Facilitating Placement of the Reactive Compensators Using a Revised Impedance Matrix

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Abstract

Determining placement and capacity of reactive-power compensators in distribution networks is an optimization problem with various objectives and technical constraints. The large number of variables and constraints in this problem can be an obstacle for the success of classical and meta-heuristic optimization methods. Therefore, having a guess of the suitable buses for installing compensators as an initial solution, improves performance of the mentioned methods. Using the network impedance matrix, an initial guess is obtained in this paper in the form of suitable or higher-priority buses. The applied matrix is a revised version in which loads connected to the buses are taken into account. The reasons for considering the loads are that, firstly, the list of bus-priorities becomes more consistent with network load pattern, and secondly, difficulties in forming the impedance matrix in radial distribution networks are obviated. Comparison of the list of suitable buses for installing the compensator obtained by the proposed method with the list of buses extracted from the sensitivity analysis indicates the effectiveness of the former method.

Keywords: Reactive-power compensation, Impedance matrix, Initial solution

1. INTRODUCTION

Operation conditions of power-distribution systems can be improved from several points of view, such as power loss, power factor and voltage profile, by utilization of reactive-power compensation. Due to local control of reactive power, this compensation reduces reactive power transmission from large and faraway generators to electricity customers. Decrease in network power loss, transmission congestion and voltage drop are important outcomes of reduction of the mentioned transmission through network branches [1, 2].

In general, the reactive power compensation problem (RCP) is an optimization problem in which decision variables are capacity and installation-place of reactive compensa-

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tors. Various objective functions and technical constraints are included in this problem. Power loss and investment cost are the most common objective functions. Among the technical constraints, power balance, acceptable voltage range, discrete values for capacity of compensation equipment and maximum rating of network branches are usually referred in literatures [3-18].

Classical optimization methods which are on the basis of differentiation have limitations to cope with RCP in large distribution networks. This is mainly due to huge numbers of optimization variables and constraints as well as non linearity of the involved functions. Meta-heuristic methods which are on the basis of searching behavior of population of leaving creatures may have better performance in dealing with the large RCPs [11]. However, it is still not easy for these methods to solve optimization problems with nonlinear and discrete constraints. Particle Swarm Optimization (PSO), Genetic Algorithm (GA), Bee Colony Optimization (BCO), Flower Pollination Algorithm (FPA) and Cuckoo Search Algorithm (CSA) are examples of the meta-heuristic methods that have been applied for the RCP [3, 5-7, 9, 10, 12-14, 16 & 17].

Due to nonlinear nature of the RCP, computational performance in both of the classical and meta-heuristic methods is considerably affected by selection of the initial solution (INIS). This is a solution from which the optimization method starts its iterative process. The INIS in the RCP is an initial guess of network nodes (buses) which seem to be preferable to install reactive compensators. In a classical method, a proper INIS facilitates convergence of the iterative method to the final solution. Having a suitable INIS in a meta-heuristic method can assist movement of the searching population to better posi-

tions and hence finding a final solution.

There are few methods that have been applied to find INIS for the RCP. One of the obvious methods in this regard is ranking of network buses according to the sensitivity analysis [3-5, 8, 10, 12-16 & 18]. In this approach, reactive-power injection is inserted in buses and effect of the injection on network loss is computed. Buses where injection has more effect on loss are given higher ranks. Weak point of the sensitivity analysis is its large computational burden. Another method for estimating the INIS, is on the basis of the voltage stability [3, 8, 12-16 & 18]. In this method, buses with higher risk of voltage instability are given higher ranks. There is no general agreement about simplification of formulas and dynamic computation approaches in the voltage-stability-based methods.

This paper proposes a novel method to obtain an INIS for the RCP. As it is described in section 2 of the paper, in the proposed method, elements of the network impedance matrix with consideration of power consumption or loads of buses are applied to determine ranking of buses. In order to evaluate performance of the proposed method, the obtained ranking is compared by the ranking that is determined by the sensitivity analysis in section 3. Concluding remarks in section 4 terminate this paper.

2. FORMULATION OF THE PROPOSED METHOD

It is well known that there is a relation between voltage drop and network loss. This is due to the observation that reactive compensation increases node voltages and at the same time has a decreasing effect on loss. This is the main point that is considered in the proposed method. Considering the mentioned point, the proposed method ranks buses ac-

cording to their voltage dependence on the reactive-power injection at different buses. In other words, the proposed method gives higher ranks to the buses which have more sensitive voltages to reactive compensation. This ranking can be applied as an INIS for the RCPs in which power-loss reduction is an objective function of the related optimization. In order to avoid computational burden of the sensitivity analysis, and as described in the following paragraphs, the proposed method applies elements of the network impedance matrix instead of the mentioned analysis.

One of the applications of the network impedance matrix is determination of the sensitivity of node voltages to injection of power in a node. So that the element in row i and column k of this matrix or $Z(i,k)$ shows sensitivity of the voltage magnitude in node i to the power injection change at node k. The proposed method applies and extends this idea from two perspectives. Firstly, it considers absolute value of row-wise summation of the impedance-matrix elements in the following way:

$$\text{rank of bus } i = \left| \sum_k \hat{Z}(i,k) \right| \qquad (1)$$

This value is an estimation for effect of reactive-power change in all of the network buses on voltage of bus i. Secondly, the proposed method considers power consumption or load at buses by inserting these loads in the network impedance matrix. Result of the load insertion is a revised impedance matrix as described in the next paragraph. A hat sign has been added above the Z in (1) to indicate that this is an element of the revised impedance matrix.

When voltage magnitude of bus i is near 1.0 per unit, which is usually the case, active and reactive loads at this bus can be approximated by the following admittance:

$$\vec{Y}_i^{\text{Load}} \approx \left(\vec{S}_i^{\text{Load}} \right)^* = P_i^{\text{Load}} - jQ_i^{\text{Load}} \quad (\text{per unit}) \qquad (2)$$

This admittance is added to the corresponding diagonal element of the network admittance matrix as follows:

$$\hat{Y}(i,i) = Y(i,i) + \vec{Y}_i^{\text{Load}} \quad (\text{per unit}) \qquad (3)$$

When this equation is applied for all loads that are connected to buses, it yields revised admittance matrix. Then, the revised impedance matrix is obtained by inverting the revised admittance matrix.

There is another interesting point regarding the revised impedance matrix which is applied in the proposed method. The point is avoiding the difficulty of finding impedance matrix in radial (without loop) distribution networks. The difficulty is due to near singularity of the admittance matrix in these networks where there are no shunt branches in the network model. In the revised impedance matrix, bus loads are treated as shunt branches and hence, the singularity problem is removed.

3. CASE STUDY BY THE PROPOSED METHOD

As mentioned in the previous section, the proposed method extracts more suitable buses on the basis of reactive-compensation effect on bus voltages. In this method, the network admittance matrix is constructed by the network branches. Then and according to (3), equivalent admittance of bus loads is added to diagonal elements of the matrix to obtain the revised admittance matrix. In the next

stage, inverse of the revised admittance matrix is determined which is the revised impedance matrix. Finally, summation of each row of the revised impedance matrix is obtained according to (1) and assigned as ranking for the corresponding bus. So, the proposed method gives a priority list of buses in which higher ranked buses seem to be better candidates for installing the compensators.

In order to evaluate performance of the proposed method, its given priority list is compared by a bus list which is determined by the sensitivity analysis. In the sensitivity analysis, 1.0 kVAR injection at each of buses is simulated and its effect on the amount of network loss is calculated. In this calculation, backward-forward sweep load-flow has been applied. Details of this load-flow method are given in [4] and [6]. A rank is assigned to any bus according to effect of 1 kVAR injection on the network loss.

The IEEE 33 bus test system is applied in this section to perform the above mentioned comparison. This is a standard distribution test network which is illustrated in Fig. 1. Its bus-load data are mentioned in Table 1. Branch data of the IEEE 33 bus test system can be found in [19]. In Fig. 1, bus numbers have "B" prefix and are enclosed by squares. Arrows in this figure, indicate connected loads to buses.

Table 2 presents list of bus rankings which is obtained by the proposed method. These ranking values have been obtained by (1) and are on the basis of 10.5 kV and 10 MVA. Table 3 compares the mentioned list with the list of buses which is determined by sensitivity analysis. In this table the prefix "r" designates "rank" of the related bus. Comparison of the lists in Table 3 shows similar ranking specially for the higher-rank buses. For instance, buses 18 to 9 in the two

lists have similar ranks from 1 to 10. It is observed that about 30% of buses which are in the above of the two lists have consistent rankings. These buses are suitable candidates for the RCP which are successfully found by the proposed method. The lower-rank buses do not have similar rankings in Table 3. This disparity is not an important problem. The reason is that lower-rank buses are not recommended for the RCP and hence it is not important to correctly rank them.

4. CONCLUSION

This paper proposed a method to determine more suitable buses to be considered as an INIS for the RCP. The suitable buses are obtained on the bases of the rows of a revised impedance matrix. The revised impedance matrix is constructed from an admittance matrix in which equivalent admittance of bus loads are included. Comparison of the bus ranking obtained by the proposed method with the ranking obtained by sensitivity analysis showed good performance of the proposed method for the higher-rank buses.

It is expected that applying the INIS obtained by the proposed method facilitates convergence of the classical or met-heuristic methods which solve the RCP optimization by an iterative procedure. For this purpose, a percent (for example 30%) of the buses in the above of the ranking list can be considered in the initial solution as places where reactive compensators will be installed. The remaining places (buses) for the compensation can be released for decision making by the optimization method.

Finally, it is worth mentioned that the proposed method avoids sensitivity analysis and hence, does not impose large computational burden.
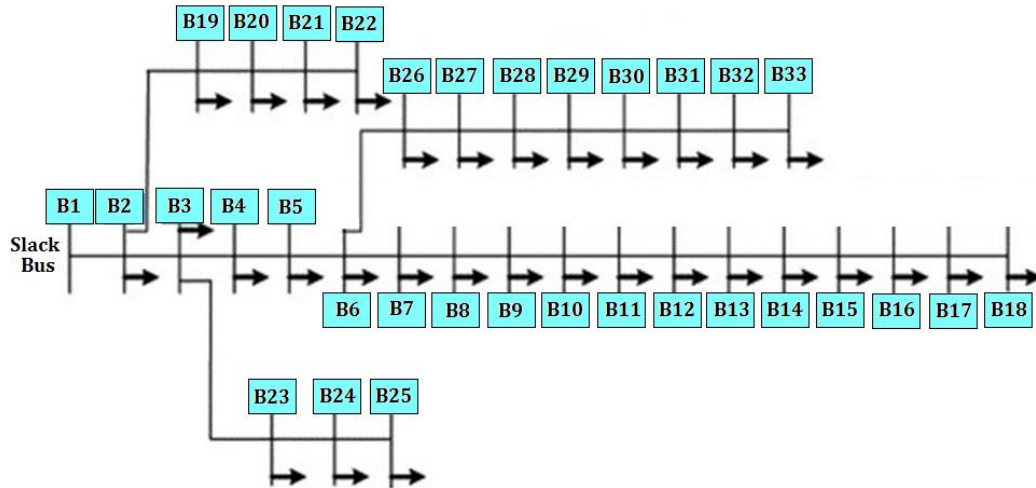
Fig. 1. *The IEEE 30 bus distribution system.*

Table 1. *Data of bus Loads for the system shown in Fig. 1.*

kVAR	kW	Bus	kVAR	kW	Bus	kVAR	kW	Bus
50	90	23	35	60	12	-	-	1
200	420	24	35	60	13	60	100	2
200	420	25	80	120	14	40	90	3
25	60	26	10	60	15	80	120	4
25	60	27	20	60	16	30	60	5
20	60	28	20	60	17	20	60	6
70	120	29	40	90	18	100	200	7
600	200	30	40	90	19	100	200	8
70	150	31	40	90	20	20	60	9
100	210	32	40	90	21	20	60	10
40	60	33	40	90	22	30	45	11

Table 2. *Ranking of the network buses obtained by the proposed method in accordance with (1).*

Value obtained by equation 1	Bus no.	Rank	Value obtained by equation 1	Bus no.	Rank	Value obtained by equation 1	Bus no.	Rank
75.402	b4	r23	75.819	b7	r12	78.046	b18	r1
75.315	b3	r24	75.658	b22	r13	78.043	b17	r2
75.181	b28	r25	75.652	b6	r14	77.891	b16	r3
75.086	b23	r26	75.628	b21	r15	77.782	b15	r4
74.837	b29	r27	75.623	b26	r16	77.645	b14	r5
74.688	b30	r28	75.597	b20	r17	77.502	b13	r6
74.653	b33	r29	75.568	b27	r18	77.125	b12	r7
74.638	b31	r30	75.495	b5	r19	77.036	b11	r8
74.629	b32	r31	75.445	b19	r20	76.979	b10	r9
74.591	b2	r32	75.432	b24	r21	76.540	b9	r10
74.345	b1	r33	75.422	b25	r22	76.043	b8	r11

Table 3. *Comparison of bus-ranking lists obtained by the proposed method and the sensitivity analysis.*

Ranking by the sensitivity analysis	Ranking by the proposed method	Bus	Ranking by the sensitivity analysis	Ranking by the proposed method	Bus	Ranking by the sensitivity analysis	Ranking by the proposed method	Bus
26r	26r	23	7r	7r	12	33r	33r	1
25r	21r	24	6r	6r	13	32r	32r	2
23r	22r	25	5r	5r	14	27r	24r	3
20r	16r	26	4r	4r	15	24r	23r	4
18r	18r	27	3r	3r	16	22r	19r	5
17r	25r	28	2r	2r	17	21r	14r	6
16r	27r	29	1r	1r	18	19r	12r	7
14r	28r	30	31r	20r	19	15r	11r	8
13r	30r	31	30r	17r	20	10r	10r	9
12r	31r	32	29r	15r	21	9r	9r	10
11r	29r	33	28r	13r	22	8r	8r	11

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