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ANALYTICAL METHOD FOR REACTIVE POWER COMPENSATORS ALLOCATION

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ABSTRACT

This paper presents a novel analytical methodology to determine the placement of reactive power devices in power systems. The proposed method modifies the Modal analysis technique and, based on the inversed reduced Jacobian matrix, develops a new formulation to compute the Reactive Contribution Factor (RCF) of each load buses. The objective of this research is to achieve the most stable condition and to minimize network losses. The proposed method is implemented at the modified IEEE 30-bus Reliability Test System (RTS) and compared with a different placement. In order to assess the method, this work compares the voltage profile, eigenvalue and network losses. The simulation results show that the proposed method can provide a solution to the ideal shunt compensator placement by improving the system's voltage stability and by minimizing losses.

Keywords: Eigenvalue; Losses reduction; Modal analysis; Reactive power compensator placement; Voltage stability

1. INTRODUCTION

For almost one century, system stability has been viewed as an important requirement for a power system to operate safely and reliably operation in (Dong & Zhang, 2009). Nowadays, modern power systems are severely stressed and work at the stability limit with smaller capacity and margin. Hence, these may cause congestion problems (Nappu et al., 2013; Nappu et al., 2014; Nappu & Arief 2016). The progressive and uncontrollable drop in voltage as a result of increase in load demand and, more especially, due to reactive loads or changes in system operation conditions, can result eventually in a widespread voltage collapse (Prada et al., 2015). Therefore, protective steps, such as load shedding, may be taken (Arief et al., 2013). In order to avoid this instability, there are several preventive steps that can be taken; one of them is the installation of a reactive power compensation scheme. This compensation device in the power system provides reactive power compensation; reduces network losses; reduces energy losses; improves the voltage profile; releases system capacity; and recovers the power factor (Sajjadi et al., 2013; Taher & Bagherpour, 2013; Arief et al., 2016).

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In placing reactive power compensation devices, there are three issues that become major concerns; these are: namely, size of compensation; number; and location of placement (Kavousi-Fard & Niknam, 2013; Lee et al., 2015). Furthermore, with high penetration of renewable energy generations into power systems and, more especially, wind power plants, this has created more challenges in reactive power compensating planning (Xu et al., 2017). Hence, the daily maintenance, reliability and security of the system's operation has become more difficult due to wind resources intermittency (Zhang et al., 2016; Zhang et al., 2017). This is especially so since countries worldwide have targeted the expansion of renewable energy resources for the electricity industry. For example, Australia targeted that 20% of their power generation supply would be provided by renewable energy by 2020 (Radzi et al., 2012).

There are various reactive compensation devices such as capacitors, SVC or STATCOM. In recent years, various methodologies have been developed for placement of these devices. In general, the reactive compensator placement can be categorized into analytical methods, heuristic methods, numerical methods and methods based on Artificial Intelligence (AI) (Aman et al., 2014). With regard to the analytical methods, the computation procedures are reduced by making some approximations. Cook (1959) developed a well-known analytical method for capacitor placement when he proposed that the optimum capacitor placement ought to be 2/3 of the reactive load factor. However, in certain cases, the application of this "2/3 rule" may give negative financial savings (Lee & Grainger, 1981). Heuristic methods are practical methods that are developed by using researchers' intuitions and experiences which provide a satisfactory solution. Hamouda & Sayah (2013) and Raju et al. (2012) applied the heuristic method in relation to reactive power compensators placements. Numerical programming is an iterative technique that uses arithmetic mathematical formulations to maximize or minimize or an objective function of decision variables which fulfil, also, a set of constraints. Nojavan et al. (2014) presented an integer nonlinear programming approach. Aguiar & Cuervo's (2005) work formulated a mixed integer linear programming that considered the discrete capacitor sizes. However, its rationality rested on the precision of the loss formula estimation. Various AI approaches have been implemented in the placement of capacitors. For example, Ramadan et al. (2014) developed a fuzzy logic based approach which combined two membership functions and Abul'Wafa (2014) combined fuzzy expert system for the placement of the capacitor and read coded Genetic Algorithm (GA) to calculate the size of the capacitor. Nonetheless, in using fuzzy logic, the main challenge is to determine accurately the fuzzy membership functions and the fuzzy rule bases. In their papers, Lee et al. (2015) and Zeinalzadeh et al. (2015) implemented the Particle Swarm Optimization (PSO) approach was. Nevertheless, the reliance of the PSO algorithm on the altering factors and the trapping in modifying parameters' probability can reduce its accuracy and efficacy for various conditions. Other researches about reactive power placement, which employed AI procedures, are Bacterial Foreaging Optimization Algorithm (BFOA) (Devabalaji et al., 2015), artificial bee colony algorithm (El-Fergany & Abdelaziz, 2014), search space of GA (Carpinelli et al., 2010), hybrid method of CODEQ (HCODEQ) (Chiou & Chang, 2015), teaching learning based optimization (Sultana & Roy, 2014), Gravitational Search Algorithm (GSA) (Shuaib et al., 2015), Clustering Based Optimization (CBO) (Vuletić & Todorovski, 2014) and bio-inspired optimization (Duque et al., 2015). The applications of AI in solving capacitor placement may have effectual operation and can handle complicated problems. However, they are more difficult to code and, potentially, can provide volatile outcomes in early stage convergence. Although AI methods have been validated on the sample systems, nevertheless, the success of these methods relies on the modification of algorithmic considerations whose optimal setting involves users' skill and knowledge (Jabr, 2008). Therefore, where this information can be obtained from the Jacobian matrix of the system, it is important to develop an effective method that is able to provide information about voltage stability within the system.

This study developed a new analytical method to improve Modal analysis for the effective placement of reactive power compensation devices. Modal analysis is an analytic solutions approach that can describe the condition of voltage stability in a complex network (Gao et al., 1992). Using the modal analysis method, the inversed reduced Jacobian matrix is computed and informs the relationship between change in the voltage and the change in reactive power injection at each buses. By utilizing the relationship of V and Q, this approach can identify weak points and areas that are vulnerable to system stability. The relationship between voltage (V) and reactive power (Q) can be used to obtain useful information about stability. This work offers a simple algorithm and it is simple to implement the method. The advantages of this approach are that it is fast, straight, accurate and does not involve composite computational processes. The novelty of this research is the modification of Modal Analysis method and, then, the formulation of the Reactive Contribution Factor (RCF) that is obtained from the inversed reduced Jacobian matrix. RCF gives information about a specific bus' contribution to improving voltage magnitude at critical buses.

2. METHODOLOGY

2.1. Elaboration of Modal Analysis: Computation of Reduced Jacobian Matrix

In order to perform modal analysis, linearized steady-state power voltage equations are used as follows:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix} \tag{1}$$

where, ΔP is the incremental change in bus real power; ΔQ is the incremental change in bus reactive power injection; Δθ is the incremental change in bus voltage angle; and ΔV is the incremental change in bus voltage magnitude

In order to assess the relationship of voltage and reactive power stability, the active power (P) is kept constant. Due to constant active power (ΔP = 0), then, Equation 1 can be reduced to:

$$\begin{bmatrix} 0 \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix}$$

$$0 = J_{P\theta}\, \Delta\theta + J_{PV}\, \Delta V$$

$$\Delta\theta = -J_{PV}\, \Delta V + {J_{P\theta}}^{-1} \tag{2}$$

$$\Delta Q = J_{Q\theta}\, \Delta\theta + J_{QV}\, \Delta V \tag{3}$$

If Equation 2 is substituted into the Equation 3, then:

$$\Delta Q = \left[J_{QV} - J_{Q\theta} {J_{P\theta}}^{-1} J_{P\theta} \right] \Delta V \tag{4}$$

$$J_R = \left[J_{QV} - J_{Q\theta} {J_{P\theta}}^{-1} J_{P\theta} \right]$$

$$\Delta Q = J_R\, \Delta V$$

$$\Delta V = {J_R}^{-1}\, \Delta Q \tag{5}$$

${J_R}^{-1}$ or the inversed reduced Jacobian matrix is a matrix that shows a direct correlation between the bus voltage and the reactive power injection. This assumes that the active power is zero and the voltage angle is substituted and, then, that, obtained from the equation, is much simpler and more focused.

2.2. Computation of Reactive Contribution Factor (RCF)

From Equation 5, it can be seen that the voltage change (ΔV) is obtained by multiplying the reactive power injection at specific buses with the inversed reduced Jacobian matrix ($J_R{}^{-1}$). When the $J_R{}^{-1}$ is further elaborated, then:

$$\begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \vdots \\ \Delta V_m \end{bmatrix} = \begin{bmatrix} \mathfrak{R}_{11} & \mathfrak{R}_{12} & \cdots & \mathfrak{R}_{1n} \\ \mathfrak{R}_{21} & \mathfrak{R}_{22} & \cdots & \mathfrak{R}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \mathfrak{R}_{m1} & \mathfrak{R}_{m2} & \cdots & \mathfrak{R}_{mn} \end{bmatrix} \begin{bmatrix} \Delta Q_1 \\ \Delta Q_2 \\ \vdots \\ \Delta Q_m \end{bmatrix} \quad (6)$$

$$J_R{}^{-1} = \begin{bmatrix} \mathfrak{R}_{11} & \mathfrak{R}_{12} & \cdots & \mathfrak{R}_{1n} \\ \mathfrak{R}_{21} & \mathfrak{R}_{22} & \cdots & \mathfrak{R}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \mathfrak{R}_{m1} & \mathfrak{R}_{m2} & \cdots & \mathfrak{R}_{mn} \end{bmatrix}$$

The RCF values at each load buses are computed by adding the elements of inversed reduced Jacobian matrix vertically so that RCF at bus j becomes:

$$RCF_j = \mathfrak{R}_{1j} + \mathfrak{R}_{2j} + \mathfrak{R}_{3j} + \ldots + \mathfrak{R}_{mj} \quad (7)$$

$$RCF_j = \sum_{i=1}^{n} \mathfrak{R}_{ij}$$

where, $\mathfrak{R}_{ij}$ is the i^{th} row and j^{th} is the column element of the inversed reduced Jacobian matrix. RCF informs the contribution of each bus to improving voltage stability. Furthermore, as the aim of compensator placement is to improve voltage stability, the computation of RCF focuses only on the effect to the unstable buses. The RCF is calculated for all buses and in respect to the unstable buses.

2.3. Computation of Eigenvalue as Stability Index

Eigenvalues are obtained from the reduced Jacobian matrix (J_R) which describes the level of stability of the system. Eigenvalues of J_R can be used to identify circumstances when the system becomes voltage unstable. The magnitude of the eigenvalues provides an estimate of relative proximity of the system to instability. For practical purposes, the reduced Jacobian matrix is a symmetric matrix, If V-Q is positive, then, all eigenvalues are positive, also; this indicates that the system is voltage stable. As the system becomes more stressed, the eigenvalues of J_R become smaller at the critical point of the system voltage stability. The eigenvalue of J_R becomes:

$$\text{Eigen}\,[J_R] = \begin{bmatrix} \lambda_1 & 0 & \cdots & 0 \\ 0 & \lambda_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & 0 \\ 0 & 0 & 0 & \lambda_n \end{bmatrix} \quad (8)$$

2.4. Procedure Algorithm of the Proposed Method

The proposed method's step by step procedure can be explained as follow: *Step 1:* perform power flow program to calculate voltage magnitude at all buses and network losses; *Step 2:* identify critical buses and buses with voltage below stability limit 0.95 pu; *Step 3*: perform modified Modal analysis to calculate the RCF from the inversed J_R. The computed RCF is focuses only on the critical buses. The location of compensator is chosen based on the highest contribution to improving the voltages at critical buses; this is indicated by the highest RCF. *Step 4*: install reactive power compensation devices with the size of 5 MVar in the buses with the highest RCF; *Step 5:* perform power flow to compute network losses and evaluate the system's voltage stability. The system is considered to be stable if the voltage in all buses is between voltage stability limit 0.95≤V≤1.05 pu; *Step 6*: If at least 1 bus has voltage below 0.95 pu, then go back to Step 3. If all voltage buses are within the stability limit, then, assess the robustness of the proposed method by comparing the results with different placements.

3. RESULTS AND DISCUSSION

3.1. The Test System: The Modified IEEE 30-bus Reliability Test System (RTS)

In order to conduct a comprehensive test of the above methods, IEEE 30-bus Reliability Test System (RTS) is used. This test system is modified in such a way as to obtain an initial state that allows it to perform testing of the proposed method. Figure 1 shows the test system with new bus numbering.

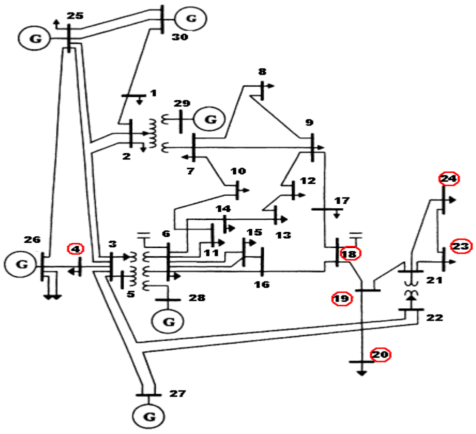

Figure 1 The IEEE 30-bus Reliability Test System (Saadat, 1999)

3.2. Computation of Reactive Contribution Factor

Figure 2 shows the system voltage profile on the initial conditions. The total active power losses are 23.383 MW, while the reactive power losses are 51.261 MVar. The smallest eigenvalue for this initial condition is 0.4673.

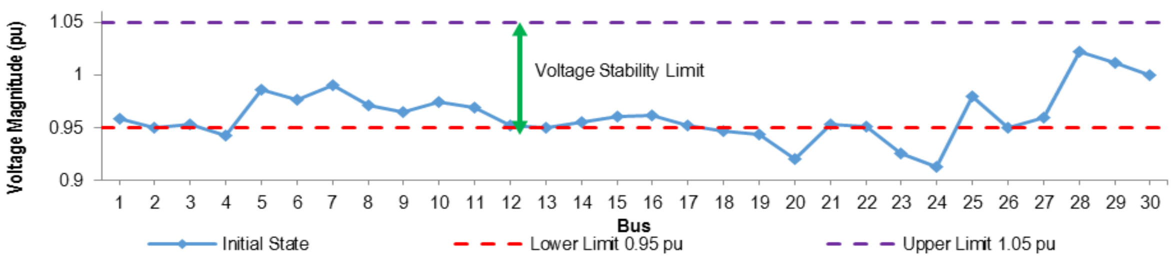

Figure 2 Voltage magnitude at the initial state

As can be seen in Figure 2, there are six critical load buses whose voltages are below 0.95 p.u. voltage stability limit These are buses 4, 18, 19, 20, 23 and 24 and are indicated with red circles in Figure 1. Table 1 shows the voltage magnitude for these unstable buses.

In order to determine the correct location for compensator placement for the purpose of covering the shortage of reactive power, the RCF is calculated for all buses so that their impacts on these critical buses can be observed. Therefore, with 6 unstable buses, the RCF of each load buses is calculated in respect of the critical buses and, hence:

$$RCF_j = \Re_{4,j} + \Re_{18,j} + \Re_{19,j} + \Re_{20,j} + \Re_{23,j} + \Re_{24,j}$$

Table 1 Buses with voltage under stability limit

Bus	Voltage Magnitude (p.u.)	Bus	Voltage Magnitude (p.u.)
4	0.943	20	0.920
18	0.947	23	0.926
19	0.944	24	0.913

For example, to compute RCF at bus 1:

$$RCF_1 = \Re_{4,1} + \Re_{18,1} + \Re_{19,1} + \Re_{20,1} + \Re_{23,1} + \Re_{24,1}$$

Table 2 shows the complete calculation of RCF values for the first iteration of all load buses. As indicated with blue font, bus 24 has the highest RCF of 1.9542. Hence, for the first iteration, bus 24 become the best location for capacitor placement.

Table 2 Reactive Contribution Factor (RCF) Computation for the first iteration

Bus	RCF	Bus	RCF	Bus	RCF	Bus	RCF
1	0.0609	7	0.1461	13	0.2830	19	1.3918
2	0.0727	8	0.2079	14	0.2849	20	1.8584
3	0.0867	9	0.2614	15	0.3790	21	1.3197
4	0.1025	10	0.2079	16	0.4055	22	0.2000
5	0.1606	11	0.2660	17	0.4752	23	1.8715
6	0.2881	12	0.2757	18	0.7578	24	**1.9542**

Figure 3 informs the computation of RCF for all buses. After the first iteration of power flow, with an injection of 5 MVar, the voltage magnitudes of the buses around bus 24 improve. The buses' voltages are close to that of bus 24 such as bus 21's and bus 23's straight increase significantly.

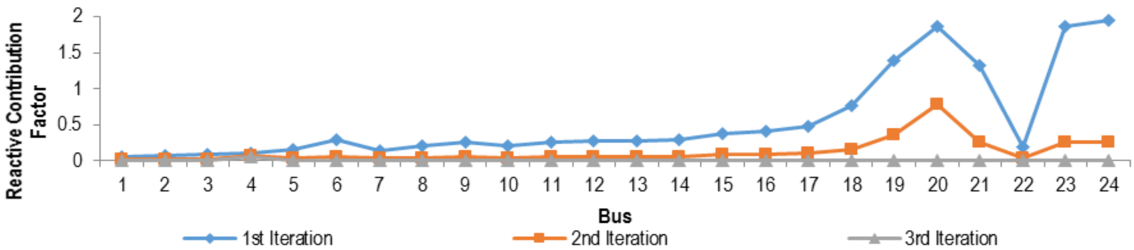

Figure 3 Reactive Contribution Factor (RCF) computation iteration process

However, the voltages of buses 24, 18, 19 and 20 are still below the stability limit 0.95 pu. Then, the reactive compensation injection still needs to be added and the RCF is calculated again to find the next location for the placement of compensator devices. In the second iteration, bus 20's RCF is the highest (Figure 3). With another addition of reactive compensation to bus 20 of 5 MVar, the system is not yet stable and, hence, another process of calculating RCF is done at the third iteration. This found that bus 4 had the highest RCF. With bus 4's 5 MVar capacitor, the system has recovered its stability and, hence, the process is stopped. Figure 4 shows the voltage profile improvement, recorded for each iteration, after the capacitor's placement at the nominated buses. Table 3 informs the detailed location of the capacitor based on the highest RCF at each iteration.

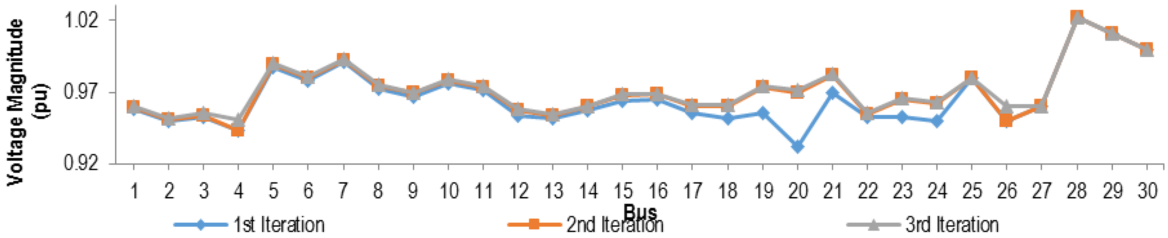

Figure 4 Voltage profile improvement at each iteration

Table 3 Location and size of compensator in each iteration

Iteration	Bus	Injected MVar
1	24	5
2	20	5
3	4	5

The total required reactive power compensation is 15 MVar with the assumption that the minimum voltage, achieved on each bus, is injected at 0.95 pu. After the installation of the above mentioned 3 nodes, the system's voltage profile has recovered to its stable condition. Buses that were previously under voltage stability limit are now above 0.95 pu.

Figure 5 illustrates the increase of eigenvalue in each iteration. Eigenvalues increased from 0.4673 to 0.5082. This explains how the stability level improves with the addition of reactive compensations.

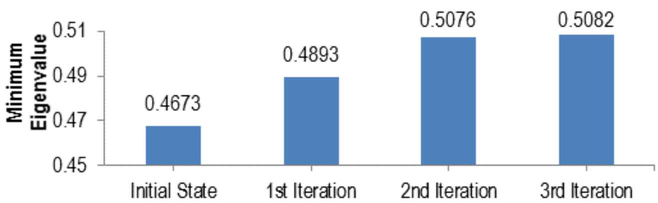

Figure 5 Eigenvalue at each iteration

The system's active power losses reduced from 23.383 MW to 23.187 MW. Also, the reactive power reduced from 51.362 MVar to 50.002 MVar. Table 4 shows the complete power losses in each iteration

Table 4 Network losses in each iteration

No	State	Total Losses	
		MW	MVAR
1	Initial State	23.383	51.362
2	1st Iteration	23.274	50.703
3	2nd Iteration	23.191	50.212
4	3rd Iteration	23.187	50.002

3.3. Evaluation of the Proposed Method

In order to assess the robustness of the proposed method, the results of reactive power compensator placement are compared with the placement of a 15 MVar compensator in one single critical/unstable bus. Figure 6 shows the voltage profile after the installation of compensators of a total of 15 MVar reactive power injections in selected buses and based on the proposed method. In this case, the location of the 15 MVar reactive power injection is in the critical buses which are buses 4, 18, 19, 20, 23 or 24. The installation of a 15 MVar reactive power in bus 4 leaves it as unstable as the other buses. There are still 5 buses with voltages below the stability limit, i.e. buses 18, 19, 20, 23, and 24. When bus 18 is selected for the placement of a 15 MVar reactive power compensator, it leaves 4 buses under the stability limit, i.e. buses 4, 20, 23 and 24. If either bus 19 or 20 or 23 or 24 is chosen as the injection site, this still leaves bus 4's voltage below the stability limit of 0.944 pu. On the other hand, if compensators are placed according to the proposed method, all the voltages are stable.

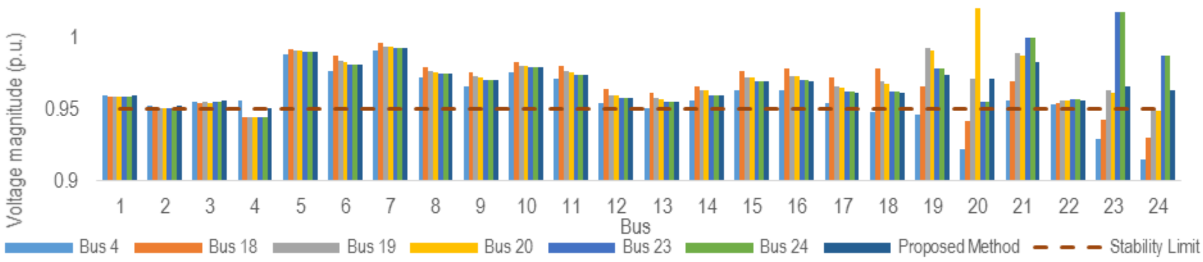

Figure 6 Comparison of voltage magnitude at different placement and proposed method

Figure 7 informs the comparison of network losses if compensators are placed based on the settings in assessment 1 and proposed method. It shows clearly that, if reactive power compensators are placed at buses 24, 20 and 4 with each having 5 MVar, both the active and reactive power losses are the smallest. This means that placing compensators in buses, according to the proposed method, gives the better stable system, better voltage profile and minimum power losses.

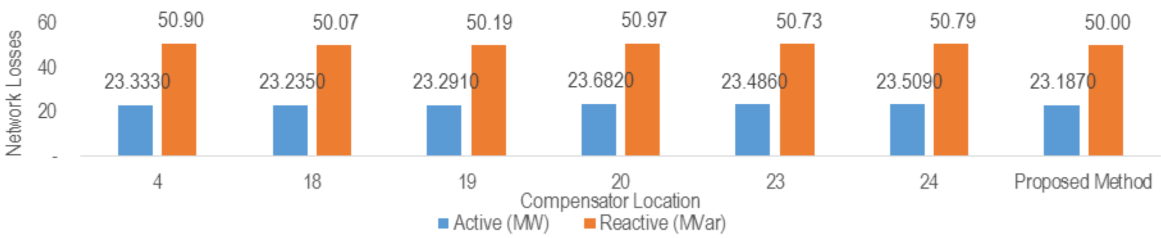

Figure 7 Comparison of network losses

4. CONCLUSION

This paper presents a new method for the placement of reactive power compensation devices by improving the Modal analysis technique by utilizing a direct connection between V & Q in the inversed reduced Jacobian matrix. This paper formulated a new Reactive Contribution Factor (RCF) computed from the elements of the inversed reduced Jacobian matrix. The RCF informs the size of the contribution of a specific bus from improving the voltage magnitude in critical buses. The greater a bus' RCF, the greater that bus' influence in improving the voltage of the critical buses.

The proposed method is tested on the modified IEEE 30-bus Reliability Test System. Based on the proposed method, the total reactive power compensator for the system is 15 MVar. With this amount, the proposed method was compared then with different compensators of 15 MVar placements. When of after capacitor placement, the system's stability condition and network losses are based on the proposed method are compared to these different placements, the system's overall voltage profile, based on the proposed method, is better than the system's overall voltage profile if 15 MVar is placed in other buses.

5. ACKNOWLEDGEMENT

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