© Universiti Tun Hussein Onn Malaysia Publisher's Office

IJIE

Journal homepage: http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

A Novel Power Quality Monitor Placement in Transmission Systems Method Using Binary Teaching Learning-Based Optimization Algorithm Considering Monitoring Redundancy

Mohammad Mohammadi[1]*

[1]Department of electrical engineering, Borujerd Branch,
Islamic Azad University, Borujerd, IRAN

*Corresponding Author

DOI: https://doi.org/10.30880/ijie.2022.14.04.022
Received 08 June 2021; Accepted 16 September 2021; Available online 20 June 2022

Abstract: This paper deals with optimal employment of power quality monitors (PQMs) in transmission networks on the basis of the idea of monitor reach area. The proposed model uses binary string, representing the installation mode of PQMs (Yes or No) in each bus of the network. In the current article, the binary version of the teaching learning-based optimization algorithm (BTLBO) is used. It has the ability to enhance the search potential and provides a rapid and secure convergence rate in the optimization process. The concept of redundancy is considered in this study. The overall cost function is formulated to optimize the two indices. The first one is the index of monitoring overlap, and the second one is the index of sag severity. Among the solutions whose objective function experiments the minimum value, the evaluating the redundancy index gives the final optimal answer. With an excellent redundancy, the buses of the system faced with faults are monitored more times, on average. In the current research, DIGSILENT software is employed in short circuit analysis, whereas the BTLBO manages the optimization process. In the proposed algorithm, the IEEE 30 Bus transmission network is considered as a case study, and results are compared to similar investigations to clarify the impressiveness of the proposed algorithm.

Keywords: Power quality, Voltage sag assessment, Power quality monitors (PQM), Monitor reach area (MRA), Monitoring redundancy, Binary teaching learning-based optimization algorithm (BTLBO).

1. Introduction

In recent years, because of the increasing of the microprocessors and power electronic devices in the customers' technology, the sensitivity of them against power quality disturbances is highlighted. Therefore, it is an eminent issue that power quality indices with noteworthy values than ever before satisfy the end-users. The power quality indices include a variety of types of disturbances. Many researches have focused on power quality improvement in the distribution system [1-3].

One of the most common types of disorders that are taking place in the transmission and distribution systems is voltage dip (sag). It is caused by short circuit faults, sudden removal of large load, and an initial spurt of large capacitor banks into the transmission system used for purpose of reactive power compensations. This kind of voltage disturbance, in accord with IEEE Standard 1159-1995, is explained as a voltage diminish between 10 percent until 90 percent of RMS voltage amplitude of more than half cycle and less than thirty seconds [4].

The voltage sag according to its characteristics (magnitude and duration) and depend on the critical voltage of the sensitive loads, has severe impacts. It leads to failure, malfunction, or even to a forced outage of sensitive equipment, which imposes significant economic losses to industry owners. In [5], the voltage sag detection is analyzed using the S

*Corresponding author: mohammadi.m.84@gmail.com

and TT-based approach to identify the voltage sag source. The mitigation of voltage sag leads to reliability improvement of the transmission system. Hence the monitoring and compensation of this disturbance are necessary [6]. The monitoring of the buses faced with a sag in voltage amplitude and simultaneously analysis the sags' characteristics (magnitude and duration), provides remarkable information which help power researchers and engineers to moderate such disturbances. This information covers the actual cause and main factors that lead to a dip in voltage magnitude. Thus, to ensure the accurate monitoring of the entire system, the PQMs should be situated at all buses. Hence it is very costly and presents uneconomical planning. Therefore, new optimal placement methods are required to address the PQMs with the minimum number and suitable locations to guarantee that all of the voltage sags are detectable under any happening. Of course, it will be obtained using an efficient assignment approach. A few optimal allocation techniques of PQMs have been reported in the last few years.

Generally, the techniques about the placement of voltage sag monitors comprise four fundamental methods, namely, monitor reach area (MRA), covering and packing (CP), graph theory (GT), and multivariable regression (MVR) [7]. Dong and Seung propose a GT based new algorithm to monitor the voltage sag in a power system. The proposed GT-based algorithm, uses a simple graph with an incidence matrix for modeling the power system network, and so makes an analysis based on the network matrix frame [8]. The GT-based topological technique on the basis of coverage matrix is utilized for PQM placement by Dong and Seung [9]. In [10] new PQMs placement technique method is discussed that designed on the basis of the CP approach. In [11], a combinatorial problem of the CP method with the Integer Linear Programming (ILP) technique is employed to minimize the cost of PQMs.

In [12], a method is presented by authors for optimal placement of PQMs that is planned based on the CP approach. They used GAMS software to simulate the faults on the system. The CP method has two drawbacks; the first one is about evaluating the system's connectivity with the aim of system observability analysis through the concepts of Kirchhoff's current and Ohm's laws. The second drawback is considering steady-state information comparison with the factual information of voltage sag as constraints of the optimization problem. In 2011, a novel technique was discussed in assigning PQMs that tracks the MVR model and concept [13].

A novel statistical-based PQM placement technique is proposed that employs the statistical indices of Cp and Rp for LV and HV power networks [14]. In the similar research, the MVR method was combined with Cp and Rp statistical indices and was used to optimal PQM placement [15]. In 2013, the heuristics approaches were mixed with Cp statistical index approach to find the best location and improve the accuracy of the solution. For example, optimal PQM placement in transmission networks was addressed by [16], which utilizes the integrated genetic algorithm with Mallow's Cp approach. Also, a similar study by the same authors was reported to conclude optimal PQMs arrangement using GA_Cp method for distribution network [17].

In 2003, Olguin et al. proposed a MRA concept-based matrix method, which constructs a binary matrix to obtain the observable area of the network from a given meter position [18]. According to the proposed method by Ref. [18], if a fault occurs only inside MAR but not outside it, then the PQM is activated by the event. Thus, the MRAs of all feasible arrangements are concluded to express the optimization process in a formula. The procedure mentioned by [18] is performed using the binary MRA matrix, which is extracted through analysis of the network's short circuits situated along lines in the electrical system. In the MRA-based methods, the heuristic optimization algorithms are employed to determine the PQMs number and the best locations through optimizing the objective function. Many studies have reported the utilization of the MRA method combined with heuristics algorithms for optimal placement of PQMs.

In [19], the authors presented an MRA-based approach integrated with the sag severity index in solving the PQMs situation, which optimization process was handled by GA. In a recently published study, the concept of fuzzy monitor reach area (FMRA) has been introduced, and it has been employed for PQMs placement in large transmission networks [20]. The improved adaptive genetic algorithm (IAGA) is presented by [21] to optimal allocation of PQMs based on the MRA and MRM matrices and redundant vector concepts.

The PQMs location in transmission systems using the MRA matrix technique is a simple performance, but distribution systems with radial structure give the ill conditions that the MRA matrix generally couldn't respond. Under radial distribution systems, the MRA-based method will not guaranty the suitable number and locations, and often it yields only one PQM in the final solution. Thus, in 2011, Ahmad Ibrahim proposed a novel idea of topological monitor reach area (TMRA) and used it to solve the optimal PQMs situation in distribution networks [22].

Not only did the proposed TMRA technique use to allow for the observability's application to transmission systems, but it also employed in radial distribution systems. In the TMRA, to enhancer the flexibility of the search algorithm in viewpoints of sensitivity and economic capability, the alpha as a supervising parameter is introduced. It is added to the MRA method and controls the area monitors to provide more coverage. Authors in [23] presented and discussed an optimal solution in PQM placement in power systems using TMRA concept-oriented with particle swarm optimization (PSO) and artificial immune system (AIS) techniques.

The quantum-inspired particle swarm optimization (QPSO) was introduced by the same authors for PQM placement [24]. The adaptive QPSO (AQPSO) was also addressed for PQM placement on the basis of the MRA approach [25]. In [26], the quantum-inspired binary gravitational search algorithm (QBGSA) and in similar research by the same authors, the adaptive version of QBGSA is utilized for optimization process in PQMs placement using topological monitor reach area [27]. A performance comparison is made by [28] among three optimization techniques, namely, GA, BPSO, and QBPSO, in the problem of PQMs optimal placement.

Some studies [29-30] have solved the PQMs optimal planning as a multi-objective problem. The author in [29] modeled this problem as a multi-objective problem to acquire a tradeoff between the data redundancy and the economic efficiency using Pareto optimal solutions obtained by adaptive genetic algorithm (AGA). In a recently published study about the PQMs placement, a non-dominated solution has been addressed. At the presented solution, the authors use a multi-objective evolutionary algorithm with tables (MEAT) and formulate it to satisfy two conflict aims simultaneously. They track two purposes, firstly try to reduce as much as possible the total cost of the PQMs and on the other side try to get the best level of the redundancy of measurements [30].

The first innovation of this study is using the DIGSILENT software combined with MATLAB program for the short circuit process which this technique increases the speed run of simulation. Also the second innovation is utilizing the binary format of teaching learning-based optimization algorithm for solving this problem (PQMs placement) as the newest study which was not performed by others. The third innovation is considering the redundancy concept in this paper and analysis its effect on the results. With an excellent redundancy, the buses of the system faced with faults are monitored more times, on average and hence the level of power quality of system will be increased.

The main sections of this paper are listed as following:

Section 2: Power Quality Monitor/Meters (Functions and Installation)

Section 3: Fundamental concepts about the residual fault voltage matrix, monitor reach area, system topology and topology monitor reach area.

Section 4: Objective function, illustrate the minimizing the number of required monitors (NRM), minimizing the monitor overlapping index (MOI) and maximizing the sag severity index (SSI).

Section 5: Optimization techniques, teaching learning-based optimization, TLBO algorithm and its binary version.

Section 6: Simulation and Results

Section 7: Conclusion

2. Power Quality Monitor/Meters (Functions and Installation)

When a three-phase system is needed to monitor and continuously supervised, there is an ideal option named PQM. It presents facilities in measuring fundamental parameters of power networks such as active and reactive powers, energy use, cost of power, power factor and frequency, and initial quantities of bus voltages and feeder currents. In Fig.1, the schematic and how installing of several types of PQM is presented.

Fig.1 - Schematic and how the installation of several types of PQM

PQM's application and the monitoring and metering function of a typical type are listed as follows:

- **Applications**

1-The providing a meter of feeders in the distribution network, power transformers, synchronous generators in power plants, shunt capacitor banks, and also induction electrical motors.

2-Capability of utilization in LV and MV power networks

3-Technical and economic applications in commercial domain and industrials

4-Flexibly supply the control of demand load shedding, power factor, etc.

- **Monitoring and Metering**

1-Analyzing of harmonic voltage and current content and obtain the THD and TIF indices

2-Recording the event information (fault type, location, and magnitude)

3-Data capturing of waveforms

3. Fundamental Concepts

The main structure of the optimal PQMs placement problem using the proposed approach is the comprehending the monitor observability concept. This principle is needed to explain the following concepts discussed earlier in sections 3.1 to 3.4.

- Residual Fault voltage matrix
- Monitor reach area
- System topology
- Topology monitor reach area

3.1 Fault voltage (FV) matrix

In the MRA-based approach of PQMs placement, the residual voltages at whole buses of the system for every kind of faults (single-phase to ground (SLG), double-line to ground (DLG), three-phase faults (LLL)), and all fault cases are required.

In the short circuit process about fault analysis, it is necessary to simulate all the various kinds of fault. This step is performed generally at each bus using the DIGSILENT software without fault impedance (i.e., zero amount for it) to form and conclude the FV matrix.

According to equation (1), It is clear the worst fault with serious and critical results is the fault with minimum impedance. In the single phase to ground and three phases to ground faults, if the impedance of point fault to ground experiment the zero value, the largest current fault will be achieved. So it is better to design the system under the worst fault with the largest fault current. The design of system with PQMs under this condition can guarantee the good performance of system for other conditions of fault.

$$I_F = \frac{E = 1^{p.u}}{X_F + X_{th}} \quad (1)$$

Which X_F, denotes the fault impedance (reactance) at fault point (fault to ground) and X_{th} denotes the equivalent thevenin impedance from the fault point which is affected by topology of system. As the smaller of X_F the higher of current fault, I_F.

Finally, the residual voltages as FV matrix are kept to employ in MRA formulation. In the FV matrix, the matrix column (j) is related to bus numbers of residual voltages, and its row (k) is correlated to the position of simulated fault for specific fault types [22,31].

To better understand the concept of FV, a simple transmission system is shown in Fig.2 and its modeling in the DIGSILENT software is shown in Fig.3.

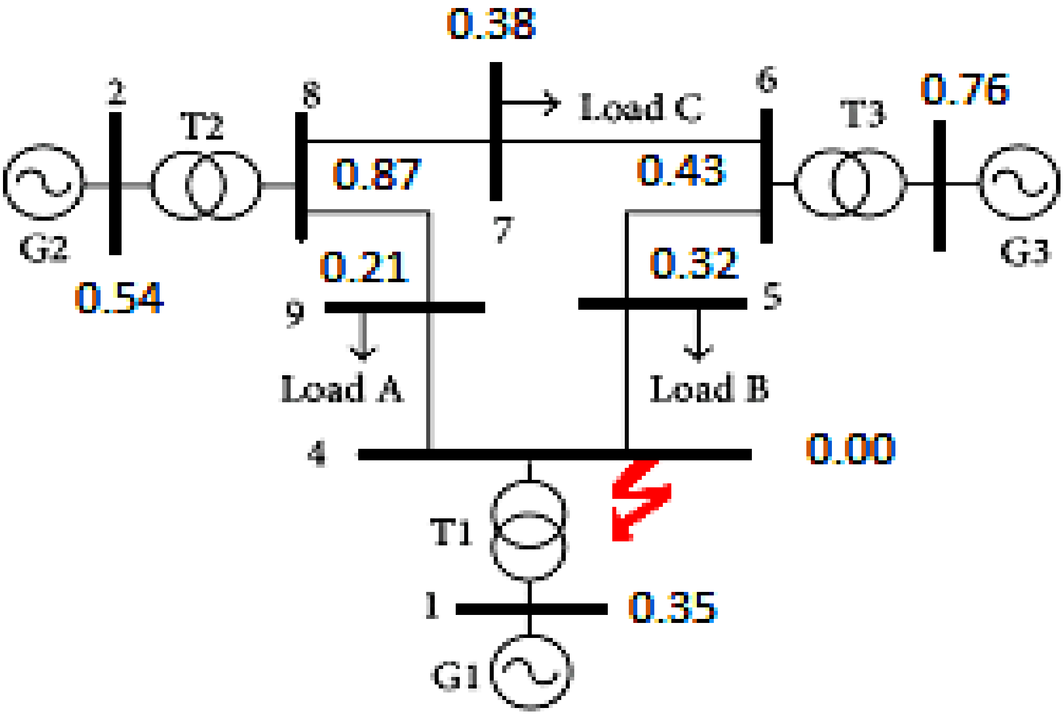

Fig.2 - A simple transmission system

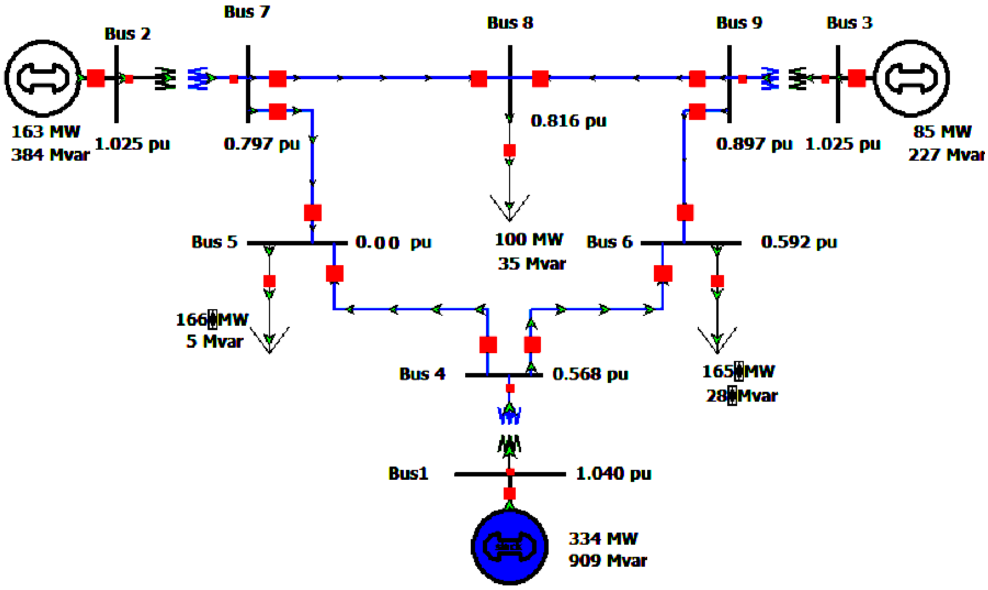

Fig.3 - The model of transmission system shown by figure 2 in the DIGSILENT environment

The short circuit analyses are performed in the simulated system which is performed in the DIGSILENT environment. During a specific fault at bus 4, the voltage readings at each bus are performed and reported using DIGSILENT.

These voltage values are highlighted with the 4th row of the concluded FV matrix for the system, reported for completely fault analysis of the system as Fig.4.

0.000	0.298	0.322	0.252	0.531	0.541	0.675	0.544	0.862
0.820	0.000	0.978	0.391	0.643	0.589	0.126	0.431	0.798
0.940	0.470	0.000	0.584	0.834	0.647	0.414	0.324	0.187
0.350	0.540	0.760	0.000	0.320	0.430	0.380	0.870	0.210
1.040	1.025	1.025	0.568	0.000	0.592	0.797	0.816	0.897
0.543	0.861	0.532	0.281	0.231	0.000	0.590	0.643	0.215
0.953	0.761	0.783	0.371	0.320	0.338	0.000	0.324	0.643
0.531	0.541	0.575	0.544	0.862	0.564	0.464	0.000	0.653
0.832	0.965	0.632	0.842	0.653	0.464	0.952	0.504	0.000

Fig.4 - an example of the FV matrix

3.2 Monitor reach area (MRA) matrix

A particular area in which every fault in that domain yields the voltage sag with the ability of capturing via a marked monitor is defined as monitor reach area (MRA) [32]. The MRA matrix, which is the purpose of this section of the current article, is a matrix in a binary format. In this matrix, the $MRA(j,k)=1$, signifies that point k is seen (observable) by installed PQM at bus j, whereas $MRA(j,k)=0$ identifies that point k is outside of the coverage area of the installed PQM at bus j.

Each element of this binary matrix is computed by comparing any FV matrix elements with an entrance value. This value defines as a threshold voltage which is represented by the α parameter. If the residual bus voltage of FV matrix is less or equal to α p.u., then $MRA(j,k)=1$ and otherwise, if the residual voltage of FV matrix is more than α p.u. at all phases, then $MRA(j,k)=0$ as expressed follows:

$$MRA(j,k)=\begin{cases}1 & if \;\; FV(j,k)\le \alpha \;\; p.u\, at\, any\, phase\\ 0 & if \;\; FV(j,k)>\alpha \;\; p.u\, at\, all\;\, phases\end{cases} \quad (2)$$

To better understand the concept of the MRA matrix, give attention to the simple distribution grid with radial topology, as shown in Fig.3. Its FV matrix is obtained in Fig.4. In this specific example, the voltage of threshold is assigned at α=0.75 p.u, and as result of the formation of the MRA matrix-based equation (2), it yields the MRA matrix as shown in Fig.5.

0	0	0	0	0	0	0	0	1
1	0	1	0	0	0	0	0	1
1	0	0	0	1	0	0	0	0
0	0	1	0	0	0	0	1	0
1	1	1	0	0	0	1	1	1
0	1	0	0	0	0	0	0	0
1	1	1	0	0	0	0	0	0
0	0	0	0	1	0	0	0	0
1	1	0	1	0	0	1	0	0

Fig. 5 - An example of the MRA matrix

3.3. System topology matrix (T)

Fundamentally, the T matrix is obtained via a similar analysis accomplished in the MRA matrix and in the FV matrix. Comparison is the base of computation. In the T matrix, the column elements are related to bus number, and rows denote the fault location. When a direct path connects the slack bus (the bus to which one generator is connected t) to a particular bus in the system, so the matrix is filled with 1 (one) and otherwise filled with 0 (zero) [33].

When a fault occurs in a particular bus, namely faulted bus, it becomes a cut vertex that splits into various vertices of the same component as many adjacent edges. Three examples of a highlighted row for a radial system with a single source, a radial system with two sources (feeding in doubly format), and a meshed system are presented in Fig.6. For instance, during fault at bus 3, depending on the number's feeders connected to this bus, the system graph can be separated into several sections.

By investigating the connectivity status between the main bus (slack) and the other nodes under mentioned criteria, the T matrix elements are then will be filled with '1' or '0'. As shown in Fig.6, in a system with mesh topology, value '1' will belong to the entire columns due to indefeasible connections between the source bus and the others. These examples are designed only with supposing active fault at the third bus of the system. So it should be repeated for whole buses similarly to extract the information about system topology through a complete T matrix.

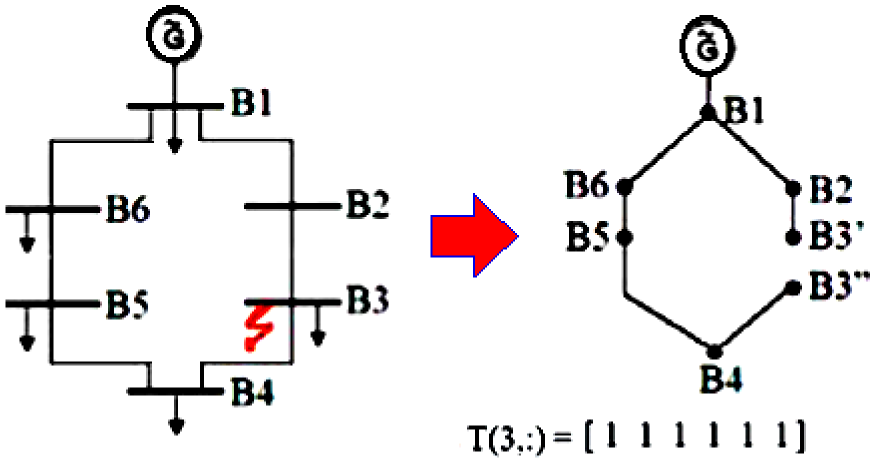

Fig.6 - Example of fault analysis and T matrix extraction under meshed based single fed system

3.4. Topology monitor reach area matrix (TMRA)

The topological monitor reach area (TMRA) is suggested to expand its usage to cover the distribution and transmission systems' fault analysis. The TMRA matrix is produced on the basis of the inner product of vectors concept and is illustrated as follows [22].

$$TMRA(j,k) = MRA(j,k) \bullet T(j,k) \quad (3)$$

4. Problem Formulation

The three main parts of a typical optimization problem are decision vector, objective function, and constraints. Therefore each item has been illustrated about the optimal solution of PQM placement.

4.1 Decision Vector

Monitor Placement (MP) vector, tracked by the optimizer program, can be represented by a decision vector filled with values of "0" and "1". So decision vector has a binary format that each bit indicates the position of the sag detector. In other words, the sag detectors are the PQMs which are installed in the network.

If $MP(n)=1$, it points out that one voltage sag detector (i.e., dip monitor) must be situated at bus n, whereas a value of "0" means that no monitor is needed for bus n. So MP vector is illustrated as relation coming after [25]:

$$MP(n)=\begin{cases}1 & if\ \ monitor\ is\ required\ \ at\ bus\ n\\ 0 & if\ \ monitor\ is\ not\ required\ \ at\ bus\ n\end{cases} \tag{4}$$

4.2 Objective Function

The PQM optimization problem discussed in this study deals with three objective functions that are addressed as follows.

- **Minimizing the number of required monitors (NRM)**

The first objective function is to minimize the number of situated monitors (***NSM***), which is addressed as (5):

$$NSM=\sum_{n=1}^{N_{bus}}MP(n) \tag{5}$$

- **Minimizing the monitor overlapping index (MOI)**

Among the optimal solutions obtained from the economic viewpoint-based analysis, the few monitor arrangements with high-level score is selected based on technical view using a new index named as Monitor overlapping index (***MOI***). This technical viewpoint-based selection considers the overlaps which could be issued by monitor coverage areas under different situated topologies in PQMs placement in the power system.

Hence, it is essential to consider these overlaps and minimize them because they represent the number of sag detectors reporting the same fault occurrence.

The index that clarifies the overlaps as a quantity value can be determined using the inner product of vectors concept and is extracted as follows by the inner product of both ***TMRA*** matrix and a vector which itself is the transposition of MP vector:

$$MOI=\frac{\sum(TMRA*MP^{T})}{NFLT} \tag{6}$$

By considering whole kinds of fault, the entire locations that faults occur in which are determined, and it is marked as ***NFLT*** value in equation (6). A lower ***MOI*** index represents situated PQMs with the better arrangement than others under that condition of system topology [24].

- **Maximizing the sag severity index (SSI)**

If several monitor configurations experiment the same ***MOI*** values, then in the next step of evaluating monitor placement, a new index will be introduced to employ in the allocation process. This new index is called as Sag Severity Index (***SSI***) that signifies the severity level of a particular bus regarding voltage sag where every fault that happens at this bus concludes a severe drop in all buses' voltage of the system. Thus, firstly it is needed to assess the severity level (***SL***). The ***SL*** is the total number of phases faced with voltage sags (***NSPB***) under amplitude below ***t*** p.u. with considering three phases in the total feeders and buses of the understudy system (***NTPB***), the SL is extracted as bellow [28]:

$$SL^{t}=\frac{\sum N_{SPB}}{\sum N_{TPB}} \tag{7}$$

Under different severity levels, the weighting factors are utilized to determine the ***SSI***. Finally, the ***SSI*** is determined by weighting factors applied for different severity levels.

$$SSI^F = \frac{1}{15}\sum_{k=1}^{5} k * SL^{\left(1-\frac{2k-1}{10}\right)} \quad (8)$$

Notably, the lowest ***t*** value is appointed with the maximum weighting factor and vice versa. Five different threshold values are considered as 0.1, 0.3, 0.5, 0.7 and 0.9 per unit in this research. Finally, the results of the ***SSI*** are saved in a two dimensions array. The rows of this array are related to kind of the events (short circuits, interruptions, and other faults), and bus numbers are represented by columns of this matrix.

When ***SSI*** has a higher value, it reflects a pleasurable configuration of sag detectors (i.e., dip monitors). Considering both criteria, i.e., the ***SSI*** and the ***MOI***, give a reasonable solution. To merge the ***SSI*** and the ***MOI*** into an applicable index, firstly, it is needed to compute them under the same optimal criteria. This criterion would be maximum or minimum.

In our study, the ***SSI*** index calculation must be revised to satisfy its level at the smallest one in the optimization procedure, as the case of the ***MOI***. It is worth noting that the highest value of ***SSI*** matrix elements experiments "1" value. So, the suitable index can be extracted by the use of a complementary matrix of ***SSI***. As a result, a negative severity sag index (***NSSI***) is proposed to assess the most pleasurable configuration of PQMs.

The ***NSSI*** index is determined through multiplying the SSI matrix in the complementary format by a vector resulted from the transposition of the MP. By considering the ***NFT*** which counts the fault types, the ***NSSI*** index is made clear as follows [14]. When NSSI meets its minimum value, it means that the best organization of PQMs is obtained.

$$NSSI = \frac{\sum\left[(1-SSI)*MP^T\right]}{NFT} \quad (9)$$

Since the three mentioned objective functions have the same optimal criteria, therefore with a combination of them, the single objective function for minimizing the proposed problem is extracted as follows:

$$f = (NRM * MOI) + NSSI \quad (10)$$

4.3 Optimization constraint

In order to better cover the monitoring action of the power system, the arrangement of PQMs must be in a manner that in the following one fault, the more busses of system can be observed. With increase in the monitoring of each bus of system the level of power quality will be enhanced and the voltage dip analysis (its detection and its compensation using compensator devices) is performed effectively. With an excellent redundancy, the buses of the system faced with faults are monitored more times, on average. Under suitable and acceptable value of redundancy, if one of PQMs fails, with the rest of PQMs, the monitoring action will be completed.

The only constraint in optimizing process in this problem is a controlling key named redundant vector or *R*. This controlling key enumerates the monitors detecting voltage sags issued from a fault at a particular bus and it should not be zero. This controlling key is obtained using the multiplication of the TMRA array by transposing of the MP array. So this constraint is formulated as follows [27]:

$$R = TMRA * MP^T \quad (11)$$

The structure of the redundant vector is similar to a column vector which has n rows. The rank of rows of ***R*** vector i.e., ***n*** is equal with the fault points counted in solving process using DIGSILENT software. The ***R(j)*** of each element in the R vector clarifies each fault point how many times it is monitored. Here ***R(j)=0*** identifies that the monitoring of the ***jth*** fault point is not provided. When each element in the ***R*** vector experiments with values higher than or equal to 1, it means that situated monitors observe whole fault points under a fault condition in the system.

To meet the governing requirements in the proposed problem and deduce optimal solutions, TLBO is utilized in the optimization process. In practice, the obtained optimal solutions will be available by the decision-maker to only select a final solution, and it is accepted as the final implementable topology. In the answers in which the objective function ***f*** meets its lowest value and on the other hand whole network is observed by the monitors, the optimal solution is exacted by assessing redundancy ***rd***, which its definition is clarified as (12):

$$rd = \sum_{i=1}^{M} R(i) / M \quad (12)$$

The worth of each element of obtained vector in the previous step of the analysis, i.e., redundant vector ***R*** is denoted by ***R(i)***, which is employed in equation (12), and ***M*** is the sum of all counted fault points in fault analysis.

The greater rd is, the more times the fault points are monitored in the system, on average. While the objective function meets its minimum point, the individual arrangement which faced with the highest level of ***rd*** is selected as the optimal solution. Redundancy index ***rd*** experiments the values in a range of [1, min (NRM)], which makes clear that each point affected by fault experiments the monitoring once at least and the maximum level of monitoring that it will be meet is equal with min (NRM) times.

5. Optimization Techniques

As mentioned earlier in Eq. (10), the minimization of a single objective function to achieve minimum number and best arrangement of PQM, is needed to employ an optimization algorithm. In this research, the binary version of the TLBO algorithm is utilized for the optimization process. This algorithm is discussed as follows:

5.1 Teaching Learning-Based Optimization, TLBO algorithm

Teaching Learning-based optimization (TLBO) is a population-based algorithm presented in 2011 and emanated from the classic version of teaching-learning phenomenon of a classroom [34].

The fundamental structure of this algorithm is based on two learning steps. The first step is named as a learning phase, and the second step is called as learner step. In the first step, the students (learners) first receive information from a teacher. He makes an effort to achieve the maximum mean result of the class, and the pleasurable answer is taken into account as the teacher (***Xteacher***) in the population. In this step, learners learn from the teacher, and the teacher makes an effort to boost the mean result of the classroom (***Xmean***) in the direction of his position, ***Xteacher***. This main is obtained through the enhancement of the result of other individuals (***Xi***). As presented in (13) for this goal, two parameters are needed, which are r produced randomly between 0 and 1 and, the second parameter ***Tf*** called the teaching factor, and is either 1 or 2.

$$X_{new} = X_i + r.\left(X_{techer} - T_f X_{mean}\right) \tag{13}$$

In this formula, ***Xnew*** is the newly generated, and ***Xi*** is the existing solution of ***i***. In the next step of the program, i.e., in the learner phase, the learning process of students (learners) through the interaction among themselves is simulated using an optimization approach. Discussing and interacting among students with together can also lead acquiring more knowledge by students. A learner will be faced with new information if other classmates experiment with more knowledge than him/her. During this step, the learner ***Xi*** interacts with another learner ***Xj*** in a random manner to refresh his/her knowledge.

If we consider that the situation of ***Xj*** experiments better situation to Xi, so ***Xi*** is transferred toward ***Xj***, and if not, it will be faced with a motion in the opposite direction of ***Xj***. This is explained as follows:

$$X_{new} = X_i + r.\left(X_i - X_j\right) \quad if \quad f(X_i) < f(X_j) \tag{14}$$

$$X_{new} = X_i + r.\left(X_j - X_i\right) \quad if \quad f(X_j) < f(X_i) \tag{15}$$

The recent solution ***Xnew*** will be accepted in the population if it is better, and the algorithm will be tracked until to face the stop criterion.

5.2 Binary TLBO algorithm (BTLBO)

As discussed further in section 4.1, the Monitor Placement (MP) vector is a binary decision vector in which the bit value $MP(n) = 1$ indicates the installation of PQM, and the 0 value means the not installation of PQM. The deamination of 0 and 1 values in each bit is the function of the optimization algorithm. Therefore in this study, we have a binary optimization problem that we can use from the binary version of the TLBO algorithm.

So in this section, the binary version of TLBO is explained detail. In two teacher and learner stages, the velocity of each learner (student) can be determined by:

$$v_i^k\,(Teacher \quad phase) = r.\left(X_{techer} - T_f \; X_{mean}\right) \tag{16}$$

$$v_i^k\,(Learnear \quad phase) = r.\left(X_i - X_j\right) \tag{17}$$

The position in the BTLBO is modeled by a vector that experiments with a binary format, and the velocity is still a floating-point vector. However, the velocity is utilized to compute the chance of changing from 0 to 1 or from 1 to 0 in the updating process of particles' position.

The sigmoid function is a suitable way to map the velocities in the [0 1]. The drawback of this function is that for a great value of vid in the positive or negative direction, it doesn't experiment any difference, and it just indicates a movement with more step size required on the basis of the previous position. To eliminate this problem, the "***tanh***" transformation is used to the component of velocity.

To outline the velocities into the range of [0, 1], the "***tanh***" transformation is implemented to the component of velocity as (18) and therefore, the equation (18) then substituted for the positions' updating formula[35]:

$$than\left(\left|v_{id}^k\right|\right) = \frac{\exp\left(2\left|v_{id}^k\right|\right) - 1}{\exp\left(2\left|v_{id}^k\right|\right) + 1} \tag{18}$$

$$x_{id}^{k} = \begin{cases} 1 & if \ \ ran < than\left(\left|v_{id}^{k}\right|\right) \\ 0 & else \end{cases} \tag{19}$$

In the current study, to minimize the number and aim to the best location, the position matrix provides a decision vector (array) with binary individuals. It clarifies the presence ('1') or the absence ('0') of PQMs in the buses of the system.

The flowchart of TLBO is presented in Fig.7.

5.3 BTLBO for Optimal PQM Placement

On the basis of BTLBO, the proposed algorithm to address the optimal placement of PQMs is illustrated as following steps:

Sep 1) Compute the binary TMRA matrix.

Sep 2) Define the optimization parameters; the number of students (***stu_size***) or the population size (***pop_size***), the design variables (***N_buses***), and the number of generation (***N_gen***)

Sep 3) Make the random solutions with the attention to boundaries of the system

Sep 4) Examine that random solutions meet the redundancy limitation of fault points and update those not fulfilling the constraint.

Sep 5) Calculate the fitness of each solution on the basis of the objective function.

Sep 6) Set the best solution as a teacher of the population.

Sep 7) For each student, apply the teacher phase, fill the place of *X* by ***Xnew*** if it presents a better fitness function (less) else, keep the old one.

Sep 8) In case of facing duplicate solutions, so it is essential to adapt the duplicate solutions to prevent them from situating in the snare of local optima.

Sep 9) Preform the learner phase for each student; fill the place of X by ***Xnew*** if it provides a more pleasurable fitness function (less); if not, keep the old one.

Sep 10) Eliminate duplicate solutions keeping the constrained satisfied, and then determine the teacher.

Sep 11) Repeat from step (5) for a maximum number of iterations

Sep 12) Set the best solution ***Xteacher*** as the final solutions.

The overall procedure in the optimal PQM placement method using BTLBO is shown in a flowchart in Fig.8.

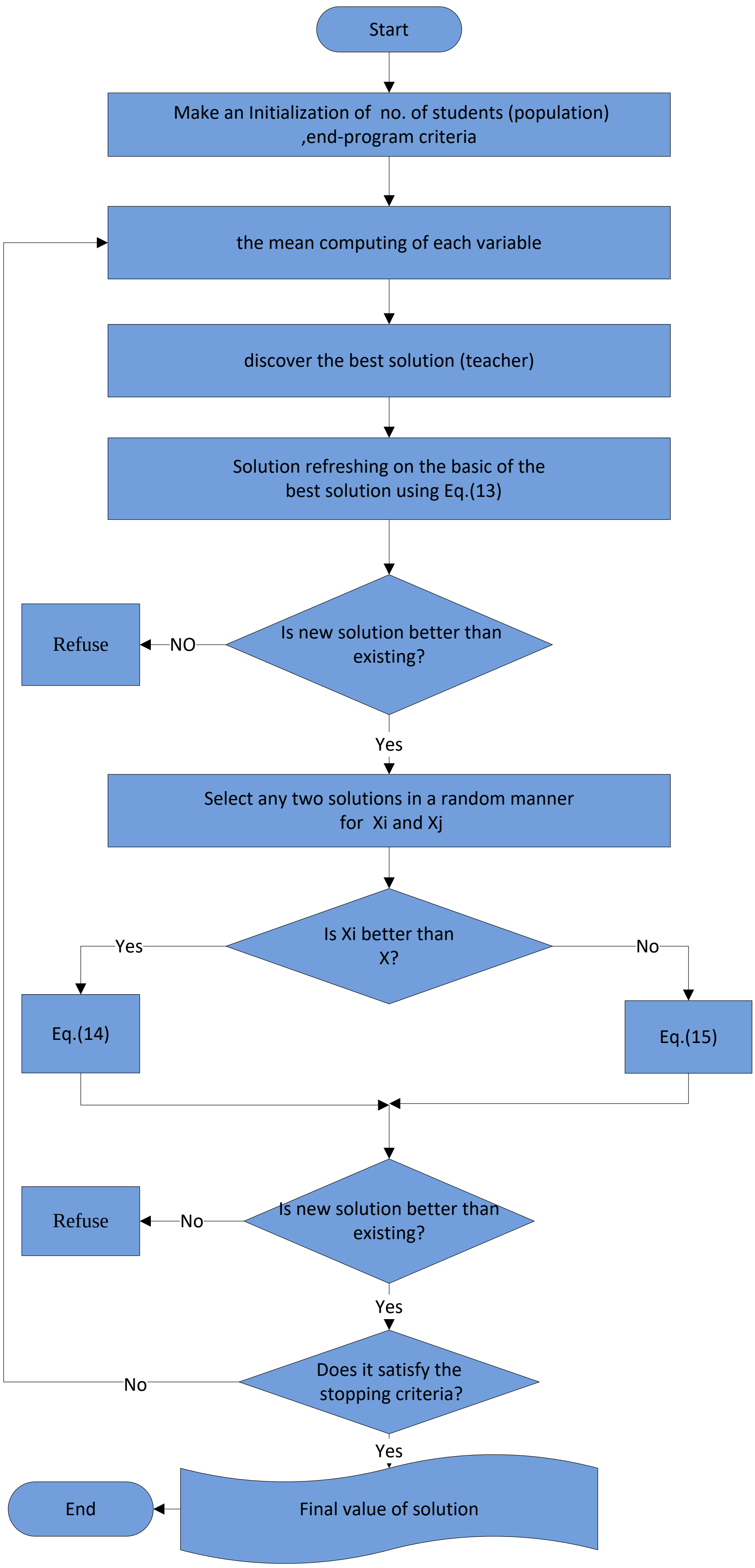

Fig.7. Flow-chart of TLBO algorithm

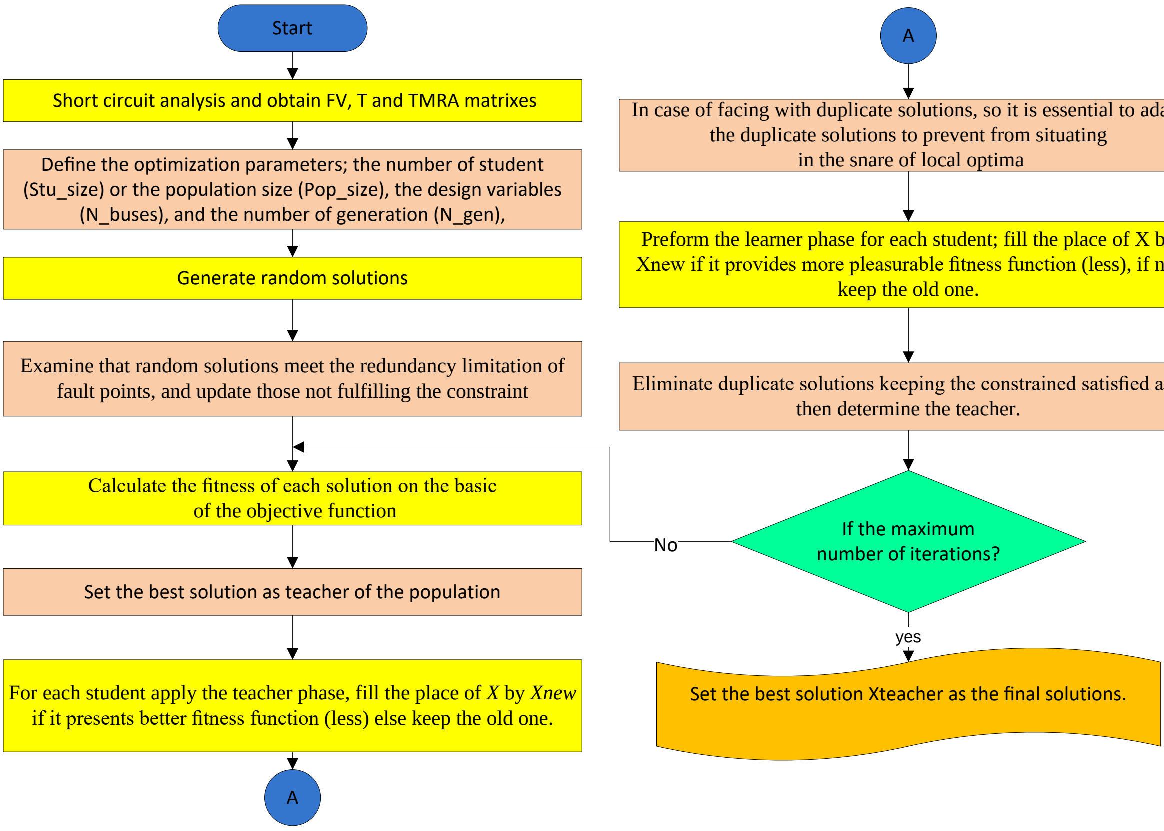

Fig.8.Implementation of BTLBO for optimal PQM placement

6. Simulation and Results

The proposed model is verified using the IEEE30 bus system. The 30Bus system is a transmission system with a balanced condition which experiments two voltage levels of 132 kV and 33 kV. This system consists of 6 generators. Three synchronous condensers with four step-down transformers are placed in the upstream network (at 132 kV). The types of these transformers are two-winding transformers (the two numbers) and three-winding transformers (also two numbers) to supply the downstream grid (at 33 kV) at three stations placed at buses 4, 6, and 28.

In the meshed topology of the system, there are 30 buses interconnected by 60 branches. The considered system' data is supported in [36]. In Fig.9, the single diagram of this system is presented.

The BTLBO program and the optimal allocation of the voltage sag detectors are made using MATLAB 2018 to obtain the results. In the current research, bolted LLL faults, DLG faults, and SLG faults with 0 Ω fault impedance are simulated at each bus in the system using the DIGSILENT software to obtain the monitor coverage matrix.

The BTLBO is implemented and compared to the improved adaptive genetic algorithm (IAGA) proposed by [16] to clarify the impressiveness of the proposed technique. All the optimization parameters are standardized where No. of students (population), maximum iterations, and teaching factor (***Tf***) are set to 70, 200, and 2, respectively.

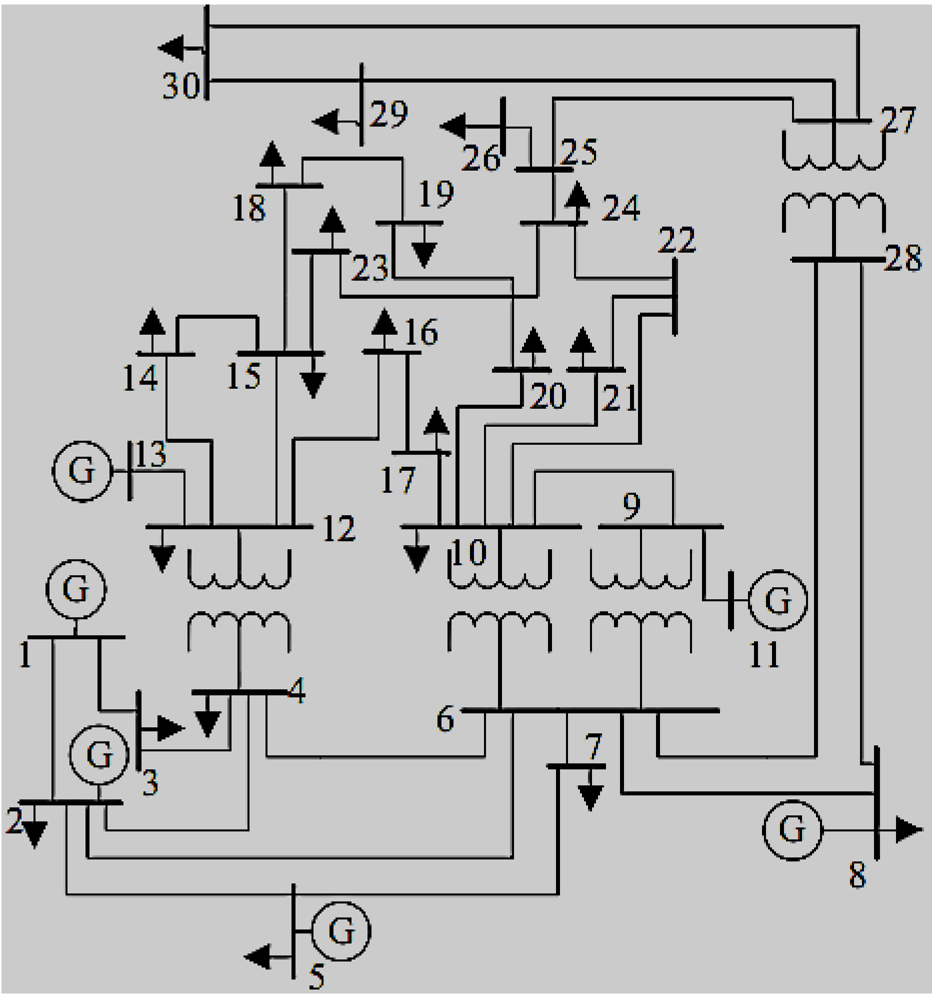

Fig.9 - The single diagram of IEEE 30Bus transmission system

In order to simulate and analysis the short circuits under different faults, the DIGSILENT software is utilized, and the model of the system in this software environment is shown in Fig.10.

Firstly, in order to make a comparison between this method and other results obtained on the 30Bus transmission test system under other heuristics methods, to validate results by BTLBO, the threshold voltage sag is considered 0.8. Table 1 lists the optimal allocation arrangements of the voltage sag monitors under various faults when α = 0.8. In accord with Table 1, under single-phase earth fault, it needs three monitors, which are situated on buses 4, 24, and 25, to get overall monitoring of the system. It indicates one more than those needed by the other three events (LLL, LL, and DLG). This main is issued from the fact that the SLGs happen more times, and so cause significant losses. The situation procedure of PQMs under any fault type is the same as SLGs.

However, under different kinds of faults, the installed points are varied. Under LLL events as well as under DLG faults it requires two monitors. The installed points are on buses 4 and 24 for LLL events, whereas under the LLG event the PQMs are located on buses 7 and 14 to observe the entire network.

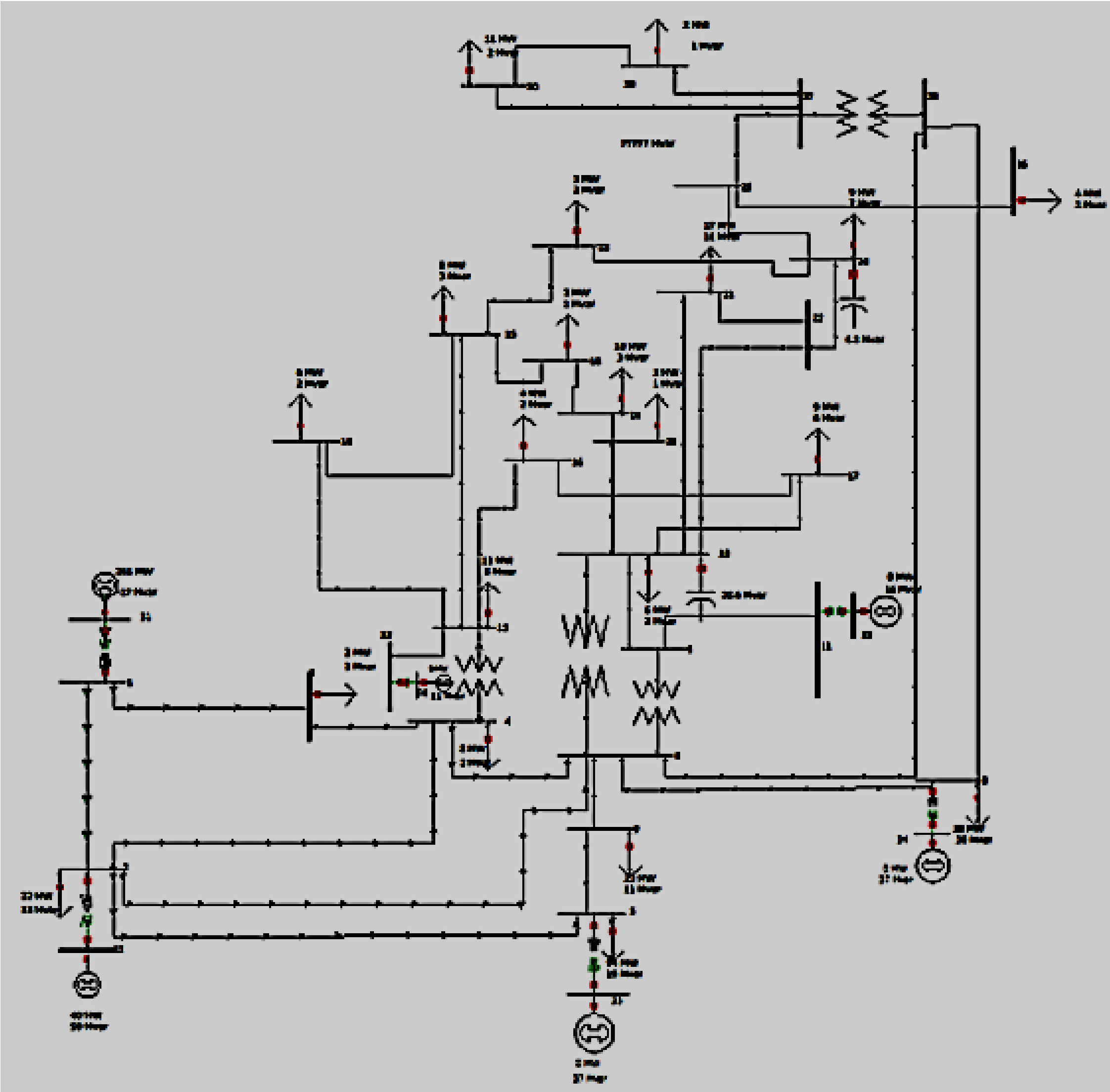

Fig.10 - DIGSILENT model of 30Bus IEEE transmission test system for short circuit analyses

Table 1 - Performance of LLBO on 30-bus transmission system for α at 0.8

Method	Fault Type	Num. PQM	Redundancy	Rd/NPQM	Optimal Scheme	Num. Iterations	Num. Solutions
TLBO	LLL	2	1.86	0.931	4,24	7	24
	SLG	3	2.34	0.781	4,24,25	8	24
	LL	2	1.86	0.931	7,14	9	24
	DLG	2	1.86	0.931	4,24	8	34
	Any Type	3	2.34	0.781	4,24,25	7	24
IAGA [16]	LLL	3	1.91	0.636	7, 14, 27	26	18
	SLG	3	2.12	0.706	4, 14, 29	35	32
	LL	3	2.27	0.756	3 ,11, 27	30	23
	DLG	2	1.43	0.715	7 ,24	19	28
	Any Type	4	2.63	0.657	4 ,7, 14 ,29	--	--

As discussed earlier, the final allocation scheme in this research is announced by the program through evaluating the size of redundancy. The bus locations listed in Table 1 clarify all of the feasible schemes which experiment the redundancy ***rd*** at a high level while the objective function is faced with its minimum value.

As shown in Table 1, in the cases of single-phase to the ground event and any fault type; the results dictate the installation of 3 PQMs with a redundancy ratio (***redundancy/optimal NPQM***) of 0.781. It is evident by Table 1 that under the other three short-circuit faults, the redundancy ratios of all are 0.931. In accord with Table 1 with making a comparison between the results of BTLBO and the ones of improved adaptive genetic algorithm called IAGA [16], it is clear the PQMs number identified by BTLBO under any fault types are smaller than those obtained by IAGA and viewpoint of economic aspect this is worthy.

As well as the redundancy ratio values obtained by BTBLO because of better configuration of PQMs are greater than those values calculated by IAGA. The results obtained by BTBLO about the redundancy ratios are more desirable for planners because the more fantastic (greater value) ***rd*** is, the more times points faced with faults are observed in the system, averagely. Also, except in double phase earth fault, in all states, the iteration number of BTLBO is much smaller than corresponding value determined by IAGA. So the BTLBO exhibits the fastest convergence compared with the IAGA. This testifies that BTLBO is a suitable approach to solve PQM optimal placement problem from the point of view speed convergence and capability of the monitoring system.

For various values of the threshold of the voltage sags, the problem is solved by BTLBO, and Table 2 lists the optimal number, optimal configuration, and the redundancy ratios of PQMs versus the threshold of the voltage sags.

Table 2 - Performance of BTLBO on 30-bus transmission system for different α values

Threshold value	Num. PQMs	Optimal Configuration	rd/NPQM	Num. Iterations
0.75	3	5,20,25	0.7026	8
0.65	5	1,5,11,24,27	0.5831	9
0.55	6	4,7,15,20,26,29	0.5276	12
0.45	10	2,4,7,11,13,14,19,23,26, 29	0.4819	15
0.35	15	1,2,4,5,7,11,13,14,19,20,23,25,26, 27,29	0.4176	23
0.25	17	1,2,4,5,7,9,11,13,14,17,19,20,23,25,26, 27,29	0.3822	35
0.15	17	1,2,4,5,7,9,11,13,15,17,19,20,23,25,26, 27,29	0.3275	37
0.05	18	1,2,4,5,7,9,11,13,14,15,17,19,20,23,25,26, 27,29	0.3103	39

The ratio of ***rd/NPQM*** in Table 2 corresponded with the MRA is reduced with decreasing of the threshold value of voltage sag. Thus, the lower threshold of the voltage sag is considered, the smaller MRA and consequent the higher number of monitors. As shown in the last columns of Table 2, the number of iterations refers to the ones that are needed for the convergency in the optimization process.

The number of iterations is the time that the algorithm is run when BTLBO converges to the optimal answer. For example, when the threshold of the voltage sag is 0.75, BTLBO iterates eight times to converge to the optimal solution while it proposes three monitors. From obtained results of the implantation of the BTLBO algorithm, it is found that only two monitors or finally three monitors are enough to observe the entire system when the threshold of the voltage sag $\boldsymbol{\alpha}$ value is set to 0.8 or 0.75 in terms of per unit.

The optimal location of PQMs when the threshold of the voltage sag $\boldsymbol{\alpha}$ value is set to 0.65 is shown in Fig.11, which yields five PQMs at buses 1, 5, 11, 24, and 27.

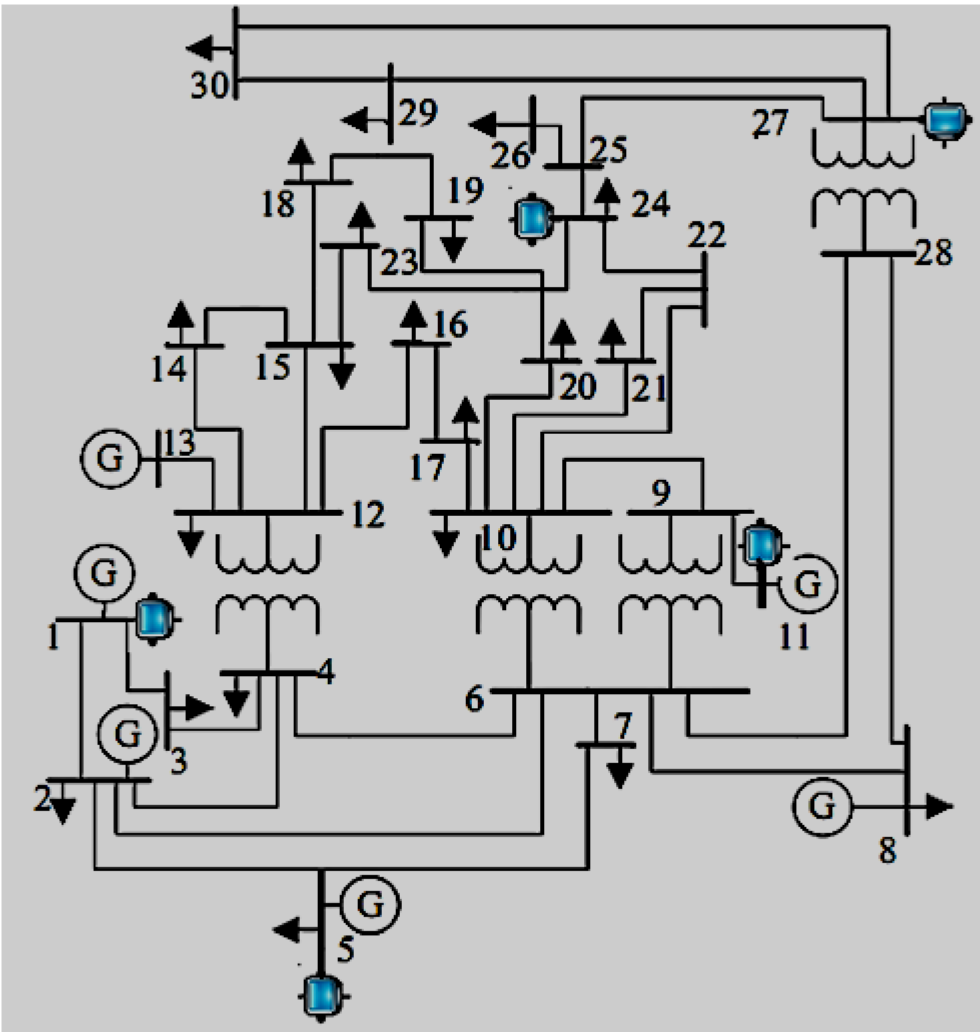

Fig.11 - Optimal location of PQMs for the threshold of the voltage sag of 0.65

However under this arrangement of monitors, perhaps some less serious faults consisting of high impedance in faraway points cannot be detected. Therefore the threshold value is adjusted at 0.55 in the optimization process to be more sensitive. For this α value, a minimum of 6 monitors is needed for the IEEE 30Bus system located on buses 4, 7, 15, 20, 26, and 29.

Table 3 shows under low threshold for example, when α is set at 0.35 to 0.05, the number of PQMs is nearly constant, about 15 until 18 monitors that only their arrangement is different. When α is set at 0.25, 0.15, and 0.05, approximately 18 monitors are needed that yield redundancy ratio of 0.3822, 0.3275, and 0.3103 under the different arrangements of PQMs. Also, if the lower value of the threshold for voltage sags is considered, the number of iterations when BTLBO experiments the optimal solution is approximately identical (≈ 37).

Fig.12 shows the convergence characteristics of the different techniques during the tracking of the best optimal solution when α is set at 0.45. The results shown in Fig.12 indicate that BTLBO exhibits the fastest convergence compared with the other techniques, IAGA [16], QBPSO [20], AQBPSO [20], and GA [28].

It is evident from this figure that the slowest convergence in contrast with the other techniques is obtained by GA. Although the QBPSO, AQBPSO and BTLBO have congregated with nearly the identical iterations, the computational time spent by BTLBO is much smaller than the time spent by the two others.

As seen earlier in results reported by Tables, unlike the QBPSO, which for the threshold of the voltage sags lower than 0.55, the computational time has greatly increased, but in BTLBO, with decreasing the threshold value, the computational time has uniformly and slowly increased.

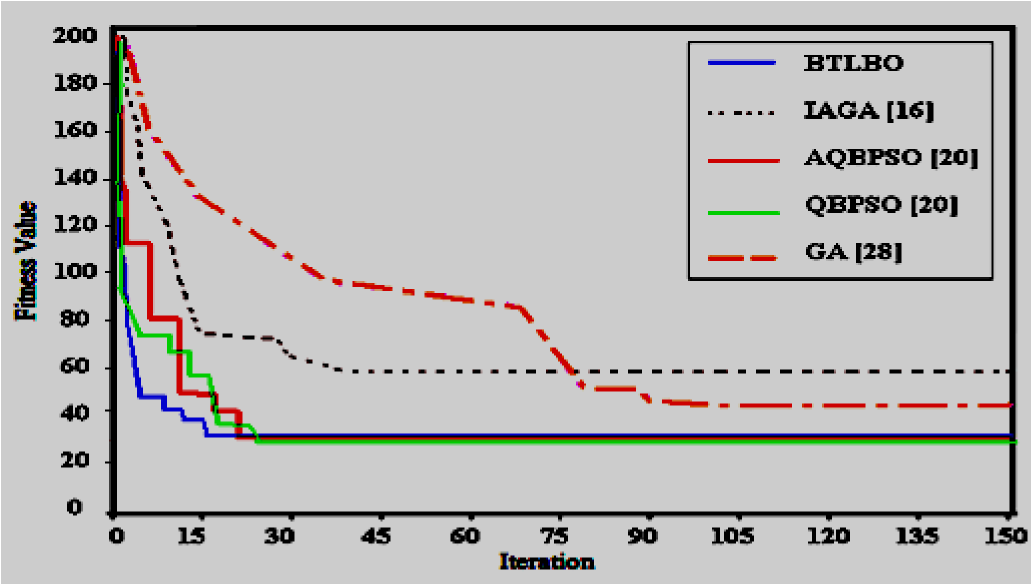

Fig.12 - Convergence characteristics of the proposed technique

According to the results, the optimal monitor placement for the 30Bus system is a topology with proposed locations at nodes 4, 7, 15, 20, 26, and 29 when ***α*** experiments value of 0.55. In this scenario, the monitoring of whole faults that yield a voltage sag with a magnitude lower than 0.60 can be achieved through six monitors.

From the results, the ***MOI*** and ***SSI*** indices are evaluated under the different cases of fault types. This result is presented in Table 3. The last column is related to ***SSI*** and ***MOI*** analysis of ***α*** value of 0.45, which concluded to 10 PQMs on buses 2, 4, 7, 11, 13, 14, 19, 23, 26, 29.

Table 3 - Analysis of the MOI and SSI under the monitor schemes of 6 and 10 PQMs on optimal locations in the 30Bus system when α experiments values of 0.55 and 0.45

PQM Placement	4, 7, 15, 20, 26, 29	2,4,7,11,13,14,19,23,26, 29
MOI	2.313	1.865
SSI (SLG on phase a)	0.575	0.643
SSI (SLG on phase b)	0.575	0.643
SSI (SLG on phase c)	0.575	0.643
SSI (DLG on phases a, b)	0.812	0.968
SSI (DLG on phases b, c)	0.812	0.968
SSI (DLG on phases a, c)	0.812	0.968
SSI (LLL on phase a, b, c)	1.585	1.761
Average SSI	0.821	0.942

In order to verify the quality performance of the BTLBO based method, for the monitor scheme of 6 PQMs for ***α*** value of 0.55, the ***MOI*** and SSI are compared with the results of the GA method [28] that hasn't considered the redundancy effect in the optimization problem. These results are listed in Table 4.

Table 4 - The performance comparison of GA and BTLBO on Optimal PQMs placement result of the 30Bus transmission system in terms of MOI and SSI values for α at 0.55

GA [28]		BTLBO	
MOI	SSI	MOI	SSI
2.057	0.708	2.313	0.821

This main result is understood that when the ***α*** value reduces, the monitoring scheme faces more sensitivity. A study is performed to discover the relationship between optimal PQM organization and the monitoring scheme's sensitivity dependent upon α value.

Table 5 makes clear that the sensitivity of the monitoring scheme enhances with the increase in the number of allocated monitors. The last column of Table 5 verifies the results of the last column of Table 2, concluded that for the lower threshold the iteration numbers are approximately identical as well as elapsed time reported by Table 5.

Table 5 - The optimum number of PQMs under different values of α

α values	The minimum required number of PQMs				Elapsed Time (s)			
	GA [28]	QBPSO [20]	AQBPSO [20]	BTLBO	GA [28]	QBPSO [20]	AQBPSO [20]	BTLBO
0.75	3	3	3	3	--	1.63	1.940	1.751
0.65	6	6	6	5	--	3.31	2.154	1.843
0.55	8	8	8	6	--	21.23	3.680	2.532
0.45	11	11	11	10	--	137.53	4.093	2.854
0.35	17	17	17	15	--	4668.46	4.286	2.947
0.25	19	19	19	17	--	55084.46	4.395	2.978

Since the monitor arrangements are affected by redundancy, for the best monitor configuration, the values of ***MOI*** and ***SSI*** are evaluated and listed as shown in Table 6.

Table 6 - The effect of redundancy on optimal PQMs placement result of the 30Bus transmission system in terms of MOI and SSI values for various α values

Consideration	α values	MOI	Average SSI
With redundancy	0.55	2.313	0.821
	0.45	1.865	0.942
Without redundancy	0.55	2.002	0.848
	0.45	1.753	0.967

Hence, a lower value of voltage sag threshold leads to a smaller index of MOI, and consequent a higher number of monitors is requested. Finally it avoids overlapping in the monitoring scheme. Therefore under the same number of monitors, the SSI index is increased and also, the modeling redundancy decreases the MOI because that each PQM's coverage area becomes small.

Finally, for reliability analysis to examine the proposed design of PQMs in monitoring and recording the dip voltages, 100 faults at different positions in the ten segments of each branch are simulated at random points. The hundred simulated faults covers three types including single-phase faults, two-phase faults and three-phase faults with occurrence number of 60, 30 and 10 respectively.

Table 7 lists a summary of the fault detection performance by 6 PQMs and 10 PQMs when α value is set 0.55 and 0.45 respectively at the optimal locations.

Table 7 - The observed Voltage sag by PQMs on 30Bus transmission system under100 faults analysis with different α values

α values	Number of PQM detecting fault				Total
	No PQM (Voltage sag wrongly monitored)	1 PQM (Voltage sag monitored by 1 PQM (no repetition)	2 PQM (Voltage sag monitored by 2 PQM (with repetition)	≥ 3 PQM (Voltage sag monitored by ≥ 3 PQM (with repetition)	
0.45	0	43	34	23	100
0.55	3	47	39	11	100

Based on the results listed in Table 7, for ***α***=0.45, no voltage sag is incorrectly monitored. However, for ***α***=0.55, three voltage sags are incorrectly observed. At ***α***=0.45, for the voltage sags monitored by more than three PQMs, 23 faults resulted dips are observed more than once, whereas it is just 11 faults at ***α***=0.55. This condition appears an overlapping in the monitor coverage area. Thus, it clarifies the acceptableness of the proposed PQMs arrangement, which is also reliable for voltage sag assessment.

7. Conclusion

In this paper, a novel method based upon the binary version of teaching learning optimization called BTLBO, is proposed to obtain an optimal solution through optimal number and placement of PQMs. The goals of minimizing ***MOI*** and achieving the maximum ***SSI*** are mathematically modeled in this study.

This method is based on the concept of redundancy, and it is seen that with a greater redundancy, the fault points are monitored more frequently. In this study, DIGSILENT software is utilized for different short circuit fault analyses while the BTLBO manages the optimization process. The algorithm was applied to IEEE 30BUS transmission systems. For different voltage sag threshold, the effect of considering redundancy on optimal number and configuration as well as on the MOI and SSI indices are analyzed. Also, Fitness values and iteration numbers are computed and reported.

Finally, for reliability analysis to examine the proposed design of PQMs in monitoring and recording the dip voltages, 100 faults at different positions in the ten segments of each branch are simulated at random points. It is supposed that a number of PQMs are exited from the proposed PQMs topology due to inner defects. This question arises that can rest of the PQMs guaranty the monitoring and recording of all faults in the system? Referring to the reliability analysis's results, nearly no voltage sag is incorrectly monitored in all cases.

Results depict that BTLBO gives the most excellent solution than the other optimization methods, GA, IAGA, QBPSO, and AQBPSO, which were earlier utilized by other researchers. Fast convergence, short run time, the ability to track global optimum, and nearly zero standard deviation are reported as other advantages of BTLBO in this research.

Acknowledgement

The author would like to acknowledge the Department of electrical engineering, Borujerd Branch,
Islamic Azad University, Borujerd, Iran.

References

[1] S. Divya, U.Shyamala (2015) "Power quality improvement in transmission systems using DPFC", 2nd International Conference on Electronics and Communication Systems, Coimbatore, India, 26-27 Feb. 2015.
[2] M.A Soomro, Z.A Memon & M. Kumar (2020) "PWM Based VSC for Power Quality Assessment of Grid Integrated DFIG-WECS", International journal of integrated engineering, Vol.12, No.6, pp.239–252.
[3] M. Mohammadi, M. Montazeri & S. Abasi (2017) "Bacterial graphical user interface oriented by particle swarm optimization strategy for optimization of multiple type DFACTS for power quality enhancement in distribution system", Journal of Central South University, Vol.24, pp.569–588.
[4] D. M. Vilathgamuwa, H. M. Wijekoon, and S. S. Choi. (2004) "Interline Dynamic Voltage Restorer: A Novel and Economical Approach for Multiline Power Quality Compensation", IEEE Trans. Ind. Appl. Vol.40, pp.1678-1685.
[5] Hussain Shareef, Azah Mohamed & Ahmad Asrul Ibrahim (2013) "Identification of voltage sag source location using S and TT transformed disturbance power", Journal of Central South University, Vol.20, pp.83–97.
[6] Yidong Hong, Tao Yu. (2013) "Reliability Improvement Strategies for HVDC Transmission System", Energy and Power Engineering, Vol.5, pp.52-56.
[7] Haiwei Jiang,Yonghai Xu, Ziteng Liu, Ning Ma, and Wenqing Lu.(2020) "A BPSO-Based Method for Optimal Voltage Sag Monitor Placement Considering Uncertainties of Transition Resistance", IEEE Access, Vol. 8, pp.80382-80394.
[8] Won D-J, Moon S-I (2006) "A new algorithm to locate power quality event source with improved realization of distributed monitoring scheme", IEEE Transaction on Power Delivery, Vol. 21, pp.1641-1647.
[9] Won D-J & Moon S-I (2008) "Optimal number and locations of power quality monitors considering system topology", IEEE Trans Power Delivery, Vol.23, pp.288-95.
[10] Eldery M, El-Saadany EF, Salama MM, Vannelli A. (2006) "A novel power quality monitoring allocation algorithm", IEEE Trans Power Delivery, Vol.21, pp.768–777.
[11] N. N. Kuzjurin (2002) "Combinatorial Problems of Packing and Coveringand Related Problems of Integer Linear Programming", Mathematical Science, Vol.108, pp.1-6.
[12] Eldery M, El-Saadany EF, Salama MM. (2004) "Optimum Number and Location of Power Quality Monitors". The 11th International Conference on Harmonics and Quality of Power, New York, USA Sept. 12-15. https://ieeexplore.ieee.org/document/1409328.
[13] O.Cortes-Robles, Emilio Barocio, Artjoms Obushevs, Petr Korba, Felix Rafael Segundo Sevilla (2020) "Fast-training feedforward neural network for multi-scale power quality monitoring in power systems with distributed generation sources", Measurement January, Vol.170, pp.108690.
[14] Kazemi A, Mohamed A, Shareef H. (2012) "A novel PQM placement method using Cp and Rp statistical indices for power transmission and distribution networks", In: Power engineering and optimization conference (PEDCO) Melaka, Malaysia, 2012 IEEE International, pp.102–7.

[15] Leila Kamyabi, Saeid Esmaeili, Mohammad Hossein Rezaeian Koochi (2018) “Power quality monitor placement in power systems considering channel limits and estimation error at unobservable buses using a bi-level approach”, Int J Electr Power Energy Syst, Vol.102, pp.302-311.
[16] Kazemi A, Mohamed A, Shareef H, Zayandehroodi H. (2013) “Optimal power quality monitor placement using genetic algorithm and Mallow’s Cp”, Int J Electr Power Energy Syst., Vol.53, pp.564–75.
[17] Asadollah Kazemi, Hajar Raihi, Azah Mohaamed, H.Shareef (2013) “Optimal Power Quality Monitor Placement Using GACp Method for Distribution Network”, 28th Power System Conference, 2013 Tehran, Iran.
[18] Olguin G, Bollen M. (2003) “Optimal dips monitoring program for characterization of transmission system”, In: Power Engineering Society General Meeting, 2003, IEEE, pp.2484–2490.
[19] Ibrahim AA, Mohamed A, Shareef H, Ghoshal S. (2010) “Optimal placement of voltage sag monitors based on monitor reach area and sag severity index”, In: Research and Development (SCOReD), 2010 IEEE Student Conference on, pp.467–470.
[20] M. Haghbin and E. Farjah. (2009) “Optimal Placement of Monitors in Transmission Systems Using Fuzzy Boundaries for Voltage Sag Assessment”, 2009 IEEE Power Tech Conference, 28th June-2nd July, Bucharest, Romania, pp.1-6.
[21] Wang Hong, Li Dan, Huang Wenqing, Dai Yuxing (2015) “Optimal allocation of power quality monitors based on an improved adaptive genetic algorithm”, Joint International Mechanical, Electronic and Information Tchnology Conferences, 5 Chongqing, China, pp.774-785.
[22] Ahmad Asrul Ibrahim, Azah Mohamed, Hussain Shareef. (2011) “Optimal Placement of Power Quality Monitors in Distribution Systems Using the Topological Monitor Reach Area”, 2011 IEEE International Electric Machines & Drives Conference, Niagara Falls, Canada, New York IEEE Press, May, 15–18.
[23] Ibrahim AA, Mohamed A, Shareef H, Ghoshal SP. (2011) “Optimal power quality monitor placement in power systems based on particle swarm optimization and artificial immune system”, Proceedings of the 3rd conference on data mining and optimization, Putrajaya, Malaysia, New York: IEEE Press, June, 28–29.
[24] Ibrahim AA, Mohamed A, Shareef H, Ghoshal SP. (2011) “An effective power quality monitor placement method utilizing quantum in spired particle swarm optimization”, Proceedings of the international conference on electrical engineering and informatics, Bandung, Indonesia, New York, IEEE Press, July, 17–19.
[25] A. A. Ibrahim, A. Mohamed, H. Shareef. (2012) “A Novel Power Quality Monitor Placement Method Using Adaptive Quantum-Inspired Binary Particle Swarm Optimization”, International Conference on Renewable Energies and Power Quality (ICREPQ’12), Santiago de Compostela (Spain), March, 28- 30.
[26] Ibrahim AA, Mohamed A, Shareef H. (2012) “Application of quantum-inspired binary gravitational search algorithm for optimal power quality monitor placement”. In Proceedings of the 11th WSEAS international conference on artificial intelligence, knowledge engineering and databases (AIKED‘12), Cambridge, UK, February, 22–24
[27] Ahmad Asrul Ibrahim, Azah Mohamed, Hussain Shareef. (2014) “Optimal power quality monitor placement in power systems using an adaptive quantum-inspired binary gravitational search algorithm”, Int J Electr Power Energy Syst., Vol.57, pp.404-413.
[28] Ahmad Asrul Ibrahim, Azah Mohamed, Hussain Shareef, Sakti Prasad Ghoshal. (2012) “Optimization Methods for Optimal Power Quality Monitor Placement in Power Systems: A Performance Comparison”, international journal on electrical engineering and informatics, Vol.4, pp.1-18.
[29] LI Hui. (2015) “Optimal Number and Location of Power Quality Monitors for Power System, Chinese Automation Congress”, Wuhan, China, 2015, IEEE Publisher, November 27.
[30] Branco HM, Oleskovicz M, Delbem AC, Coury DV, Silva RP. (2015) “Optimized allocation of power quality monitors in transmission systems: A multi-objective approach”, Int J Electr Power Energy Syst. Vol.64, pp.156-66.
[31] C.F.M. Almedia and N. Kagan. (2009) “Allocation of Power Quality Monitors by Genetic Algorithms and Fuzzy Sets Theory”, The 15th International Conference on Intelligent System Applications to Power Systems, Curitiba, Brazil, Nov. 12-19.
[32] Olguin G, Vuinovich F, Bollen MH. (2006) “An optimal monitoring program for obtaining voltage sag system indexes”, IEEE Trans Power Syst., Vol.21, pp.378-84.
[33] Reis D, Villela P, Duque C, Ribeiro P. (2008) “Transmission systems power quality monitors allocation”, In: Power and energy society general meeting-conversion and delivery of electrical energy in the 21st Century, IEEE, 1-7.
[34] R.V.Roa, V.J.Savsani, D.P.Vakharia (2011) “Teacher-learning-based optimization: a novel method for constrained mechanical design optimization problems”, Comput. Aided Des, Vol.43, pp.303-315.
[35] Majid Akhlaghi, Farzin Emami, Najmeh Nozhat (2014) “Binary TLBO algorithm assisted for designing plasmatic nano bi-pyramids-based absorption coefficient”, Journal of Modern Optics, Vol.61, No.13, pp.1092-1096.
[36] University of Washington, Data files for the test cases of IEEE 30 buses power system, [Online] Available: