Determination of VAR Compensator Placement for System Stability Improvement on Java Bali Network

A E Apriyanto\textsuperscript{1,5}, A R Virgiawan\textsuperscript{1}, H Pariaman\textsuperscript{1,2}, M Hisjam\textsuperscript{3}, N Hariyanto\textsuperscript{4}

\textsuperscript{1} Power Generation Engineering Department, PT. Pembangkitan Jawa Bali, Surabaya, Indonesia  
\textsuperscript{2} Institut Teknologi PLN, Jakarta, Indonesia  
\textsuperscript{3} Department of Industrial Engineering, Faculty of Engineering, Universitas Sebelas Maret, Surakarta, Indonesia  
\textsuperscript{4} School of Electrical Engineering and Informatics, Institut Teknologi Bandung, Bandung, Indonesia  
\textsuperscript{1} Corresponding author Email address : adhie.eko@ptpjb.com

Abstract. Quality of a power system network can be evaluated from its voltage performance. There are several bus/substation of Java Bali networks that frequently operate in unsatisfied voltage level. As an important part of Indonesian electricity system, quality improvement of this network should be sustainably maintained. The occurring problem can be solved by reactive power compensation. Compensation can be done by installing reactive power compensator into the network. To get an optimal improvement level of voltage performance, the installation location of reactive power compensator must be carefully selected. The selection process can be done by consider the operating voltage, bus sensitivity factor, power angle sensitivity factor and geographic location factor on each location in the network. With consideration of these parameters then the optimal location and configuration of the reactive power compensator can be obtained.

1. Introduction
Java Bali power system consists of many 500kV extra high voltage substations and 150 kV substations. Java Bali network transmission system interconnected at 500 kV, Java Bali transmission system interconnected via north and south path with loop configuration. The main substation that supports this power transfer is Ngimbang substation - Ungaran substation – Mandirancan substation - South Bandung substation for north line and for south line is Kediri substation – Pedan substation – Kesugihan substation – Tasikmalaya substation – Depok substation. During peak load, undervoltage problem often occur in the Jakarta and West Java because this location is center of the load of the Java-Bali Systems. Meanwhile, power generation with large capacity is on East Java so that occur large transfer of power flow from East Java to West Java.

Undervoltage disturbances in West Java can reach 0.89 per unit and overvoltage disturbances up to 1.05 per unit, where the grid code standard for Java-Bali, the minimum voltage allowed is 0.9 per unit and the maximum is 1.05 per unit.
Voltage stability is a critical issue in power system planning. Voltage stability is defined as ability of power system to sustain fixed tolerable voltage at every single bus of the network under standard operating conditions as well as after being subjected to a disruption, corresponding to the balance of reactive power [1] and [2]. If the reactive power supply setting is not done properly, it can cause voltage instability in the power system. One of the solution to avoid voltage instability is using VAR compensator installation.

VAR compensator is electrical power device/equipment used to compensate for changes reactive power in the event of fault. If the system voltage is high, the VAR compensator will absorb reactive power, while if the system voltage is low, the VAR compensator will supply reactive power. Passive VAR compensator includes shunt reactor and shunt capacitor. Active VAR compensator includes Static VAR Compensator (SVC) and Static Synchronous Compensator (STATCOM).

Many researchers have been done a research about methods of shunt VAR compensator placement. [3] divides the methods into three categories: conventional method, heuristic method, and sensitivity-based method. Sensitivity-based methods use index, modal, or eigenvalue analysis. [4] use genetic algorithm based method to determine SVC placement. [5] use novel global harmony search algorithm to optimize allocation of SVC. [6] use cuckoo search algorithm and [7] use BAT and firefly algorithm to optimize sizing and placement of SVC. [8] use particle swarm optimization method and [9] use cluster identification to optimize allocation of SVC. [10] use dragonfly algorithm, [11] use heuristic optimization method, and [12] use hybrid GA-PSO algorithm to optimize SVC placement. [13,14,15,16,17] use sensitivity approach to determine SVC and STATCOM placement. This paper propose a new optimization technique, referred to sensitivity approach (voltage sensitivity factor and power angle sensitivity factor) with geographic location factor to determine sizing and placement of VAR compensator. This method will be tested on the Java-Benz network transmission system with simulation on DLgSilent software.

2. Literature Review

2.1. Voltage Sensitivity Factor

Based on Newton-Raphson method for load flow analysis. The following formula is obtained:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial Q} \\ \frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial Q} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix}$$

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PQ} \\ J_{Q\theta} & J_{QQ} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix}$$

Where J is Jacobian matrix.

With linearization, the equation can be written as

$$\begin{bmatrix} J_{P\theta} & J_{PQ} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix} = \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}$$

To obtain, for example $\partial v/\partial Q$, assuming $\Delta P=0$:

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

$$\Delta \theta = -\frac{J_{PV}}{J_{P\theta}} \Delta V$$

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

Substituting equation (5) to (6):

$$\Delta Q = \left(-J_{Q\theta} \frac{J_{PV}}{J_{P\theta}} + J_{QV}\right) \Delta V$$
The magnitude of the voltage sensitivity factor will be used to determine the location of the reactive power compensator. Voltage sensitivity can also be used as an indication of system stability. A high voltage sensitivity value means that a small injection of reactive power can cause large changes in the value of the voltage level.

2.2. Power Angle Sensitivity Factor

Load flow sensitivity analysis is used to obtain power angle sensitivity by assuming $\Delta Q=0$ in equation (3). The influence of active power injection at buses is showed by power angle sensitivity that contribute to overall angle changes. Buses with high power angle sensitivity will be located around maximum transfer capability on $\delta$-$P$ curve.

![Figure 1. Operating point with high angle sensitivity on $\delta$-$P$ curve](image)

Figure 2 represent the use of angle sensitivity index to differentiate the placement of SVC and STATCOM could be explained by using rotor angle stability. Curve B of the $\delta$-$P$ curve represent power transfer between two buses when subjected to fault. The maximum electrical power transfer between the two buses can be lowered because the $\delta$-$P$ curve changes from curve A to curve B due to increasing impedance between two buses during fault. The $\delta$-$P$ curve change from curve B to curve C after the fault is solve (post-fault). Curve C is lower than curve A because of larger impedance between the two buses.

![Figure 2. Simplified model of system representation (a) and its $\delta$-$P$ curve (b): pre-fault (curve A), under fault (curve B), and post-fault (curve C)](image)

Assume that $P_m$ is the power to be transferred. Point O is the initial condition. On curve B ($\delta$-$P$ curve under fault), the point moves to O’ if fault occurs in the system. The angle increase to m’ because point O’ is located below $P_m$. On curve C (post-fault $\delta$-$P$ curve), the point move to m after the
fault is isolated. There are two important areas; area A1 and area A2. Kinetic energy that was produced during fault represented by Area 1 and potential energy that can absorb the kinetic energy represented by area A2. The system will become unstable as the excess kinetic energy will accelerate the turbine further from its nominal frequency, if area A1 is larger than area A2. The important parameter in fault isolation to keep system stable after subjected to fault is critical clearing time which means maximum time allowed to isolate the fault. Area A1 will be equal to area A2 when the fault is isolated at the critical clearing time. The system become unstable if isolating fault is done after critical clearing time.

System voltage will drop during fault. The closer fault location to a point, the voltage at that point will getting closer to zero. To raise the voltage and resulting smaller area A1, shunt compensator can be used.

2.3. SVC and STATCOM

2.3.1. Static VAR Compensator (SVC)
Static VAR Compensator is one of the first generation of FACTS and is now widely used in electric power systems. SVC is a reactive power compensator that can absorb and supply reactive power to the system. SVC consists of thyristor-switched capacitor (TSC), thyristor controlled reactor (TCR), and harmonic filter. Usually SVC is also added mechanically switched capacitors (MSC) for certain cases. The SVC model can be seen in Figure 3.

![Figure 3. SVC model](image-url)
The capacity of reactive power that can be supplied or absorbed by the SVC is very dependent on the voltage. If the voltage is very low, the SVC can only supply less of reactive power. SVC is usually considered as a constant impedance so that when the voltage drops, the current also decreases so that the reactive power also falls.

2.3.2. Static Synchronous Compensator (STATCOM)
A STATCOM is a voltage source converter (VSC)-based device, with the voltage source behind a reactor. The voltage source is created from a DC capacitor and therefore a STATCOM has very little active power capability. However, its active power capability can be increased if a suitable energy storage device is connected across the DC capacitor. The reactive power at the terminals of the STATCOM depends on the amplitude of the voltage source.

![Figure 4. Curve V-I SVC](image)

![Figure 5. Model STATCOM](image)
3. Methodology

3.1. Bus candidate selection with scoring

To determine the location of VAR compensator placement, several scores are used. The score are voltage score, voltage sensitivity score, and power angle sensitivity score.

3.1.1. Voltage score [17]

To assess the level of voltage problem of each bus, voltage index as formulated below is used.

\[
V_{\text{Score},x} = \begin{cases} 
1 - \frac{V_{\min} - V_x}{V_{\max} - V_{\min}}, & V_x > 1 \\
1 - \frac{V_{\max} - V_x}{1 - V_{\min}}, & V_x \leq 1 
\end{cases}
\]  

(8)

Using the index, it can address the severity of voltage problem at each bus. The more severe voltage problem at bus, the voltage index at that bus is higher. It happened for both undervoltage and overvoltage problems. The index will give score more than 1, when voltage level in a bus break the threshold value.

3.1.2. Voltage sensitivity score [17]

Based on equation (7), voltage sensitivity score as shown below is used:

\[
d\frac{V}{dQ_{\text{Score},x}} = \frac{d\frac{V}{dQ_x} - d\frac{V}{dQ_{\min}}}{d\frac{V}{dQ_{\max}} - d\frac{V}{dQ_{\min}}}
\]  

(10)

\[
d\frac{V}{dQ_{\text{average},x}} = \frac{\sum_{i=1}^{n} d\frac{V}{dQ_{\text{Score},i}}}{n}
\]  

(11)

Where

\[
d\frac{V}{dQ_x} = \text{voltage sensitivity at bus } x
\]
The highest voltage sensitivity of the buses in the system is given by $dV/dQ_{\text{max}}$, while the lowest voltage sensitivity is given by $dV/dQ_{\text{min}}$. A score for voltage sensitivity will give a value between 0-1, with score 0 indicating the bus with the lowest voltage sensitivity factor in the system, and score 1 indicating the bus with the highest voltage sensitivity factor.

### 3.1.3. Power angle sensitivity score [17]

Power angle sensitivity factor is defined as follows:

$$
\frac{d\delta}{dP_{\text{score bus } x}} = \frac{d\delta/dP_x - d\delta/dP_{\text{min}}}{d\delta/dP_{\text{max}} - d\delta/dP_{\text{min}}}
$$

(12)

$$
\frac{d\delta}{dP_{\text{score range-range}}} = \frac{\Sigma x d\delta/dP_{\text{score bus } x}}{n}
$$

(13)

Where:

- $d\delta/dP_x$ = power angle sensitivity at bus $x$
- $d\delta/dP_{\text{max}}$ = the highest power angle sensitivity of the buses in the system
- $d\delta/dP_{\text{min}}$ = the lowest power angle sensitivity of the buses in the system

### 3.1.4. Geographic location factor

Geographical location factor is a method to optimize location selection based on geographic location. This factor is used because the reactive power injection is local, meaning it only affects substations that are close to the location where the VAR compensator is installed. If, at the time of determining the candidate bus, it is found that two or more highest scores are in close range based on geographical location, then the substation with the highest score is selected.

### 3.2. Determine bus candidate

In this paper, 4 operating system scenarios were used to obtain accurate results. The four scenarios are wet season and peak load (scenario A), wet season and light load (scenario B), dry season and peak load (scenario C), and dry season and light load (scenario D). For each of the above scenarios, different generating and loading data were used.

SVC and STATCOM can drain or inject reactive power into the system depending on the condition of the system, which means that SVC and STATCOM can operate in any condition. Based on the voltage index and voltage sensitivity index, and addition of angle sensitivity index, the bus candidate for SVC and STATCOM placement is chosen. Figure 5 illustrates the selection.
Voltage score
Voltage sensitivity score
Angle sensitivity score

Figure 7. Selection of SVC and STATCOM (a): SVC (yellow) and STATCOM (green); placements of SVC and STATCOM (b): best locations for SVC and STATCOM placement are buses indicated by green area.

At the figure 7(a), bus candidates for STATCOM are represented by green area, while bus candidates for SVC are represented by yellow area. Figure 7(b) represent the placement of SVC or STATCOM. The best bus candidates for SVC and STATCOM placement are represented by green area. Yellow and blue area represent additional bus that can be installed SVC and STATCOM, if bus with VAR compensator in green area is not enough to improve system voltage.

Based on the load flow simulation results will be obtained the voltage score, voltage sensitivity score and angle sensitivity score in the 4 scenarios above. Then from this score, the top 10 buses with the highest score will be selected. From that 10 bus candidates will be eliminated using the geographical location factor, so that several buses were selected to be installed with SVC or STATCOM. After being selected, 3 test will be carried out, that is critical clearing time and PV curve.

4. Result

4.1. Candidate bus location of SVC and STATCOM

In the Java Bali transmission system this allowed working voltage limitation is between 0.9 per unit up to 1.05 per unit. Using scoring result of the indexes, SVC and STATCOM locations are obtained as shown in table below. There are 5 SVCs and 6 STATCOMs needed to be installed in Java Bali system.

| Substasion       | Grid          | Capacity (MVA) |
|------------------|---------------|----------------|
| Ampra            | Bali          | 25             |
| CSW              | Region 1      | 100            |
| Maximangando     | Region 1      | 100            |
| Rancacek         | Region 2      | 50             |
| Cepu             | Region 3      | 25             |
| Wlingi           | Region 4      | 50             |

| Substasion   | Grid          | Capacity (L/-C) Mvar |
|--------------|---------------|----------------------|
| Dukuh Atas   | Region 1      | 50/-50               |
| Lengkong     | Region 1      | 50/-50               |
| Cianjur      | Region 2      | 25/-25               |
4.2. Testing of SVC and STATCOM Installation

4.2.1. Critical clearing time with disturbance at 50% lines
By installing SVC and STATCOM, critical clearing time of buses in the system increase, thus improving system stability. The result are shown in table 3 below.

Table 3. Critical Clearing Time Comparison of Several Lines in Java Bali Power System, With and Without Installation of SVC and STATCOM

| Line Transmission     | Critical Clearing Time (second) | Without SVC STATCOM | With SVC STATCOM |
|-----------------------|--------------------------------|---------------------|------------------|
| BRINGIN-JELOK1        | 0.577                          | 0.587               |
| BRINGIN-JELOK2        | 0.577                          | 0.587               |
| BWNGI-T KTP-1         | 0.3543                         | 0.369               |
| BWNGI-T KTP-3         | 0.3543                         | 0.369               |
| CIBNG-CLGSI 1         | 0.664                          | 1                   |
| CIBNG-CLGSI 2         | 0.664                          | 1                   |
| CWANG-DEPOK 1         | 0.727                          | 1                   |
| CWANG-DEPOK 2         | 0.727                          | 1                   |
| GNDL-PTKNG 1          | 0.8644                         | 0.896               |
| GNDL-PTKNG 2          | 0.8644                         | 0.896               |
| JAWA-BALI 1           | 0.3246                         | 0.332               |
| JAWA-Bali 2           | 0.3246                         | 0.332               |
| KRAPYAK-RANDUGARUT1   | 0.5102                         | 0.518               |
| KRAPYAK-RANDUGARUT2   | 0.5102                         | 0.518               |
| PTKNG-BNTRO           | 0.6066                         | 0.621               |
| SBBRT-DRYJO           | 0.4137                         | 0.421               |
| SKLNG-BLBN 1          | 0.821                          | 1                   |
| SKLNG-BLBN 2          | 0.821                          | 1                   |
| WARU-RNKUT 1          | 0.4063                         | 0.414               |
| WARU-RNKUT 2          | 0.4063                         | 0.414               |

4.2.2. PV Curve
The P-V curve test is to determine the critical point of a bus where the bus has collapsed. The result are shown in figure 8 below.
In the picture above, it can be seen that the comparison of the P-V curve before (red) and after (green) the SVC STATCOM installation, it has shift at the voltage collapse point. With this shifting point, the maximum power that can be transfer is increased.

5. Conclusion
The use of sensitivity methods for determining SVC and STATCOM laying locations provides good results. The parameters used are voltage, bus sensitivity, and power angle sensitivity also geographic location factor. In Java Bali system required installation of STATCOM on Ampra Substation (Bali), CSW Substation and Maximangando Substation (region 1), Rancaekek Substation (region 2), Cepu Substation (region 3), and Wlingi Substation (region 4). SVC installation on Upper Dukuh Atas Substation and Lengkong Substation (region1), Cianjur Substation (region 2), Ngoro Substation and Sumenep Substation (region 4). Based on running critical clearing time, after installation of SVC and STATCOM gives higher results.

References
[1] Prabha Kundur 1994 Power System Stability and Control (United States of America: McGraw-Hill Education)
[2] Taylor Carson W 1994 Power System Voltage Stability (United States of America: McGraw-Hill Education)
[3] Zhang W, Fangxing L, Tolbert L M 2006 Optimal Allocation of Shunt Dynamic Var Source SVC and STATCOM: A Survey. 7th IET Int. Conf. on Advances in Power System Control, Operation and Management (Hongkong)
[4] Pisica I, Bulac C, Toma L, and Eremia M 2009 Optimal SVC Placement in Electric Power Systems Using A Genetic Algorithms Based Method. 2009 IEEE Bucharest PowerTech. (Bucharest) (New York: IEEE) pp 1-6
[5] Sirjani R, Mohamed A, and Shareef H 2012 Optimal Allocation of Shunt Var Compensators in Power Systems Using A Novel Global Harmony Search Algorithm. Int. Journal of Electrical Power & Energy Systems 43 562-572
[6] Nguyen K, Fujita G, and Dieu V 2016 Cuckoo Search Algorithm for Optimal Placement and Sizing of Static Var Compensator in Large-Scale Power Systems. Journal of Artificial Intelligence and Soft Computing Research 6 59-68
[7] Rao B and Kumar G 2015 A Comparative Study of BAT and Firefly Algorithms for Optimal Placement and Sizing of Static VAR Compensator for Enhancement of Voltage Stability. International Journal of Energy Optimization and Engineering 4 68-84
[8] Sundareswaran K, Hariharan B, Parasseri F P, Antony D S, and Subair B 2010 Optimal
Placement of Static VAr Compensators (SVC's) Using Particle Swarm Optimization. 2010 International Conference on Power, Control and Embedded Systems (Allahabad) (New York: IEEE) pp 1-4.

[9] Jumaat S A, Musirin I, Othman M M, and Mokhlis H 2013 Cluster Identification for Optimal Placement of Static Var Compensator. 2013 IEEE 7th International Power Engineering and Optimization Conference (PEOCO)(Langkawi) pp 546-551

[10] Vanishree J and Ramesh V 2018 Optimization of Size And Cost of Static VAR Compensator Using Dragonfly Algorithm For Voltage Profile Improvement in Power Transmission Systems. International Journal of Renewable Energy Research 8 56-66

[11] Dubey R, Dixit S, and Agnihotri G 2014 Optimal Placement of Shunt Facts Devices Using Heuristic Optimization Techniques: An Overview. 2014 Fourth International Conference on Communication Systems and Network Technologies (Bhopal) pp 518-523

[12] Gacem A, Benattous D 2017 Hybrid GA–PSO For Optimal Placement of Static VAR Compensators in Power System. Int J Syst Assur Eng Manag 8 247–254

[13] Samimi A and Golkar M A 2011 A Novel Method for Optimal Placement of STATCOM in Distribution Networks Using Sensitivity Analysis by DlgSILENT Software 2011 Asia-Pacific Power and Energy Engineering Conference (Wuhan) pp 1-5

[14] Apribowo C H B, Listiyanto O, and Ibrahim M H 2019 Placement Static Var Compensator (SVC) for Improving Voltage Stability Based on Sensitivity Analysis : A Case Study Of 500 KV Java-Bali Electrical Power System. 2019 6th International Conference on Electric Vehicular Technology (Bali) pp 276-280

[15] Swapna G, Rao J S, and Amarnath J 2012 Sensitivity Approach to Improve Transfer Capability Through Optimal Placement of TSCS and SVC. International Journal of Advances in Engineering & Technology 4 525 536

[16] Jadhao C W and Vadrajacharya K 2015 Performance Improvement of Power System Through Static VAR Compensator Using Sensitivity Indices Analysis Method. 2015 International Conference on Energy Systems and Applications (Pune) pp 200-202

[17] Nurdin M., Rahman F, Rahmani R., and Hariyanto N 2014 Placement of Shunt VAR Compensator Based on Sensitivity Analysis. International Journal on Electrical Engineering and Informatics 6 435-446