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Original scientific paper

# Optimal PMU Placement for Türkiye 400 kV Interconnected Power System Observability with Dragonfly Algorithm

Beytullah BOZALİ*, Ali OZTÜRK, Salih TOSUN, Bülent HOŞ

**Abstract:** The Phasor Measurement Unit (PMU) is a modern measuring device built on the system for monitoring, controlling, and protecting power systems. Since the costs of PMU devices are very high, they must be placed in the system in optimum numbers and in a way that monitors the whole system. This study determined the locations and numbers of the optimal number of PMU devices that can monitor the whole system. Integer Linear Programming (ILP) and Binary Particle Swarm Optimization (BPSO) methods are proposed to solve the optimum PMU placement (OPP) problem. Then, the solution to the problem is carried out using Dragonfly Algorithm (DA), which is proposed as a new heuristic method. Solution methods were applied to the IEEE 14-Bus Test System and Türkiye 400 kV Interconnected Power System, and the results were compared. In addition, the results of the proposed methods were compared with the results of different studies in the literature. Thanks to the ILP, BPSO, and DA methods proposed in this study, it has been determined that power systems can be observed with fewer PMU devices. The DA method offers a great cost advantage as it is the method that provides a solution with 5 fewer PMU devices for the 400 kV Interconnected Power System in Türkiye.

**Keywords:** dragonfly algorithm (DA); integer linear programming (ILP); optimal PMU placement (OPP); observability; PMU

## 1 INTRODUCTION

Large interconnected power systems must be reliably observed for stable planning and operation. Observation of the power system is provided by PMU devices. PMU devices measure basic electrical quantities such as voltage, current, phase angle, and frequency [1]. PMU measurements have become important in power systems due to the benefits they provide in studies to reduce risks against cyber-attacks, Volt-VAr control, which is expressed as reactive power control, and transmission network state estimation studies [2-5]. They have done different studies using power systems and IEEE bus systems [6-9]. They applied state estimation for different power systems with synchronized phasor measurements provided using PMU [10]. PMU devices play an important role in condition forecasting, wide-area monitoring, and control, as they provide voltage and current phasor measurements for the power grid [11]. PMU devices are very costly devices and therefore large budgets are needed for the use of these devices [12, 13]. OPP studies include the determination of the optimal number of PMUs and their corresponding locations to ensure the observability of the entire power system [14]. The PMU at any bus also observes neighboring buses and transmission lines in accordance with Ohm's Law and Kirchhoff's Current Law (KCL). This allows the power system to be observable with fewer PMU devices. [11, 12, 15].They have implemented overload reduction using System Integrity Protection Schemes (SIPS) powered by PMU technology [16]. Different methods have been used for OPP, such as Depth First Search Method (DFSM), Graph Theory Method, Simulation Annealing (SA) Method, Recycled Tree, and Direct Spanning Tree, using the Power System Analysis Toolbox (PSAT). In addition, the PMU placement results obtained by applying the ILP method to the power system were compared [17]. Kumar et al. in their study proposed OPP solutions using ILP and Genetic Algorithm (GA). The proposed methods have been applied to the Institute of Electrical and Electronics Engineers (IEEE) Bus Test Systems and the Indian Southern Grid system [18]. For OPP, the GA-based search method, which consists of using the GA method and the GA toolbox, was compared with the ILP method. Its results have been applied to IEEE test systems [19]. In his study, Gou suggested the ILP method for OPP, taking into account cases with and without Zero-injection bus (ZIB) [20]. A new ILP method was used to include the ZIB effect in OPP. The visualization technique was used to show the positions of the PMUs obtained from the OPP [21]. The OPP is investigated considering the inclusion of ZIBs in normal system states and the contingency of PMU interruption. The proposed method was tested on IEEE 14, 24, 30, 118 Bus Test Systems and the Polish 2383-bus test system [22]. Modified Whale Optimization Algorithm (MWOA) and Fuzzy-based Modified Whale Optimization Algorithm (FMWOA) based on simultaneous optimization are proposed for the OPP problem [23]. Binary Dragonfly Algorithm (BDA) is used for optimum placement of PMU and smart meters in distribution networks. Arshia et al. emphasized that BDA's method of working in quality, cost, accuracy, and the minimum number of measuring devices had excellent achievements [24].

In this study, a new method, ILP, DA methods, and BPSO is proposed to solve the OPP problem, different from the methods studied in the literature. The proposed methods have been applied to IEEE 14-Bus Test System and real-time Türkiye 400 kV Interconnected Power System. The results of the proposed methods were compared with the OPP results found for IEEE 14-Bus Test System in the literature for better understanding. The DA method has not been applied in the literature for the solution of OPP problems before, and it has been used for the first time in this study and it has been seen that it produces better solutions. DA is a new heuristic method and it has not been applied to IEEE bus systems and Türkiye 400 kV Interconnected Power System before. BOI and SORI values were found for IEEE 14-Bus Test System and the Türkiye 400 kV Interconnected Power System using the DA method. The application of ILP, DA, and BPSO methods on the 400 kV Interconnected Power System of Türkiye for the solution of the OPP problem has been carried out for the first time with this study. The DA method used in our study has the ability to optimize different and complex problems. In addition, the results obtained are reliable and have a faster convergence rate. These features make the DA method superior to other methods used in the literature. The costs of PMU devices are quite high. For this reason, it is of great importance to determine the minimum number of PMU devices that can monitor the entire power system and to determine the places where these devices will be connected. In this study, solutions are provided for the IEEE test systems and the Türkiye interconnected power system, and solutions for the optimum number of PMUs and settlements are produced. The obtained solutions reveal that fewer PMU devices can be used compared to the solutions in the literature. Observing the power system with the PMU provides great convenience for those who plan the operation of the system and those who control it.

## 2 PMU TECHNOLOGY AND STRUCTURE

The PMU device is produced in such a way that it can measure voltage and current phasors in the power system, instantaneously and in time synchronization [15]. For the monitoring and control of the power system, the fact that the PMU devices have synchronized phasor calculation capability increases the importance of the device. A block diagram of PMU is given in Fig. 1 [25, 26].

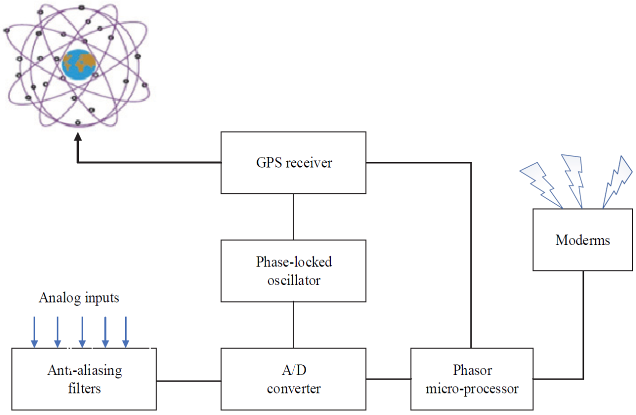

**Figure 1** PMU block diagram

## 3 PMU PLACEMENT PROBLEM FORMULATIONS

Due to the high costs of the PMU devices, it would not be possible to place PMUs on the entire bus system of electrical power system [27]. The objective function is to reduce the number of PMUs and find their optimal location [22]. The definition of the location of the PMU is a mathematical optimization problem. OPP's problem is to identify the location of the buses on which the least number of PMUs will be installed for the whole system to be completely observable [28]. There is a need for an objective function in optimization studies to lessen the number of PMUs. This objective function must satisfy some conditions.

Eq. (1) expresses the case where at least one PMU is connected to any bus in the power system. Where $x_i$ refers to the $i^{th}$ bus wherein PMU is placed. Eq. (2) expresses the objective function that includes the cost and number of the PMU. Where, $x_i$ is the expression showing the PMU location information, $w_i$, is the PMU installation cost on the $i^{th}$ bus, and $N$ is the total number of buses in the system. Eq. (3) and Eq. (4) express constraints. In Eq. (4), $X$ is the decision vector given in binary number system values and each line of the matrix $[A]$ expresses whether there are any transmission lines between a bus and the other buses based on the bus number. If there is a transmission line connection between two buses, it is indicated by "1", otherwise it is indicated by "0".

$$x_i = \begin{cases} 1 \text{ if } PMU \text{ is placed at } i^{th} \text{ bus} \\ 0 \text{ otherwise} \end{cases} \tag{1}$$

$$Obj = \min \sum_{i=1}^{N} w_i x_i \tag{2}$$

$$\text{Subject to}: f(x) \geq [b] = \begin{bmatrix} 1 \\ 1 \\ . \\ . \\ 1 \end{bmatrix} N \times 1 \tag{3}$$

$$f(x) = [A][X] \tag{4}$$

$$\text{s.t.}: f(x) \geq 1 \tag{5}$$

The OPP formulation lessens PMUs and ensures simultaneous observability of each bus geometrically. When its observability is provided in Eq. (5), the power system is considered to be fully observable [29]. $f(x)$ expresses whether there is a PMU on a bus and the number of PMUs, it is calculated by multiplication of matrix $[A]$ and $[X]$. The element values of the matrix $[A]$ are determined using Eq. (6).

$$amn = \begin{cases} 1, & \text{if } m = n \\ 1, & \text{if bus } m \text{ is connected to bus } n \\ 0, & \text{if otherwise} \end{cases} \tag{6}$$

In this study, unit prices ($w_i$) of buses placed on the power system are considered to be 1 so the optimal PMU placement problem is represented by Eq. (7), and the constraint equation is re-organized based on Eq. (3) and Eq. (4).

$$\min \sum_{i=1}^{N} x_i \tag{7}$$

For a power system with $N$ number of buses, OPP calculates the location and number of buses to be placed through Eqs. (1) to (6) [30]. Placement of PMUs is considered from Eq. (6). The decision variable, by this equation, holds the value of "1" if PMUs exist, and holds the value of "0" in the absence of them.

### 3.1 Bus Observability Index

*SORI* is a requirement to solve the problem of fully observing the optimum PMU system. The *SORI* is used to calculate all system observability by summing the *BOI*s of all the buses in a power system [31].

$$TSORIs = \sum_{i=1}^{N_B} BOI_i \tag{8}$$

where *TSORIs* is the total power system observability redundancy index. From Eq. (8), *BOI* represents the actual number of PMUs that can follow bus *i*. *BOI* defines the whole number of buses connected to the *i* bus, including the *i* bus. *SORI* is the sum of all *BOI*s observed by the PMU. The largest number of *SORI*s is considered the best solution for the power system. For full observability, the bus *i* ($\tau_i$) should be in the range of one to maximum connectivity. The reason for adding ($\tau_i$) from Eq. (9) is when the PMU is placed on the busbar, it can measure the voltage phasor information of the bus and all the buses [23].

The limitation of *BOI* is expressed as:

$$1 \leq BOI_i \leq (\tau_I + 1) \tag{9}$$

### 3.2 System Observability and Reliability

To solve complex OPP problems, the $SORI_m$ index is considered to maximize the observable and reliable levels of the power system and is expressed as follows [23, 32].

$$SORI_m = \left( \sum_{i \varepsilon r} LRBOI_i + \sum_{i \varepsilon N-r} BOI_i \right) \tag{10}$$

From Eq. (10), $LRBOI_i$ is the number of PMUs that can monitor the low-reliability bus. *i* and *r* are the number of low-reliability buses.

The limitation of *LRBOI* is expressed as:

$$2 \leq LRBOI_i \leq (\tau_i + 1) \tag{11}$$

From Eq. (9) and Eq. (11), since the PMU placed on a busbar can measure the voltage phasors of that busbar and all the neighboring busbars connected to it, it is added with the number of branches ($\tau_i$) connected to it

## 4 METHODS FOR INSTALLATION OF PMUS ON POWER SYSTEM

The constraints of the power grid must be observable by at least one PMU of each node [33]. Strategic bus is determined in the power system to monitor the system with least number of PMUs. [32, 34]. In our study, solutions were obtained with a new graphically visualized method, ILP, BPSO and a new heuristic method, DA, and the solutions were compared with the studies in the literature.

### 4.1 Integer Linear Programming

ILP is commonly used in the literature mathematical technique. In this study, a new ILP method is formulated to find the optimum PMU number and locations for OPP by considering ZIBs.

$$\text{Minimize} \sum\nolimits_{i=1}^{N} c_i \, X_i \tag{12}$$

$$\text{Subject to}\, f_i = \sum\nolimits_{j=1}^{N} a_i,_j \, X_j \geq 1 \forall i \tag{13}$$

$$X_i = \begin{cases} 1 \text{ if a PMU is installed at Bus} - i \\ 0 \text{ otherwise} \end{cases} \tag{14}$$

where $c_i$ is the total installation cost of PMU-*i*; $a_{i,j}$ is the *i*, *j*-th entry of the connectivity matrix

$$a_{i,j} \begin{cases} 1 \text{ if } i = j \\ 1 \text{ if } i \text{ and } j \text{ are connected} \\ 0 \text{ otherwise} \end{cases} \tag{15}$$

where *N* power is the total number of buses in the system.

From Eq. (12), it is the objective function. It provides the optimum number of PMUs to fully monitor a power system. Eq. (13), ensures that all transmission lines in the Power Systems are observable with at least one PMU. The number of times it is reached by a bus PMU, a term such as $R_i$ is added to the objective function [35].

$$\text{Minimize} \sum\nolimits_{i=1}^{N} c_i \, X_i - \sum\nolimits_{i=1}^{N} R_i \tag{16}$$

In Eq. (16) $R_i$, *i* - is the measurement redundancy of the bus. A negative sign is added to the measurement redundancy to transform the maximization problem into the goal of the optimal target model [21].

### 4.2 Dragonfly Algorithm

The DA optimization technique, which has been developed in recent years and finds better solutions than other heuristic optimizations, has been applied to solve the OPP problem in the best way. Unique and rare intelligent behavior is seen in hunting traits. Moving back and forth for prey, dragonflies fly in small groups in a static flock. Local movement and sudden changes in flight path are key features of the static swarm. However, in dynamic flocks, large numbers of dragonflies make long journeys in large groups for migration [36]. Reynold allocated three basic principles of herd behavior [37].

Separation means avoiding collision with other people in the neighborhood. Alignment shows speed and harmony with other individuals in the neighborhood. Harmony refers to the tendency of individuals toward the center of the neighborhood mass. The main purpose of any herd is to survive and therefore individuals must tend towards their food source. Besides this main action, the pack can be disturbed by outside enemies. If these two behaviors are added, five main factors are used in the location update process and are given in Fig. 2 [38].

According to Rahman et al. in their work, they emphasize that DA has the ability to optimize different and complex problems in various fields [39]. They discovered that DA is one of the practical techniques in the field. The simplicity of DA is one of the reasons that encourages researchers to use the algorithm to optimize the problems at hand. Another reason is the accuracy of the algorithm and the speed of convergence [40].

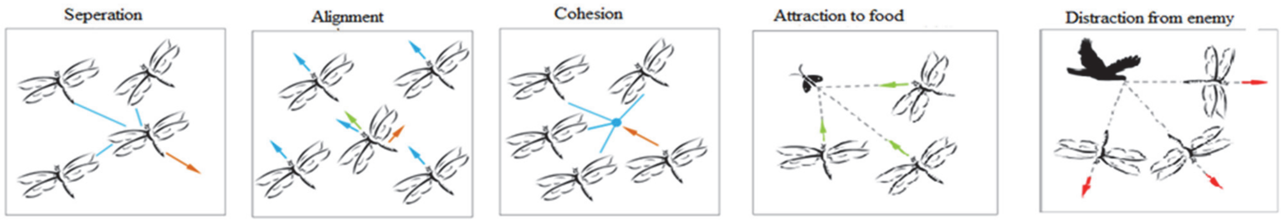

**Figure 2** Corrective patterns among members of the herd

The mathematical models of each of these behaviors are as follows [34].

The separation is calculated as follows

$$S_i = -\sum_{j=1}^{N} X - X_j \tag{17}$$

$X$ in Eq. (17) is the position of the current individual, and $j$ in $Xj$ indicates the position of the neighboring individual. $N$ is the number of neighboring individuals. Alignment is calculated as follows:

$$A_i = \frac{\sum_{j=1}^{N} V_j}{N} \tag{18}$$

In the value of $V_j$ in Eq. (18) $j$ - indicates the speed of the neighboring individual. The cohesion is calculated as follows:

$$C_i = \frac{\sum_{j=1}^{N} X_j}{N} - X \tag{19}$$

Attraction towards a food source is calculated as follows:

$$F_i = X^{+} - X \tag{20}$$

The $X^{+}$ expression in Eq. (20) indicates the position of the food source. The outward behavior in the face of an enemy threat is calculated as follows. The $X^{-}$ in Eq. (21) indicates the position of the threatening enemy.

$$E_i = X^{-} + X \tag{21}$$

Two vectors, $\Delta X$ step and $X$ position, are considered to update the positions of artificial dragonflies and simulate their movements.

$$\Delta X_{t+1} = (sS_i + aA_i + cC_i + fF_i + eE_i) + w\Delta X_t \tag{22}$$

In Eq. (22), $s$ - separation, $a$ - alignment, $c$ - cohesion, $f$ - nutrient, $e$ - enemy, represent the weight values of the factors. Also, the value of $w$ is $t$ and it shows the inertia weight in the loop. After calculating the step vector, the position vector in Eq. (23) below is calculated.

$$X_{t+1} = X_t + \Delta X_{t+1} \tag{23}$$

Random walking (Le'vy flight) was used to improve the randomness, stochastic behavior, and exploratory properties of artificial dragonflies. The positions of the dragonflies are updated using the equation below.

$$X_{t+1} = X_t + \text{Le'vy}(d) * X_t \tag{24}$$

From Eq. (24) $t$ represents the current loop and $d$ represents the size of the position vector. The pseudo-code of the DA algorithm is given in Fig. 3 [38].

```
Start the dragonfly's population $X_i$ ($i$ = 1, 2, ..., $n$)
Start step vectors $\Delta X_i$ ($i$ = 1, 2, ..., $n$)
while the end condition is not satisfied
    Calculate the aim values of all dragonflies
    Modernize the food source and enemy
    Modernize $w$, $s$, $a$, $c$, $f$, and $e$
    Calculate $S$, $A$, $C$, $F$, and $E$ using Eqs. (17) to (21)
    Modernize neighboring radius
    if a dragonfly has at least one neighboring dragonfly
        Modernize velocity vector using Eq. (22)
        Modernize position vector using Eq. (23)
    else
        Modernize position vector using Eq. (24)
    end if
    Check and correct the new positions based on the boundaries of
variables
end while
```

**Figure 3** Pseudo-codes of the DA algorithm

## 4.3 Binary Particle Swarm Optimization (BPSO)

Considering the studies with swarm-based algorithms, Particle Swarm Optimization (PSO) and BPSO swarm-based algorithms are among the most used studies [41]. BPSO was developed by Kennedy and Eberhardt to overcome discrete problems and improve the applicability of PSO [42]. PSO steps and BPSO steps are similar. The only difference between BPSO and PSO is that location update is done differently in BPSO. Sigmoid function values are calculated according to the velocity value of each particle and the position of the particles is updated. [43, 44].

# 5 SOLUTIONSTO THE PROBLEM

The applied methods provided a solution for the IEEE 14-Bus Test System given in Fig. 4 [45]. The proposed methods have been applied to IEEE 14-Bus and real-time Türkiye 400 kV Interconnected Power System. The results of the proposed methods are compared with the studies in the literature for a better understanding.

In Eq. (25), $N$ = 14, and $i$ = 1, 2, 3, 4, 5, ..., 14 were taken and the objective function (Eq.(25)) is obtained for IEEE 14-Bus Test System [46].

$$\min = \sum_{i=1}^{14} w_i \cdot x_i \tag{25}$$

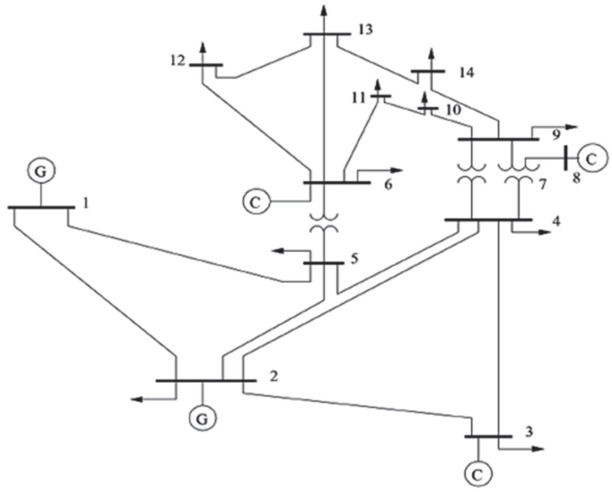

**Figure 4** Single line diagram of IEEE 14-bus modified test system

Matrix [*A*] form for the IEEE 14-Bus Power System is obtained using the rules presented in Eq. (6) and presented in Eq. (26).

$$[A]=\begin{bmatrix} 1\,1\,0\,0\,1\,0\,0\,0\,0\,0\,0\,0\,0\,0 \\ 1\,1\,1\,1\,1\,0\,0\,0\,0\,0\,0\,0\,0\,0 \\ 0\,1\,1\,1\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0 \\ 0\,1\,1\,1\,1\,0\,1\,0\,1\,0\,0\,0\,0\,0 \\ 1\,1\,0\,1\,1\,1\,0\,0\,0\,0\,0\,0\,0\,0 \\ 0\,0\,0\,0\,1\,1\,0\,0\,0\,0\,1\,1\,1\,0 \\ 0\,0\,0\,1\,0\,0\,1\,1\,1\,0\,0\,0\,0\,0 \\ 0\,0\,0\,0\,0\,0\,1\,1\,0\,0\,0\,0\,0\,0 \\ 0\,0\,0\,1\,0\,0\,1\,0\,1\,1\,0\,0\,0\,1 \\ 0\,0\,0\,0\,0\,0\,0\,0\,1\,1\,1\,0\,0\,0 \\ 0\,0\,0\,0\,0\,1\,0\,0\,0\,1\,1\,0\,0\,0 \\ 0\,0\,0\,0\,0\,1\,0\,0\,0\,0\,0\,1\,1\,0 \\ 0\,0\,0\,0\,0\,1\,0\,0\,0\,0\,0\,1\,1\,1 \\ 0\,0\,0\,0\,0\,0\,0\,0\,1\,0\,0\,0\,1\,1 \end{bmatrix} \quad (26)$$

Function equations of the IEEE 14-Bus Testing System, which were converted into constraint functions in the matrix [*A*] are presented in Eq. (27).

$$f(x)=[A][X]=\begin{cases} f1 = x1+x2+x5 & \geq 1 \\ f2 = x1+x2+x3+x4+x5 & \geq 1 \\ f3 = x2+x3+x4 & \geq 1 \\ f4 = x2+x3+x4+x5+x7+x9 & \geq 1 \\ f5 = x1+x2+x4+x5+x6 & \geq 1 \\ f6 = x5+x6+x11+x12+x13 & \geq 1 \\ f7 = x4+x7+x8+x9 & \geq 1 \\ f8 = x7+x8 & \geq 1 \\ f9 = x4+x7+x9+x10+x14 & \geq 1 \\ f10 = x9+x10+x11 & \geq 1 \\ f11 = x6+x10+x11 & \geq 1 \\ f12 = x6+x12+x13 & \geq 1 \\ f13 = x6+x12+x13+x14 & \geq 1 \\ f14 = x9+x13+x14 & \geq 1 \end{cases} \quad (27)$$

### 5.1 OPP for IEEE 14-Bus Systems with ILP

Since the price of the PMU device is high and its use is costly, the minimum number of PMUs and positions obtained by considering the ZIBs in the system have been found. The ILP method uses graph theory and GIS to visualize OPP results on a map. Tab. 1 shows the OPP results when ZIBs are included in the system. When the results were compared with the studies in the literature, better results were obtained with the ILP method.

**Table 1** Results of IEEE 14-bus test system simulations

| Systems | Number of PMUs | Location of PMUs |
|---|---|---|
| IEEE-14 bus | 3 | 2, 6, 9 |

For OPP in Fig. 5, the ILP method is used to visualize busbar systems on a map using graph theory and GIS. PMU positions in red with ZIB buses in yellow with lines directly controlled by the PMU in blue with lines not directly observable by the PMU (which become observable using Ohm Law and KCL) in green, both ZIB bus and PMU placed in dark red, by two PMUs observed lines are visualized in red.

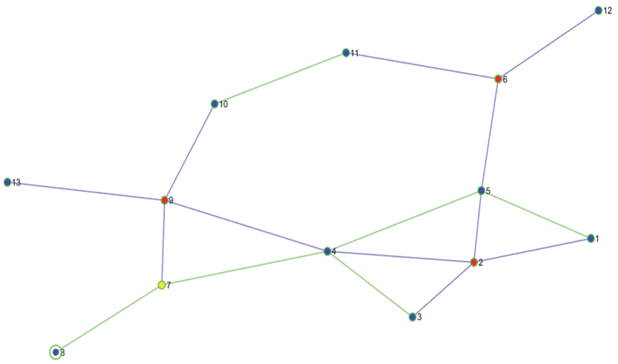

**Figure 5** PMU locations for EEE 14-bus (red), ZIB (yellow), lines with PMU (blue), and lines with no PMU (green)

### 5.2 Comparison of Results with Different Methods

### 5.2.1 IEEE 14-Bus System

In the literature, many different methods have been studied for OPP for IEEE bus systems. Tab. 2 shows ILP, GA, Nonlinear Programming (NLP), (MWOA), and Flower pollination algorithm (FPA) OPP results obtained using such methods. In addition, the results of a new heuristic method DA and a new visualized ILP method are given in Tab. 2. The optimum number of PMUs and positions obtained under normal operating conditions of the DA and ILP method, and the optimum number and positions of PMUs obtained by considering ZIB are given. In Tab. 2, the OPP results obtained using DA, BPSO, and ILP methods for the IEEE 14-bus system are compared with the results found in the literature. Similar results were found to those found in the literature. For this reason, DA, BPSO, and ILP methods are presented as alternative and reliable solution techniques. After DA, BPSO and ILP proved that it is the correct and reliable method, The Türkiye 400 kV Interconnected Power System was applied.

The OPP results obtained for the DA method IEEE 14-Bus Test System proposed in this study and the OPP results of the BPSO, GA, MWOA, NLP, FPA, ILP, and Groebner bases methods in the literature are given in Tab. 2. The results obtained are almost the same as the results of the DA method. This situation proved the reliability of the DA method used as an alternative solution proposed in this study. The reliable DA method has been applied for the first time in this study to solve the OPP problem on the 400 kV Interconnected Power System in Türkiye and reliable results have been obtained.

**Table 2** Comparison of OPP results for IEEE 14-bus system

| Methods | Number of PMUs | PMU locations | *TSORIs* |
|---|---|---|---|
| **DA** | **4*** | **2, 6, 7, 9** | **19** |
| **DA** | **3*** | **2, 6, 9** | **17** |
| **ILP** | **3**** | **2, 6, 9** | **---** |
| **BPSO** | **4*** | **2, 6, 7, 9** | **19** |
| **BPSO** | **3**** | **2, 6, 9** | **15** |
| Groebner bases algorithm [22] | 4* | 2, 8, 10, 13 | ---- |
| | 3** | 2, 6, 9 | --- |
| GA [47] | 4 | **2, 6, 7, 9** | **19** |
| | | 2, 6, 8, 9 | 17 |
| | | 2, 8, 10, 13 | 14 |
| | | 2, 7, 11, 13 | 16 |
| | | 2, 7, 10, 13 | 16 |
| ILP [14] | 4 | 2, 6, 7, 9 | --- |
| NLP [14] | 4 | 2, 8, 10, 13<br>2, 6, 8, 9<br>2, 7, 11, 13<br>2, 7, 10, 13<br>**2, 6, 7, 9** | 14<br>17<br>16<br>16<br>**19** |
| ILP [48] | 4* | 2, 6, 7, 9 | |
| | 3** | **2, 6, 9**<br>3, 6, 9 | **15**<br>13 |
| MWOA [23] | 4* | **2, 6, 7, 9**<br>2, 7, 10, 13<br>2, 6, 8, 9<br>2, 7, 11, 13<br>2, 8, 10, 13 | **19**<br>16<br>16<br>16<br>14 |
| | 3** | 2.6,9 | 16 |
| FPA [49] | 4* | 2,6,7, 9<br>2,6, 8, 9 | 19<br>17 |
| | 3** | 2, 6, 9 | 15 |

*The optimal number of PMUs and positions were obtained under normaloperating conditions.

**The optimal number of PMUs and positions obtained considering ZIB.

### 5.3 OPP for IEEE 14 Bus Systems with DA

In this study, the OPP process is used for the first time for IEEE 14-Bus System, the DA method, which is a new heuristic method. The optimum PMU number and positions obtained under normal operating conditions of the DA method, and the optimum PMU number and positions obtained considering ZIB are given in Tab. 3.

**Table 3** IEEE 14-buses system optimal for PMU placement results

| Number of PMUs | Optimal PMU locations | *BOI* | *TSORIs* |
|---|---|---|---|
| 4* | 2, 7, 10, 13 | 1, 1, 1, 2, 1, 1, 1, 1, 2, 1, 1, 1, 1, 1 | 16 |
| | 2, 7, 11, 13 | 1, 1, 1, 2, 1, 2, 1, 1, 1, 1, 1, 1, 1, 1 | 16 |
| | 2, 8, 10, 13 | 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1 | 14 |
| | 2, 6, 8, 9 | 1, 1, 1, 2, 1, 1, 2, 1, 1 ,1, 1, 1, 1, 1 | 16 |
| | **2, 6, 7, 9,** | **1, 1, 1, 3, 2, 1, 2, 1, 1, 1, 1, 1, 2, 1** | **19** |
| 3** | **2, 6, 9** | **1, 1, 1, 2, 1, 1, 2, 1, 1, 1, 1, 1, 2, 1** | **17** |
| | 3, 6, 9 | 1, 1, 1, 2, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1 | 15 |

### 5.4 Simulation of Türkiye 400 kV Interconnected Power System

The Türkiye 400 kV Interconnected Power System was modeled using PSAT, which is a computer-aided simulation program. Türkiye 400 kV Interconnected Power System consists of 160 buses and 257 transfer lines. Türkiye 400 kV Interconnected Power System was modeled on the PSAT program using MATLAB 2018b. If the Türkiye 400 kV Interconnected Power System is to be modeled as per Eq. (2), the problem formulation of the power system would be as depicted in Eq. (28).

$$\min = \sum_{i=1}^{160} w_i \cdot x_i \tag{28}$$

When taking the values $x_i \in \{0, 1\}$ in Eq. (28), $i$ takes the values $i = 1, 2, 3, 4, 5, \ldots, 160$. When the bus matrix forms for the Türkiye 400 kV Interconnected Power System are generated, matrix forms similar to the ones in Eq. (26) are generated using Eq. (6). The dimension of this matrix form generated is 160 × 160. Eq. (3) and Eq. (4) are used to convert the matrix form into a limit function. The limit function is generated as $f1, f2, f3, f4, f5, \ldots, f160 \geq 1$ similar limit functions given in Eq. (27).

#### 5.4.1 OPP for Türkiye 400 kV Interconnected Power System with ILP

By using the ILP method, the bus locations and bus numbers where the optimal PMU should be placed for the 400 kV Interconnected Power System to be fully observable in Türkiye are given in Tab. 4 and visualized in Fig. 6. It will be sufficient to use 50 PMU devices to observe the whole system, and line currents that cannot be directly measured by the PMU can be found by using Ohm's law.

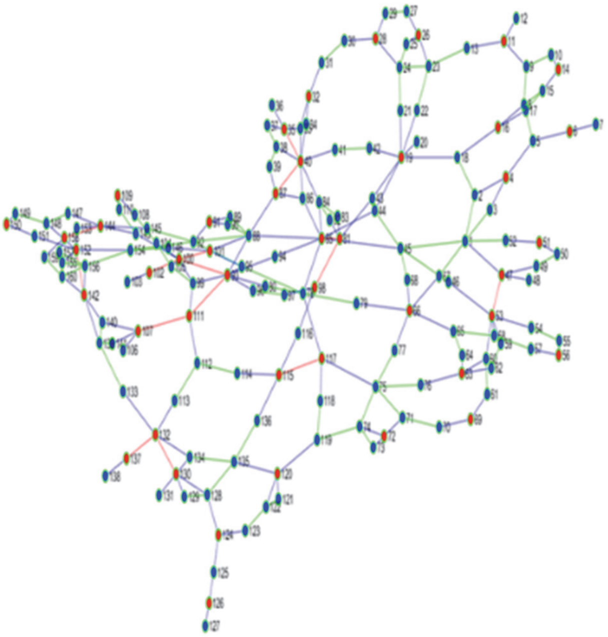

**Figure 6** Türkiye 400 kV Interconnected Power System, PMU locations (red), lines observed by PMU device (blue), lines not observed by PMU (green), lines observed by two PMUs (red)

**Table 4** OPP results for Türkiye 400 kV interconnected power system

| Number of buses | The optimal number of PMUs | Optimal PMU Locations |
|---|---|---|
| Türkiye 400 kV interconnected power system (160-bus) | 50 | 1, 4, 6, 11, 14, 16, 19, 23, 26, 28, 32, 35, 40, 47, 51, 53, 56, 59, 63, 66, 69, 72, 75, 81, 85, 87, 91, 92, 93, 98, 100, 101, 102, 107, 109, 111, 115, 117, 120, 124, 126, 130, 132, 137, 142, 144, 150, 152, 156, 158 |

### 5.4.2 OPP for Türkiye 400 kV Interconnected Power System with DA

DA method has been applied to the existing 400 kV interconnected power system in Türkiye. Results are found by solving the problem formulation of the Optimal Layout of PMUs which aim to minimize the installation of the required number of PMUs subject to DA full network observability and maximize reliability for better operation of power systems. Also, *BOI* and *SORI* were used to better rank multiple solutions. Optimal PMU placement results using the DA method are given in Tab. 5. The DA method shows the ability to analyze all power systems in a short time and to determine the minimum PMU number and location.

According to the results of Tab. 5, 49 PMU devices must be connected to fully observe the system. The solution with the maximum *SORI* value is considered the best optimal solution. In Tab. 5, 49 PMU solutions with a *SORI* of 302 are considered the best optimal solution. It will be sufficient to use 49 PMU devices to observe the whole system, and line currents that cannot be directly measured by the PMU can be found by using Ohm's Law.

**Table 5** OPP results using DA method for Türkiye 400 kV interconnected power system

| Number of PMUs | Optimal PMU Locations | *BOI* | *TSORIs* |
|---|---|---|---|
| **49** | **2, 7, 13, 15, 20, 24, 26, 32, 36, 41, 42, 48, 51, 56, 58, 61, 71, 72, 74, 78, 80, 81, 85, 92, 95, 96, 98, 101, 102, 103, 104, 107, 109, 111, 114, 116, 118, 119, 121, 123, 124, 126, 127, 135, 136, 141, 143, 150, 156** | **3, 2, 1, 2, 3, 2, 2, 3, 2, 1, 2, 2, 2, 2, 1, 1, 2, 1, 2, 2, 1, 2, 1, 1, 2, 1, 2, 2, 1, 2, 2, 2, 1, 1, 4, 1, 1, 1, 2, 2, 1, 1, 2, 1, 4, 1, 1, 2, 2, 2, 1, 2, 5, 2, 2, 1, 2, 2, 2, 2, 2, 2, 1, 2, 1, 4, 1, 1, 1, 3, 1, 1, 2, 2, 1, 1, 3, 2, 1, 1, 1, 2, 1, 4, 1, 2, 2, 1, 2, 3, 3, 4, 2, 1, 2, 2, 1, 2, 1, 3, 1, 1, 2, 1, 2, 1, 2, 1, 1, 2, 1, 2, 1, 2, 1, 4, 2, 1, 2, 1, 2, 2, 2, 1, 2, 1, 2, 3, 4, 2, 3, 2, 2, 2, 2, 2, 1, 3, 2, 2, 4, 1, 2, 1, 2, 1, 3, 2, 2, 2, 5, 2, 4, 3, 5, 2, 1, 2, 2, 2** | **302** |
| 50 | 1, 2, 7, 8, 10, 14, 15, 16, 27, 28, 31, 34, 40, 43, 48, 53, 54, 56, 57, 58, 61, 63, 65, 69, 70, 71, 72, 75, 83, 85, 91, 98, 99, 103, 105, 112 ,113, 117, 118, 123, 134, 135, 140, 143, 144, 145, 147, 150, 153, 156 | 3, 1, 1, 2, 3, 2, 1, 3, 2, 1, 2, 2, 1, 2, 1, 1, 2, 1, 2, 2, 1, 1, 1, 1, 2, 1, 2, 2, 1, 1, 2, 2, 1, 1, 4, 1, 1, 1, 2, 2, 1, 1, 1, 1, 4, 1, 1, 1, 2, 2, 1, 2, 5, 2, 2, 1, 2, 2, 2, 2, 2, 2, 1, 1, 1, 4, 1, 1, 1, 3, 1, 1, 2, 2, 1, 1, 3, 2, 1, 1, 1, 1, 1, 4, 1, 2, 2, 1, 2, 3, 3, 4, 1, 1, 2, 2, 1, 1, 1, 3, 1, 1, 2, 1, 2, 1, 1, 1, 1, 1, 1, 2, 1, 2, 1, 4, 2, 1, 1, 1, 2, 2, 2, 1, 1, 1, 2, 3, 4, 2, 3, 2, 2, 2, 1, 2, 1, 3, 2, 2, 4, 1, 1, 1, 2, 1, 3, 2, 2, 2, 6, 1, 4, 3, 5, 2, 1, 2, 2, 2 | 285 |
|  | 1, 2, 7, 8, 10, 14, 15, 16, 27, 28, 31, 34, 40, 43, 48, 53, 54, 56, 57, 58, 61, 65, 69, 70, 71, 72, 75, 83, 85, 91, 98, 99, 103, 105, 112, 113, 117, 118, 123, 126, 134, 135, 140, 143, 144, 145, 147, 150, 153, 156 | 1, 1, 1, 2, 3, 2, 1, 3, 2, 1, 2, 2, 1, 2, 1, 1, 2, 1, 2, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 2, 1, 1, 2, 1, 1, 1, 1, 2, 1, 1, 1, 1, 1, 1, 1, 1, 2, 2, 1, 2, 2, 2, 2, 1, 2, 2, 1, 1, 2, 2, 1, 1, 1, 1, 1, 1, 1, 3, 1, 1, 2, 2, 1, 1, 3, 2, 1, 1, 1, 1, 1, 4, 1, 1, 1, 1, 1, 1, 3, 4, 1, 1, 2, 2, 1, 1, 1, 3, 1, 1, 2, 1, 1, 1, 1, 1, 1, 1, 1, 2, 1, 2, 1, 4, 2, 1, 1, 1, 2, 2, 2, 1, 1, 1, 2, 2, 4, 2, 3, 2, 2, 2, 1, 2, 1, 3, 2, 2, 4, 1, 1, 1, 2, 1, 3, 2, 2, 2, 6, 1, 4, 3, 5, 2, 1, 1, 2 | 255 |
|  | 1, 4, 5, 6, 7, 8, 9, 11, 13, 14, 18, 19, 27, 30, 33, 34, 37, 39, 41, 42, 48, 50, 52, 61, 63, 64, 66, 67, 74, 75, 80, 81, 84, 85, 87, 88, 89, 90, 92, 99, 109, 116, 117, 120, 123, 124, 133, 141,151, 160 | 1, 1, 1, 2, 3, 2, 1, 3, 2, 1, 2, 2, 1, 2, 1, 1, 2, 1, 2, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 2, 1, 1, 2, 1, 1, 1, 1, 2, 1, 1, 1, 1, 1, 1, 1, 1, 2, 2, 1, 2, 2, 2, 2, 1, 2, 2, 1, 1, 2, 2, 1, 1, 1, 1, 1, 1, 1, 3, 1, 1, 2, 2, 1, 1, 3, 2, 1, 1, 1, 1, 1, 4, 1, 1, 1, 1, 1, 1, 3, 2, 1, 1, 2, 2, 1, 1, 1, 3, 1, 1, 2, 1, 1, 1, 1, 1, 1, 1, 1, 2, 1, 2, 1, 4, 2, 1, 1, 1, 2, 2, 2, 1, 1, 1, 2, 2, 4, 2, 3, 2, 2, 2, 1, 2, 1, 3, 2, 2, 2, 1, 1, 1, 2, 1, 3, 2, 2, 2, 4, 1, 4, 3, 3, 2, 1, 1, 2 | 247 |

### 5.4.3 OPP for Türkiye 400 kV Interconnected Power System with BPSO

Optimal PMU placement results using the BPSO method are given in Tab. 6. Also, *BOI* and *SORI* were used to better rank multiple solutions. According to the results of Tab. 6, 54 PMU devices must be connected to fully observe the system. The solution with the maximum *SORI* value is considered the best optimal solution. *SORI* of 272 is considered the best optimal solution. BPSO and DA methods designed with inspiration from the herd were applied separately on the 400 kV Interconnected Power System in Türkiye to solve the OPP problem.

According to the results obtained with BPSO, the whole system is observed with 54 PMUs. According to the results obtained with DA, the whole system is observed with 49 PMUs. When a solution is provided with the DA method for the 400 kV Interconnected Power System in Türkiye, a solution is provided with 5 PMU fewer devices compared to the BPSO method. Taking into account all the constraints of the OPP problem, providing a solution with less than 5 PMU devices offers a great cost advantage.

**Table 6** OPP results using BPSO method for Türkiye 400 kV interconnected power system

| Number of PMUs | Optimal PMU Locations | *BOI* | *TSORIs* |
|---|---|---|---|
| 54 | 2, 7, 9, 13, 15, 20, 24, 26, 32, 36, 41, 42, 48, 51, 56, 58, 61, 65, 69, 71, 72, 74, 78, 80, 81, 85, 88, 92, 95, 96, 98, 101, 102, 103, 104, 107, 109, 111, 114, 116, 118, 119, 121, 123, 124, 126, 127, 135, 136, 141, 143, 145, 150, 156 | 3, 2, 1, 2, 1, 2, 2, 1, 2, 1, 2, 2, 2, 2, 1, 1, 2, 1, 2, 2, 1, 2, 1, 1, 1, 1, 2, 2, 1, 2, 2, 2, 1, 1, 2, 1, 1, 1, 2, 2, 1, 1, 2, 1, 4, 1, 1, 2, 2, 2, 1, 2, 5, 2, 2, 1, 1, 2, 2, 2, 2, 2, 1, 2, 1, 2, 1, 1, 1, 3, 1, 1, 1, 2, 1, 1, 3, 2, 1, 1, 1, 2, 1, 2, 1, 2, 2, 1, 2, 3, 3, 2, 2, 1, 2, 2, 1, 2, 1, 1, 1, 1, 2, 1, 2, 1, 2, 1, 1, 2, 1, 2, 1, 2, 1, 2, 2, 1, 2, 1, 2, 2, 2, 1, 2, 1, 2, 3, 2, 2, 3, 2, 1, 2, 2, 2, 1, 3, 2, 2, 2, 1, 2, 1, 2, 1, 3, 2, 2, 2, 3, 2, 2, 3, 3, 2, 1, 2, 2, 2 | 272 |

## 6 CONCLUSION

In the study, BPSO, a new heuristic method DA, and a new ILP method are proposed. Suggested methods 14-Bus Test System and Türkiye 400 kV Interconnected Power System were applied. The visualization ILP technique is proposed to show the positions of PMUs derived from OPP. *BOI* and *SORI* were used to rank multiple solutions with the DA and BPSO methods.

It is seen that the ILP, BPSO, and DA methods used are successful in determining the optimal number of PMU placements and settlements by resolving all power systems in a short time. As a result of this study, by applying ILP, BPSO and DA methods to the 400 kV interconnected power system in Türkiye, it was found in which busbars the optimum number of PMUs should be placed to both reduce the cost and ensure that the entire power system is observed.

As a result of the study, it has been observed that the DA method works better than other heuristics for power systems with many bus and transmission lines.

With the study, the location information of PMUs, which are of great importance for the management and control of the power system, has been determined for IEEE 14-Bus Test System and Türkiye 400 kV Interconnected Power systems.

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**Contact information:**

**Beytullah BOZALİ**, PhD
(Corresponding author)
Duzce Vocational School, Department of Electricity and Energy,
Uzunmustafa neighborhood, Uzunmustafa Street No: 23, Türkiye
E-mail: beytullahbozali@duzce.edu.tr

**Ali OZTURK**, PhD, Professor
Faculty of Engineering, Department of Electric and Electronic Engineering,
Duzce University, Konuralp Campus, 81620, Türkiye
E-mail: aliozturk@duzce.edu.tr

**Salih TOSUN**, Associate Professor
Faculty of Engineering, Department of Electric and Electronic Engineering,
Duzce University, Konuralp Campus, 81620, Türkiye
E-mail: salihtosun@duzce.edu.tr

**Bülent HOŞ**, PhD
Electric, and Electronic Engineering USA, Graduate Institute of Education,
Duzce University, Konuralp Campus, 81620, Türkiye
E-mail: bulent.hos@pakmaya.com