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- Cover letter (initial submission)
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- Graphical abstract
- Review history (Comments and suggestions from Reviewers)
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**Title:**

Analytical Method for Reactive Power Compensators Allocation

**Abstract:**


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

**Keywords:**

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

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Dr. Mohammed Ali Berawi  
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Dear Dr. Mohammed Ali Berawi,,

We would like to submit the enclosed manuscript "*Analytical method for reactive power compensators allocation*" for your consideration for publication as a research paper in International Journal of Technology.

We confirm that this manuscript has not been published elsewhere and is not under consideration by another journal. All authors have approved the manuscript and agree with submission to International Journal of Technology. The authors have no conflicts of interest to declare.

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We look forward to hearing from you at your earliest convenience.

Yours sincerely,  
Ardiaty Arief, Ph.D.

## **ANALYTICAL METHOD FOR REACTIVE POWER COMPENSATORS ALLOCATION**

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### **ABSTRACT**

This paper presents a novel analytical methodology to determine location for reactive power devices placement in power systems. The proposed method modifies modal analysis technique and develops new formulation to compute the Reactive Contribution Factor (RCF) of each load buses based on the inversed reduced Jacobian matrix. The objective of this research is to achieve the most stable condition as well as to minimize network losses. The proposed method is implemented at the modified IEEE 30-bus Reliability Test System (RTS) and compared with different placement. This work compares the voltage profile, eigenvalue and network losses to assess the method. The simulation results show the proposed method can provide a solution to the ideal shunt compensator placement to improve the system's voltage stability and 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 safe and reliable operation in a power system (Dong and Zhang 2009). During peak load state, network losses as result of reactive power flow can be very substantial (Jabr 2008). Large problems occur in case of voltage stability because of the huge transits of power along the long transmission lines. Nowadays, modern power systems are severely stressed and working at the stability limit with smaller capacity and margin hence may cause congestion problems (Bachtiar Nappu, Arief and Bansal 2014, Nappu, Bansal and Saha 2013). The progressive and uncontrollable drop in voltage as a result of increase in load demand, especially reactive loads or change in system operation conditions could eventually result in a wide spread voltage collapse (Arya, Choube and Shrivastava 2008, Prada, de Souza and Lafitte Vega 2015, Echavarren, Lobato and Rouco 2009). Therefore protective step may be taken, such as load shedding (Arief et al. 2013). To avoid this

instability, there are several preventive step that can be done, which one of them is installation of reactive power compensation scheme. These compensation device in power system provides reactive power compensation, reduces network losses, decreases energy losses, improves voltage profile, releases system capacity and recovers power factor (Taher and Bagherpour 2013, Sajjadi, Haghifam and Salehi 2013, Abul'Wafa 2013, Safari, Ahmadian and Golkar 2013). In placing reactive power compensation devices, there are three issues that become a major concern, namely size of compensation, number and location of placement (Lee, Ayala and Coelho 2015, Kavousi-Fard and Niknam 2013). Furthermore, with high penetration of renewable energy generations into power systems especially wind power plants, this has created more challenges in reactive power compensating planning (Xu et al. 2017a), as well as they can affect the power system dynamic voltage stability (Xu et al. 2017b). Hence, maintaining reliability and security of daily operational of the system has become more difficult due to wind resources intermittency (Zhang et al. 2016, Zhang et al. 2017). Countries around the world have targeted to expand renewable energy resources for the electricity industry, for example Australia targeted that 20% of their power generation supply is 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. Particle swarm optimization (PSO) approach is implemented in papers (Lee et al. 2015, Elsheikh et al. 2014, Devi and Geethanjali 2014, Zeinalzadeh, Mohammadi and Moradi 2015). In (Elsheikh et al. 2014), loss sensitivity factor is employed to determine capacitor location then use PSO to compute the size of capacitor. PSO algorithm is also used in paper (Lee et al. 2015) which is based on Gaussian and Cauchy probability distribution functions. In reference (Devabalaji, Ravi and Kothari 2015), loss sensitivity factor and voltage stability index are calculated for capacitor location and optimal size is determined using bacterial foraging optimization algorithm (BFOA). BFOA is also utilized in (Tabatabaei and Vahidi 2011) to find optimal location for capacitor. Artificial bee colony algorithm is applied to find location and size of capacitor in (El-Fergany and Abdelaziz 2014, El-Fergany 2014). Reference (Ramadan et al. 2014) develops a fuzzy logic based approach which develops two membership functions; membership function of voltage sensitivity and membership function incorporating active and total network losses. An integer nonlinear programming approach with objective to reduce network losses and investment cost is presented in (Nojavan, Jalali and Zare 2014). Search space of genetic algorithms (GAs) is occupied in (Carpinelli et al. 2010) for capacitor placement. A hybrid method of CODEQ (HCODEQ) is developed in (Chiou and Chang 2015) by using chaotic search concepts, opposition-based learning and quantum mechanics. Teaching learning based optimization is presented in (Sultana and Roy 2014) to minimize network losses and energy cost in determining capacitor allocation. Paper (Mohamed Shuaib, Surya Kalavathi and Christofer Asir Rajan 2015) develops two methods for capacitor allocation, that are sensitivity analysis then gravitational search algorithm (GSA). Clustering based optimization (CBO) is utilized for capacitor placement to minimize power losses cost and capacitor cost in reference (Vuletić and Todorovski 2014). Author in (Abul'Wafa 2014) combines fuzzy expert system for capacitor placement and read coded GA to calculate capacitor size. Bio-inspired optimization technique is presented in (Duque et al. 2015) by improving monkey search optimization for capacitor placement. The applications of artificial intelligence in solving capacitor placement might have effectual operation and can handle complicated problems, however, they are more difficult to code and could potentially providing volatile outcomes in early stage convergence. Therefore, there is a need for an effective method that is not only able to provide information about voltage stability in the system, but also to indicate its location.

This study developed an analytical method that 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, Morison and Kundur 1992). In modal analysis method, the inversed reduced Jacobian matrix is computed that informs relation between change in voltage and 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 of stability. This work offers simple algorithm and the method is simple to be implemented. The advantage with this approach is fast, straight, accurate and do not involve composite computational processes. This study further formulates new Reactive Contribution Factor (RCF) that is obtained from the inversed reduced Jacobian matrix. RCF gives information about contribution of a specific bus in improving voltage magnitude at critical buses.

## 2. THE PROPOSED METHOD

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

To perform modal analysis, linearized steady-state power voltage equations is used as follow:

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

Where,  $\Delta P$  is the incremental change in bus real power;  $\Delta Q$  is the incremental change in bus reactive power injection;  $\Delta\theta$  is the incremental change in bus voltage angle and  $\Delta V$  is the incremental change in bus voltage magnitude

To asses the relationship of voltage and reactive power stability, then the active power (P) is kept constant. Due to constant active power ( $\Delta P = 0$ ), Equation 1 then can be reduced to,

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

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

$$\Delta\theta = -J_{PV} \Delta V + J_{P\theta}^{-1} \Delta Q \quad (2)$$

$$\Delta Q = J_{Q\theta} \Delta\theta + J_{QV} \Delta V \quad (3)$$

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

$$\Delta Q = [J_{QV} - J_{Q\theta} J_{P\theta}^{-1} J_{P\theta}] \Delta V \quad (4)$$

If,

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

Then:

$$\begin{aligned} \Delta Q &= J_R \Delta V \\ \Delta V &= J_R^{-1} \Delta Q \end{aligned} \quad (5)$$

$J_R^{-1}$  or the inversed reduced Jacobian matrix is a matrix that shows direct correlation between the bus voltage and reactive power injection. Assuming the active power is zero and the voltage angle is substituted, then obtained form 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 ( $\Delta V$ ) is obtained by multiplying the reactive power injection at specific bus 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,

$$\text{RCF}_j = \mathfrak{R}_{1j} + \mathfrak{R}_{2j} + \mathfrak{R}_{3j} + \dots + \mathfrak{R}_{mj} \quad (7)$$

$$\text{RCF}_j = \sum_{i=1}^n \mathfrak{R}_{ij}$$

Where,  $\mathfrak{R}_{ij}$  is the  $i^{\text{th}}$  row and  $j^{\text{th}}$  column element of the inversed reduced Jacobian matrix.

RCF informs the contribution of each bus in improving voltage stability. Furthermore, as the aim of compensator placement is to improve voltage stability, therefore the computation of RCF is focusing only on the effect to the unstable buses. The RCF is calculated at all buses in respect to the unstable buses. So that, to ensure all the buses voltage are stable then this method is done with few iterations by adding reactive power compensation until all the voltage are at the stable value. Once the bus voltage is becomes stable, it is excluded from the next process of RCF calculation.

### 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 eigenvalues provide an estimate of relative proximity of the system to instability. For practical purposes, the reduced Jacobian matrix is a symmetric matrix, If V-Q positive, then all eigenvalues are also positive, which indicates the system is voltage stable. As the system becomes more stressed, the eigenvalues of  $J_R$  will become smaller at the critical point system voltage stability. By identifying the smallest eigenvalues of the system, this can be used to assess the system's stability and evaluating the robustness of the proposed method. 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 step by step procedure of the proposed method 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, that 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 RCF is computed only focuses on the critical buses. The location of compensator is chosen based on the highest contribution to improve the voltages at critical buses which is indicated by the highest RCF.

Step 4 Install reactive power compensation devices with the size of 5 MVar at the buses with highest RCF.

Step 5 Perform power flow to compute network losses and evaluate the voltage stability of the system. The system is considered stable if voltage at all buses are between voltage stability limit  $0.95 \leq V \leq 1.05$  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 between the stability limit, then assess the robustness of the proposed method by comparing the results with different placements.

### 3. TEST RESULTS AND ANALYSIS

#### 3.1 The test system: The modified IEEE 30-bus Reliability Test System (RTS)

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 to obtain an initial state that allows it to perform testing of the proposed method. The voltage at slack bus is set to 1 p.u., whereas the voltages of the voltage controller buses are set at various values and can be seen in Table 1. Figure 1 shows the test system with new bus numbering.

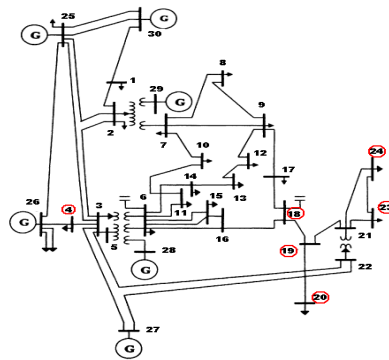


Figure 1 The IEEE 30-bus Reliability Test System (Saadat 1999)

#### 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.

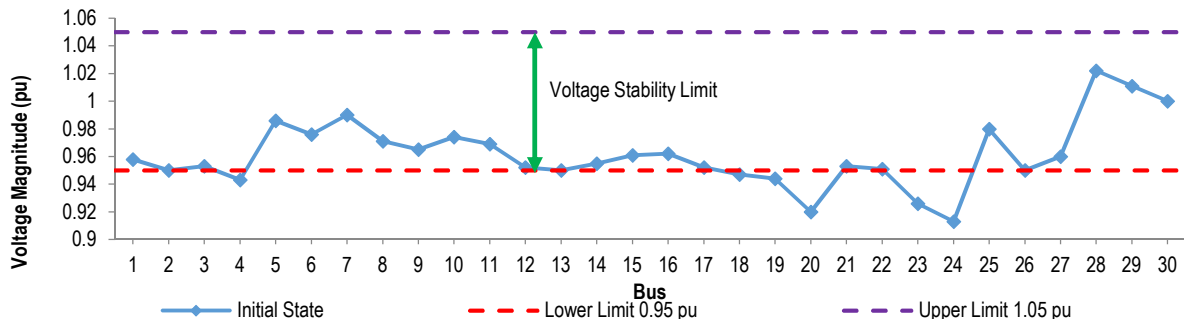


Figure 2 Voltage magnitude at the initial state

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

Table 1 Buses with voltage under stability limit

Bus	Voltage Magnitude (p.u.)	Bus	Voltage Magnitude (p.u.)
4	0.943	20	0.92
18	0.947	23	0.926
19	0.944	24	0.913

To determine the right location for compensator placement for covering the shortage of reactive power, then the RCF is calculated at all buses to observe their impacts to these critical buses. Therefore with 6 unstable buses, RCF at each load buses is calculated in respect of the critical buses, hence.

$$RCF_j = \mathfrak{R}_{4,j} + \mathfrak{R}_{18,j} + \mathfrak{R}_{19,j} + \mathfrak{R}_{20,j} + \mathfrak{R}_{23,j} + \mathfrak{R}_{24,j}$$

For example, to compute RCF at bus 1:

$$RCF_1 = \mathfrak{R}_{4,1} + \mathfrak{R}_{18,1} + \mathfrak{R}_{19,1} + \mathfrak{R}_{20,1} + \mathfrak{R}_{23,1} + \mathfrak{R}_{24,1}$$

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

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	0.283	19	1.3918
2	0.0727	8	0.2079	14	0.2849	20	1.8584
3	0.0867	9	0.2614	15	0.379	21	1.3197
4	0.1025	10	0.2079	16	0.4055	22	0.2
5	0.1606	11	0.266	17	0.4752	23	1.8715
6	0.2881	12	0.2757	18	0.7578	24	<b>1.9542</b>

Figure 3 informs the computation of RCF at all buses. After the first iteration of power flow, with an injection of 5 MVar, voltage magnitude at buses around bus 24 improve. The voltages at buses close to the bus 24 such as bus 21 and bus 23 straight increases significantly. However, the voltage at buses 24, 18, 19 and 20 are still below the stability limit 0.95 pu, then reactive compensation injection is still need to be added and the RCF is calculated again to find the next location for compensator devices placement. In the second iteration, RCF at bus 20 is the highest (Figure 3). With another addition of reactive compensation at bus 20 of 5 MVar, the system is not stable yet, hence another process of calculating RCF is done again at the third iteration and found that bus 4 has the highest RCF. With 5 MVar capacitor at bus 4, the system has recovered its stability, hence the process is stopped. Figure 4 shows the voltage profile improvement at each iteration after capacitor placement at the nominated buses. Table 3 informs the detail of location of capacitor based on the highest RCF at each iteration.

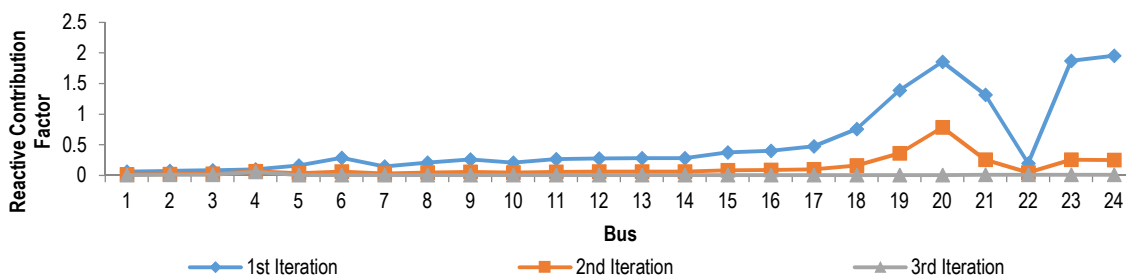


Figure 3 Reactive Contribution Factor (RCF) computation iteration process

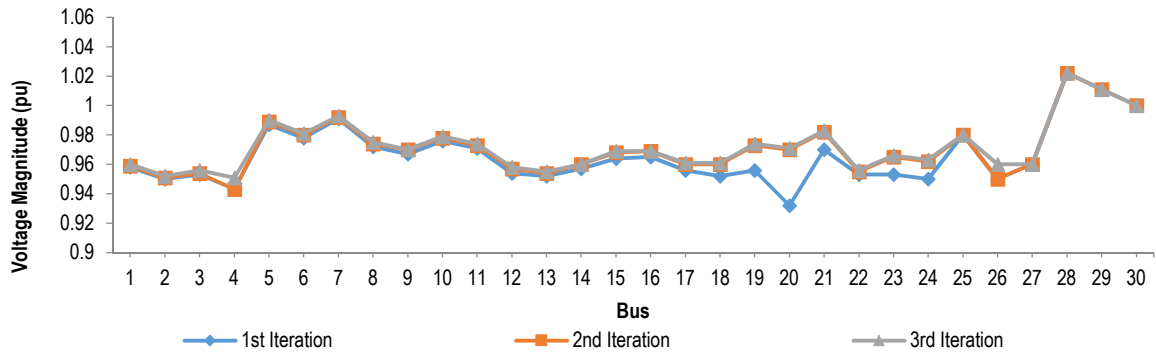


Figure 4 Voltage profile improvement at each iteration

Table 3 Location and size of compensator in each iteration

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

Total reactive power compensation required is 15 MVar with the assumption that the minimum voltage is achieved on each bus that is injected is 0.95 pu. After the installation of the 3 node above, then the voltage profile of the system has recovered to its stable condition. Buses that were previously under voltage stability limit is now above 0.95 pu.

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

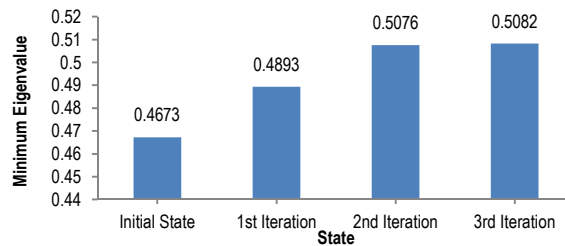


Figure 5 Eigenvalue at each iteration

Active power losses of the system decreased from 23.383 MW to 23.187 MW. While the reactive power is also reduced from 51.362 MVar to 50.002 MVar. The complete power losses at each iteration can be seen in Table 4.

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

To assess the robustness of the proposed method, the results of reactive power compensator placement are compared with placement of 15 MVar compensator at one single critical/unstable bus. Figure 6 shows the voltage profile after installation of compensators of total 15 MVar reactive power injection at selected buses and based on proposed method. In this case, the location of 15 MVar reactive power injection is at the critical buses, which are buses 4, 18, 19, 20, 23 or 24. Table 7 gives voltage magnitude of all buses if 15 MVar is placed at each selected bus alone and compares them with voltage magnitude based on the proposed method. Installation of 15 MVar reactive power at the bus 4 leaves many instability at other buses. There are still 5 buses with voltage below the stability limit, i.e. buses 18, 19, 20, 23, and 24. When bus 18 is selected as placement of 15 MVar reactive power compensator, it leaves 4 buses under stability limit, i.e. buses 4, 20, 23 and 24. If bus 19 is chosen, or 20, 23 and 24 as the injection site, still leaving voltage at bus 4 below stability limit, 0.944 pu. On the other hand, if compensators are placed according to the proposed method, all the voltages are stable.

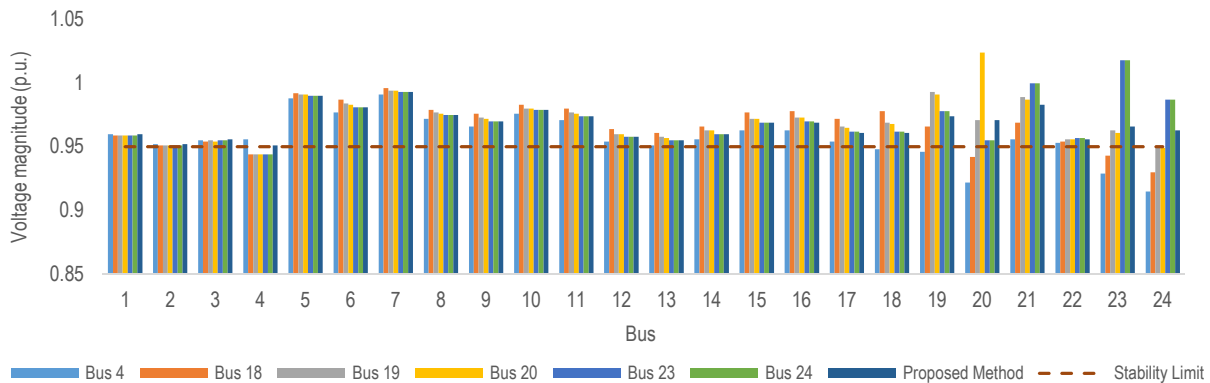


Figure 6 Comparison of voltage magnitude at different placement and proposed method

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

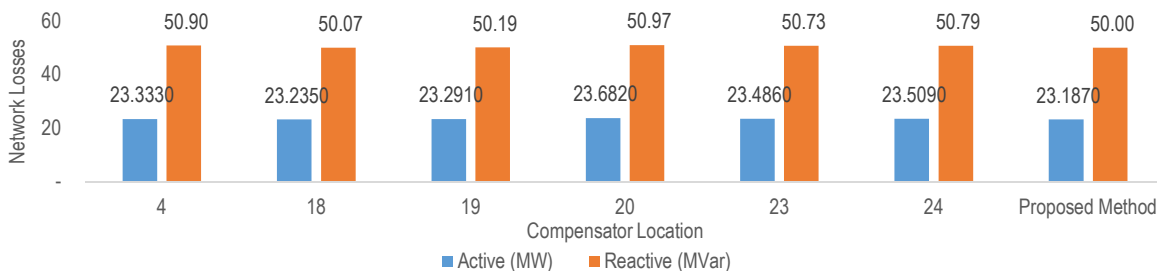


Figure 7 Comparison of network losses

## 4. CONCLUSIONS

This paper presents a new method of reactive power compensation devices placement by improving modal analysis technique that utilizing a direct connection between V & Q in the inversed reduced Jacobian matrix. A new Reactive Contribution Factor (RCF) is formulated in this paper which is computed from the elements of the inversed reduced Jacobian matrix. The RCF informs how big the contribution of a specific bus in improving voltage magnitude at critical

buses. The bigger the RCF of a bus, the bigger the influence of that bus 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 15 MVar. With this amount, the proposed method is then compared with different compensators of 15 MVar placements. When the stability condition and network losses of the system after capacitor placement based on proposed method are compared to these different placements, the overall voltage profile of the system based on proposed method is better than the overall voltage profile of the system if 15 MVar is placed at other buses.

The proposed method is very simple, straightforward and computationally very efficient for reactive power compensation equipment placement. For further research, this method can be compared with other methods in the compensator placement.

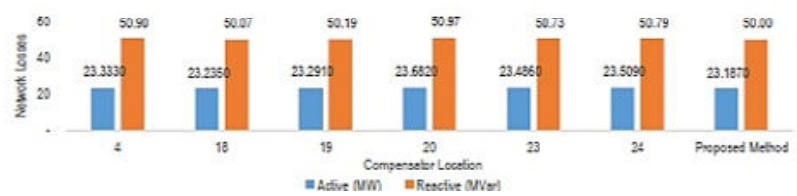
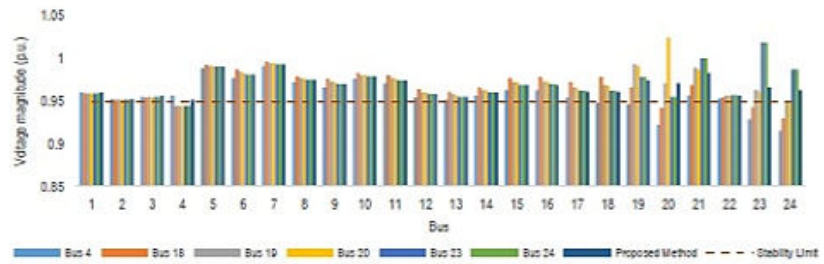
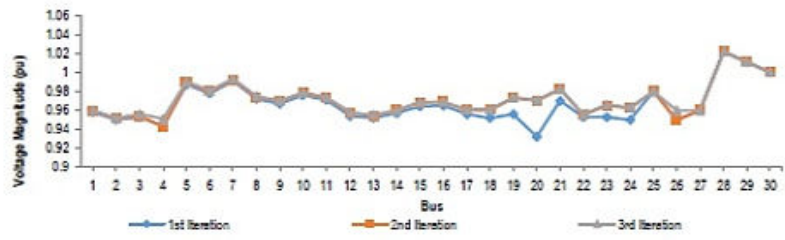
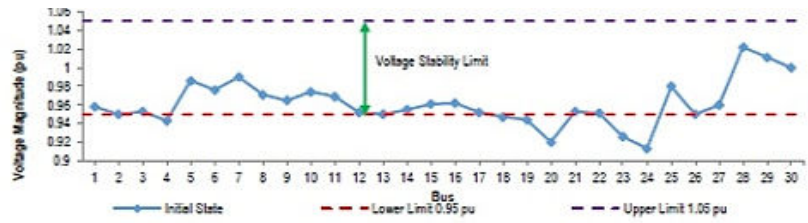
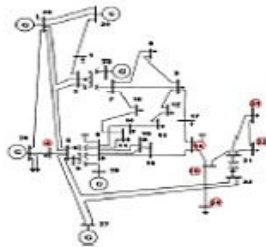
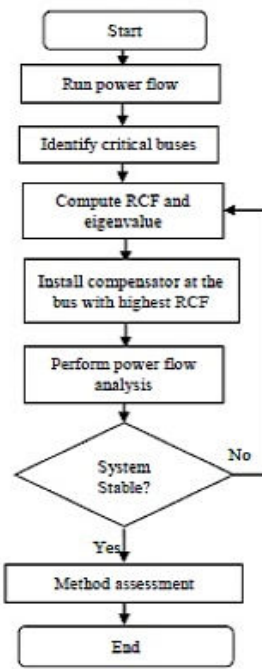
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## Review History

**Reviewer Comment**

**Reviewer** 1

**Date Review** : 22 Jan 2018 - 21:44

**Introduction** : This paper part introduces the current trend and some well developed reactive compensation methods. However, the author needs to compare the exiting methods and clarify the importance and novelty of the proposed method.

**Methodology** : The analytic method is applied based on simplified Jacobian matrix. The illustration is enough and the procedures are introduced in detail.

**Results and Discussion** : The reviewer encourages the authors to emphasis more on the computation results comparison, and use large systems to demonstrate the effectiveness of the proposed method.

**References** : The literature review is inadequate. The background section could be updated and little more complicated.

**Other** :

**Originality** 4 (above average)

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Originality	4 (above average)
Technical	3 (average)
Methodology	4 (above average)
Readability	3 (average)
Practicability	3 (average)
Organization	3 (average)
Importance	4 (above average)

**Attachment** :-

**Result** : **Done, Revisions Required**

**Reviewer** 2

**Date Review** : 22 Jan 2018 - 09:58

**Introduction** : The references format of the introduction are not cited consistently. Please check the required format and revise accordingly.

**Methodology** : In section 2.4, how the value of reactive power injection which is 5MVar is determined? Either by calculation or assumption?

**Results and Discussion** : 1. Figure 1 is too small and hard to be seen. Please enlarge the figure.  
2. In section 3.3, paragraph 1 line 3, author refers to the wrong table. Table 7 is not shown in the paper.  
3. In section 3.3, paragraph 1 line 8, spelling error, please change from 'comparrison' to comparison.

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Reviewer 2

Date Review : 22 Jan 2018 - 09:58

Introduction : The references format of the introduction are not cited consistently. Please check the required format and revise accordingly.

Methodology : In section 2.4, how the value of reactive power injection which is 5MVar is determined? Either by calculation or assumption?

Results and Discussion : 1. Figure 1 is too small and hard to be seen. Please enlarge the figure.  
2. In section 3.3, paragraph 1 line 3, author refers to the wrong table. Table 7 is not shown in the paper.  
3. In section 3.3, paragraph 1 line 8, spelling error, please change from 'compaprison' to comparison.  
4. Instead of improving the voltage stability do the author investigate the effect of power factor in the power system for the proposed method?

References : Good.

Other : For the abstract, it is suggested to point out the problem statements of the project.

Originality	5 (excellent)
Technical	4 (above average)
Methodology	4 (above average)
Readability	4 (above average)
Practicability	4 (above average)
Organization	5 (excellent)
Importance	5 (excellent)

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3. In section 3.3, paragraph 1 line 8, spelling error, please change from 'compaprison' to comparison.  
4. Instead of improving the voltage stability do the author investigate the effect of power factor in the power system for the proposed method?

References : Good.

Other : For the abstract, it is suggested to point out the problem statements of the project.

Originality	5 (excellent)
Technical	4 (above average)
Methodology	4 (above average)
Readability	4 (above average)
Practicability	4 (above average)
Organization	5 (excellent)
Importance	5 (excellent)

Attachment :-

Result : **Done, Accept**

Reviewer Comment (R1)

Factor (RCF) of each load buses based on the inversed reduced Jacobian matrix. The objective of this research is to achieve the most stable condition as well as to minimize

Graphical Abstract - Images  
Cover Letter

Dr. Mohammed Ali Berawi  
Editors in Chief  
International Journal of Technology

Makassar, 28 January 2018

Dear Dr. Mohammed Ali Berawi,

We would like to submit the revised manuscript "*Analytical method for reactive power compensators allocation*" for your consideration for publication as a research paper in International Journal of Technology. We have revised this manuscript according to the reviewer's comments.

We confirm that this manuscript has not been published elsewhere and is not under consideration by another journal. All authors have approved the manuscript and agree with submission to International Journal of Technology. The authors have no conflicts of interest to declare.

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We look forward to hearing from you at your earliest convenience.

Yours sincerely,  
Ardiaty Arief, Ph.D.

## **ANALYTICAL METHOD FOR REACTIVE POWER COMPENSATORS ALLOCATION**

(Received: Month Year / Revised: Month Year / Accepted: Month Year)

### **ABSTRACT**

This paper presents a novel analytical methodology to determine location for reactive power devices placement in power systems. The proposed method modifies modal analysis technique and develops new formulation to compute the Reactive Contribution Factor (RCF) of each load buses based on the inversed reduced Jacobian matrix. The objective of this research is to achieve the most stable condition as well as to minimize network losses. The proposed method is implemented at the modified IEEE 30-bus Reliability Test System (RTS) and compared with different placement. This work compares the voltage profile, eigenvalue and network losses to assess the method. The simulation results show the proposed method can provide a solution to the ideal shunt compensator placement to improve the system's voltage stability and 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 safe and reliable operation in a power system (Dong & Zhang, 2009). Nowadays, modern power systems are severely stressed and working at the stability limit with smaller capacity and margin hence may cause congestion problems (Bachtiar Nappu et al., 2014; Nappu et al., 2013). The progressive and uncontrollable drop in voltage as a result of increase in load demand, especially reactive loads or change in system operation conditions could eventually result in a wide spread voltage collapse (Prada et al., 2015). Therefore protective steps may be taken, such as load shedding (Arief et al., 2013). To avoid this instability, there are several preventive step that can be done, which one of them is installation of reactive power compensation scheme. These compensation device in power system provides reactive power compensation, reduces network losses, decreases energy losses, improves voltage profile, releases system capacity and recovers

power factor (Sajjadi et al., 2013; Taher & Bagherpour, 2013). In placing reactive power compensation devices, there are three issues that become major concern, 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 especially wind power plants, this has created more challenges in reactive power compensating planning (Xu et al., 2017), hence maintaining reliability and security of daily operational of the system has become more difficult due to wind resources intermittency (Zhang et al., 2016; Zhang et al., 2017). Especially as countries around the world have targeted to expand renewable energy resources for the electricity industry, for example Australia targeted that 20% of their power generation supply is 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). In analytical methods, the computation procedures are reduced by making some approximations. A well known analytical method for capacitor placement is by (Cook, 1959) who proposed the optimum capacitor placement should be  $2/3$  of the reactive load factor. However, the application of this “ $2/3$  rule” in certain cases may give negative financial savings (Lee & Grainger, 1981). Heuristic methods are practical methods that are developed by using researchers’ intuitions and experiences that provide a satisfactory solution. Applications of heuristic method into reactive power compensators placements are written by (Hamouda & Sayah, 2013; Ramalinga Raju et al., 2012). Numerical programming is an iterative technique using arithmetic mathematical formulations by maximizing (or minimizing) an objective function of decision variables which also fulfil a set of constraints. An integer nonlinear programming approach was presented in (Nojavan et al., 2014). Work in (Aguilar & Cuervo, 2005) 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 capacitors placement. Reference (Ramadan et al., 2014) developed a fuzzy logic based approach which develops two membership functions and author (Abul’Wafa, 2014) combined fuzzy expert system for capacitor placement and read coded genetic algorithm (GA) to calculate capacitor size. Nonetheless, the main challenge in using fuzzy logic is to determine the fuzzy membership functions and the fuzzy rule bases accurately. Particle swarm optimization (PSO) approach was implemented in papers (Lee et al., 2015; Zeinalzadeh et al., 2015). Nevertheless, the reliance of the PSO algorithm on the altering factors and the trapping in modifying parameters’ probability can decrease its accuracy and efficacy for various conditions. Other research in reactive power placement that employed AI procedures are bacterial foraging 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) (Mohamed 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 might have effectual operation and can handle complicated problems, however, they are more difficult to code and could potentially providing volatile outcomes in early stage convergence. Even though AI methods have been validated on the sample systems, nevertheless the success of these methods rely on modifying algorithmic considerations whose optimal setting involves users’ skill and knowledge (Jabr, 2008). Therefore, it is important to develop an effective method that is able to provide information about voltage stability in the system, where this information can be obtained from the Jacobian matrix of the system.

This study developed a new analytical method that 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). In modal analysis method, the inversed reduced Jacobian matrix is computed that informs relation between change in voltage and 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 of stability. This work offers simple algorithm and the method is simple to be implemented. The advantage with this approach is fast, straight, accurate and do not involve composite computational processes. The novelty of this research is the modification of Modal Analysis method then the formulation of Reactive Contribution Factor (RCF) that is obtained from the inversed reduced Jacobian matrix. RCF gives information about contribution of a specific bus in improving voltage magnitude at critical buses.

## 2. THE PROPOSED METHOD

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

To perform modal analysis, linearized steady-state power voltage equations is used as follow:

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

Where,  $\Delta P$  is the incremental change in bus real power;  $\Delta Q$  is the incremental change in bus reactive power injection;  $\Delta\theta$  is the incremental change in bus voltage angle and  $\Delta V$  is the incremental change in bus voltage magnitude

To asses the relationship of voltage and reactive power stability, then the active power (P) is kept constant. Due to constant active power ( $\Delta P = 0$ ), Equation 1 then can be reduced to,

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

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

$$\Delta\theta = -J_{PV} \Delta V + J_{P\theta}^{-1} \quad (2)$$

$$\Delta Q = J_{Q\theta} \Delta\theta + J_{QV} \Delta V \quad (3)$$

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

$$\Delta Q = [J_{QV} - J_{Q\theta} J_{P\theta}^{-1} J_{P\theta}] \Delta V \quad (4)$$

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

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

$$\Delta V = J_R^{-1} \Delta Q \quad (5)$$

$J_R^{-1}$  or the inversed reduced Jacobian matrix is a matrix that shows direct correlation between the bus voltage and reactive power injection. Assuming the active power is zero and the voltage angle is substituted, then obtained form 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 ( $\Delta V$ ) is obtained by multiplying the reactive power injection at specific bus 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,

$$\text{RCF}_j = \mathfrak{R}_{1j} + \mathfrak{R}_{2j} + \mathfrak{R}_{3j} + \dots + \mathfrak{R}_{mj} \quad (7)$$

$$\text{RCF}_j = \sum_{i=1}^n \mathfrak{R}_{ij}$$

Where,  $\mathfrak{R}_{ij}$  is the  $i^{\text{th}}$  row and  $j^{\text{th}}$  column element of the inversed reduced Jacobian matrix.

RCF informs the contribution of each bus in improving voltage stability. Furthermore, as the aim of compensator placement is to improve voltage stability, therefore the computation of RCF is focusing only on the effect to the unstable buses. The RCF is calculated at all buses 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 eigenvalues provide an estimate of relative proximity of the system to instability. For practical purposes, the reduced Jacobian matrix is a symmetric matrix, If V-Q positive, then all eigenvalues are also positive, which indicates the system is voltage stable. As the system becomes more stressed, the eigenvalues of  $J_R$  will become smaller at the critical point system voltage stability. The eigenvalue of  $J_R$  becomes,

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

### 2.4 Procedure Algorithm of the Proposed Method

The step by step procedure of the proposed method 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, that 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 RCF is computed only focuses on the critical buses. The location of compensator is chosen based on the highest contribution to improve the voltages at critical buses which is indicated by the highest RCF; *Step 4*: install reactive power compensation devices with the size of 5 MVar at the buses with highest RCF; *Step 5*: perform power flow to compute network losses and evaluate the voltage stability of the system. The system is considered stable if voltage at all buses are between voltage stability limit  $0.95 \leq V \leq 1.05$  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 between the stability limit, then assess the robustness of the proposed method by comparing the results with different placements.

### 3. TEST RESULTS AND ANALYSIS

#### 3.1 The test system: The modified IEEE 30-bus Reliability Test System (RTS)

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 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.

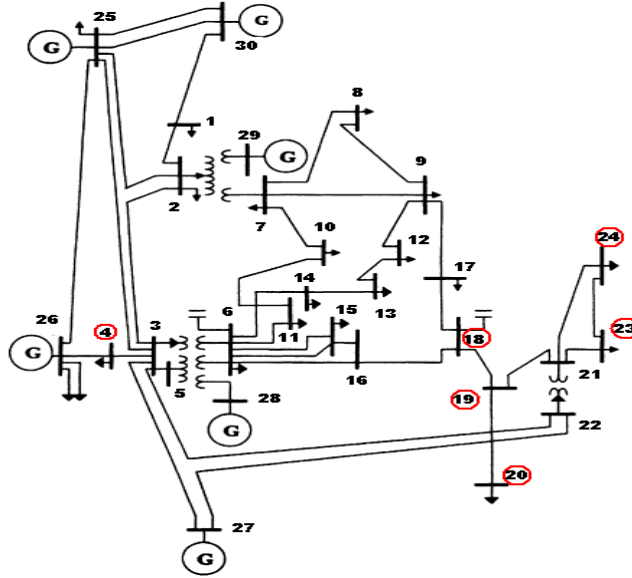


Figure 1 The IEEE 30-bus Reliability Test System (Saadat, 1999)

#### 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.

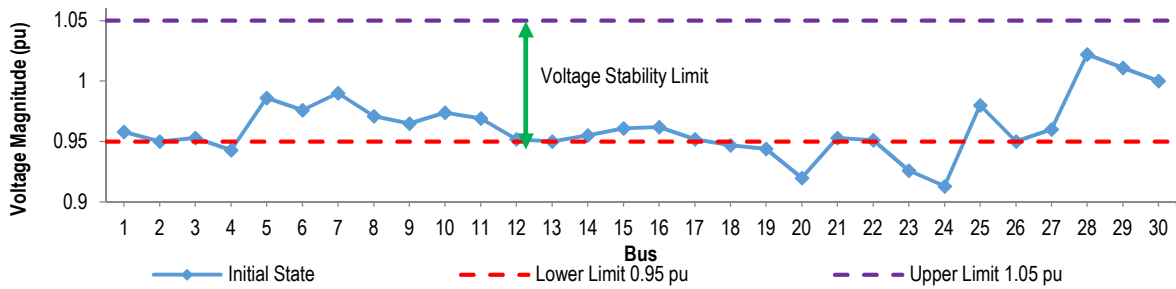


Figure 2 Voltage magnitude at the initial state

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

To determine the right location for compensator placement for covering the shortage of reactive power, then the RCF is calculated at all buses to observe their impacts to these critical buses. Therefore with 6 unstable buses, RCF at each load buses is calculated in respect of the critical buses, hence.

$$RCF_j = \mathfrak{R}_{4,j} + \mathfrak{R}_{18,j} + \mathfrak{R}_{19,j} + \mathfrak{R}_{20,j} + \mathfrak{R}_{23,j} + \mathfrak{R}_{24,j}$$

Table 1 Buses with voltage under stability limit

Bus	Voltage Magnitude (p.u.)	Bus	Voltage Magnitude (p.u.)
4	0.943	20	0.92
18	0.947	23	0.926
19	0.944	24	0.913

For example, to compute RCF at bus 1:

$$RCF_1 = \mathfrak{R}_{4,1} + \mathfrak{R}_{18,1} + \mathfrak{R}_{19,1} + \mathfrak{R}_{20,1} + \mathfrak{R}_{23,1} + \mathfrak{R}_{24,1}$$

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

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	0.283	19	1.3918
2	0.0727	8	0.2079	14	0.2849	20	1.8584
3	0.0867	9	0.2614	15	0.379	21	1.3197
4	0.1025	10	0.2079	16	0.4055	22	0.2
5	0.1606	11	0.266	17	0.4752	23	1.8715
6	0.2881	12	0.2757	18	0.7578	24	<b>1.9542</b>

Figure 3 informs the computation of RCF at all buses. After the first iteration of power flow, with an injection of 5 MVar, voltage magnitude at buses around bus 24 improve. The voltages at buses close to the bus 24 such as bus 21 and bus 23 straight increases significantly. However, the voltage at buses 24, 18, 19 and 20 are still below the stability limit 0.95 pu, then reactive compensation injection is still need to be added and the RCF is calculated again to find the next location for compensator devices placement. In the second iteration, RCF at bus 20 is the highest (Figure 3). With another addition of reactive compensation at bus 20 of 5 MVar, the system is not stable yet, hence another process of calculating RCF is done again at the third iteration and found that bus 4 has the highest RCF. With 5 MVar capacitor at bus 4, the system has recovered its stability, hence the process is stopped. Figure 4 shows the voltage profile improvement at each iteration after capacitor placement at the nominated buses. Table 3 informs the detail of location of capacitor based on the highest RCF at each iteration.

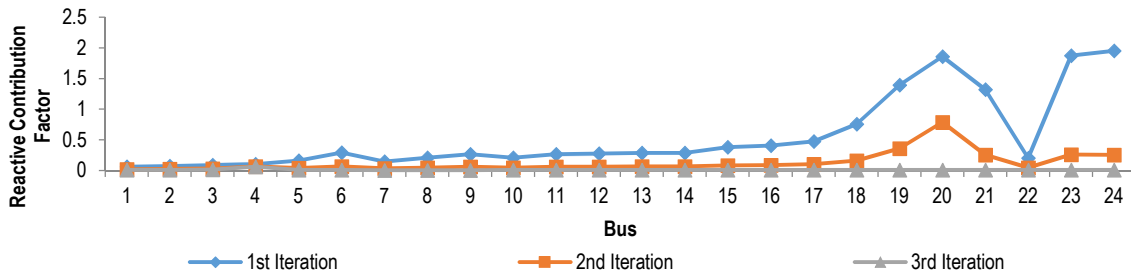


Figure 3 Reactive Contribution Factor (RCF) computation iteration process

Table 3 Location and size of compensator in each iteration

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

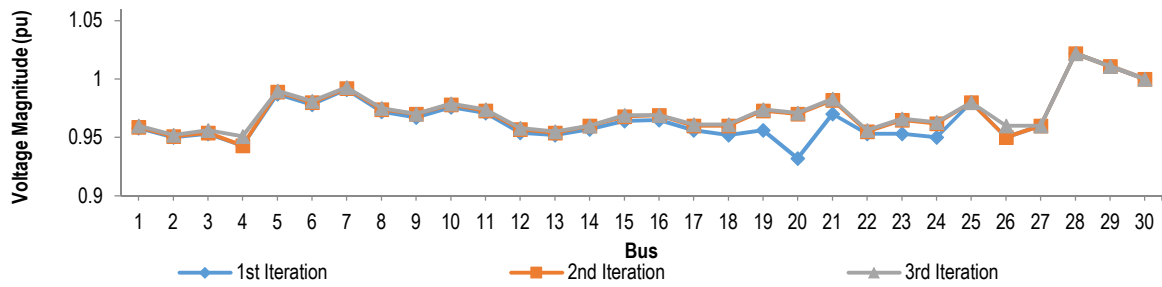


Figure 4 Voltage profile improvement at each iteration

Total reactive power compensation required is 15 MVar with the assumption that the minimum voltage is achieved on each bus that is injected is 0.95 pu. After the installation of the 3 node above, then the voltage profile of the system has recovered to its stable condition. Buses that were previously under voltage stability limit is now above 0.95 pu.

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

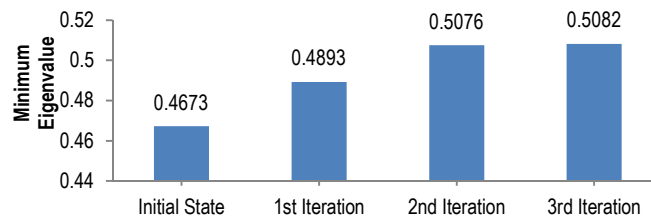


Figure 5 Eigenvalue at each iteration

Active power losses of the system decreased from 23.383 MW to 23.187 MW. While the reactive power is also reduced from 51.362 MVar to 50.002 MVar. The complete power losses at each iteration can be seen in Table 4.

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

To assess the robustness of the proposed method, the results of reactive power compensator placement are compared with placement of 15 MVar compensator at one single critical/unstable bus. Figure 6 shows the voltage profile after installation of compensators of total 15 MVar reactive power injection at selected buses and based on proposed method. In this case, the location of 15 MVar reactive power injection is at the critical buses, which are buses 4, 18, 19, 20, 23 or 24. Installation of 15 MVar reactive power at the bus 4 leaves many instability at other buses. There are still 5 buses with voltage below the stability limit, i.e. buses 18, 19, 20, 23, and 24. When bus 18 is selected as placement of 15 MVar reactive power compensator, it leaves 4 buses under stability limit, i.e. buses 4, 20, 23 and 24. If bus 19 is chosen, or 20, 23 and 24 as the

injection site, still leaving voltage at bus 4 below stability limit, 0.944 pu. On the other hand, if compensators are placed according to the proposed method, all the voltages are stable.

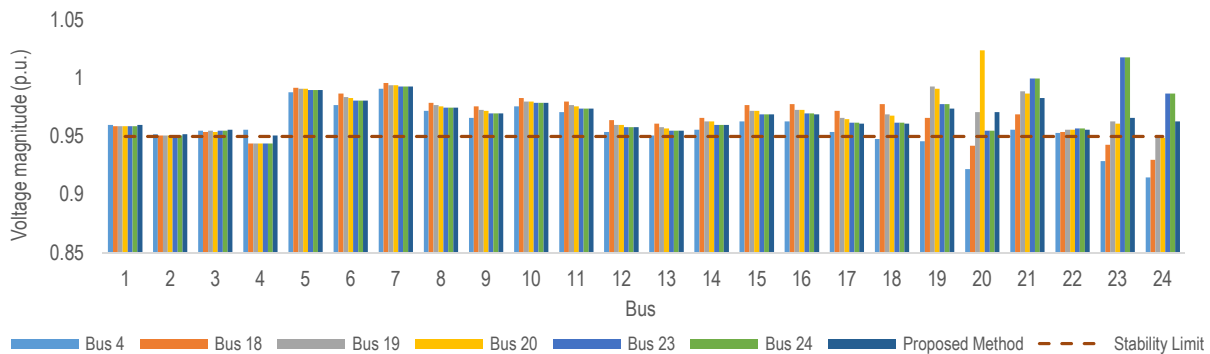


Figure 6 Comparison of voltage magnitude at different placement and proposed method

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

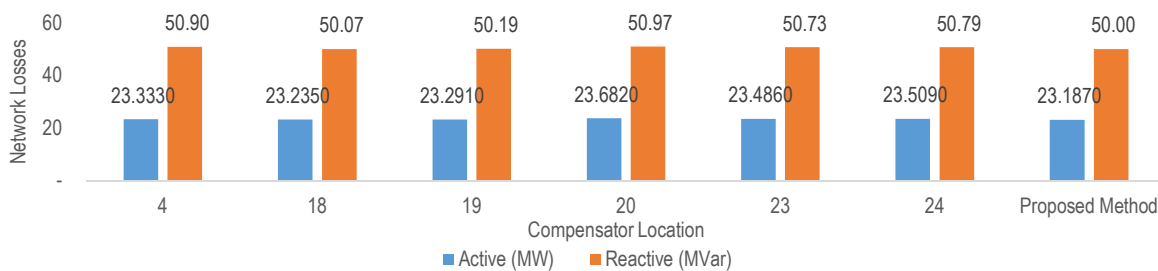


Figure 7 Comparison of network losses

#### 4. CONCLUSIONS

This paper presents a new method of reactive power compensation devices placement by improving modal analysis technique that utilizing a direct connection between V & Q in the inversed reduced Jacobian matrix. A new Reactive Contribution Factor (RCF) is formulated in this paper which is computed from the elements of the inversed reduced Jacobian matrix. The RCF informs how big the contribution of a specific bus in improving voltage magnitude at critical buses. The bigger the RCF of a bus, the bigger the influence of that bus 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 15 MVar. With this amount, the proposed method is then compared with different compensators of 15 MVar placements. When the stability condition and network losses of the system after capacitor placement based on proposed method are compared to these different placements, the overall voltage profile of the system based on proposed method is better than the overall voltage profile of the system if 15 MVar is placed at other buses.

#### 5. ACKNOWLEDGEMENT

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### List of Changes

Manuscript:

### **ANALYTICAL METHOD FOR REACTIVE POWER COMPENSATORS ALLOCATION**

*Response and Revision made by Author(s)*

**Reviewer #1:**

No	Comments	Revision/Changes
1	This paper part introduces the current trend and some well developed reactive compensation methods. However, the author needs to compare the exiting methods and clarify the importance and novelty of the proposed method.	The authors have included the comparison with existing method, clarify the importance and novelty of the proposed method.
2	The analytic method is applied based on simplified Jacobian matrix. The illustration is enough and the procedures are introduced in detail.	Thank you
3	The reviewer encourages the authors to emphasis more on the computation results comparison, and use large systems to demonstrate the effectiveness of the proposed method.	Thank you for your suggestion. We are working on improving the method and can use larger systems for future works.
4	The literature review is inadequate. The background section could be updated and little more complicated.	The authors have updated the literature review and made it more complete and complicated.
5		
6		

**Reviewer #2:**

No	Comments	Revision/Changes
1	The references format of the introduction are not cited consistently. Please check the required format and revise accordingly.	The references has been revised according to the required format.
2	In section 2.4, how the value of reactive power injection which is 5MVar is determined? Either by calculation or assumption?	The value is determined based on assumption of approximately 10% from the total load and losses of the modified data.
3	Figure 1 is too small and hard to be seen. Please enlarge the figure.	The authors have enlarged Figure 1
4	In section 3.3, paragraph 1 line 3, author refers to the wrong table. Table 7 is not shown in the paper.	The authors have fixed the sentences.
5	In section 3.3, paragraph 1 line 8, spelling error, please change from 'compaprison' to comparison.)	The authors have fixed the error.

6	Instead of improving the voltage stability do the author investigate the effect of power factor in the power system for the proposed method?	This paper is only focusing on assessing the voltage stability improvement and network losses reduction, however thank you for the suggestion, we can assessing the proposed method on both the voltage stability, network losses and power factor for future work.

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**Date Review** : 31 Jan 2018 - 08:24

**Introduction** : The contents is enough

**Methodology** : The methodology is clearly defined

**Results and Discussion** : The contents is improved

**References** : The reference is adequate

**Other** :

Originality	3 (average)
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**Reviewer** 1

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**Methodology** : The methodology is clearly defined

**Results and Discussion** : The contents is improved

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Originality	3 (average)
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Methodology	3 (average)
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Importance	3 (average)

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2

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Introduction : Ok

Methodology : Ok

Results and Discussion : Ok


References : Ok

Other :

Originality	5 (excellent)
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Methodology	4 (above average)
Readability	4 (above average)
Practicability	4 (above average)
Organization	4 (above average)
Importance	4 (above average)

Attachment :-

Result : **Done, Accept**



## ANALYTICAL METHOD FOR REACTIVE POWER COMPENSATORS ALLOCATION

(Received: Month Year / Revised: Month Year / Accepted: Month Year)

### ABSTRACT

This paper presents a novel analytical methodology to determine ~~the placement location for of~~ reactive power devices ~~placement~~ 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 ~~based on the inversed reduced Jacobian matrix~~. The objective of this research is to achieve the most stable condition ~~as well as~~ 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 ~~to assess the method~~. The simulation results show ~~that~~ the proposed method can provide a solution to the ideal shunt compensator placement ~~to improve~~ ~~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 a ~~power system~~ (Dong & Zhang, 2009). Nowadays, modern power systems are severely stressed and ~~working~~ at the stability limit with smaller capacity and margin. ~~Hence, these~~ may cause congestion problems (Bachtiar Nappu et al., 2014; Nappu et al., 2013). 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 could eventually result eventually~~ in a wide-spread voltage collapse (Prada et al., 2015). Therefore, protective steps ~~may be taken~~, such as load shedding, ~~may be taken~~ (Arief et al., 2013). ~~In order to~~ to avoid this instability, there are several preventive steps that can be ~~taken done~~, which one of them is ~~the~~ installation of a reactive power compensation scheme. ~~These~~ This compensation device in ~~the~~ power system provides reactive power compensation; reduces network losses; ~~decreases~~ ~~reduces~~ energy losses, improves ~~the~~ voltage profile; releases system capacity; and recovers ~~the~~ power factor (Sajjadi et al., 2013; Taher & Bagherpour, 2013). 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, maintaining~~ reliability and security of ~~daily~~

~~operational of~~ the system's operation has become more difficult due to wind resources intermittency (Zhang et al., 2016; Zhang et al., 2017). ~~This is E~~especially so since ~~as~~ countries ~~around the~~ world wide have targeted ~~to expand the expansion of~~ renewable energy resources for the electricity industry. ~~F~~for example, Australia targeted that 20% of their power generation supply ~~is~~ 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 ~~A~~artificial ~~I~~intelligence (AI) (Aman et al., 2014). ~~In~~With regard to the analytical methods, the computation procedures are reduced by making some approximations. ~~Cook (1959) developed A a~~ well-known analytical method for capacitor placement ~~is by (Cook, 1959) who when he~~ proposed ~~that~~ the optimum capacitor placement ~~should~~ ought to be 2/3 of the reactive load factor. However, ~~in certain cases,~~ the application of this "2/3 rule" ~~in certain cases~~ may give negative financial savings (Lee & Grainger, 1981). Heuristic methods are practical methods that are developed by using researchers' intuitions and experiences ~~that~~ which provide a satisfactory solution. ~~Hamouda & Sayah (2013) and Ramalinga Raju et al. (2012). Applications of applied the~~ heuristic method ~~into in relation to~~ reactive power compensators placements ~~are written by (Hamouda & Sayah, 2013; Ramalinga Raju et al., 2012).~~ Numerical programming is an iterative technique ~~that uses~~ using arithmetic mathematical formulations ~~by to maximize or minimize maximizing (or minimizing)~~ an objective function of decision variables which ~~also fulfil,~~ also, a set of constraints. ~~Nojavan et al. (2014) presented A an~~ integer nonlinear programming approach ~~was presented in (Nojavan et al., 2014). Aguiar & Cuervo's (2005) Wwork in (Aguiar & Cuervo, 2005)~~ 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 placement. Reference For example,~~ (Ramadan et al., (2014) developed a fuzzy logic based approach which ~~develops combined~~ two membership functions and ~~Abul'Wafa (2014) author (Abul'Wafa, 2014)~~ combined fuzzy expert system for ~~the placement of the capacitor placement~~ and read coded ~~Genetic A~~algorithm (GA) to calculate ~~the size of the capacitor size.~~ Nonetheless, ~~in using fuzzy logic,~~ the main challenge ~~in using fuzzy logic~~ is to determine ~~accurately~~ the fuzzy membership functions and the fuzzy rule bases ~~accurately.~~ ~~In their papers, Lee et al. (2015) and Zeinalzadeh et al. (2015) implemented the Particle S~~swarm ~~O~~ptimization (PSO) approach ~~was implemented in papers (Lee et al., 2015; Zeinalzadeh et al., 2015).~~ Nevertheless, the reliance of the PSO algorithm on the altering factors and the trapping in modifying parameters' probability can ~~decrease reduce~~ its accuracy and efficacy for various conditions. Other researches ~~in about~~ reactive power placement, ~~which that~~ 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) (Mohamed 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 ~~might may~~ have effectual operation and can handle complicated problems. ~~H~~however, they are more difficult to code and, ~~could~~ potentially ~~can providing provide~~ volatile outcomes in early stage convergence. ~~Even Although~~ AI methods have been validated on the sample systems, nevertheless, the success of these methods ~~rely relies on~~ ~~modifying 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, ~~where this information can be obtained from the Jacobian matrix of the system.~~

This study developed a new analytical method ~~that 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). ~~In~~ Using the modal analysis method, the inversed reduced Jacobian matrix is computed ~~that 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 ~~of about~~ stability. This work offers a simple algorithm and it is simple to implement the method ~~is simple to be implemented~~. The advantages ~~of with~~ 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 ~~of a specific bus in to~~ improving voltage magnitude at critical buses.

## 2. THE PROPOSED METHOD

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

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

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

Where,  $\Delta P$  is the incremental change in bus real power;  $\Delta Q$  is the incremental change in bus reactive power injection;  $\Delta\theta$  is the incremental change in bus voltage angle; and  $\Delta V$  is the incremental change in bus voltage magnitude

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

$$\begin{bmatrix} 0 \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} \quad (2)$$

$$0 = J_{P\theta} \Delta\theta + J_{PV} \Delta V \quad (2)$$

$$\Delta\theta = -J_{PV} \Delta V + J_{P\theta}^{-1} \Delta Q \quad (3)$$

$$\Delta Q = J_{Q\theta} \Delta\theta + J_{QV} \Delta V \quad (3)$$

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

$$\Delta Q = [J_{QV} - J_{Q\theta} J_{P\theta}^{-1} J_{P\theta}] \Delta V \quad (4)$$

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

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

$$\Delta V = J_R^{-1} \Delta Q \quad (5)$$

$J_R^{-1}$  or the inversed reduced Jacobian matrix is a matrix that shows a direct correlation between the bus voltage and the reactive power injection. ~~Assuming- This assumes that the~~

active power is zero and the voltage angle is substituted and, then, that, ~~obtained from 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 ( $\Delta V$ ) 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:

$$\text{RCF}_j = \mathfrak{R}_{1j} + \mathfrak{R}_{2j} + \mathfrak{R}_{3j} + \dots + \mathfrak{R}_{mj} \quad (7)$$

$$\text{RCF}_j = \sum_{i=1}^n \mathfrak{R}_{ij}$$

Where,  $\mathfrak{R}_{ij}$  is the  $i^{\text{th}}$  row and  $j^{\text{th}}$  is the column element of the inversed reduced Jacobian matrix.

RCF informs the contribution of each bus ~~in to~~ improving voltage stability. Furthermore, as the aim of compensator placement is to improve voltage stability, ~~therefore~~ the computation of RCF ~~is focusing~~ focuses only on the effect to the unstable buses. The RCF is calculated ~~at for~~ 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 ~~also~~ positive, also; this which indicates that the system is voltage stable. As the system becomes more stressed, the eigenvalues of  $J_R$  ~~will~~ 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

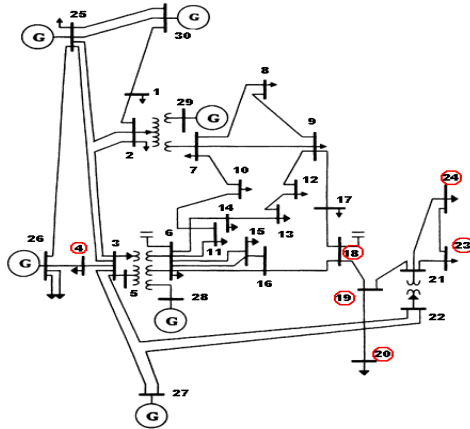
The proposed method's step by step procedure ~~of the proposed method~~ can be explained as follow: *Step 1*: perform power flow program to calculate voltage magnitude at all buses and network losses; *Step 2*: identify critical buses, ~~that and~~ buses with voltage below stability limit 0.95 pu; *Step 3*: perform modified Modal analysis to calculate the RCF from the inversed  $J_R$ . The computed RCF is ~~computed only~~ focuses only on the critical buses. The location of

compensator is chosen based on the highest contribution to ~~improve~~ improving the voltages at critical buses; ~~this which~~ is indicated by the highest RCF; *Step 4*: install reactive power compensation devices with the size of 5 MVar ~~at in~~ the buses with ~~the~~ highest RCF; *Step 5*: perform power flow to compute network losses and evaluate the ~~system's~~ voltage stability ~~of the system~~. The system is considered ~~to be~~ stable if ~~the~~ voltage ~~at in~~ all buses ~~are is~~ between voltage stability limit  $0.95 \leq V \leq 1.05$  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 ~~between~~ within the stability limit, then, assess the robustness of the proposed method by comparing the results with different placements.

### 3. TEST RESULTS AND ANALYSIS

#### 3.1 The test system: The modified IEEE 30-bus Reliability Test System (RTS)

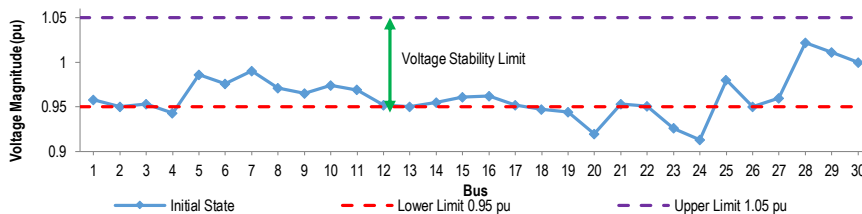
~~In order to~~ conduct a comprehensive test of the above methods, IEEE 30-bus Reliability Test System (RTS) is used. This test system is modified in such a way ~~as~~ to obtain an initial state that allows it to perform testing of the proposed method. Figure 1 shows the test system with new bus numbering.



**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

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

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

$$RCF_j = \mathfrak{R}_{4,j} + \mathfrak{R}_{18,j} + \mathfrak{R}_{19,j} + \mathfrak{R}_{20,j} + \mathfrak{R}_{23,j} + \mathfrak{R}_{24,j}$$

**Table 1: Buses with voltage under stability limit**

Bus	Voltage Magnitude (p.u.)	Bus	Voltage Magnitude (p.u.)
4	0.943	20	0.92
18	0.947	23	0.926
19	0.944	24	0.913

For example, to compute RCF at bus 1:

$$RCF_1 = \mathfrak{R}_{4,1} + \mathfrak{R}_{18,1} + \mathfrak{R}_{19,1} + \mathfrak{R}_{20,1} + \mathfrak{R}_{23,1} + \mathfrak{R}_{24,1}$$

~~Table 2 shows~~ The complete calculation of RCF values for the first iteration ~~for~~ of all load buses ~~are shown in Table 2.~~ 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 ~~for the first iteration.~~

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

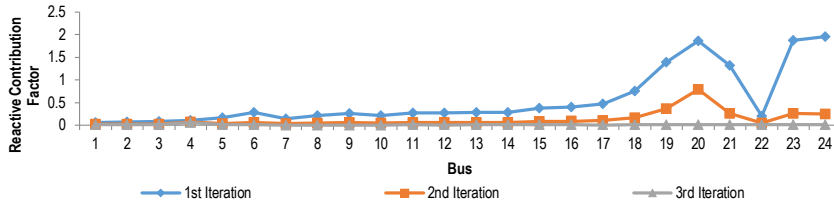
Bus	RCF	Bus	RCF	Bus	RCF	Bus	RCF
1	0.0609	7	0.1461	13	0.283	19	1.3918
2	0.0727	8	0.2079	14	0.2849	20	1.8584
3	0.0867	9	0.2614	15	0.379	21	1.3197
4	0.1025	10	0.2079	16	0.4055	22	0.2
5	0.1606	11	0.266	17	0.4752	23	1.8715
6	0.2881	12	0.2757	18	0.7578	24	<b>1.9542</b>

Figure 3 informs the computation of RCF ~~at~~ for all buses. After the first iteration of power flow, with an injection of 5 MVar, ~~the~~ voltage magnitudes ~~of the~~ ~~at~~ buses around bus 24 improve. The ~~buses'~~ voltages ~~at buses~~ are close to ~~the~~ that of bus 24 such as bus 21's and bus 23's straight increases significantly. However, the voltages ~~of~~ ~~at~~ buses 24, 18, 19 and 20 are still below the stability limit 0.95 pu. ~~Then~~, ~~the~~ reactive compensation injection ~~is~~ still needs to be added and the RCF is calculated again to find the next location for ~~the placement of~~ compensator devices ~~placement~~. In the second iteration, ~~RCF at~~ bus 20's RCF is the highest (Figure 3). With another addition of reactive compensation ~~at~~ to bus 20 of 5 MVar, the system is not ~~yet~~ stable ~~yet~~ ~~and~~, hence, another process of calculating RCF is done ~~again~~ at the third iteration. ~~This~~ ~~and~~ found that bus 4 ~~has~~ ~~had~~ the highest RCF. With ~~bus 4's~~ 5 MVar capacitor ~~at bus 4~~, the system has recovered its stability ~~and~~, hence, the process is stopped. Figure 4 shows the voltage profile improvement, ~~recorded for~~ ~~at~~ each iteration, after ~~the~~ capacitor's placement at the nominated buses. Table 3 informs the detailed ~~of~~ location of ~~the~~ capacitor based on the highest RCF at each iteration.

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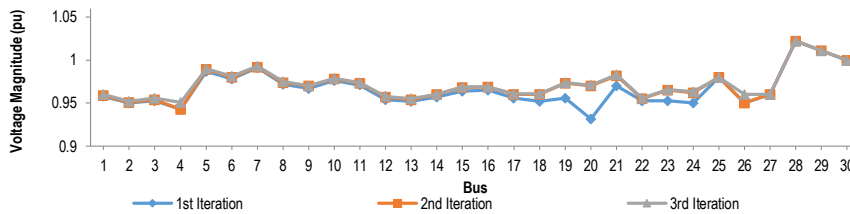
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**Figure 3: Reactive Contribution Factor (RCF) computation iteration process**

**Table 3: Location and size of compensator in each iteration**

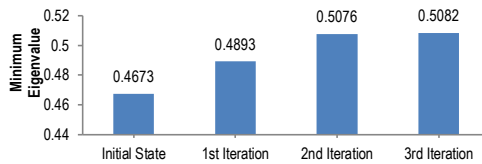
Iteration	Bus	Injected MVar
1	24	5
2	20	5
3	4	5



**Figure 4: Voltage profile improvement at each iteration**

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

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



**Figure 5: Eigenvalue at each iteration**

The system's Active power losses of the system decreased reduced from 23.383 MW to 23.187 MW. While Also, the reactive power is also reduced from 51.362 MVar to 50.002 MVar. Table 4 shows The complete power losses at in each iteration can be seen in Table 4

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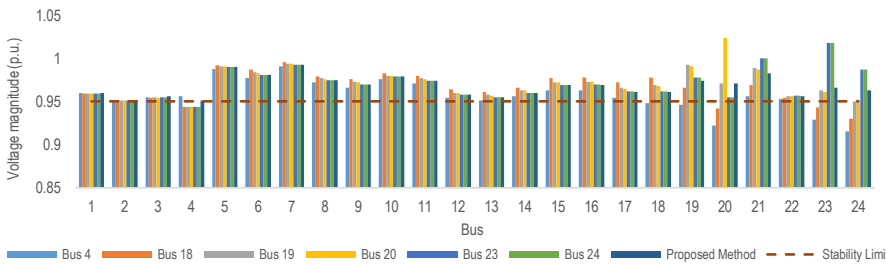
**Table 4: Network Losses in each iteration**

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

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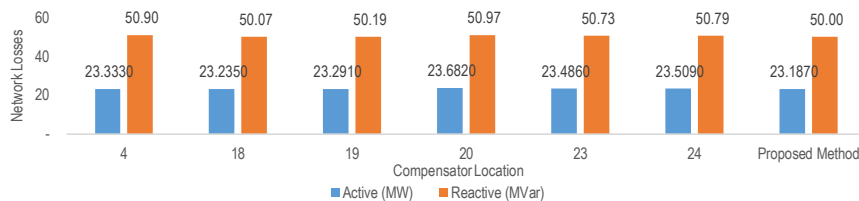
### 3.3 Evaluation of the Proposed Method

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 at 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 at-selected buses and based on the proposed method. In this case, the location of the 15 MVar reactive power injection is at in the critical buses, which are buses 4, 18, 19, 20, 23 or 24. The installation of a 15 MVar reactive power at the in bus 4 leaves many instability it as unstable as the at-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 as 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 is chosen, or 20 or 23 and or 24 is chosen as the injection site, this still leaving leaves bus 4's voltage at bus 4 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**

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Figure 7 informs the comparison of network losses if compensators are placed based on the settings in assessment 1 and proposed method. It clearly 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 is are the smallest. This means that placing compensators at 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**

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#### 4. CONCLUSIONS

This paper presents a new method ~~of for the placement of~~ reactive power compensation devices ~~placement~~ by improving the Modal analysis technique ~~that by~~ utilizing a direct connection between V & Q in the inversed reduced Jacobian matrix. ~~This paper formulated A~~ a new Reactive Contribution Factor (RCF) ~~is formulated in this paper which is~~ computed from the elements of the inversed reduced Jacobian matrix. The RCF informs ~~how big the size of~~ the contribution of a specific bus ~~in from~~ improving the voltage magnitude ~~at in~~ critical buses. The ~~bigger greater~~ a bus' RCF ~~of a bus~~, the ~~bigger greater the that bus'~~ influence ~~of that bus 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 ~~is then was~~ compared ~~then~~ with different compensators of 15 MVar placements. When ~~the stability condition and network losses of the system~~ 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 ~~of the system~~ based on ~~the~~ proposed method, is better than the ~~system's~~ overall voltage profile ~~of the system~~ if 15 MVar is placed ~~at in~~ other buses.

#### 5. ACKNOWLEDGEMENT

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