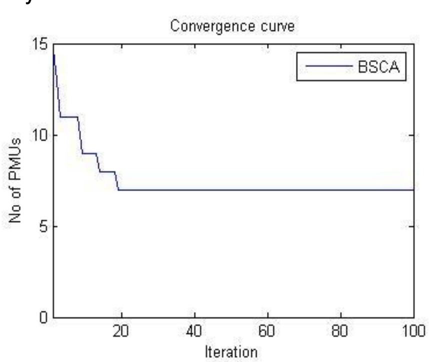

Fig. 2. Convergence curve for IEEE-30 bus system for base case.

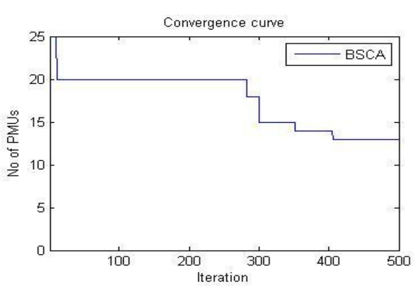

Fig. 3. Convergence curve for IEEE-30 bus system for single line outage case.

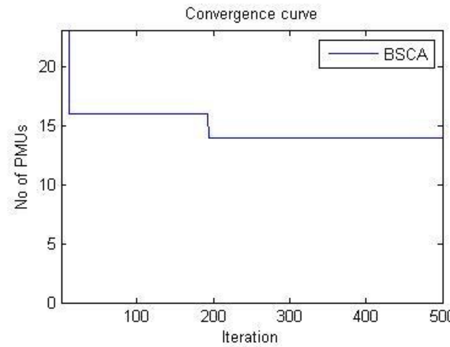

Fig. 4. Convergence curve for IEEE-30 bus system for single PMU outage case.

VI. CONCLUSION

In this paper, BSCA has been incorporated to solve optimal PMU placement problems and ensure full network observability. In this regard, a mathematical formulation of the considered problem is presented. Optimized results obtained taking into consideration pre-installed PMUs have been presented. Furthermore, it has been presented that consideration of ZIB has a significant impact on optimal PMU placement problems. It has been demonstrated that consideration of contingencies (single line-outage/PMU-outage) results in more number of PMUs requirements in comparison to the normal (base case) condition. The efficacy of the proposed approach is validated by implementing it on the various standard (IEEE 14 bus and IEEE 30 bus) test systems. Comparison of results with those presented in literature has been prepared.

VII. FUTURE SCOPE

In the future, the presented work can be extended with more constraints like channel limit, minimum deviation in state estimation during contingency etc. The presented work can be extended as multi-objective or co-optimization problem with consideration of communication infrastructure.

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Conflict of Interest. No.

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