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Optimal Placement of Power Quality Monitors

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Power quality is becoming a major concern due to increase penetration of power electronics devices and smart grid initiatives. This paper presents an effective methodology to optimally place the Power Quality Monitors (PQMs) to get complete information of the network even under the some outages which makes the system completely observable. Binary Particle Swarm Optimization (BPSO) technique has been used to minimize the numbers of PQM required to make system completely observable and to maximize the measurement redundancy. An index based two-step method has been proposed. Simulation result of the proposed method on IEEE-14 bus system, IEEE-24 bus system IEEE-30 bus system, 13 bus feeder system, 34 bus feeder system, 37 bus feeder system are presented to demonstrate the suitability of the proposed method.

Keywords: *Power quality monitors, Binary particle swarm optimization, Observability, Optimal placement.*

1.0 INTRODUCTION

Due to increased penetration of power electronics based non-linear load to improve the system performance, the Power Quality (PQ) problem has attained considerable attention in the last decades. On one hand these devices introduce power quality problem and on other hand these devices mal-operate due to the induced power quality problems. Large penetration of power electronics based controllers, variable loads and devices along with restructuring of the electric power industry and small-scale distributed generation require more stringent demand on the quality of electric power supplied to the customers.

Thus, in the emerging power systems, it is essential to monitor the system, either to know the sources and causes of PQ disturbances for appropriate mitigation actions or to penalize the PQ problem source to ensure a contracted level of power quality in the system [1–2]. Power quality monitoring provides a key opportunity for a utility to remain competitive and to retain/attract the customers. As the PQ monitoring systems are flexible, reliable and fast, more utilities are using them in order to guarantee the customers supply in a satisfactory manner. Therefore, the determination of minimal number of power quality monitors and appropriate monitoring location required to monitor a power network become important.

The literature suggests the installation of a power quality monitor (PQM) in each bus of a power system where all these PQM are integrated through communication facility like internet [3–5].

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But the limitation of this approach is the number of devices required and the capability of the equipment to analyze large amount of data to be captured. Installing PQM at every node, results in the enormous amount of redundant data as the number of buses increase. Moreover, the cost of PQM system increases. A methodology to determine the minimal number of PQM and the buses where these PQM should be installed is a critical problem and as it is directly related to the efficiency and economy. The number of monitors required to monitor a power network and their location must be optimally determined as the economic efficiency is directly related to the monitoring capability [6]. Reducing the number of monitors reduces the redundancy of data being measured by the monitors in addition to the reduction in cost, thereby, making the system more efficient [7]. To determine the locations at which the PQM must be placed in order to maximize the monitored area of the power system under study, the optimum power quality monitor allocation model is should be designed.

To determine the optimum placement of the PQM many optimization techniques have been used in last few years. The optimization problem in [7] was formulated using covering and packing concept which was solved using GAMS. In [8,9], for making computation, easy branch and bound algorithm was implemented by dividing the solution space into smaller space. Evolutionary Computation techniques have proved to be efficient and robust in solving multi-objective optimization problems in different fields [10]. GA is also one of the commonly used techniques to solve the optimization problem of PQM placement [11–12]. But one of the limitations of GA is its slow convergence rate. An alternative optimization technique with fast convergence rate is required. One such optimization technique is Particle Swarm Optimization (PSO) which has been used successfully in a number of power system applications [13].

In this paper, a Binary Particle Swarm Optimization (BPSO) based method is used for optimal placement of power quality monitors for complete observability of the power system. The proposed method is simple and can be applicable for both the messed and radial networks. The effectiveness of the proposed method is demonstrated in six IEEE test systems.

Basic principle of optimal placement of PQMs is discussed in Section 2. A brief overview of Binary Particle Swarm Optimization is given in Section 3. Section 4 gives the implementation of the proposed approach by BPSO, when some buses are left unobserved by index method. Simulation results are discussed and demonstrated in section 5. Section 6 concludes the paper. References are given in Section 7.

2.0 PQM PLACEMENT FOR OBSERVABILITY

This section provides a method for optimal placement of PQMs for complete observability of power system. In a power system, the bus is said to be observable if its voltage can be measured directly or can be calculated by using other known voltages. If all buses are observable in the power system, then the power system can be defined as with a full observablity [14]. Our main objective is to make the system observable by using least number of PQMs. In case of more than one solution, priority has been given to the solution resulting in maximum redundancy. Few guidelines that can be used to select appropriate monitor location to analyze the topological observability of the bus in the power system under study are

1. All the buses adjacent to the bus with PQM installation are observable since PQM installed at the bus can measure the voltage at that bus as well as of all the incident buses using measured current phasors and the line parameters [15–16].
2. The power flow to any one of the lines connected to an observable zero injection bus can theoretically be determined using Kirchoff's Current Law (KCL) and Ohms Law when power flow in remaining of the connected lines are known.

To minimize the number of PQM required to make the power system completely observable and to maximize the measurement redundancy at the buses are the two main objectives of the PQM placement methodology presented in this paper.

The PQM placement problem is handled in two steps:

- In first step, a number of favourable bus locations depending on their connectivity with rest of the system is selected. Two indexes are introduced to carry out the selection process. Then, the selected locations are assigned as optimal locations for PQM placements. This step is very important because it reduces the computational burden for subsequent step.
- In the second step, a Binary Particle Swarm Optimization (BPSO) technique to determine the other optimal locations for PQMs is used. BPSO technique is a modified version of the heuristics optimization technique known as Particle Swarm Optimization (PSO). PSO along with BPSO are discussed in section 3.0.

Since, a PQM installed at bus makes all the buses incident on it is observable. An easy way to determine all such observable buses is by using the binary connectivity matrix as defined below

$A(i,i) = 1$ for all bus

$A(i,j) = 1$ if bus i and bus j are connected

$A(i,j) = 0$ if bus i and bus j are not connected

Index method starts with selecting the *terminal bus* in the system. Terminal bus is the bus which is connected to only a single bus of the entire system. According to the definition of terminal bus, one can infer that to observe any terminal bus, a PQM is to be put either at the terminal bus itself or at the bus connected to that terminal bus. It is unwise to put PQM at terminal bus because by doing so, one cannot observe more than two buses. Thus, the alternative option is selected in case of all terminal buses. After that, a unique bus having the highest *connectivity index*, if any, is to be found out. Connectivity index of a bus is defined by the number of unobserved buses that can be observed by placing a PQM at that particular bus.

For jth bus, it will be given by the sum of all elements of jth row of matrix A minus 1. If several buses have the same connectivity index then we should choose the unique one with highest *evolution index*, if any. If an additional PQM is placed at a particular bus, keeping PQMs at all other previously assigned locations unaltered then the sum of all elements of resulting A matrix will denote the evolution index of that particular bus. High *evolution index* signifies that the bus is connected to those buses which have less connectivity with the rest of the system. In other words, they are less accessible. That is why priority should be given to that particular bus which connects less accessible unobserved buses.

From the flow chart of index method shown in Figure 1, it can be observed that there are two possible reasons for termination of index method as

1. Matrix ‘A’ becomes a null matrix.
2. Lack of a unique bus having the highest connectivity index or having both the highest connectivity index as well as the highest evolution index.

Both the condition cannot be satisfied simultaneously. Either of them has to be satisfied. Their significance is as follows.

- When condition 1 is satisfied, it means that the set of assigned locations are sufficient to make the system completely observable. Thus, there is no need to go for BPSO algorithm.
- When condition 2 is satisfied, it means that there will be unobserved buses even after placement of PQMs at set of assigned locations. So, we have to go for BPSO algorithm to obtain complete set of optimal locations.

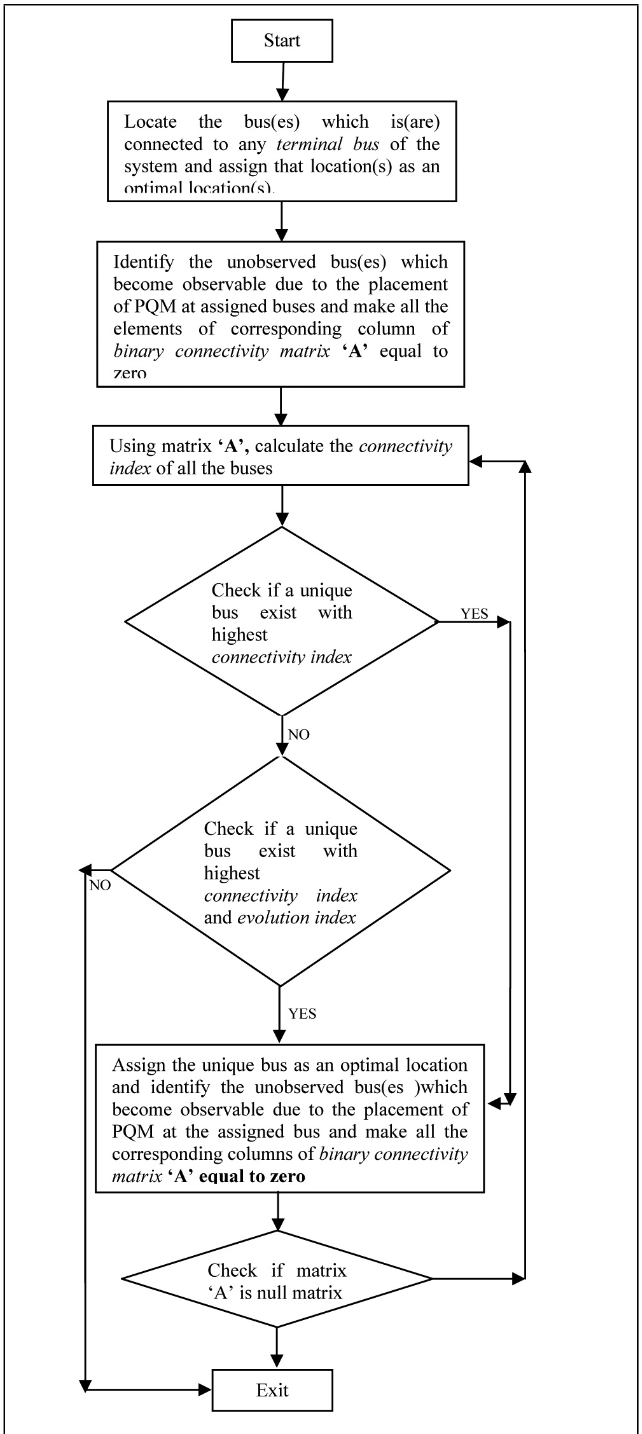

FIG. 1 FLOW CHART OF INDEX METHOD

3.0 BINARY PARTICLE SWARM OPTIMIZATION

3.1 Particle Swarm Optimization

The particle swarm optimization (PSO) first developed by Kennedy and Eberhart [17] is a self-educating population based optimization algorithm that can be applied to any nonlinear optimization problem. Concept of PSO originated from the collective movement of the flock of birds, a school of fish or a swarm of bees [13,17]. In PSO, the potential solutions, called particles fly through the problem space by following the best fitness of the particles. It is easily implemented in most programming languages and has proven to be both very fast and effective when applied to a diverse set of optimization problems.

In PSO, the particles are "flown" through the problem space by following the current optimum particles. Each particle keeps the track of its coordinate in the problem space, which is associated with the best solution (fitness) that it has achieved so far. This implies that each particle has memory, which allows it to remember the best position on the feasible search space that has ever visited. This value is commonly called as *pbest*. Another best value that is tracked by the particle swarm optimizer is the best value obtained so far by any particle in the neighborhood of the particle. This location is commonly called as *gbest*.

The position and velocity vectors of the i^{th} particle of a n-dimensional search space can be represented as $X_i=(x_{i1},x_{i2},.....x_{in})$ and $V_i = (v_{i1}, v_{i2} ,.....v_{in})$, respectively. On the basis of the value of the evaluation function, the best previous position of a particle is recorded and represented as $pbest_i = (P_{i1},P_{i2} ,......P_{in})$. If the *gth* particle is the best among all particles in the group so far, it is represented as $gbest = pbest_g$ $(P_{g1},P_{g2},......P_{gn})$. The modified velocity and position of each particle for fitness evaluation in the next iteration are calculated using the following equations

$$\begin{aligned} v_{in}^{k+1} &= w \times v_{in}^{k} + c_1 \times rand_1 \times (pbest_{in} - x_{in}^{k}) \\ &\quad + c_2 \times rand_2 \times (gbest_{gin} - x_{in}^{k}) \end{aligned} \tag{1}$$

$$x_{in}^{k+1} = x_{in}^{k} + v_{in}^{k+1} \tag{2}$$

where, w is the inertia weight parameter, which controls the global and local exploration capabilities of the particle. c_1, c_2 are cognitive and social coefficients and $rand_1$ and $rand_2$ are random numbers between 0 and 1. A large inertia weight factor is used during initial exploration and its value is gradually reduced as the search proceeds. The concept of time-varying inertial weight (TVIM) is given by

$$w = (w_{max} - w_{min}) \times \frac{iter_{max} - iter}{iter_{max}} + w_{min} \quad (3)$$

where $iter_{max}$ is the maximum number of iterations.

The velocity update expression (1) can be explained as follows. Without the second and third terms, the first term (representing inertia) will keep a particle flying in the same direction until it hits the boundary. Therefore, the first term tries to explore new areas and corresponds to the diversification in the search procedure. In contrast, without the first term, the velocity of the flying particle is only determined by using its current position and its best positions in history. Therefore, the second representing memory and third terms (representing cooperation) try to converge the particles to their *pbest* and/or *gbest* and correspond to the intensification in the search procedure [18].

3.2 Binary Particle Swarm Optimization

The position array X of PSO algorithm can be considered as an array of PQM installation location for the problem of optimal placement of PQM. The array will be a binary array where value '1'means that the PQM is located at the corresponding bus whereas the value '0' means no PQM installation at the corresponding bus. Therefore, for the problem of optimal placement of PQM, binary particle swarm optimization is applied where each element of position vector can take only binary values 1 or 0. The elements of the position vector x_i are updated at each iteration as follows

$$\begin{aligned} x_{in}^{k+1} &= 0, \text{ if}: \sigma \geq Sig(v_{in}^{k+1}) \\ &\quad 1, \text{ if}: \sigma < Sig(v_{in}^{k+1}) \end{aligned} \quad (4)$$

$$Sig(u) = \frac{1}{1 + \exp(-u)} \quad (5)$$

where σ is a random no between 0 and 1.

4.0 PROBLEM FORMULATION FOR BPSO

An objective function and some constraint conditions are the basic building blocks of an optimization problem. For optimal placement of PQMs the objective function is to minimize the number of PQM and maximize the measurement redundancy and the constraint condition is the complete observability of power system.

Define binary position vector 'X' as follows

$$X(i) = \begin{cases} 1 & \text{If PQM is placed at ith bus} \\ 0 & \text{otherwise} \end{cases}$$

Define BPSO problem as follows

Minimize $w_1J_1+w_2J_2$

Subject to $AX^T \geq U$

where,

$A=(n\times n)$ binary connectivity matrix of the *n* bus system

$X=(1\times n)$ position vector

$U=(n\times 1)$ unity vector

$J_1=X^TX$ represents total number of PQMs

$J_2 = (N - AX)^T(N - AX)$ is a function of measurement redundancy

$N=(n\times 1)$ vector corresponding to desired measurement redundancy (If the desired measurement redundancy level is 2 over the entire system, set all elements of N equal to 3)

$w_1 w_2$ weights to make J_1 and J_2 comparable in magnitude

Here, the entries of the product AX denotes the number of times a bus is observed by the PQM placement set defined by X. Since the elements in X are either 0 or 1, J_1 represents the total number of PQMs in the system. The vector N can be chosen according to the desired level of measurement redundancy in the system. Here, we considered desired measurement redundancy level of 3 at all buses, so all the elements of N are set to 4. The vector (N-AX) computes the difference between the desired and actual number of times a bus is observed. Minimization of this difference is, therefore, equivalent to maximizing the measurement redundancy. The term J_2 therefore maximises the measurement redundancy offered by the PQM placement set.

It is clear that the inequality constraint ensures complete observability of the system. To take the constraints into account, let us define the fitness function J(x) as follows

$J(X) = K$ if the constraint violated

$= w_1 J_1 + w_1 J_2$ otherwise

where K is a very large number

During the entire BPSO optimization process, all the elements of X corresponding to the previously assigned locations are held equal to 1. This will improve the convergence property of the search process and help it to reach to the global optimum in less number of iterations.

5.0 TEST RESULT AND DISCUSSION

The effectiveness of proposed optimal PQM placement approach is demonstrated on six test systems including three meshed networks and three radial distribution networks. The three IEEE meshed networks are IEEE-14 bus system shown in Figure 2, IEEE-24 bus system shown in Figure 3 and IEEE-30 bus system shown in Figure 4. The IEEE bus diagrams are taken from [16]. The feeder systems diagrams used are 13 bus feeder system shown in Figure 5, 34 bus feeder system shown in Figure 6 and 37 bus feeder system shown in Figure 7 and are exactly similar in topology to the IEEE test feeder systems shown in [19]. However, modification is done on the bus numbering to make it a continuous one. This not only helps in defining connectivity matrix 'A' without introducing any sparsity but also in computing fitness values for different position vectors in BPSO in less time.

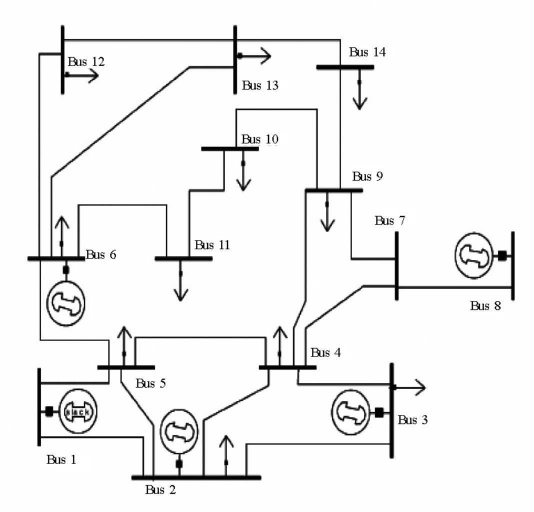

FIG. 2 IEEE-14 BUS SYSTEM [16]

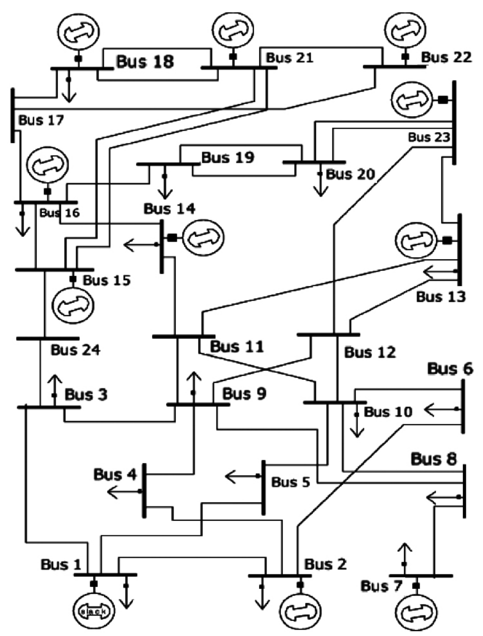

FIG. 3 IEEE-24 BUS SYSTEM [16]

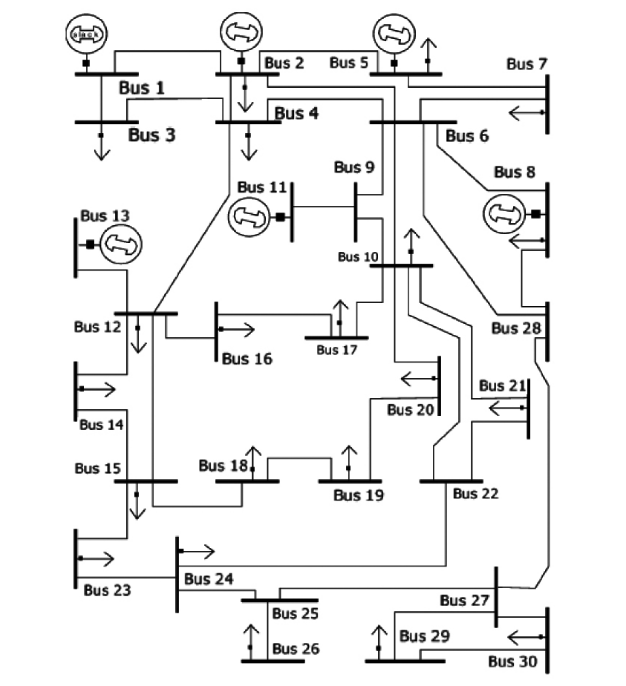

FIG. 4 IEEE-30 BUS SYSTEM [16]

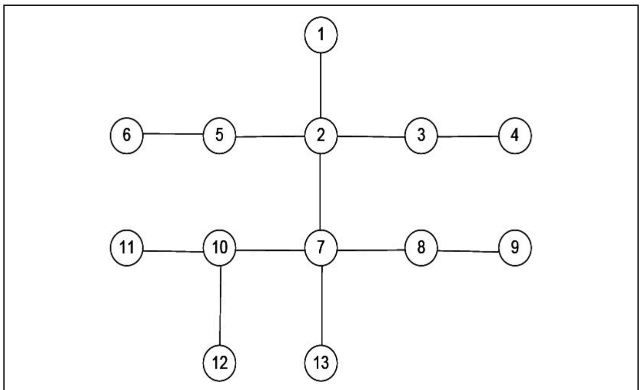

FIG. 5 13 BUS FEEDER SYSTEM

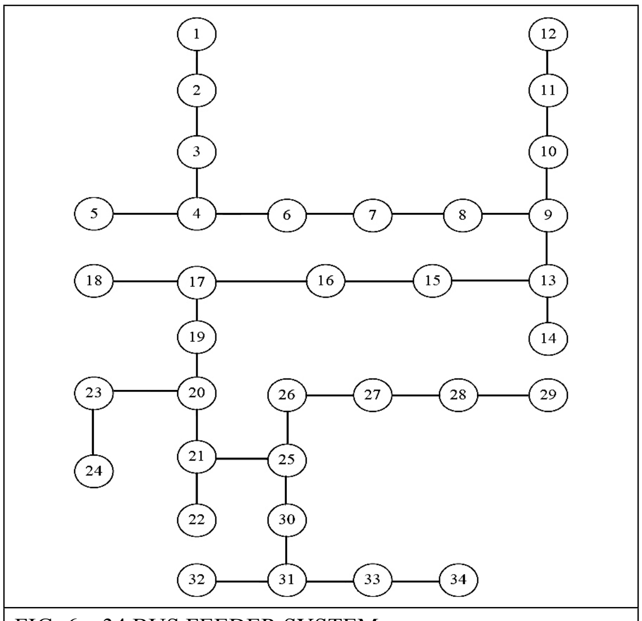

FIG. 6 34 BUS FEEDER SYSTEM

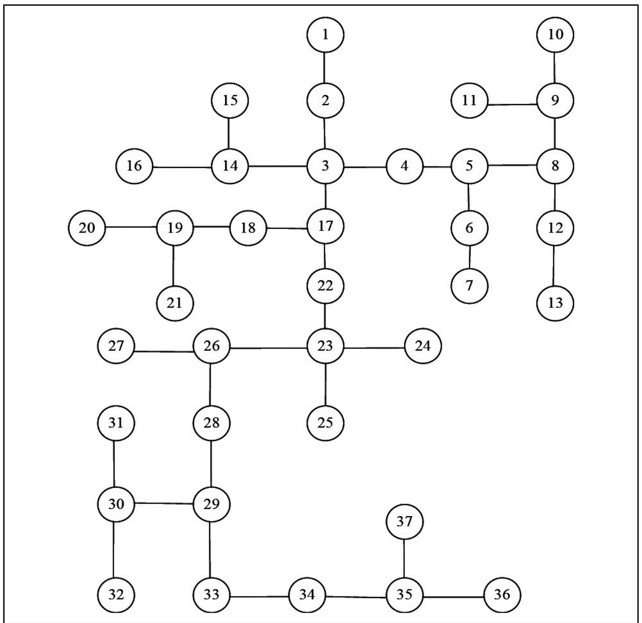

FIG. 7 37 BUS FEEDER SYSTEM

The proposed optimization algorithm was run in Matlab with desired measurement redundancy level of 3 at all buses, so all the elements of N are set to 4. All BPSO parameters except number of particles (p) and maximum number of iteration (k_{max}) are chosen to be constant. These two parameters, p and k_{max} will depend upon the size of the system as well as the performance of index method for that particular system. When system is small and performance of index method is good, low values of p and k_{max} are to be chosen to reduce the computational burden. However, for large system and/or poor performance of index method, we have to select higher value of p and k_{max} to ensure the convergence to the global optimum. Obviously computational time will be more under such cases.

Assessment of performance of index method can be done by looking at the number of unobserved buses after placing PQMs at all assigned locations. Number of unobserved buses is given by number of nonzero columns of ‘A’ at the end of index method. Small number of unobserved buses will indicate good performance of index method and vice versa. Other BPSO parameters are as chosen as follows:

- Individual acceleration constant (C_1) = 2.0
- Social acceleration constant (C_2) = 2.0

- Maximum inertia weight (w_{max}) = 0.9
- Minimum inertia weight (w_{min}) = 0.4

Table 1 and Table 2 give the results of the applied proposed methodology on IEEE systems and radial feeders. Since the identification of optimal location is done in two steps, index based method is followed by BPSO. Table 1 shows the result after first step ie after applying index method to find the optimal number of PQM for complete observability. Table 2 gives the total number of optimal PQMs, after applying BPSO for making the buses observable which were unobserved in index method ie in first step. As it is clear from Table 1 that there is no need of performing BPSO for small bus systems and radial feeders. The performance index of the index method is good for small and moderate size system. However, for large system BPSO needs to be applied to find optimal location of PQM to make the system completely observable.

For complete observability, the optimal number of PQMs required for IEEE-30 bus system by the proposed method are comparable to the number of monitors obtained by the method proposed in [20] ie equal to 10. Using the proposed approach the optimal numbers of PQMs required for complete observability of the IEEE-37 node test feeder are 12 which is almost half of the PQM monitors calculated by the method proposed in [21]. In [21] the optimal monitors required are 25.

6.0 CONCLUSION

A new methodology for the optimal placement of Power Quality Monitors (PQMs) for complete observability of power system is presented in this paper. Identification of optimal location is done in two steps utilizing the index based method followed by Binary Particle Swarm Optimization (BPSO). The proposed method has been successfully applied on IEEE test systems and modified IEEE feeder distribution systems. Comparison of test result with the work reported in [16] shows effectiveness of the proposed method. From the test results, it can be concluded that performance of index method

TABLE 1

ASSIGNED LOCATION OF PQM IN STEP -1

Test system	Assigned locations found in index method	Whether BPSO is required	Unobserved buses
IEEE-14 bus	2,6,7,9	No	–
IEEE-24 bus	2,8,16,21,23	Yes	3,5,11,24
IEEE-30 bus	6,9,10,12,25	Yes	1,3,5,18,19,23,29,30
13 bus feeder	2,3,5,7,8,10	No	–
34 bus feeder	2,4,11,13,17,21,23,28,31,33	Yes	7,8,26
37 bus feeder	2,3,6,9,12,14,19,23,26,30,35	Yes	33

TABLE 2

OPTIMAL LOCATION OF PQM USING PROPOSED METHOD

Test system	Complete set of optimal locations	Optimal locations obtained using algorithm proposed in [16]
IEEE-14 bus	2,6,7,9	2,6,7,9
IEEE-24 bus	2,3,8,10,16,21,23	2,3,8,10,16,21,23
IEEE-30 bus	1,2,6,9,10,12,15,19,25,27	1,2,6,9,10,12,15,19,25,27
13 bus feeder	2,3,5,7,8,10	–
34 bus feeder	2,4,7,11,13,17,21,23,25,28,31,33	–
37 bus feeder	2,3,6,9,12,14,19,23,26,29,30,35	–

is very good for radial distribution systems as number of unobserved buses are less even for moderate system size. Sometime, simple manual inspection of network topology may be sufficient to determine rest of the optimal locations, thus, avoiding BPSO optimization process. However, for large inter-connected transmission system, BPSO along with index method is necessary to locate the optimal locations for PQMs.

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