

# The voltage profile improvement using static var compensator (SVC) in power system transmission

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**Abstract.** In transmission system named ‘Subsistem Bandung Selatan dan New Ujungberung’ there are the voltage drop which relatively high and the voltage profile at the receiving ends below 0.95 p.u. Therefore, this research proposed a method to improve the voltage profile in the transmission system using one of Flexible Alternating Current Transmission System (FACTS) technology which is Static Var Compensator (SVC) and ‘Subsistem Bandung Selatan dan New Ujungberung’ as the object. This research aims to get the voltage profile in ‘Subsistem Bandung Selatan dan New Ujungberung’ before and after connected to SVC and to set optimal location and rating of SVC to maintain the voltage profile at the system that has desire range (0.95 p.u – 1.05 p.u). To get the result in accordance with these objects, Newton –Raphson power flow solution is applied to the system. The result of Newton- Raphson power flow solution of the system shows the voltage profile before connecting to SVC are averagely 140.95 kV or 0.94 p.u while after connecting to SVC are 145.28 kV or 0.97 p.u. The SVC installation is connected to ‘Bandung Utara I’ as the weakest bus, and the SVC rating is -250 Mvar to 300 Mvar.

## 1. Introduction

In electric power system, significantly voltage change is affected by the load variation and the network topology changes. Voltage can drop considerably and even to a voltage collapse when the network is operating under heavy loading. When voltage drop highly, it will affect the phase voltage at the receiving end to become low, that case can affect performance of the equipment and possibly cause them damage [1]. Whereas when voltage collapse happens, it can operate under-voltage relay and other protection system, leading to extensive disconnection of load and thus affecting consumer loss. On the other hand, when the load level in the system is low, over-voltage can arise due to Ferranti effect. Capacitive over-compensation and over-excitation of synchronous machines can also occur [2].

Controlling voltage regulation is needed to inject or absorb reactive power to the network. Power reactive supports the buses which has voltage level outside acceptable limits. It can be improved by power reactive compensator (inject or absorb). FACTS (Flexible Alternating Current Transmission System) technology is suggested by Narian G. Hingorani from Electrical Power Research Institute (EPRI). It is one the advanced compensator for reactive power support. SVC, widely used member of FACTS family, supports to maintain voltage profile when connected at the weakest bus by injection of current [3]. Static Var Compensator (SVC) is shunt connected static generators and/or absorber whose outputs are varied so as to control specific parameter of the electric power system. The term “static” is used to indicate that SVC, unlike synchronous compensator, have no moving or rotating main

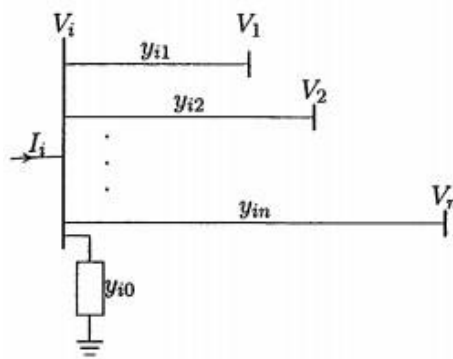


component. Thus SVC consists of Static Var Generator (SVG) or absorber device and a suitable control device [1]. Identification of bus which is connected by SVC is using power flow analysis.

### 1.1. Newton-Raphson Power Flow Solution

Figure 1 shows a typical bus of a power system network. For large power system, the NewtonRaphson method is found to be more efficient and practical. The number of iteration required to obtain a solution is independent of the system size. Since in the power flow problem real power and voltage magnitude are specified for the voltage-controlled buses, the power flow equation is formulated in polar form. For the typical bus of the power system shown in figure 1, the current entering bus  $i$  is given by (1).

$$I_i = \sum_{j=1}^n Y_{ij} V_j \quad (1)$$



**Figure 1.** A typical bus of the power system.

In the above equation,  $j$  includes bus  $i$ . Expressing this equation in polar form, we have

$$I_i = \sum_{j=1}^n |Y_{ij}| |V_j| \angle \theta_{ij} + \delta_j \quad (2)$$

The complex power at bus  $i$  is

$$P_i - jQ_i = V_i^* I_i \quad (3)$$

Substituting from (2) for  $I_i$  in (3),

$$P_i - jQ_i = |V_i| \angle -\delta_i \sum_{j=1}^n |Y_{ij}| |V_j| \angle \theta_{ij} + \delta_j \quad (4)$$

Separating the real and imaginary parts,

$$P_i = \sum_{j=1}^n |V_i| |V_j| |Y_{ij}| \cos(\theta_{ij} - \delta_i - \delta_j) \quad (5)$$

$$Q_i = - \sum_{j=1}^n |V_i| |V_j| |Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \quad (6)$$

Equation (5) and (6) constitute a set of nonlinear algebraic equation in term of the independent variables, voltage magnitude in per unit, and phase angle in radians. We have two equation for each load bus, given by (5) and (6), and one equation for each voltage-controlled bus, given by (5). Expanding (5) and (6) in Taylor's series about the initial estimate and neglecting all higher order terms produce results in the following set of linear equation.

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \\ \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta_n} & \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_n} & \frac{\partial P_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_n^{(k)}}{\partial |V_n|} \\ \hline \frac{\partial Q_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n} & \frac{\partial Q_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n} & \frac{\partial Q_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_n^{(k)}}{\partial |V_n|} \end{bmatrix} \begin{bmatrix} \Delta \delta_2^{(k)} \\ \vdots \\ \Delta \delta_n^{(k)} \\ \Delta |V_2^{(k)}| \\ \vdots \\ \Delta |V_n^{(k)}| \end{bmatrix}$$

As the equation above, bus 1 is assumed as the slack bus. The Jacobian matrix gives the linearized relationship between small changes in voltage angle  $\Delta \delta_i^{(k)}$  and voltage magnitude  $\Delta |V_i|^{(k)}$  with the small changes in real and reactive power  $\Delta P_i^{(k)}$  and  $\Delta Q_i^{(k)}$ . Elements of the Jacobian matrix are the partial derivatives of (5) and (6). In short form, it can be written as

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \quad (7)$$

For voltage-controlled buses, the voltage magnitude are known. Therefore, if  $m$  buses of the system are voltage-controlled,  $m$  equation involving  $\Delta Q$  and  $\Delta V$  and the corresponding columns of the Jacobian matrix are eliminated. Accordingly, there are  $n - 1$  real power constraints and  $n - 1 - m$  reactive power constraints, and the Jacobian matrix is of order  $(2n - 2 - m) \times (2n - 2 - m)$ .  $J_1$  is of the order  $(n - 1) \times (n - 1)$ ,  $J_2$  is of the order  $(n - 1) \times (n - 1 - m)$ ,  $J_3$  is of the order  $(n - 1 - m) \times (n - 1)$ , and  $J_4$  is of the order  $(n - 1 - m) \times (n - 1 - m)$ .

The diagonal and the off-diagonal elements of  $J_1$  are

$$\frac{\partial P_i}{\partial \delta_i} = \sum_{j \neq i} |V_i| |V_j| |Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \quad (8)$$

$$\frac{\partial P_i}{\partial \delta_i} = -|V_i| |V_j| |Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \quad j \neq i \quad (9)$$

The diagonal and the off-diagonal elements of  $J_2$  are

$$\frac{\partial P_i}{\partial |V_i|} = 2|V_i| |Y_{ii}| \cos \theta_{ii} + \sum_{i \neq j} |V_j| |Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \quad (10)$$

$$\frac{\partial P_i}{\partial |V_j|} = |V_i| |Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \quad j \neq i \quad (11)$$

The diagonal and the off-diagonal elements of  $J_3$  are

$$\frac{\partial Q_i}{\partial \delta_i} = \sum_{j \neq i} |V_i| |V_j| |Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \quad (12)$$

$$\frac{\partial P_i}{\partial \delta_j} = -|V_i| |V_j| |Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \quad j \neq i \quad (13)$$

The diagonal and the off-diagonal elements of  $\mathbf{J}_4$  are

$$\frac{\partial Q_i}{\partial |V_i|} = -2|V_i||Y_{ii}| \sin \theta_{ii} + \sum_{j \neq i} |V_j| |Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \quad (14)$$

$$\frac{\partial Q_i}{\partial |V_j|} = -|V_i| |Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \quad j \neq i \quad (15)$$

The terms  $\Delta P_i^{(k)}$  and  $\Delta Q_i^{(k)}$  are different between the schedule and calculated values, known as the power residuals, given by

$$\Delta P_i^{(k)} = P_i^{sch} - P_i^{(k)} \quad (16)$$

$$\Delta Q_i^{(k)} = Q_i^{sch} - Q_i^{(k)} \quad (17)$$

The new estimates for voltages are

$$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta \delta_i^{(k)} \quad (18)$$

$$|V_i^{(k+1)}| = |V_i^{(k)}| + \Delta |V_i^{(k)}| \quad (19)$$

### 1.2. Flexible Alternating Current Transmission System (FACTS)

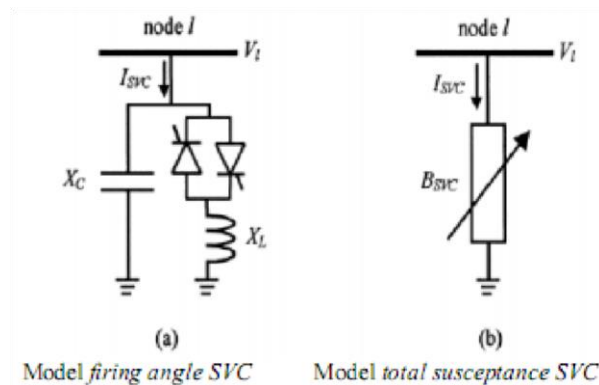
The FACTS is a concept based on power-electronic controller, which enhance the value of transmission networks by increasing the use of their capacity. As these controllers operates very fast, they enlarge the safe operating limits of a transmission system without risking stability. Needless to say, the era of FACTS is triggered by the development of new solid-state electrical switching device. Gradually, the use of the FACTS has given a development of new controllable system.

### 1.3. Static Var Compensator (SVC)

Static Var Compensator (SVC) is one of FACTS controllers, which can control one or more variables in a power system [7]. In its simplest form, the SVC behaves of a Thyristor Controlled Reactor (TCR) in parallel with a bank of capacitor [8], the SVC configuration is shown in figure 2. The working principle of the SVC is set on the thyristor firing angle. Thyristor firing angle would regulate reactive power output of the SVC. The magnitude voltage of the system is output to the controller which will adjust the thyristor firing angle. Therefore the SVC will compensate the reactive power according to the system requirements [9].

To analyse the SVC reactive power compensation of the power system, SVC can be modeled in several ways as follows [10]:

1. SVC firing angle model, that is the SVC modelling of SVC's equivalent reactance  $X_{SVC}$ , which constitutes a function of a changing firing angle  $\alpha$ , it consists by the parallel combination of a Thyristor Controlled Reactor (TCR) equivalent admittance and a fixed capacitive susceptance as shown in figure 2(a). This model provides information on the SVC firing angle required to achieve a given level of compensation.
2. SVC total susceptance model. A changing susceptance  $B_{SVC}$  represents the fundamental frequency equivalent susceptance of all shunt modules making up the SVC. As shown in figure 2(b).



**Figure 2.** SVC modelling [10].

The most popular configuration for SVC is a combination of fixed capacitor (FC) and Thyristor Controlled Reactor (TCR). SVC modelling as variable sources shown in figure 2(b), we can set the maximum and minimum limits on reactive power output as following the inductive and capacitive susceptance available and voltage reference ( $V_{ref}$ ). This limitation can be written by (20) and (21).

$$Q_{max} = B_{ind} \times V_{ref}^2 \quad (20)$$

$$Q_{min} = B_{cap} \times V_{ref}^2 \quad (21)$$

Where:  $B_{cap} = \frac{1}{X_c}$  and  $B_{ind} = \frac{1}{X_L}$

$X_L$  = Inductive reactance

$X_C$  = Capacitive reactance

whereas SVC can be expressed as a function of the firing angle  $\alpha$ , shown in equation (22), as follows:

$$B_{svc} = B_{cap} - (\alpha) \quad (22)$$

Reactive power generated by SVC is calculated by an equation (22) are

$$Q_{svc} = -V_1^2 \times B_{svc} \quad (23)$$

with the balance of reactive power and voltage magnitude on bus  $k$  at the voltage range in accordance with the maximum and minimum limits of SVC's susceptance. Meanwhile, from figure 2(b), the current is supplied by SVC is expressed by (24)

$$I_{svc} = jB_{svc}V_1 \quad (24)$$

3. Power reactive injection model that is SVC can be used to compensate inductive reactive power or capacitive reactive power to the system. The power flow analysis, SVC can be modeled as an ideal reactive power injection on bus  $i$  as (25)

$$\Delta Q_i = Q_{svc} \quad (25)$$

## 2. Research Methodology

This research is located in PT. PLN (PERSERO) Area Pengaturan Beban (APB) Jawa barat. The data which is used in this research are single line diagram of 'Subsistem Bandung Selatan 150 kV dan New

Ujungberung 150 kV', power generation and loading, and line parameters. All data which is collected is the data on October 22, 2014.

To set the optimal location and rating of SVC that is connecting the SVC to the weakest bus (smallest voltage profile) to get voltage profile at each buses in the system in the acceptable range which is 0.94 p.u – 1.05 p.u [4]. After getting a suitable capacity, then the SVC is connecting to the other bus one by one, and record the voltage magnitude in the system at any different SVC position.

### 3. Results and Discussion

The results of Newton-Raphson power flow solution have got optimal location and rating of SVC in order to maintain the voltage magnitude in the system at range 0.95. p.u – 1.05 p.u. Optimal rating of SVC is 250 Mvar for reactive power capacitive and 300 Mvar for inductive power reactive (or -250 Mvar and 300 Mvar). Optimal location of SVC is the SVC installation at bus 'Bandung Utara I' because it shows the greatest of voltage profile increase. 'Bandung Utara I' is the bus which has weakest voltage profile before installment of the SVC. The voltage profile at the system before and after connected to SVC are shown by Table 1.

Table 1. Voltage profile increase before and after installment of the SVC.

No.	Id Bus	Rating (kV)	Operating (kV)	
			Without SVC	With SVC
1	Cibereum I	150	140.40	142.53
2	Cibereum II	150	140.40	142.53
3	Bandung Selatan I	150	144.22	146.30
4	Bandung Selatan II	150	144.22	146.30
5	Wayang Windu I	150	142.45	145.34
6	Wayang Windu II	150	142.45	145.34
7	Cigereleng I	150	141.10	143.22
8	Panasia I	150	143.91	146.00
9	Panasia II	150	143.91	146.00
10	Kiaracondong I	150	138.69	143.91
11	Kiaracondong II	150	138.69	143.91
12	Kamojang I	150	141.59	145.24
13	Kamojang II	150	141.59	145.24
14	Darajat Swasta	150	141.92	145.58
15	Darajat I	150	141.92	145.58
16	Ujungberung I	150	137.82	144.59
17	Ujungberung II	150	137.82	144.59
18	Rancakasumba I	150	140.64	143.89
19	rancakasumba II	150	140.64	143.89
20	Cikasungka I	150	140.95	144.65
21	Cikasungka II	150	140.95	144.65
22	Dagopakar I	150	136.25	146.52
23	Dagopakar II	150	136.25	146.52
24	New Ujungberung I	150	145.32	148.00
25	New Ujungberung II	150	145.32	148.00
26	Bandung Utara I	150	134.97	148.64
27	Rancaekek	150	141.42	145.62

In table 1 there are voltage profile increase at all the buses in the system after SVC is connected to the bus 'Bandung Utara I' and the voltage profile at the entire bus is at 0.95 p.u – 1.05 p.u. the voltage profile which marked with red color means that the operating voltage is below 0.95 p.u or below 142.5 kV.

#### 4. Conclusion

150 kV transmission system region II 'Jawa Barat Subsistem Bandung Selatan and New Ujungberung' have the low voltage profile at the some buses, there are 21 buses with the voltage magnitude below 0.95 p.u. After connecting SVC to the system, it can enhance the voltage profile at the acceptable value (0.95 p.u – 1.05 p.u) with the smallest voltage profile at bus 'Cibereum I' and 'Cibereum II' are 142.53 kV, and the highest voltage profile at bus 'Bandung Utara I'. Optimal location and SVC rating in order to maintain the voltage profile at entire buses that are connecting the -250 Mvar – 300 Mvar SVC rating to bus 'Bandung Utara I'.

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