Power System Optimization of Static VAR Compensator Using Novel Global Harmony Search Method

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***Abstract*—The increasing number of electrical loads and their far away location from the power plant sites are becoming the main causes of the degradation of voltage quality and the increase of power system losses. The problems may be difficult to be handled if the reactive power supply is limited. One effort to overcome can be done through the use of reactive power compensation using bank capacitors and Static VAR Compensator (SVC). In this paper, the optimal location and rating of capacitor bank and SVC are determined by exploring the novel global harmony search (NGHS) method. The performance of the NGHS method is tested by using the real data of JAMALI-500 kV system. Two considered methods in controlling the SVC covered the Voltage Control (VC) and the reactive power control (QC). The optimization using the NGHS method resulted in the optimal location of the SVC on buses 15, 20 and 25 with a total rating of 1443.14 MVAR for the VC method and on the 15, 19, 20 buses with a total rating of 1773.84 MVAR for the QC method. The achieved power losses improvements using Bank Capacitors, SVC with VC, and SVC with QC were 9.27%, 13.19%, and 15.63% respectively, being compared to a given base-case. The simulation results showed that the SVC with reactive power control is better than the use of the other compensation approach considered.**

***Index Terms*—bank capacitor, novel global harmony search method, power loss, reactive power control, SVC, voltage control**

I. Introduction

Reliable and efficient power supply systems must always be fulfilled by the power supply providers. The increasing amount of electrical load as well as the location of the main substation being away from the power plants bring about a significant voltage drop and power losses increase along the power line. The voltage drop greatly affects the quality of power provided, and may cause the damage of connected electrical equipment or even the black out of certain service area. One way to improve the voltage profile of a substation is done through the reactive power compensation. It is usually undertaken by using a bank capacitor but it is not flexible because the capacity of the reactive power injection cannot be dynamically regulated. The need for reactive power injection will vary depending on the loading conditions of the system. Therefore, the power compensation equipment using power semiconductors have much been developed, known as the flexible AC transmission (FACTS) devices.

FACTS devices can be categorized based on the type of variable impedance and the voltage source converter (VSC) considered [1]. Some of the most widely used FACTS devices are static synchronous compensator (STATCOM), thyristor controlled series capacitor (TCSC), thyristor controlled phase shifting transformer (TCPST), unified power flow control (UPFC), dynamic voltage restorer (DVR), and other equipment [2].

Considering the large of coverage area, the length of current carrying conductors, and the number of substations connected to the power system, finding the optimal location and rating of the compensator equipment become the main challenge to be solved. Many of the optimization methods that have been previously investigated to determine the optimal location and rating of the existing compensators are artificial bee colony algorithm [3], [4], simulated annealing (SA) [5], genetic algorithm (AG) [6], [7], particle swarm optimization (PSO) [8], fuzzy EP algorithm [9], harmony search technique (HST) [10]-[16], and several other algorithms.

HST has been implemented to some applications such as the reactive power management with the integration of renewable distributed generation (DG) and reactive power control of under-load tap changer and shunt capacitors [14], optimal design of the proportional-integral (PI) controllers of a grid-side voltage source cascaded converter [15], and the determination of controller gain parameter estimation of DG [16].

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Improvements to the HST method were then done through the development of the harmony search (HS) method by adopting the evolution of living things [10], [13] and known as the novel global harmony search (NGHS) method. This NGHS method is inspired by the intelligence of a musician in finding multiple tones which match the pitch adjustment of the tone. The implementation of NGHS in determining the location and rating of the compensators required in the power system is of concern in this paper.

II. Steady State Analysis SVC

A. Load-Flow Analysis

The power flow analysis is performed to determine the magnitude and angle of the voltage of each bus, line impedance, active and reactive power flowing on the transmission line, and power losses [17]. Representation of the transmission line is shown in Fig. 1.

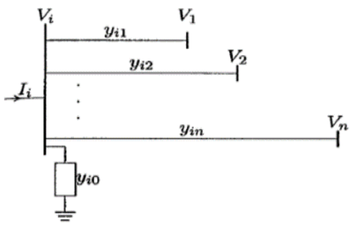

Fig. 1. Bus and line representations in power system [17].

Based on Fig. 1 the current equation can be formulated as follows [17]:

$$I_i = y_{i0}V_i + y_{i1}\left(V_i - V_1\right) + y_{i2}\left(V_i - V_2\right) + \ldots + y_{in}\left(V_i - V_n\right) \tag{1}$$

or

$$I_i = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij} V_j, \quad j \neq i \tag{2}$$

where I_i is the injected current to bus i, V_i is the bus voltage at bus i, and y_{ij} is the line admittance between i and j.

Based on (2), the injected current in bus i can be represented as admittance matrices:

$$I_i = \sum_{j=1}^{n} \left|Y_{ij}\right|\left|V_j\right| \angle \theta_{ij} + \delta_j \tag{3}$$

The apparent power of bus i is given as follows:

$$P_i - jQ_i = V_i^* I_i \tag{4}$$

Subtituting (3) to (4) will result in the following equation:

$$P_i - jQ_i = \left|V_i\right| \angle -\delta_i I_i \sum_{j=1}^{n} \left|Y_{ij}\right|\left|V_j\right| \angle \theta_{ij} + \delta_j \tag{5}$$

If the real and imaginary parts are differentiated, the active and reactive powers injected in the bus i are formulated as follows:

$$P_i = \sum_{j=1}^{n} \left|V_i\right|\left|V_j\right|\left|Y_{ij}\right| \cos(\theta_{ij} - \delta_i + \delta_j) \tag{6}$$

$$Q_i = -\sum_{j=1}^{n} \left|V_i\right|\left|V_j\right|\left|Y_{ij}\right| \sin(\theta_{ij} - \delta_i + \delta_j) \tag{7}$$

where I_i is the injected current on bus i, V_i is the voltage bus i, V_j is the voltage bus j, Y_{ij} is the admittance component between bus i and j, P_i is the active power on bus i, Q_i is the reactive power on bus i, Q_{ij} is the polar angle of admittance Y_{ij}, and δ_j is the voltage angle of V_j.

The next step is to use the Newton-Raphson method by forming a Jacobian matrix. The Jacobian matrix provides the relationship between small changes in voltage angle $\Delta\delta_i^k$ and voltage magnitude $\Delta|V_i^k|$ associated with the small changing on the active power ΔP_i^k and reactive power ΔQ_i^k , respectively. Therefore, the angle and magnitude of voltage are becoming the state-variable of load flow analysis, which can be formulated as follows:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \tag{8}$$

ΔP_i^k and ΔQ_i^k are the difference between the calculated value and the expected value (specified), and known as *power mismatch*, i.e.:

$$\Delta P_i^k = P_i^{sch} - P_i^k \tag{9}$$

$$\Delta Q_i^k = Q_i^{sch} - Q_i^k \tag{10}$$

The Jacobian matrix is then inverted, thus the approximate new value for the angle and magnitude of the voltage can be determined as follows:

$$\delta_i^{(k+1)} = \delta_i^k + \Delta\delta_i^k \tag{11}$$

$$\left|V_i^{(k+1)}\right| = \left|V_i^k\right| + \left|\Delta V_i^k\right| \tag{12}$$

The calculation process with Jacobian matrix is done repeatedly to determine the angle and magnitude of voltage such that the power mismatch reaches or less than the specific error value.

B. Static VAR Compensator (SVC)

SVC is a FACTS device with impedance variable type which can work in both to generate and absorb reactive power. The SVC consists of a thyristor controlled reactor (TCR) mounted in parallel with a bank capacitor. The working principle of SVC in general is to compensate the reactive power by adjusting the ignition angle of the thyristor such that reactive power output from the SVC can be regulated [2]. The representation of the SVC modeling connected to line i and j is shown in Fig. 2.

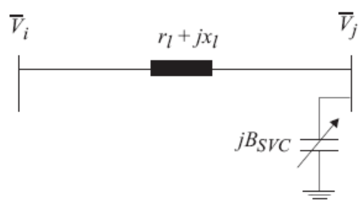

Fig. 2. SVC represention using shunt variable susceptance model [2].

Based on Fig. 2 the SVC injected current can be calculated by the equation:

$$I_{SVC} = jB_{SVC}V_{(j)} \quad (13)$$

The reactive power equation in SVC, which is also the reactive power injected to bus j is given as follows:

$$Q_{SVC} = Q_k = -V_k^2 B_{SVC} \quad (14)$$

Another SVC modeling is using the equivalent reactance X_{SVC} which is a function of the change in the angle of ignition α. This model provides information on the angle of SVC power required to achieve a certain level of compensation [1].

$$Q_{SVC} = Q_k = \frac{-V_k^2}{X_C X_L}\left\{X_L - \frac{X_C}{\pi}\left[2\left(\pi - \alpha_{SVC}\right) + \sin(2\alpha_{SVC})\right]\right\} \quad (15)$$

C. Modal Analysis

Modal analysis is a method which provides an accurate estimation of the system probability against instability by using eigenvalues on the system, and detects the element on the system with the greatest contribution to voltage instability [12]. In modal analysis, the Jacobian matrix is taken into account.

The voltage stability of the system is influenced by the values of P and Q. However, in each operation, P can be maintained as constant values and voltage stability can be sought by considering the relation between Q and V. If P is considered as constant values then $\Delta P = 0$, so

$$\Delta Q = J_R \Delta V \quad (16)$$

where J_R is reduction of the Jacobian matrix:

$$J_R = J_{QV} - J_{Q\theta} J_{P\theta}^{-1} J_{PV} \quad (17)$$

The characteristic of the system mode can be defined as eigenvalues and eigenvectors of J_R.

Assume

$$J_R = \xi \Lambda \eta \quad (18)$$

where ξ is the right eigenvector matrix of J_R, η is the left eigenvector matrix of J_R, and Λ is the diagonal eigenvalue matrix of J_R,

$$J_R^{-1} = \xi \Lambda^{-1} \eta \quad (19)$$

The relationship between small changes of reactive power to voltage is given in (16). The substitution of (19) to (16) results in:

$$\Delta V = (\xi \Lambda^{-1} \eta)\Delta Q \quad (20)$$

or

$$\Delta V = \sum \left(\frac{\xi_i \eta_i}{\lambda_i}\right)\Delta Q \quad (21)$$

where λ_i is the i^{th} eigenvalue, ξ_i is the i^{th} column right eigenvector of J_R, and η_i is the i^{th} row left eigenvector of J_R. λ_i, ξ_i, and η_i are the i^{th} mode of the system. Therefore, the i^{th} modal reactive power variation can be defined as:

$$\Delta Q_{mi} = K_i \xi_i \quad (22)$$

where K_i is the normalisation factor, where:

$$K_i^2 \sum_j \xi_{ij}^2 = 1 \quad (23)$$

and ξ_{ij} is the j^{th} element of ξ_i, thus the i^{th} modal voltage variation can be written as follows:

$$\Delta V_{mi} = 1/\lambda_i \Delta Q_{mi} \quad (24)$$

From equation (24), the stability of a mode i with the reactive power change is defined by the modal eigenvalue λ_i. The large value of λ_i indicates a small change in the voltage modal for a reactive power changes. The critical bus or node can be determined with the right and left eigenvectors of the critical mode, which gives the information on the elements participating in the voltage instability. The bus participation factor measuring the participation of the k^{th} bus in the i^{th} mode is given as follows:

$$P_{ki} = \xi_{ki} \eta_{ik} \quad (25)$$

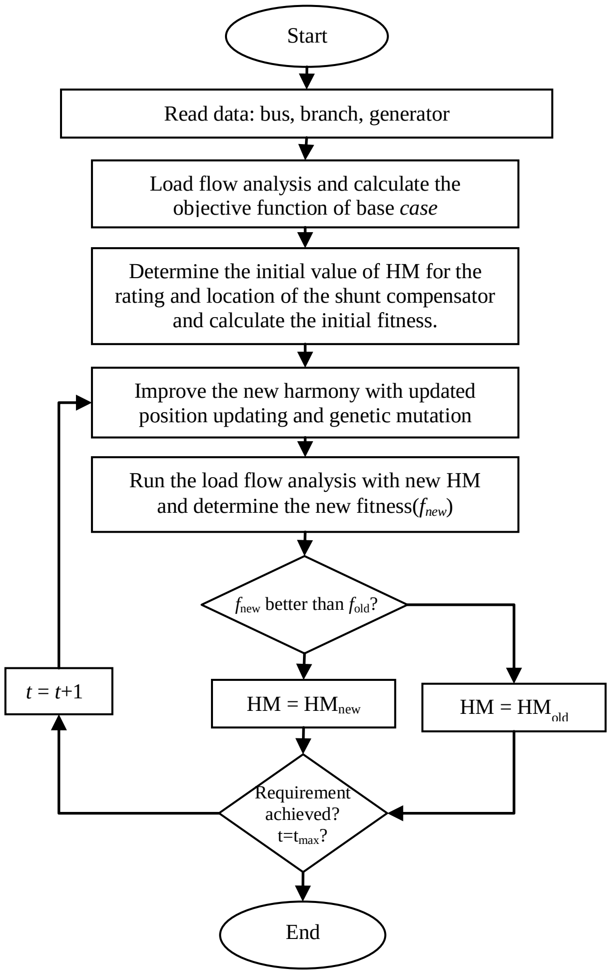

Fig. 3. Flowchart of the NGHS method.

III. Implementation of Novel Global Harmony Search (NGHS) Method

A. NGHS Optimization Method

One of the optimization methods which can be used to solve non-linear algebra problems is the HS algorithm. In this paper, the improvement of the HS method, being called as the NGHS, is implemented. The optimum location and the sizing of the SVC are the main concern of the study. In general, the flowchart of the SVC optimization by NGHS method is given in Fig. 3. The main process of the implementation of the NGHS method are given as follows [13]:

1) Initialization and setup parameters

The parameters to be determined as initial value/initial parameter include the size of HMS or the number of solution vectors in the memory of harmony; number of selection variables (*N*); maximum number of iteration; and stop criteria.

2) Preparing memory of harmony

Harmonic memory (HM) is a matrix filled with random vector solutions for HMS, being sorted by objective function values *f*(*x*) or fitness, and then being followed with the initial fitness analysis using the harmony memory.

3) Develop new harmony memory

After the initial fitness is done then the next step is the development of new harmony memory based on position updating and genetic mutation. The development steps are given as follows.

$$X_R = \begin{cases} 2x_{best,j} - x_{worst,j}, & \text{if rand} < O(k) \\ (1+\text{rand}_1)\,x_{best,j} - (1+\text{rand}_2)\,x_{r,j}, & \text{else} \end{cases} \quad (26)$$

$$x_{new,j} = x_{r,j} + \text{rand}_3(x_R - x_{r,j}) \quad (27)$$

In this case, x_{new} is the newest harmony vector, x_{best}, j is the best harmony in component *j* in HMS, x_{worst}, *j* is the worst harmony in component *j* in HMS. Rand is a random number with boundary [0, 1]. The pseudocode of the NHGS process is shown as follows [13]:

```
For j = 1 to D do
  If rand < O(k)
    x_R = 2 × x_best,j − x_worst,j
  Else
    x_R = (1 + rand) × x_best,j − (1 − rand) × x_r,j, r ∈ (1,2,...,HMS)
  End If
  If x_R < x_j,L
    x_R = x_j,L
  Elseif x_R > x_j,U
    x_R = x_j,U
  End If
  x_new,j = x_r,j + rand() × (x_R − x_r,j) % position updating
  If rand < p_m then
    x_new,j = x_j,L + rand() × (x_j,U − x_j,L) % genetic mutation
  End If
End For
```

where *O*(*k*) is the rate of convergence given, *k* denotes the current iteration, and *K* represents the maximum number of iterations.

4) Substitution (update) memory harmony

The new harmony will replace the old harmony if the fitness value in the new harmony is better than the old harmony.

5) Repeat the improvisation step

In this new harmony step the fitness analysis is done. If the result of the objective function has not met the criteria then the harmony improvisation process will be repeated until it reaches the desired result.

B. Optimization Problems

Multi-objective function optimization is applied to location and compensator rating determination. Optimization is based on maximizing the index of voltage stability, reduction of voltage deviation and active power loss. Total active power losses in the system are formulated as follows:

$$P_{loss} = \sum_{i=1}^{n}\sum_{j=1, j\neq i}^{n}\left[V_i^2 + V_j^2 - 2V_iV_j\cos(\theta_i - \theta_j)\right]Y_{ii}cos\varphi_{ij} \quad (28)$$

The voltage deviation on the system can be defined as follows:

$$L_v = \sqrt{\sum_{i=1}^{n}\left(\frac{V_{iref} - V_i}{V_{iref}}\right)^2} \quad (29)$$

The objective function (*fitness*) of the optimization problem is given as follows:

$$f(x) = w = c_1\frac{P_{loss}}{P_{lossbase}} + c_2\frac{L_v}{L_{vbase}} + c_3\frac{\lambda_{critical(base)}}{\lambda_{critical}} \quad (30)$$

where $c_1 + c_2 + c_3 = 1$; $0 < c_1, c_2, c_3 < 1$

IV. Result and Discussion

A. JAMALI-500kV Power System

Single line diagram for real data of JAMALI-500 kV system can be seen in Fig. 4. The system consists of 26 buses (substations), 31 branches, and 8 generators.

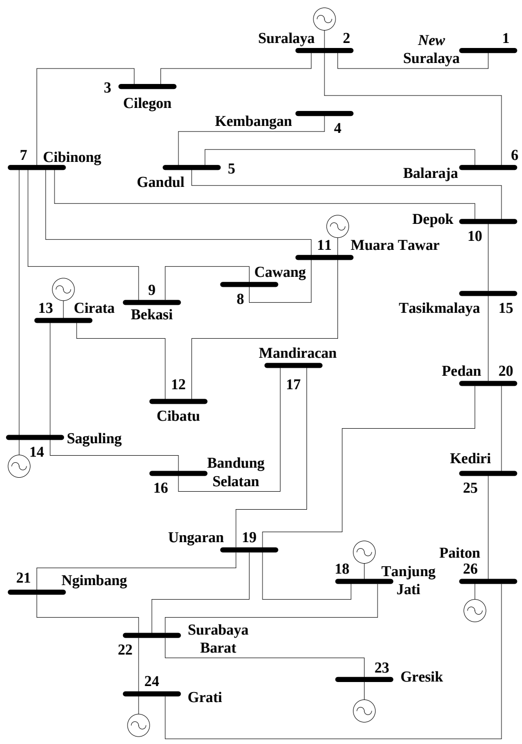

Fig. 4. Single line diagram of JAMALI-500kV power system.

B. Simulation Results of Base Case – Without Any Compensators Placement

Simulations on the JAMALI-500 kV system are performed without any compensator placement to show the voltage profile on the existing system. The voltage profile of each bus, based on the simulation results is given in Fig. 5.

There are 6 (six) locations experiencing under voltage on the power system i.e. bus no# 15, 16, 17, 19, 20, and 25. The lowest voltage profile is found on bus 20 (Pedan substation) with a voltage value of 0.903 p.u. The loss of active power on the system is about 151.504 MW. The largest contribution of the power loss is the branch no#21 (line between bus no#19 and bus no#18) with an active power loss of 31.475 MW.

Based on the modal analysis calculation, the list of bus which have the largest participation factor are given in Table I. Those buses are the candidate for optimal location where the additional reactive power compensation will be injected. In addition, those buses are also selected as initial locations for the NHGS optimization.

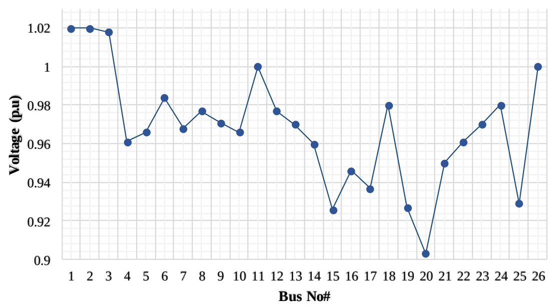

Fig. 5. Voltage profile of base case – without any compensators.

TABLE I. BUS WITH THE LARGEST PARTICIPATION FACTOR BASED ON MODAL ANALYSIS

No.	Bus No#	Participation Factor
1	15	0,3940
2	20	0,2776
3	25	0,1747
4	19	0,0528
5	17	0,0212

C. Optimization of the SVC

The simulation for SVC placement optimization on JAMALI-500 kV system is performed by using two (2) methods namely voltage control (VC) and reactive power control (QC). The results for each of these methods can be explained as follows:

1) Voltage Control (VC)

In this assessment, the Jacobian matrix on Newton-Raphson was modified such that the bus that was installed with SVC increased to 1.0 pu. To avoid over compensation, reactive power injection is limited to 0.9 pu. In the Jacobian matrix, the angle of ignition thyristor becomes the state variable. The location of the bus for SVC placement is determined based on the highest participation factor value i.e. on bus no#15, 20, 25. The required reactive power injection of the SVC will be obtained according to the desired output voltage. The result of required reactive power of SVC to achieve the specific voltage by controlling the voltage is given in Table II.

TABLE II. THE RESULT OF REACTIVE POWER CALCULATION OF SVC BY USING THE VOLTAGE CONTROL

Bus No#	Reactive power injection (p.u.)	Suceptance (p.u.)	TCR angle (°)	Output voltage (p.u.)
15	-0,29877	0,29877	135,331	1,00
20	-0,68171	0,69555	148,411	1,00
25	-0,44882	0,44882	139,457	1,00

2) Power Reactive Control (QC)

In this simulation, the controlled parameter is the output of the reactive power injection of the SVC. The determination of the reactive power injection and optimum bus locations is determined by using NGHS method and the result is given in Table III.

TABLE III. THE RESULT OF REACTIVE POWER CALCULATION OF SVC BY USING THE POWER REACTIVE CONTROL

Bus No#	Reactive power injection (p.u.)	Suceptance (p.u.)	Output voltage (p.u.)
15	-0,57384	0,54197	1,029
19	-0,60000	0,61227	0,990
20	-0,60000	0,60309	0,997

The optimization is performed based on the reduction of active power losses, improvement of voltage deviation, and improved system stability. The SVC optimization convergence profile to determine the optimum reactive power injection by using NGHS method is shown in Fig. 6. The optimum fitness value achieved is about 0.6890, which is obtained after 40th iteration.

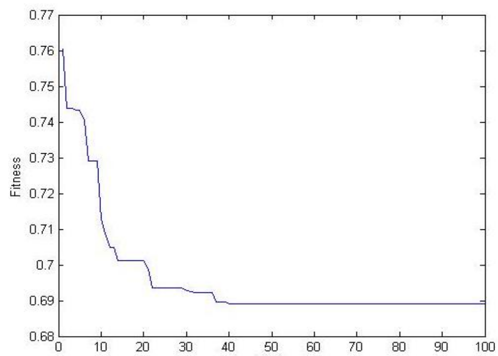

Fig. 6. Graph of SVC optimization convergence by NGHS method.

D. Comparison Result

Comparison of simulation results of base case (without any compensators placement), with capacitor bank and with SVC in both VC and QC control methods is given in Table IV. Based on the simulation result, the best objective function is indicated by SVC optimization with reactive power control (QC) method.

TABLE IV. COMPARISON OF SIMULATION RESULT

Case#	Bus No# Location	Injected Reactive Power (MVAR)	*P* Loss (MW)	Improve *P* Loss (%)	Voltage Stability (eigenvalue)
Base Case (BC)	-	-	151,504	-	5,615
Capacitors	19,20,25	900	137,464	9.27%	6,027
SVC (VC)	15,20,25	1443,14	131,516	13.19%	6,445
SVC (QC)	15,19,20	1773,84	127,820	15.63%	6,890

Note: The percentage of the improvement of the power losses is calculated with respect to the base-case reactive power losses.

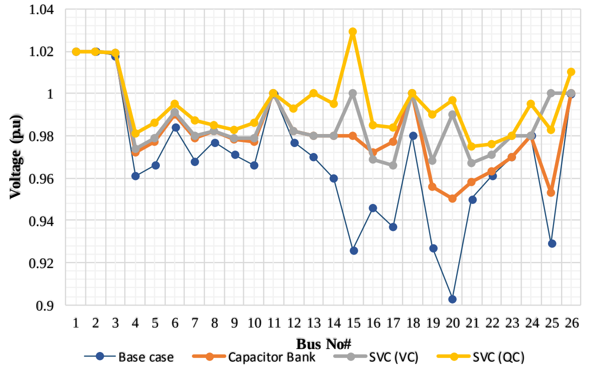

Fig. 7. Voltage profil comparison for four (4) cases.

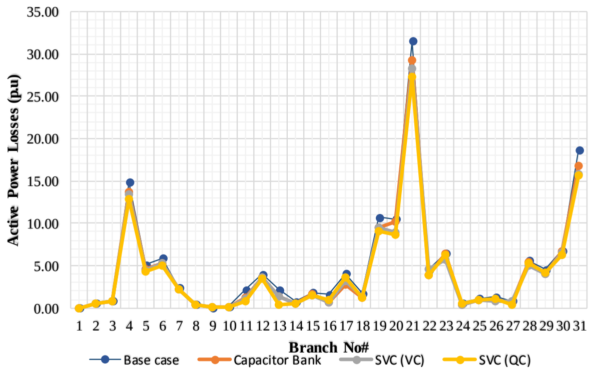

Fig. 8. Branch active power losses for four (4) cases

The comparison of the voltage profile between base case, capacitor bank implementation, and SVC implementation in both voltage and reactive power control are shown in Fig. 7. Based on the active power losses calculation, the percentage improvements achieved were about 9.27%, 13.19%, and 15.63% for implementation of capacitor bank, SVC (VC), and SVC (QC) respectively.

Fig. 8 shows the comparison of branch active power losses for each case: base case, capacitor bank implementation, SVC (VC), and SVC (QC). It is seen that the smallest active power losses are found in case SVC (QC).

V. Conclusion

From the results of research that has been done, it can be concluded that:

- Optimal placement for SVC and STATCOM can minimize active power losses on transmission line, minimize voltage deviation, and raise voltage stability index in the JAMALI-500 kV power system
- Application of the NGHS method on optimization using SVC (QC) shows more optimal results than using bank capacitors and SVC (VC) based on multi-objective optimization.
- Based on the active power losses calculation, the percentage improvements achieved were about 9.27%, 13.19%, and 15.63% for implementation of capacitor bank, SVC (VC), and SVC (QC) respectively.

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