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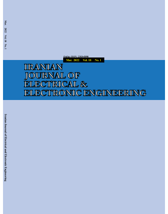

A New Regionalization Scheme for Wide-Area Backup Protection of Power Network

Gh. Khandar-Shahabad*, J. Beiza*(C.A.), J. Pouladi*, and T. Abedinzadeh*

Abstract: A new regionalization algorithm is presented to improve wide-area backup protection (WABP) of the power system. This method divides the power system into several protection zones based on the proposed optimal measurement device (MD) placement and electrical distances. The modified binary particle swarm optimization is used to achieve the optimal MD placement in the first step. Next, the power system is divided into small protection zones (SPZ) using the topology matrix of the power system and MD locations. Finally, the SPZs are combined to accomplish the main protection zones and protection centers according to electrical distances, degree of buses, and communication link constraints. The introduced regionalization formulation can help provide a rapid and secure WABP for power systems. This method was applied to several IEEE standard test systems, and the simulation results demonstrated the effectiveness of the proposed scheme.

Keywords: Communication Constraints, Electrical Distance, MD Placement, Power System Regionalization, Protection Zone, Wide-Area Backup Protection.

1 Introduction

TRANSMISSION lines constitute a significant part of the power system, and the extreme spreading nature of the power system increases the risk of fault occurrence in transmission lines. Faults on transmission lines affect the normal condition of the power system and, in some cases, cause system instability. Thus, protection systems of transmission lines are designed to protect the power network against abnormal conditions. The primary and backup protection systems are an inseparable part of power networks to increase power system security and reliability [1, 2].

Nowadays, with the recent developments in communication networks, information technology, and digital measuring devices, wide-area backup protection (WABP) schemes have been utilized to overcome the shortcomings of traditional backup protection systems.

Conventional protection has some problems such as the coordination between protection zones, poor adaptability, and mal-operation, and therefore causes cascaded outages under stressed conditions of the power system [3]. To overcome the inherent time delay in wide-area protection schemes [4, 5] power network regionalization can be the best option to enhance WABP performance in the large-scale power network. Here, measurement device (MD) refers to a phasor measurement unit (PMU) or advanced digital relays equipped with GPS.

Two categories of studies on WABP have been reviewed: fault identification methods in the transmission network [6-16] and regionalization schemes of the large power system [17-27].

A backup wide-area protection scheme is presented in [6] based on PMUs data. In the presented method [6], positive sequence voltage magnitudes at each bus during fault conditions are used to detect the nearest bus to the fault. Then, the faulty line is identified based on absolute differences of positive sequence current angles of all lines connected to the mentioned bus. In [7], a transmission network WABP is presented based on current phasor measurements. The presented algorithm in [7] can discriminate between short-circuit faults and other stresses in the power system. A fast and robust

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WABP scheme to detect the faulty condition and identify the faulted line in power systems is presented in [8]. The method in [8] uses positive-sequence synchrophasor data captured by PMUs dispersed over the network. A wide-area protection scheme against asymmetrical faults is presented in [9]. The method uses available phasor measurements to identify the faulty line. To preserve accuracy, the method limits the calculations to the assessment of the negative-sequence circuit of the network. A modified WABP scheme for shunt-compensated transmission lines is presented in [10]. In the presented scheme in [10], the buses with the minimum magnitude of the positive-sequence voltages or maximum magnitude of negative (or zero)-sequence voltages are selected as the nearest buses to the fault location based on data of PMUs. The line with the maximum absolute difference of positive or negative-sequence current angle is identified as the faulty line. A wide-area protection scheme based on voltage measurements from PMUs is presented in [11]. The presented method is validated on IEEE 14-bus standard test system. A wide-area fault location of transmission lines is formulated in [12] based on hybrid synchronized and unsynchronized voltage measurements. The method uses phase angles of synchronized measurements and magnitudes of both synchronized and unsynchronized measurements. The presented method can identify high impedance faults. A wide-area differential protection method based on composite impedance is represented in [13] for quick detection the faulty line. The method uses the information of one-terminal voltage phasor and the transmission line differential current phasors to construct the protection criteria. In [14], a scheme is presented based on symmetrical components of three-phase voltages and currents to formulate a wide-area robust fault analysis in transmission lines. A fault location scheme based on PMU is presented in [15] for shunt-compensated transmission lines. The first fault section is determined by the positive (or negative) -sequence current angle index. Then the fault point and fault resistance are calculated by solving an optimization problem. In [16] a new fault location method is proposed for power distribution network by using an improved Whole Optimization Algorithm (WOL) by investigating the voltage values recorded through the network.

The second category of research divides the power system into protection regions to enhance WABP performance. Then, the faulty line is identified in the faulty zone. In [17], the transmission network is divided into backup protection zones (BPZs) based on the PMU placement and network topology. The sum of zero and positive-sequence currents entering the zones are used to distinguish the faulty zone [17, 18]. To minimize the computational burden in [19], a large power system is divided into several intersected areas called bus zones (BZs) and the variation of voltage magnitude at each bus equipped with PMU serves as an index to identify the faulty zone. Based on PMU placement and network topology, subsets of lines and buses called backup protection zones (BPZs) are formed in [20], and the sum of zero- and/or positive-sequence currents entering the protection zones is used to specify the faulty zone. The fault zone identification vector (FZIV) index is presented in [21] to determine the faulty zone based on the connection matrix and current vector. In [22], a criterion is proposed to overcome the shortage in formulating the backup protection zones (BPZs).

In the WABP algorithm of [23], correlation regions (PCRs) are formed based on the network topology and PMU placement. The steady-state component of the differential current is used to determine the PCR in which the fault exists.

To limit the total latency of the WABP scheme, [24] introduces a comprehensive formulation by regionalization of power systems. An integer linear programming (ILP) model is used to divide the power system into several protection regions.

In [25], a simultaneous optimization problem of partitioning and optical communication link (CL) placement is presented with the objective of minimizing the construction cost of wide-area protection system. A cluster-based genetic algorithm is proposed to solve the simultaneous optimization problem.

A primary substation selection model of regional protection based on an exhaustive method is proposed in [26], using the Floyd–Warshall algorithm. The partition model is established according to the several factors that affect the communication delay time for regional protection.

In [27], a multi-objective optimization method of power grid partitioning is presented. An objective function is formulated comprehensively considering the communication performance, the overlap rate, and the balance of different regions. The brainstorm optimization algorithm is used to obtain the optimal result.

Communication media used in power system include PLC, radio system, microwave, and fiber optics. According to the requirements of the project, their capabilities and restrictions should be evaluated in terms of efficiency, reliability, security, transmission speed, influence from the environment, capacity and bandwidth, error rate, and controllability. In addition, developments in communication network have greatly reduced the limitation caused by them. Today, optical fiber as an optimal communication technology can be used in wide-area schemes in the power system. The main advantages of optical fiber are high bandwidth, security, electromagnetic interface immunity, and low attention, but the cost of its communication infrastructure in the network is high.

In WABP schemes, the communication network is responsible for the synchronized data transfer between stations and protection centers. In transmission system, an Optical Power Ground Wire (OPGW) contains several optical fibers. These optical fibers are used as a fast and reliable communication link, which can reduce the implementation and maintenance costs of the schemes.

In the proposed WABP scheme, information is transmitted through OPGWs using standard communication protocols (e.g. IEC61850). The active components of the communication network include a number of switches and routers which are chosen according to communication capacity [25]. At present, internet protocol (IP)/synchronous digital hierarchy (SDH)/fiber technology is widely used in the wide-area communication systems [27].

In this paper, a new scheme is presented for partitioning the power system to improve the performance of WABP schemes based on several network indexes. Moreover, in the proposed scheme, time delay of the protection scheme and its accuracy are considered as two main factors. The significant contributions of this paper are summarized as follows:

- A new MDs placement is presented for wide-area protection of the power system. This method results in minimum MDs numbers compared with other methods for different standard test systems.
- The network topology matrix, electrical distances, and communication constraints are considered in the proposed algorithm. Therefore, the optimal protection zones are obtainable for different power systems.
- The proposed scheme ensures secure and fast wide-area backup protection.

The remainder of this article is organized as follows. Section 2 presents the proposed optimized MD placement. In Section 3, the proposed scheme for power system regionalization to enhance WABP is described in detail. Protection zones are defined for several IEEE standard test systems based on the proposed method in Section 4. Finally, the conclusions appear in Section 5.

2 The Proposed Optimized MD Placement

In this section, the formulation of MD placement in the power system is presented for the proposed regionalization scheme. Then, modified binary particle swarm optimization (MBPSO) is formulated and finally, the proposed MD placement is applied to several standard power systems.

2.1 Problem Formulation

A bus is observable when its voltage phasor either can be calculable using other measurements or measurable directly using the MD placed on it. The voltage phasor of the bus can be calculated using the data of adjacent buses which equipped with MDs. The observability of the line currents and bus voltage is analyzed based on the rules. In other words, the bus voltage or line current is observable when one of the following rules is satisfied [28]:

- When an MD is placed on the bus, then the bus is directly observable. In other words, the voltage phasor of the bus and current phasors of incident lines are directly measurable.
- If the bus voltage phasor and the line current phasor are known, then the bus on the other side of the line is observable.
- If bus voltage phasors at both ends of a line are known, current phasors of the line are calculated using the line parameters.

The other two rules are related to the zero-injection bus effect as follows:

- In a zero-injection bus, if the currents of all of the incident lines except one are available, then the current of the unavailable line is calculable.
- A zero-injection bus with unknown voltage is observable using node equations if voltage phasors of all adjacent buses are available.

Two additional rules are assumed in the proposed method for the requirements of WABP scheme. These rules are as the following:

- The buses that include generators or transformers with OLTC or series compensated elements are equipped with MDs.
- Measurement redundancy of buses without MDs must be greater than one.

A simple solution for solving the Optimal MD Placement Problem (OMDPP) is placing an MD on each bus. However, the MD is an expensive device. Therefore, it is important to find the minimum number of MDs for proposed goals. To solve the problem, it is sufficient to know the system topology and the types of buses. The number of MDs is an objective function, and the above-mentioned rules are the constraints of the problem. Therefore, the problem can be formulated as follows:

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

$$\text{Subject to}: Y = T.X \geq b \tag{1}$$

$$X = [x_1\ x_2\ x_3 \ldots\ldots\ldots x_N]^T \tag{2}$$

$$x_i \in \{0,1\} \tag{3}$$

$$b = [b_i\ b_2\ b_3 \ldots\ldots\ldots b_N]^T \tag{4}$$

where, *N* and *T* are the numbers of buses and topology matrix. *T*, *X*, and *b* matrixes are defined as follows:

$$x_i = \begin{cases} 1 & \text{if MD installed in bus } i \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

$$T_{ij} = \begin{cases} 1 & \text{if } i = j \\ 1 & \text{if } i^{\text{th}} \text{ bus is connected to bus } j \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

$$b_i = \begin{cases} 1 & \text{if MD installed in bus } i \\ 2 & \text{otherwise} \end{cases} \tag{7}$$

2.2 Zero-Injection Measurements

Zero-injection buses effect reduces the number of MDs. For modeling this effect *Y* defines as follows:

$$Y = T.X \tag{8}$$

where, y_i (i-th element of Y) indicates the number of times that the i-th bus is observable using MDs data. Without considering zero-injection effect y_i must be non-zero, in order to the observability of the i-th bus. However, with considering the zero-injection effect, the i-th bus may be observable while y_i is zero.

For a detailed discussion, Fig. 1 shows a sample grid where bus m is a zero-injection bus. For the simple grid depicted in Fig. 1, the following inequality needs to be held:

$$y_a + y_b + y_c + y_d + y_m \geq 4 \tag{9}$$

Then, the constraint of considering zero-injection measurements in OMDPP can be written as follows:

$$\begin{bmatrix} I_{M\times M} & 0 \\ 0 & T_{meas} \end{bmatrix} (PY) = T_{con}PY = T_{con}PTX \geq b_{con} \tag{10}$$

where T_{meas} and b_{con} are formed as introduced above, P is a permutation matrix, and M is the number of buses that are not associated with zero-injection buses. The full description of this method is available in [29].

Therefore considering zero-injection buses in OMDPP, Eq. (1) is rewritten as follows:

$$\begin{aligned} &\text{Min} \sum_{k=1}^{N} x_k \\ &\text{Subject to:} \, T_{con}PT\ X \geq b_{con} \end{aligned} \tag{11}$$

2.3 Modified Binary Particle Swarm Optimization

In this paper, the MBPSO algorithm is implemented to solve the proposed OMDPP. Each particle is presented by the N-dimension vector, where N is the number of buses. This vector is defined as follows:

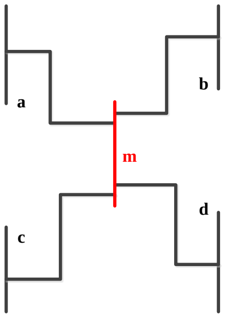

Fig. 1 A simple grid with zero-injection bus.

$$X = [x_1\ x_2\ x_3 \ldots\ldots\ldots x_N]^T \tag{12}$$

where $x_i = 1$ if there is a MD at bus i, otherwise $x_i = 0$. In the proposed method, better performance is achieved by initialing a feasible population. For this purpose, the probability of placing an MD at a bus is supposed 0.9 at the initial population. Then, these particles move in a binary search space and change their positions according to (13) to (15), as the time is varying:

$$\begin{aligned} v_i(k+1, j) = {} & v_i(k, j) \\ & + e_1\left(Pbest_i(k, j) - x_i(k, j)\right) \\ & + e_2\left(Gbest(k, j) - x_i(k, j)\right) \end{aligned} \tag{13}$$

$$v_i \in \{-1, 0, 1\} \tag{14}$$

$$x_i(k+1, j) = x_i(k, j) + v_i(k+1, j) \tag{15}$$

$$x_i \in \{0, 1\} \tag{16}$$

where, k is the number of iterations and j is the number of buses. For example, $x_3(5, 7) = 0$ means the 7th bus of the 5th particle at the 3rd iteration has no MD. The value of e_1 and e_2 are equal to 1 with a probability of 0.7 and they are zero with a probability of 0.3 [30, 31].

The algorithm is repeated m times. In this process, the particles of the initial population update their positions using (13)-(15) until a minimum number of MDs is achieved in each iteration.

A new stage namely “disturbance” is added to the algorithm for recuperating the search capability of the algorithm. This stage is determined to change the particle in a special condition. A disturbance will be applied randomly to one of the elements of a particle if after *d* iterations the algorithm cannot find a better position, compared to its current position. To apply a disturbance to the selected element, the status of the element will be changed to 0 if the current position is 1 and conversely to 1 if the current position of the element is 0.

3 The Proposed Regionalization Scheme

The total time lag of a WABP consists of several components. They are data acquisition, wide-area network (WAN) associated with data transmission, phasor data concentrators (PDCs), application algorithm, and WAN associated with command transmission [32, 33]. The power system regionalization is an appropriate option to reduce the WABP latency. In addition, it reduces the complexity of the protection structure, information exchange, and decision time.

In this section, the proposed regionalization scheme to improve the power system WABP is described. The main purpose of the proposed scheme is to shorten the time delay of wide-area protection.

When a power system is divided into several protection regions, the system-wide WAN structure is replaced by the regional WAN structure. Because in each region, less information is sent to the protection center and the execution time of the protective algorithm is reduced, so the time delay is decreased as well [24]. In the case of using a centralized protection center in the network, the volume of exchange information is greatly increased, especially in the event of a fault in transmission lines, and therefore the algorithm execution time and time delay of the WABP scheme increase.

By increasing the number of protection zones, the time delay of each region is clearly reduced and the load amount tends to be uniform. In practice, to regionalization of the network, requirements of the WABP scheme, the constraints of the control systems and communication network, and as well as economic issues should be considered to determine the appropriate number of regions [25].

In the following subsections, small protection zones (SPZs) are first created based on optimized MD placement in Section 2 The electrical distances between buses are then calculated. Finally, the formation of main protection zones (MPZs) WABP is presented based on the electrical distances and communication links constraints.

3.1 Formulation of Small Protection Zones

In this subsection, the formulation of SPZs is explained based on the proposed MDs placement and the power network topology. In the first step, the power system is divided into several SPZs. An SPZ is a subset of lines and buses that is surrounded by MD-equipped buses. Then, these SPZs are combined in order to create a few MPZs. The SPZs are developed as bellows:

Step1: Topology matrix of the power system is reformed into 4 sub-matrices as the following:

$$T = \begin{bmatrix} T_{PP} & T_{pn} \\ T_{nP} & T_{nn} \end{bmatrix} \tag{17}$$

In (17), T_{pp} and T_{nn} are topology sub-matrices of buses with MDs and buses without MDs, respectively. Also, T_{pn} and T_{np} denote the topology between two different types of buses.

Step 2: SPZs are selected based on a simple rule: “Each protection zone consists of the lines and buses that are surrounded by MD equipped buses”.

3.2 Electrical Distance Calculation

Electrical distance calculation is presented in detail in [34]. The step-by-step method to obtain the electrical distance between two buses is given below:

1) The Jacobian matrix J is calculated and the submatrix $J_4 = [\partial Q/\partial V]$ is obtained.

2) J_4 is inverted: $B = J_4^{-1}$. The elements of matrix B are written as $b_{ij} = \partial V_i/\partial Q_j$.

3) The attenuation matrix between all the buses is calculated using (18):

$$\alpha_{ij} = b_{ij} \big/ b_{jj} \tag{18}$$

4) Electrical distance, D_{ij}, between the i-th and j-th buses are calculated:

$$D_{ij} = -\log(\alpha_{ij} . \alpha_{ji}) \tag{19}$$

5) The electrical distances are normalized as follows:

$$D_{ij} = D_{ij} / Max(D_{i1}, ..., D_{iN}) \tag{20}$$

3.3 Formulation of Main Protection Zones

The power system regionalization steps based on SPZs and electrical distances are as follows:

Step 1: The number of lines connected to each bus with MD is assumed as the bus degree. Then, buses are listed and sorted in descending order of degree.

Step 2: Buses with degrees of more than 3 are chosen as protection centers in the initial protection regions and named the protection central buses (PCBs). Subsequently, the electrical distances between the PCBs are determined. If the electrical distance between two chosen PCBs is less than a specific electrical distance (SED), the PCB with a lower degree is removed. Eventually, the remaining PCBs are rearranged to designate MPZs.

Step 3: The electrical distance of the bus without MD in each SPZ is calculated from the final PCBs and compared. The SPZ with the shortest electrical distance from a PCB is then allocated within the protection region of that PCB. This means the sum of the electrical distances SPZs from the PCB in each protection region is optimized. Finally, MPZs in the power system are identified, and their number will be equal to the number of PCBs.

Data transmission and decision process times must be limited to a specific period in wide-area schemes due to protection restrictions. Therefore, the maximum number of MDs in each protection zone has an upper limit due to communication link constraints (h_{max}) [24]. In each iteration of the regionalization algorithm, h_{max} is checked for MPZs. The allocation of SPZs for the specified PCB is terminated if the number of MDs in this MPZ reaches the h_{max} index. In the next iterations, the remaining SPZs will be allocated to PCBs with the number of MDs less than h_{max}. This procedure is repeated for each PCB. Another constraint on the creation of MPZs is the minimum number of MDs in each zone (L_{min}). Therefore, at the end of SPZ allocation, if an MPZ has not met the L_{min} constraint, the associated PCB will be removed from the PCB list and the algorithm allocates SPZs to the new PCB list. These constraints satisfy the appropriate number of PCBs in the power network.

Fig. 2 presents the proposed algorithm for power network regionalization. In the first step, power network data are collected. In the next step, optimal MD placement is applied to the assumed power system based on the method proposed in Section 2. In the third step, SPZs are created based on the method described in Section 3.1. Subsequently, the degree of the buses with MD is defined. Next, the PCBs are specified based on bus degrees and electrical distances. Afterward, the SPZs are allocated to the protection region of these PCBs according to the electrical distances, h_{max} and L_{min} constraints. Finally, the PCBs and the boundaries of MPZs are determined.

4 Simulation Results

In this section, to evaluate the proposed scheme, simulation is carried out in MATLAB as follows:

First, the proposed MD placement is accomplished in different standard test systems. Then, the proposed regionalization algorithm of the power system is applied to IEEE standard 14, 39, 57, and 118-bus test systems for WABP enhancement.

In the simulation, h_{max} and SED are assumed to be 40 and 0.3, respectively. In each protection region, L_{min} is supposed to be 6 for the IEEE standard 118-bus test and 4 for other IEEE systems. Minimum MDs in each protection region must be greater than maximum MDs in the SPZs and, therefore, the value of this index depends on the power network topology.

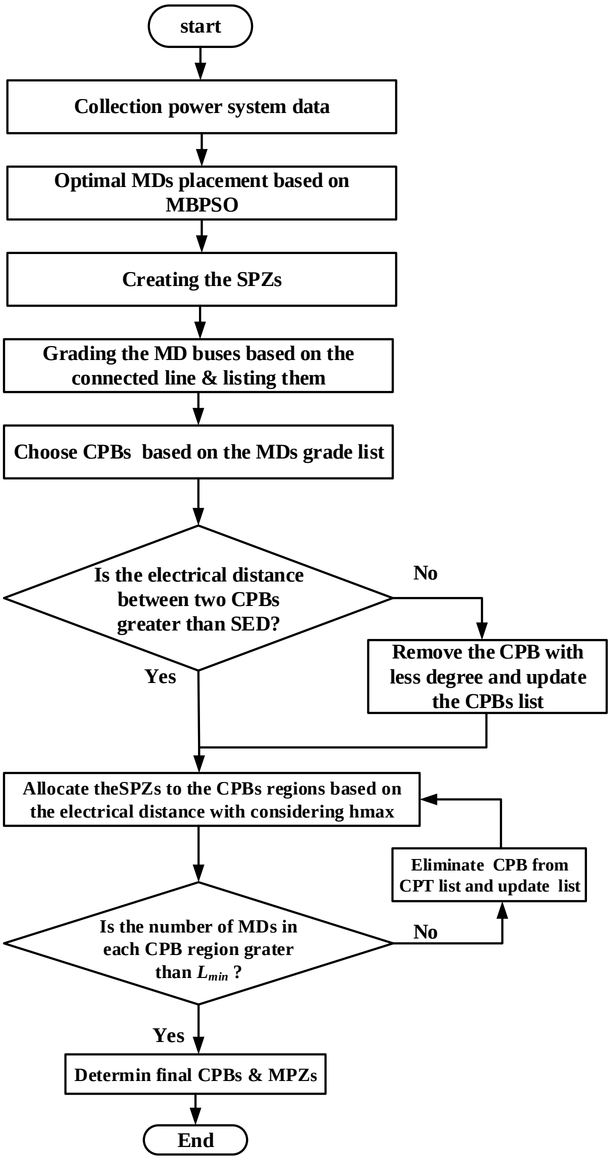

Fig. 2 The proposed regionalization algorithm.

4.1 MD Placement Evaluation

The proposed MD placement developed in Section 2 is used to obtain the minimum number of MDs in IEEE 14, 39, 57, and 118-bus test systems. The results are given in Table 1.

According to Table 1, the proposed optimization method provides a minimum number of MDs in most of the IEEE test systems compared to the method of [8]. The IEEE 118-bus test system with 177 transmission lines is similar to the large-scale power systems. Furthermore, the efficiency of the proposed MD placement, compared to other methods, is prominent in large-scale power systems.

4.2 Comprehensive Assessment of the Regionalization Scheme

The number of SPZs of IEEE standard test systems based on the approach in Section 3.1 is presented in Table 2. There is a bus without MD in each SPZ, surrounded by other buses that have MDs. Fig. 3 illustrates the SPZs of the WSCC 9-bus test system as an example. There are four MDs and three SPZs in the system. In SPZ1, bus 9 is surrounded by MD buses 4 and 8. This is true for buses 5 and 7 in SPZ2 and SPZ3, respectively.

The obtained results are compared with other studies in Table 3. As can be seen, the results of the proposed method have optimal values compared to the IEEE 39-Bus Test system.

Considering the practical constraints in the number of Protection and control Centers, communication links, and Phasor Data Concentrators (PDC), it is necessary to limit SPZs to an appropriate number of Protection regions, named MPZs.

To achieve the MPZs, the SPZs in Table 2 are combined using the regionalization scheme proposed in Section 3.3. The initial number of PCBs for the IEEE standard 14-, 39-, 57- and 118- bus test systems is 3, 6, 7, and 23, respectively. These initial PCBs are rearranged in several steps due to the mentioned limitations. For example, in the IEEE 57-bus test system, buses 11 and 54 are removed from the PCB list, and the associated SPZs are allocated to the PCB of the bus 9 region due to the SED limitation. On the other hand, the PCBs of buses 1, 12, 15, and 41 are removed due to the L_{min} constraint.

Table 1 Total number of MDs and locations for different standard test systems.

Test system	Total number of MDs		MDs locations
	Ref [8]	Proposed method	
IEEE 14-Bus	8	8	2, 4, 5, 6, 8, 9, 11, 13
IEEE 39-Bus	25	24	2, 3, 6, 8, 10, 12, 14, 16, 17, 20, 21, 23, 26, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39
IEEE 57-Bus	30	29	1, 3, 5, 7, 9, 11, 12, 15, 18, 20, 22, 23, 25, 26, 28, 31, 33, 34, 36, 39, 41, 44, 46, 47, 49, 51, 52, 54, 56
IEEE 118-Bus	64	60	2, 3, 5, 6, 9, 10, 11, 12, 15, 17, 18, 20, 22, 25, 27, 29, 30, 31, 34, 35, 37, 40, 41, 44, 46, 49, 50, 51, 53, 56, 59, 62, 64, 66, 68, 70, 71, 72, 73, 75, 76, 78, 80, 83, 85, 88, 90, 92, 94, 96, 100, 102, 103, 107, 108, 109, 111, 112, 113, 114

Table 2 The number of SPZs for IEEE standard test systems.

Test system	The number of SPZs
IEEE 14-Bus	7
IEEE 39-Bus	15
IEEE 57-Bus	28
IEEE 118-Bus	58

Table 3 The number of MDs and Small sized protection regions in the IEEE 39-Bus test system.

Method	Ref. [23]	Ref. [24]	Proposed method
Number of MDs	25	27	24
Number of small protection regions	25 BPZs	22 PCRs	15 SPZs

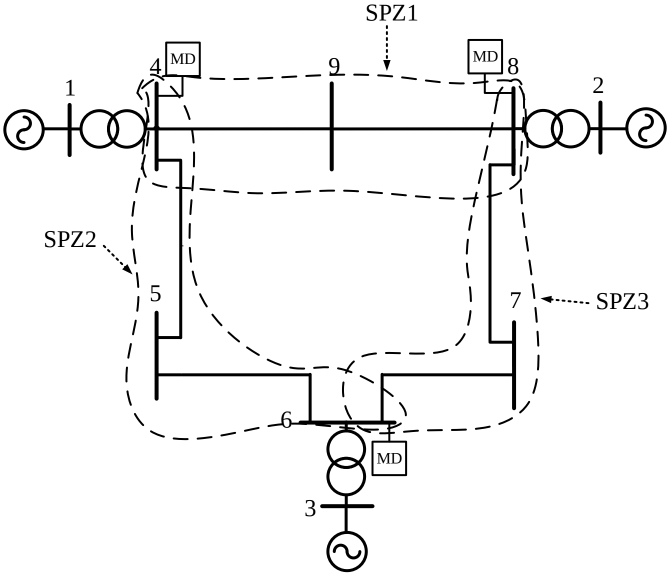

Fig. 3 SPZs of the WSCC 9-bus IEEE test system.

Table 4 The final PCBs and MPZs for IEEE standard test systems.

Test system	Number of regions	PCBs locations	MDs buses belonging to each region
IEEE 14-Bus	1	6	Region 1: 2, 4, 5, 6, 8, 9, 11, 13
IEEE 39-Bus	2	6, 16	Region 1: 2, 3, 6, 8, 10, 12, 14, 30, 31, 32, 39
			Region 2: 2, 3, 14, 16, 17, 20, 21, 23, 26, 29, 33, 34, 35, 36, 37, 38
IEEE 57-Bus	2	9, 56	Region 1: 1, 3, 5, 7, 9, 11, 12, 15, 18, 26, 28, 44, 46, 49, 51, 52, 54
			Region 2: 11, 18, 20, 22, 23, 25, 26, 31, 33, 34, 36, 39, 41, 44, 47, 49, 56
IEEE 118-Bus	3	12, 49, 100	Region 1: 2, 3, 5, 6, 9, 10, 11, 12, 15, 17, 18, 20, 22, 25, 27, 29, 30, 31, 34, 35, 37, 70, 72, 113, 114
			Region 2: 30, 34, 37, 40, 41, 44, 46, 49, 50, 51, 53, 56, 59, 62, 64, 66, 68, 70, 71, 72, 73, 75, 76, 78, 80
			Region 3: 75, 76, 80, 83, 85, 88, 90, 92, 94, 96, 100, 102, 103, 107, 108, 109, 111, 112

Table 4 indicates the final PCBs and MPZs for the IEEE standard test systems. For the 118-bus test system, three MPZs are obtained and implemented with three PCBs to improve WABP performance. Fig. 4 displays the final protection regions of this large-scale power system. The IEEE 57 and 39-bus test systems are divided into two protection regions with two PCBs, whereas the IEEE 14-bus test system is protected by one PCB and one protection region.

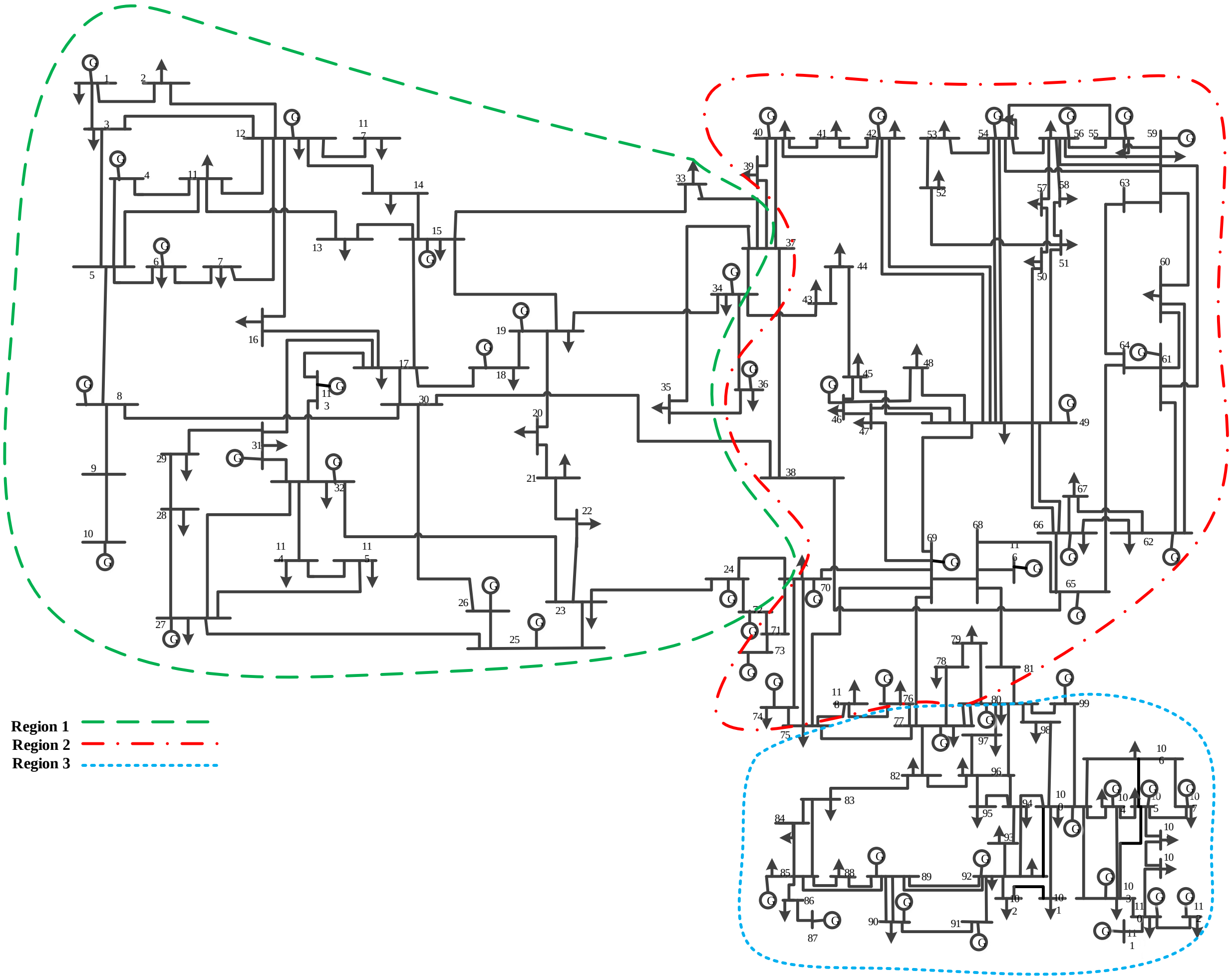

Fig. 4 Protection regions of 118- Bus IEEE test system.

Table 5 The number of MDs and main protection regions in the IEEE 118-Bus test system**.**

Method		Ref. [25]		Proposed method
		Stage 2	Stage 3	
Number of MDs		64		60
Number of main protection regions		3		3
Allocations of protection centers		38,65,100	15,75,92	12,49,100
Number of MDs in protection regions	Region 1	30	25	25
	Region 2	30	30	25
	Region 3	26	16	18

Table 5 shows the results of the proposed method with h_{max} = 40, compared to [24]. The number of Protection regions is equal. However, the number of MDs in the protection regions, especially compared to the second stage [24], has decreased significantly. Because, in the proposed method fewer MDs are located in protected regions, thus the boundaries of protection regions are also optimized. According to the explanations in Section 3, it is concluded that the total WABP latency will be less in the proposed method.

5 Conclusion

A new regionalization method was proposed to enhance WABP performance and reduce its time lags. The proposed scheme divided the power system into protection regions based on concepts such as optimal MD placement, power network topology, electrical distances, and degree of buses. Data transmission and communication constraints were also considered in the proposed algorithm. This method reduced the total time lag of the WABP scheme. MBPSO was utilized to achieve the optimal number and locations of MDs. The results indicated that the minimum number of MDs was obtained compared with other studies. So, data transmission in the PDCs and the execution time of WABP algorithm was reduced. Subsequently, the proposed algorithm was applied to several IEEE standard test systems. The simulation results in the IEEE 14, 39, 57, and 118-Bus test systems revealed the efficiency of the proposed method.

Intellectual Property

The authors confirm that they have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property.

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Gh. Khandar-Shahabad: Idea & conceptualization, Research & investigation, Data curation, Analysis, Methodology, Software and simulation, Original draft preparation. **J. Beiza:** Analysis, Project administration, Supervision, Verification, Revise & editing. **J. Pouladi:** Verification, Revise & editing. **T. Abedinzadeh**: Verification, Revise & editing.

Declaration of Competing Interest

The authors hereby confirm that the submitted manuscript is an original work and has not been published so far, is not under consideration for publication by any other journal and will not be submitted to any other journal until the decision will be made by this journal. All authors have approved the manuscript and agree with its submission to “Iranian Journal of Electrical and Electronic Engineering”.

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