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Allocation of Reactive Power Compensation Devices to Improve Voltage Profile Using Reactive Participation Index

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Abstract: *This study proposed new method of improving voltage profile utilizing addition of inversed reduced Jacobian matrix elements vertically with the aim of determining location of reactive power compensation installation.This method is tested using actual network in Indonesia. In this analysis, enhancement of power system stability includes of voltage improvement and increase in stability index. By using this proposed method several buses appear as an ideal place for installation of capacitors. The results are also compared to different configuration to validate and demonstrate the effectiveness of the method.*
Keywords – *voltage profile, voltage stability, voltage collapse, modal analysis, steady-state analysis, reactive power compensations, reactive participation index.*

I. INTRODUCTION

Power system stability has been considered as a main requisitefor a safe and trustworthy process in a power system for over ninety years[1-3]. Voltage stability is a common problem that occurs anywhere in the world.Nowadays, electrical systems are thoroughly stressed and running at the stability limit with smaller capacity and margin [4] hence may cause congestion problems [5, 6]. This occurs due to the small and large disturbances that affect the stability of operation.In addition, increasein active and reactive power also contributes to the decrease in the voltage. Voltage dropdue to uncontrolled reactive power can lead the system to collapse.

As the system are getting stressed,it is necessary for an evaluation of the weak point where potential instability occurs, so that preventive action can be taken earlier and to avoid cascading failures. As it is well known, that voltage problem has resilient relation with reactive power injections. To find out the weak points in a system, there are several algorithms in the growing literature. One of the advanced method developed is Modal Analysis by [7]. In this technique,relationship between voltage (V) and reactive power (Q) is used to exploit the most contributed bus to system instability.The system is voltage stable, if the injection of reactive power increases and at the same time voltage magnitude also increases. The system is voltage unstable if at the same time reactive power increased and the voltage magnitude decreases[7, 8].

To overcome the voltage drop as described above, it is required compensation equipment to maintain the voltage magnitude remains at the desired level. There are many type of reactive compensation devices, such as: capacitor banks, static Var compensator (SVC) or static compensator (STATCOM). These reactive compensation devices have imperative function in improving voltage stability. Capacitor banks is one of the foremost and commonly used reactive compensators equipment. Capacitors have a very important role in the power system network because apart from being usedas reactive power compensation device, it can help to increase active power delivery and reduce transmission losses[9-15], therefore overall it can improve voltage profile of the system. However, installation of capacitor banks should be at the right buses so it can perform effectively.

Various methods have been developed for placement of capacitor. References [16, 17] create Loss Sensitivity Factor to find capacitor placement location. Artificial bee colony algorithm is applied for capacitor allocation in [18]. Paper [19] designs two-stage approach using fuzzy logic and bat algorithm to determine location and size of capacitor. Authors in[20] propose opposition based differential evolution algorithm for reconfiguration and capacitor placement. However, these works only focus on the network losses reduction. In [21], fast decoupled method was employed to determine size for capacitor, but this work only assesses the voltage improvement, not the network losses. Nonetheless, the appropriate location and size of capacitor can reduce both network losses as well as enhance voltage stability.

It is essential to develop an effective method that able to confirm both voltage stability of the system and location to improve the stability.This study enhances modal analysis technique for the effective placement of capacitor banks. Modal analysis is an analytic solutions approach that can give information about the voltage stability in a complex power system. In this work, the element of inversed reduced Jacobian matrix is added vertically to compute Reactive Participation Index (RPI). RPI informs about participation of a specific bus in improving voltage magnitude at critical buses based on its reactive power injection. The bus with the biggest RPI has the biggest influence in enhancing voltage profile after injected reactive power hence it is chosen as the location of capacitor banks placement. This method is simple but accurate and do not need complicated computational processes.

This paper consist of five parts. Part 1 is introduction, Part 2 isthe breakdown of modal analysis approach and development of participation factor, Part 3describes method proposed, Part 4 informs about the South Sulawesi interconnected system in Indonesia as the case study, Part 5 presentsresearch data, results analysis, and validation,Part 6 is the final conclusion and closing of this research.

II. BREAKDOWN OF MODAL ANALYSIS APPROACH TO COMPUTE REACTIVE PARTICIPATION INDEX (RPI)

To evaluate the system stability, it often requires extensive and in-depth examination of the condition of the system. Therefore linearized steady state analysis is used to see the problems that exist on the voltage and reactive power.

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

Where :
ΔP = Incremental change in bus real power
ΔQ = Incremental change in bus reactive power injection
$\Delta\theta$ = Incremental change in bus voltage angle
ΔV = Incremental change in bus voltage magnitude

The stability of the power system is influenced by P & Q factors. However, for voltage stability analysis purpose, it is necessary to note relationship between V and Q. For that purpose P is considered constant at all node, hence change of active power is considered 0 (zero), hence,

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

Then obtained,

$$\Delta Q = \left[J_{QV} - J_{Q\theta} {J_{P\theta}}^{-1} J_{P\theta} \right] \Delta V \tag{2}$$

Then,

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

$$\Delta V = {J_R}^{-1} \, \Delta Q \tag{3}$$

Where,

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

J_R is the reduced Jacobian matrix. This matrix make a discern between ΔP,ΔQ and ΔV so it is easier to perform voltage stability analysis.This approach computationally efficient rather than performing full Jacobian matrix. This J_R demonstrate direct relationship between reactive power injection and voltage magnitude for each buses. Each buses which most contributed to the voltage instability can be obtained by extracting reactive participation index from J_R^{-1}. To see voltage changes on each buses, equation 3 is formed in matrix, hence,

$$\begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \vdots \\ \Delta V_m \end{bmatrix} = \begin{bmatrix} \wp_{11} & \wp_{12} & \cdots & \wp_{1n} \\ \wp_{21} & \wp_{22} & \cdots & \wp_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \wp_{m1} & \wp_{m2} & \cdots & \wp_{mn} \end{bmatrix}^{-1} \begin{bmatrix} \Delta Q_1 \\ \Delta Q_2 \\ \vdots \\ \Delta Q_m \end{bmatrix} \tag{4}$$

To obtain the best location among weak buses then elements of inversed J_R are summed up vertically. The highest reactive participation index is ideal for capacitor placement. Every voltage changes in each buses depend on multiplication between elements of inversed J_R and ΔQ. Reactive participation index (RPI) can be used to determine which buses is the most ideal for capacitor placement, which is formulated as,

$$\frac{\begin{matrix} \wp_{11} & \wp_{12} & \cdots & \wp_{1n} \\ \wp_{21} & \wp_{22} & \cdots & \wp_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \wp_{m1} & \wp_{m2} & \cdots & \wp_{mn} \end{matrix}}{\begin{matrix} RPI_1 & RPI_2 & \cdots & RPI_n \end{matrix}} + \quad (5)$$

Eigenvalue of reduced Jacobianmatrix is used to portray how close the system to instability. As the system becomes more stressed, eigenvalue will become smaller.The smaller the eigenvalue is, the closer the system to instability. When minimum eigenvalue is equal to zero, then system is collapse since it undergoes infinite changes for reactive power changes. The formula for eigenvalue is as follow:

$$\lambda = \text{Eigen}\ [J_R] \quad (6)$$

III. PROPOSED METHOD FOR FINDING IDEAL BUSES

Figure 1 shows the flowchart of the proposed method. To perform this research new method is developed using new technique of finding ideal buses for capacitor placement as described in Part II.

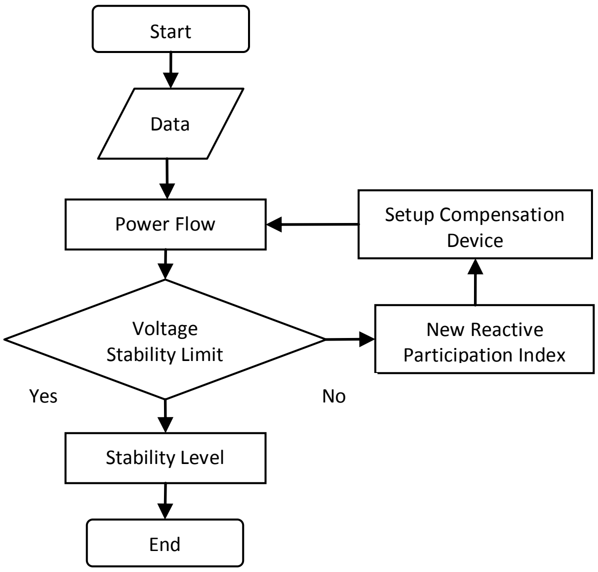

Figure 1. Flowchart of reactive participation index method for placement of capacitors

Figure 1 shows process of improving voltage profile of the system. When all of the area of the system is 0.95<V<1.05 pu, then the process is stop. Stability of system is measure by extracting eigenvalue.

IV. THE TEST SYSTEM: THE SOUTH SULAWESI SYSTEM IN INDONESIA

The proposed method is simulated at a real large power system in Indonesia, the South Sulawesi System. This section gives a brief review on the case study system.

South Sulawesi is located in the center of Indonesia and it is an interconnected system comprises of many different power generations which are associated by transmission lines of 150 kV, 70 kV and 30 kV. This system has unique attribute where the main cost-effective power generation centers are located in the northern part of the system, whereas the predominant load center is located in the southern part. Figure 2 shows the interconnected system of South Sulawesi. The total power generations in the northern part of the system is around 559 MW with details as follow [22] :

- Bakaru hydro power plant (PLTA Bakaru) 127.7 MW
- Suppa diesel power plant (PLTD Suppa) 62.2 MW
- Sengkang steam and gas power plant (PLTGU Sengkang) 320 MW
- Barru steam power plant (PLTU Barru) 50 MW

Whereas total generation in the southern part is 444 MW from:

- Tello power plants (gas, steam and diesel) 169 MW
- BiliBili hydro power plant 20 MW
- Sewatama diesel power plant 15 MW

- Jeneponto steam power plant 240 MW

with total load of the system is around 860 MW.

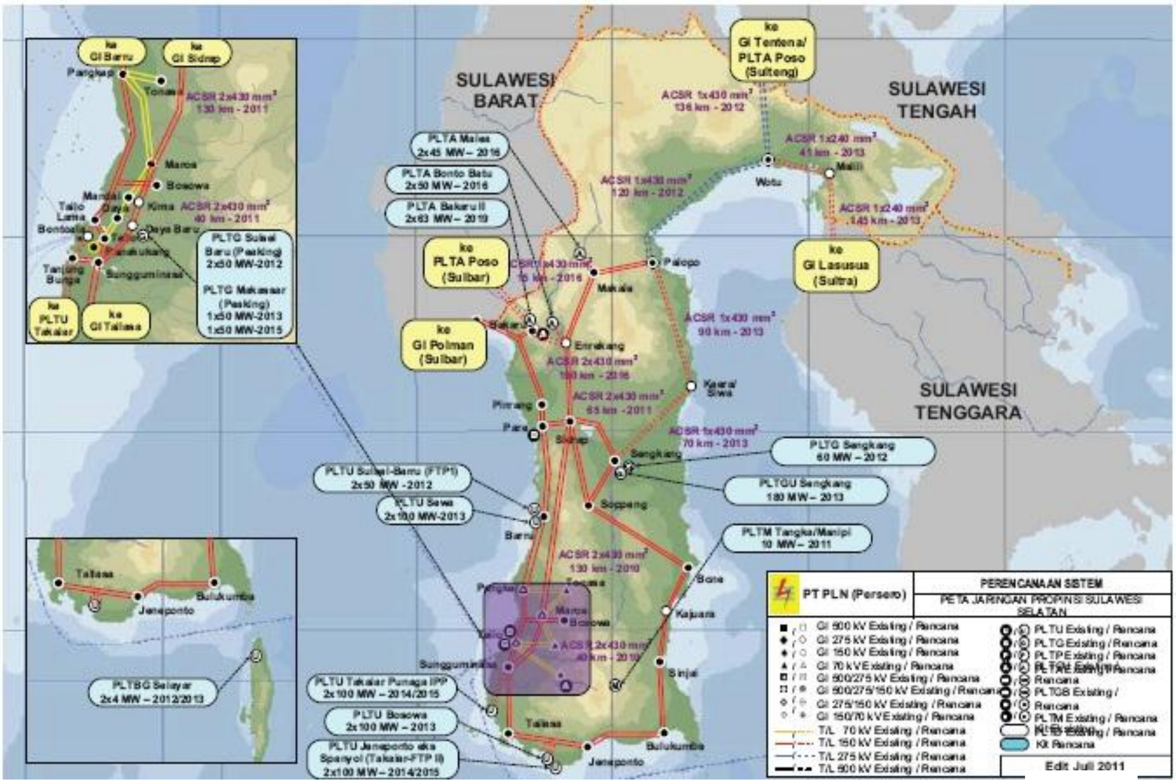

Figure 2. The South Sulawesi interconnected power system, Indonesia [23]

V. RESULTS AND ANALYSIS

The simulation uses data from the Indonesian state electricity company (PT. PLN) as of 11 November 2014). Figure 3 shows initial voltage profile condition of the system. There are several under voltage stability buses which potentially lead the system to voltage collapse. Table 1 below shows the unstable buses with their voltages.

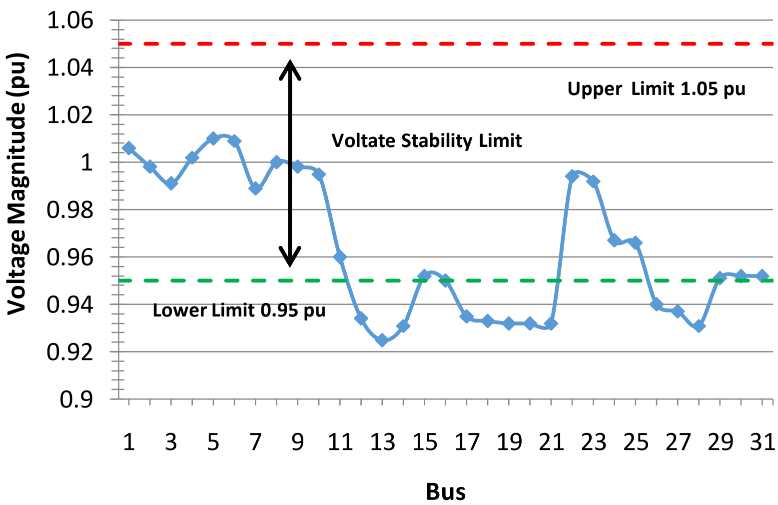

Figure 3. Voltage profile of Sulsel system at peakload [23]

Table 1. Under voltage buses

Buses /Substations	Voltage Magnitude (pu)
12/Pangkep(150)	0.934
13/Bosowa	0.925
14/Kima	0.931
17/Mandai	0.935
18/Daya	0.933
19/Tello(150)	0.932
20/Tello(70)	0.932
21/Tallo Lama(150)	0.932
26/Tallo Lama(70)	0.94
27/TanjungBunga	0.937
28/Panakkukang	0.931

In order to find ideal buses for capacitor banks then the reactive participation index (RPI) at all load buses are calculated. At the first iteration, bus 14 (Kima) has the highest RPI, hence this bus is selected as the location for reactive power injection. For the first time, the injection is 10 MVar and this is repeated until the highest value of RPI changes to other bus. For optimal size of capacitors found for bus 14 (Kima) is 80 MVar. Then at the next process, bus 13 (Bosowa) has the biggest RPI, and chosen as location for the second reactive power injection. The optimal size for capacitors at this bus is 50 MVar. Figure 4 shows the RPI value for every steps in determining location for reactive power injection, which is concluded in Table 2. There are totally of 210 MVar reactive compensation injections needed to bring the system back to the stability limit. Figure 5 shows the voltage profile of the system before and after capacitor banks placement. All voltage at all buses are between the stability limit. Network losses around 24.251 MW and reactive losses 29.869 MW.

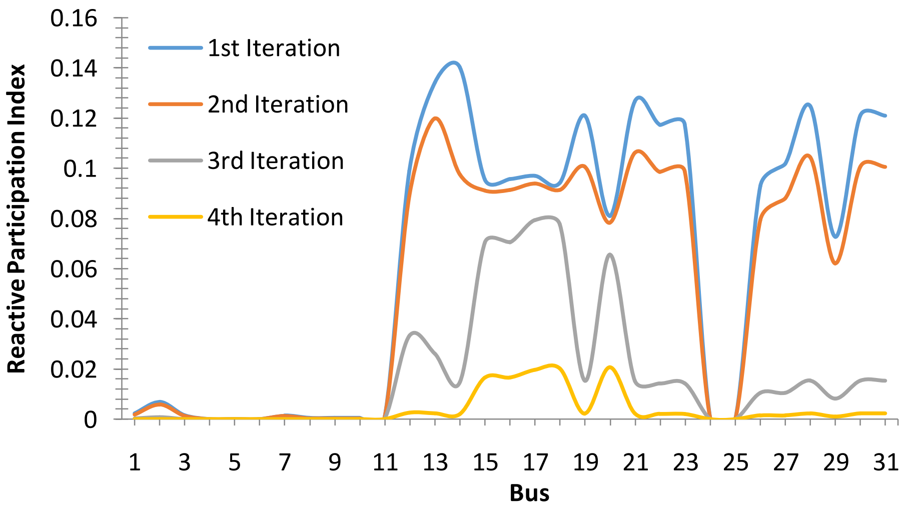

Figure 4. Reactive Participation Index of each load buses

Table 2. Buses, Size and Number of Capacitor based on proposed method

Bus No.	Substations	Injected MVar
13	Bosowa	50
14	Kima	80
17	Mandai	60
20	Tello	20
	Total	210

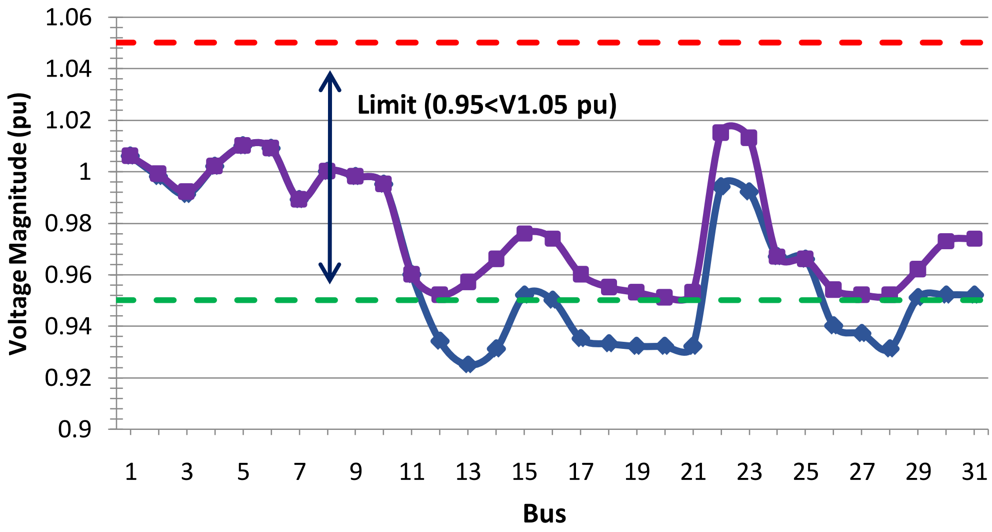

Figure 5. Voltage profile shows an improvement after capacitor installation

Figure 6 and 7 show the increase of eigenvalue for every iterations and comparison of eigenvalue before and after reactive power injection, respectively. As can be seen in Figure 6, there is an improvement in stability in every iteration. Eigenvalue increases from 1.7379 to 1.753. Eigenvalue at initial state 1.7096 and potentially increase to 1.753 if 210 MVar of capacitor banks are injected to the system. This informs that the system is more stable after the injection of reactive power.

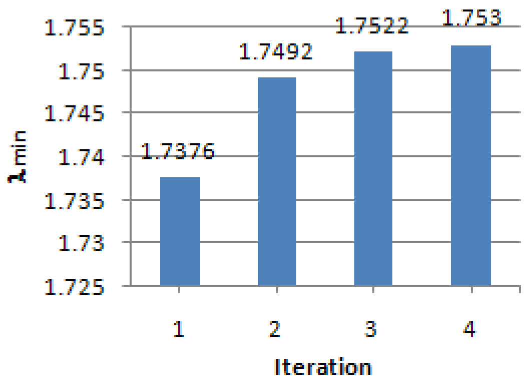

Figure 6. Increase eigenvalue in each iteration

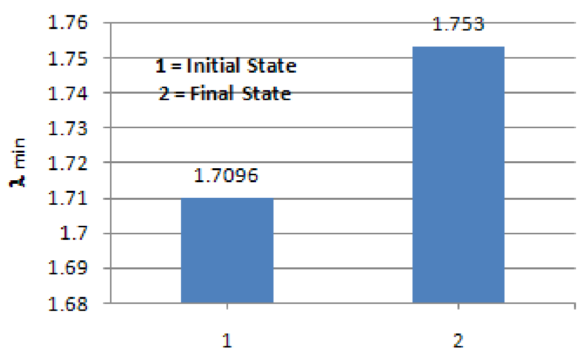

Figure 7. Eigenvalue of initial and proposed capacitor installation

To evaluatethe robustness of proposed method above, this results are compared using 3 different configurations. 1st configuration using same capacity of capacitor but divided by 4 evenly at all buses with high RPI which is as shown below,

Table 3. Placement and size of MVar injection for 1st configuration

Bus No.	Injected Mvar
Bus 13	52.5
Bus 14	52.5
Bus 17	52.5
Bus 20	52.5
Total	210

Figure 8 shows the voltage profile of the system after the injection of capacitors based on Table 3. Eventhough with the same total injection of 210 MVar, but there are still several buses with under voltage condition. Buses 21, 27 and 28 are still under stability limit (<0.95 pu) and minimum eigenvalue is achieved only 1.7453. This configuration generate losses of active power around 24.756 MW and reactive power 30.827 MVar. This means dividing the MVar injection into 4 equal size is no better than the proposed method which is present lower nework losses

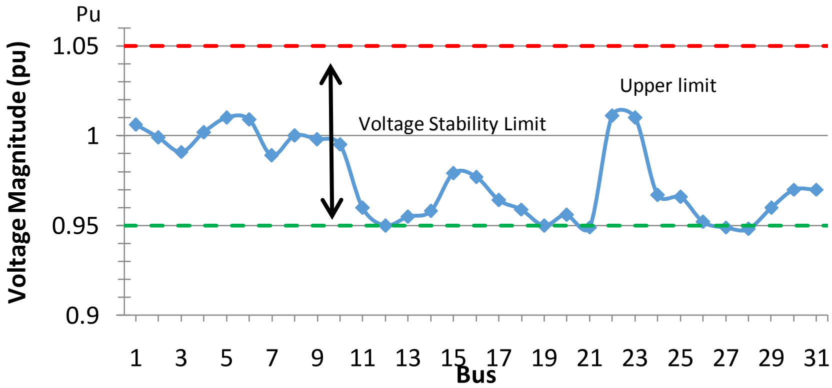

Figure 8. Voltage profile of 1st configuration

2nd configuration using same size of capacitor, but total 210 MVar are injected at one single bus. In this configuration, the simulations are done by injecting 210 MVar at each of these buses: 13, 14, 17, and 20 separetely, and test is performed one by one. Figure 9 shows voltage profile of the system if 210 MVar capacitor installed. None of the voltage profile based on these placement meet voltage stability required for the system. Table 4 presents the eigenvalue and network losses of 2nd configuration. The lowest losses can be achieved in this configuration is installation at bus 14 but still higher than proposed method.

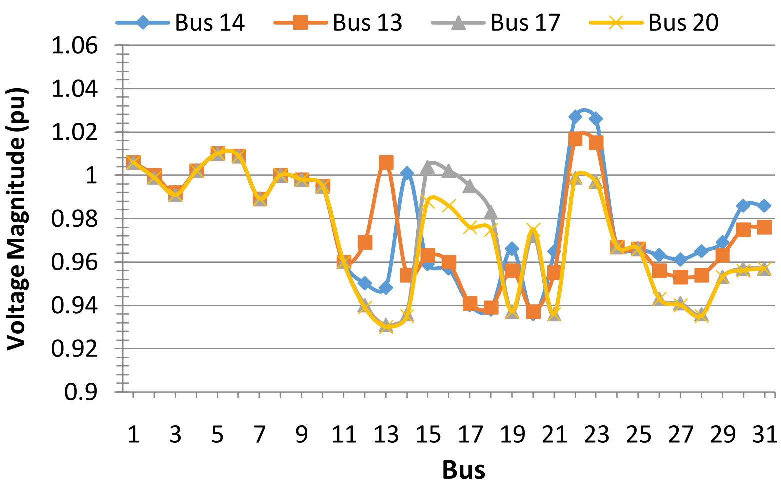

Figure 9. Voltage profile 2nd configuration.

Table 4. Eigenvalue and network losses 2nd configuration

Bus No.	Eigenvalue	Network Losses	
		MW	MVar
14	1.7791	24.366	34.009
13	1.7562	24.869	34.967
17	1.7193	31.417	47.117
20	1.7184	28.876	41.766

3rd Configuration using buses with small RPI of the proposed method and using the same size of capacitors. Bus 1, 4, 6 and 9 are chosen, since they have small RPI. Each of them are injected 52.5 MVar. Figure 10 shows the voltage profile of the South Sulawesi system after the injection of capacitors based on 3rd configuration. As can be seen, misplacement of capacitor injection can also increase voltage higher than 1.05 pu, which cause over voltages. Improper placement of these capacitor can lead system out of voltage stability limit which degrade system quality. Eigenvalue obtained is 1.7099. Losses of active power and reactive power are 23.021 MW and 32.687 MVar, respectively. This configuration generate higher reactive power losses and lower stability than proposed method.

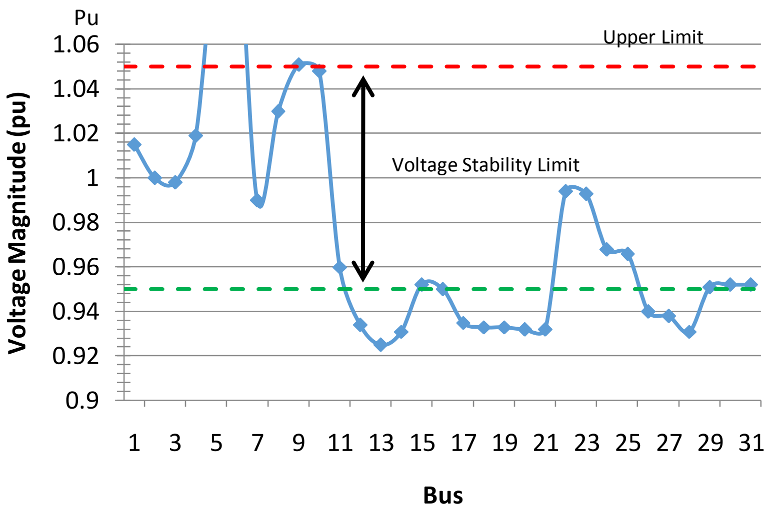

Figure 10. Voltage profile of 3rd configuration

VI. CONCLUSIONS

Conclusions that can be taken from this research are:

1. Based on simulation results, before capacitors installation at peak load, some areas are under voltage and this condition potentially interfere system stability. These bus are buses 12 13, 14, 17, 18, 19, 20, 21, 26, 27 and 28. 4 Based on proposed method bus 14, 13, 17 and 20 are the best buses for reactive power injection.
2. By using reactive participation index, it is successfully choose the right buses for capacitors placement to improve voltage profile compared to 3 other configurations.
3. Method used in this paper demonstrates its strength to overcome problem in voltage stability. By using the method, voltage profile improved with minimum injection of capacitor in size and number. Voltage profile is align in 0.95<V<1.05 pu.

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