Modeling of static var compensator-high voltage direct current to provide power and improve voltage profile

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Article Info

ABSTRACT

Transmission lines react to an unexpected increase in power, and if these power changes are not controlled, some lines will become overloaded on certain routes. Flexible alternating current transmission system (FACTS) devices can change the voltage range and phase angle and thus control the power flow. This paper presents suitable mathematical modeling of FACTS devices including static var compensator (SVC) as a parallel compensator and high voltage direct current (HVDC) bonding. A comprehensive modeling of SVC and HVDC bonding in the form of simultaneous applications for power flow is also performed, and the effects of compensations are compared. The comprehensive model obtained was implemented on the 5-bus test system in MATLAB software using the Newton-Raphson method, revealed that generators have to produce more power. Also, the addition of these devices stabilizes the voltage and controls active and reactive power in the network.

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NOMENCLATURE

S	:	Apparent power	Y	:	Line and element admittance
P	:	Active power	G	:	Line and element conductance
Q	:	Reactive power	B	:	Line and element susceptance
U, V, E	:	Voltages of terminal, effective, bus	J, J_1, J_2, J_3, J_4	:	Jacobin matrix and its elements
I	:	Line current	x	:	State variable in power flow equation
δ, θ	:	Phase angles	f(x)	:	State variables function
X	:	Line and element reactance	Rdc	:	Resistance in the connection line of HVDC

1. INTRODUCTION

The use of flexible alternating current transmission system (FACTS) and high-voltage direct current (HVDC) equipments are considered by designers of electrical transmission networks due to the increased demand for transmission networks, the creation of long transmission line routes, long distance of production centers from consumption centers, accumulation of energy resources in specific places and wide distribution of consumption centers [1]–[8]. This equipment can control both active and reactive power simultaneously, regulate voltage range and reduce power flow on overloaded lines by creating the desired voltage level [9]–[12]. Flexible alternating current transmission system devices can increase load capacity, portability and

reliability and improve system line density [13]. Load flow studies are essential for the analysis, design, control, and economic planning of the future of transmission and power systems [11].

The Newton-Raphson power flow method is an effective and practical method due to its quadratic convergence and the fact that the number of iterations is independent of the system size and has a high convergence rate [11], [14]. Power transmission capacity is influenced by factors such as thermal constraints, voltage constraints, and limited stability, which leads to dense lines and reduction of security margins and definitive load [8], [12], [15], [16].

In order to meet the requirements for system control, a set of equipment is used that include tools that control power and voltage [10]. Low portability means the need for more production resources [13]. Therefore, practical measures should be taken to improve portability. FACTS devices are used for increasing portability and power quality [13]. Energy systems can be developed by installing HVDC transmission lines [17]–[20], which resolve the problems of low impedance and unbalanced power flow because they control power based on electronic power devices [13]. A combination of series and parallel controllers with line impedance control and voltage regulator manage the active and reactive power in the system [13]. High-voltage direct current systems are of particular importance due to the accumulation of energy resources in specific locations, wide distribution of consumption centers, the need to connect to adjacent networks, the need for transmission by underground and sea routes and the economic benefits of high-power transmission over long distances [13], [21].

The disadvantages of HVDC lines, on the other hand, include high energy conversion costs and reactive power requirements of converters [17]. Flexible alternating current transmission system controllers used in this paper included static var compensator or static var compensator (SVC) and HVDC link was also used in the transmission line. High-voltage direct current systems are comprised of two converters, one capable of regulating voltage and the other capable of quickly transmitting and controlling active power [9]. Provided that direct current (DC) converters inherently absorb reactive power, a reactive power source such as an SVC can be used near the converter [10]. SVC is used to generate or absorb reactive power in parallel in the network to control the bus voltage [13]. Much research has been carried out on the use of FACTS devices and HVDC lines, included proposing two suitable multi-terminal VSC-HVDC models for load flow study using the Newton-Raphson algorithm [22], Newton-Raphson HVDC power flow modeling [23]–[25], and multi-terminal VSC-HVDC load flow was modeled using the AC/DC load flow algorithm by MATLAB and MATPOWER software programs [26], [27].

In Vinkovic and Mihalic [28], the general method for dual modeling of FACTS devices and their series and parallel modeling were studied. SVC has been used to optimize the Newton-Raphson power flow modeling [29], [30]. In [31], a control method for the coordination of HVDC and FACTS was proposed with the aim of obtaining small signal stability of the power system, which indicated that by changing the parameters, the oscillation between adjacent areas for production was reduced. In [32], a multiple optimal power flow (OPF) solution method was presented with the presence of FACTS devices, which were very powerful and fine-tuned the unequal constraints of the system. The optimal multi-objective placement of FACTS controllers including SVC, thyristor-controlled series compensation (TCSC), and unified power flow controller (UPFC) for power system operational planning has been investigated in [33]–[37]. The optimal power flow of the HVDC two-terminal system was obtained with the help of a genetic algorithm and a backtracking search algorithm in [17], [38]. The integration of an SVC into the distribution generator in the network, led to an improvement in voltage regulation and a reduction in distribution network losses [39]. For optimal reactive power and coordination between FACTS devices such as SVC and TCSC with other sources, simple particle swarm optimization (SPSO), evolutionary particle swarm optimization (ESPO), and adaptive particle swarm optimization (APSO) algorithms were used [40]–[51]. Power flow modeling of the AC-DC hybrid HVDC multi-terminal system was presented in [52], [53], which achieved a very good power flow and convergence solution. In [54], a new power flow method including FACTS and HVDC devices was investigated in which the bass equations included a P-Q bus (in this bus the real power (P) and reactive power (Q) are specified) in the alternating current (AC) system to remove components from the AC system and increase the convergence speed. In none of the previous works the simultaneous use of FACTS devices has been investigated using comprehensive modeling. In this article, the simultaneous combination of two devices and between two buses has been used, but in previous works, either these devices have been used individually or not simultaneously between two buses to investigate its effects. We sought to investigate the modeling of SVC and HVDC devices and to obtain comprehensive modeling of the simultaneous application of all the two devices by the Newton-Raphson power flow method and determine the effects of series and parallel compensations on the network. Simulations were implemented with the help of MATLAB software on a 5-bus test system.

2.   RESEARCH METHOD

2.1. Modeling of FACTS devices

The general model of FACTS devices when used in series on the network as Figure 1 is formulated in the manner [28].

$$S_{ST} = P_{ST} + jQ_{ST} = U_S(-I_S^*) \tag{1}$$

$$S_{RT} = P_{RT} + jQ_{RT} = U_R(-I_S^*) \tag{2}$$

$$P_T = P_{ST} + P_{RT} \tag{3}$$

The model of the parallel application of FACTS devices is as Figure 2 [28].

$$S_{PT} = P_{PT} + jQ_{PT} = U_P(-I_P^*) \tag{4}$$

$$P_{PT} = -U_P(Re[I_P] \cos \delta_P + Im[I_P] \sin \delta_P) \tag{5}$$

$$Q_{PT} = -U_P(Re[I_P] \sin \delta_P - Im[I_P] \cos \delta_P) \tag{6}$$

In these equations, S, P, Q and I are the apparent power, active and reactive powers, and line current, respectively. Power control by FACTS devices according to the power as shown in (7) [34].

$$P = \frac{V_i V_j}{X_{ij}} \sin(\theta_i - \theta_j)$$
$$V_i V_j ===> SVC \ \sin(\theta_i - \theta_j), V_i V_j, X_{ij} => UPFC$$
$$X_{ij} ====> TCSC \tag{7}$$

2.2. SVC modeling

In this paper, SVC is modeled as an ideal reactive power source injected into bus A. Static VAR compensator can continuously generate reactive power compensation by operating in inductive and capacitive modes. Static VAR compensator model and structure are specified in Figure 3 [55]. The role of SVC is to keep the voltage in the bus constant, which is done by injecting power into the bus [30]. In modeling, we considered SVC as a parallel variable susceptance as Figure 3 [9], [30], [55].

$$I_{SVC} = jB_{SVC}V_a \tag{8}$$

The power absorbed or injected into the bass is as (9) [30][55].
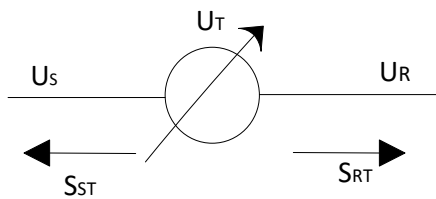$$Q_{SVC} = Q_a = -V_a^2 B_{SVC} \tag{9}$$
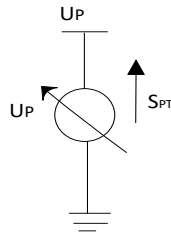
Figure 1. Model of a FACTS series branch [28]

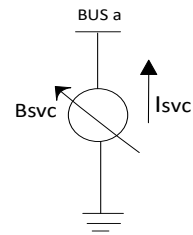Figure 2. Model of a FACTS parallel branch [28]

Figure 3. Model of parallel variable susceptance for SVC

2.3. HVDC system modeling

A HVDC system consists of two voltage source converters connected to busbars A and B by transformers. The equivalent circuit of the HVDC system includes a combination of the voltage source and transformer impedance series. Depending on their application, both converters are connected back to back or by a DC cable [21], [24]. The HVDC system is conveniently modeled with two voltage sources along with an equation that states the active power condition. With the introduction of HVDC, the range of transmission power increased (from below 1000 W to 3 to 4 GW) [56]. High-voltage alternative current (HVAC) design

and construction are not economical for long distances, but using HVDC improves the cost and transmission of high voltages [57]. In the system HVDC and FACTS devices, due to less insulation and resistance DC less than AC, fewer losses[58], the need for two conductors in the system and as a result of the volume and space of the less to install, reduce of the thickness and cross-section of the cable in a certain power, use of the ground as a return wire, it has lower costs than HVAC, which in Figure 4, we see the difference in costs based on references [59], [60]. Moreover, the HVDC is able to improve stability of inter-connected HVAC by modulating power in response to small/large disturbances [61]. The DC terminals will always be more expensive than AC terminals simply because they have to have the components to transform DC voltage as well as convert the DC to AC. But the DC voltage conversion and circuit breakers have been dropping in price, the break-even price continues to drop. The HVDC model in power flow studies is as Figure 5 [23], [24], [62].
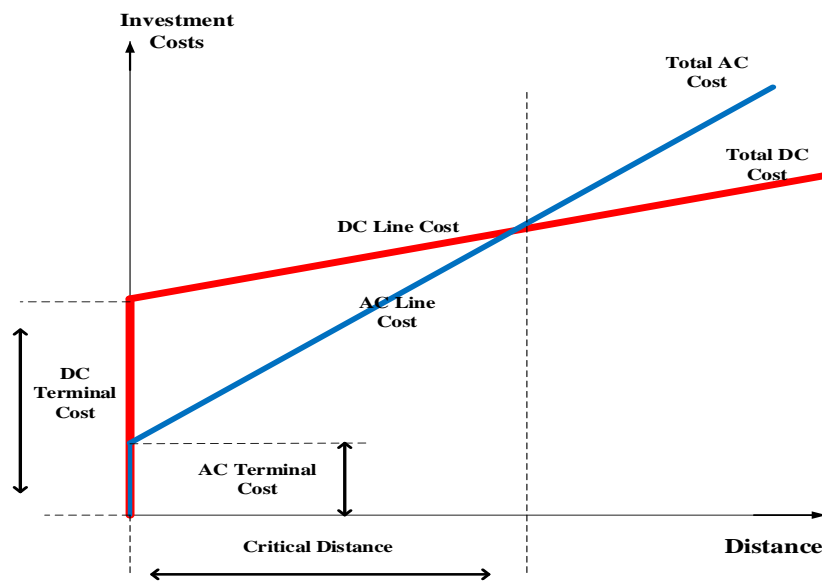

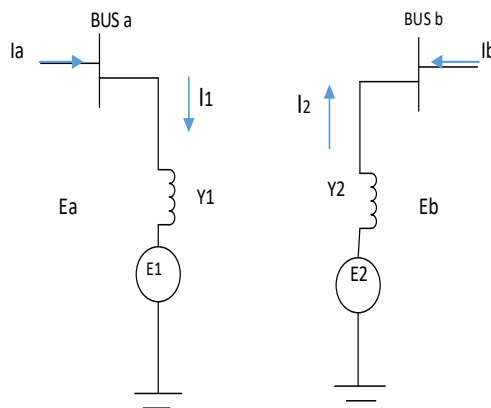Figure 4. Compare the costs of HVDC and HVAC systems [60]

Figure 5. Model of HVDC for power flow [9]

$$E_1 = V_1(cos\,\delta_1 + j\,sin\,\delta_1) \tag{10}$$

$$E_2 = V_2(cos\,\delta_2 + j\,sin\,\delta_2) \tag{11}$$

$$\begin{bmatrix} I_a \\ I_b \end{bmatrix} = \begin{bmatrix} Y_1 & -Y_1 & 0 & 0 \\ 0 & 0 & Y_2 & -Y_2 \end{bmatrix} \cdot \begin{bmatrix} E_a \\ E_1 \\ E_b \\ E_2 \end{bmatrix} \tag{12}$$

$$P = Re\{E_1 I_1^*\} \tag{13}$$

$$Q = Im\{E_1 I_1^*\} \tag{14}$$

For both HVDC components connected by a DC cable [9], [23].

$$Re\{V_1 I_1^* + V_2 I_2^* + V_{DC} I_{DC}\} = 0 \tag{15}$$

And if $Rdc = 0$ (That Rdc resistor connection line in HVDC) then: [9], [23].

$$Re\{V_1 I_1^* + V_2 I_2^*\} = 0 \tag{16}$$

2.4. Comprehensive SVC-HVDC modeling for power flow

Due to the limitations of transmission lines and the advantages of using FACTS devices as parallel and series compensators in the network, also, for connecting the power grid and taking into account the advantages of HVDC lines, establishing HVDC connections as a complement to AC systems is essential. In this paper, a comprehensive model for modeling SVC and HVDC devices was used as Figure 6. Then, the Newton-Raphson power flow on the final model was applied. According to the Figure 6, an SVC is used as a parallel compensator and an HVDC as a link.
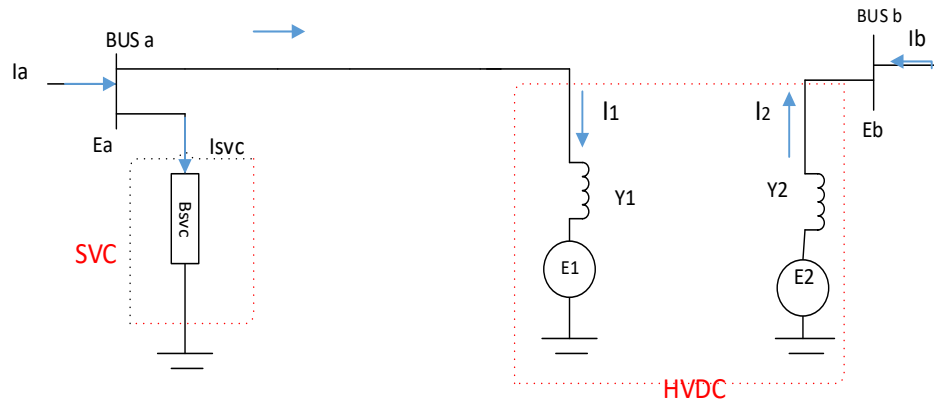

Figure 6. Model of SVC-TCSC-HVDC for power flow

By writing the relations of currents passing through buses and lines and the relation of power and separation of their real and imaginary parts,

$$S_i = P_i + jQ_i = E_i I_i^* \tag{17}$$

$$E_i = V_i(\cos \theta_i + j \sin \theta_i) \tag{18}$$

$$E_a = V_a(\cos \theta_a + j \sin \theta_a) \tag{19}$$

$$E_b = V_b(\cos \theta_b + j \sin \theta_b) \tag{20}$$

$$E_1 = V_1(\cos \delta_1 + j \sin \delta_1) \tag{21}$$

$$E_2 = V_2(\cos \delta_2 + j \sin \delta_2) \tag{22}$$

$$Y_i = G_i + jB_i \tag{23}$$

$$Y_0 = jB_{SVC} \tag{24}$$

$$Y_1 = G_1 + jB_1 \tag{25}$$

$$Y_2 = G_2 + jB_2 \tag{26}$$

$$Y_3 = Y_0 + Y_1 = G_1 + jB_3 \tag{27}$$

$$B_3 = B_{svc} + B_1 \tag{28}$$

where:

$$P_a = G_1 V_a^2 - G_1 V_1 V_a \cos(\theta_a - \delta_1) - B_1 V_1 V_a \sin(\theta_a - \delta_1) \tag{29}$$

$$Q_a = -B_3 V_a^2 - G_1 V_1 V_a \sin(\theta_a - \delta_1) + B_1 V_1 V_a \cos(\theta_a - \delta_1) \tag{30}$$

$$P_b = -G_2 V_b^2 + G_2 V_2 V_b \cos(\theta_b - \delta_2) + B_2 V_2 V_b \sin(\theta_b - \delta_2) \tag{31}$$

$$Q_b = B_2 V_b^2 + G_2 V_2 V_b \sin(\theta_b - \delta_2) - B_2 V_2 V_b \cos(\theta_b - \delta_2) \tag{32}$$

$$Q_{SVC} = -V_a^2 B_{SVC} \tag{33}$$

$$P_1 = -G_1 V_1^2 + G_1 V_1 V_a \cos(\theta_a - \delta_1) - B_1 V_1 V_a \sin(\theta_a - \delta_1) \tag{34}$$

$$Q_1 = B_1 V_1^2 - G_1 V_1 V_a \sin(\theta_a - \delta_1) - B_1 V_1 V_a \cos(\theta_a - \delta_1) \tag{35}$$

$$P_2 = -G_2 V_2^2 + G_2 V_2 V_b \cos(\theta_b - \delta_2) - B_2 V_b V_2 \sin(\theta_b - \delta_2) \tag{36}$$

$$Q_2 = B_2 V_2^2 - G_2 V_2 V_b \sin(\theta_b - \delta_2) - B_2 V_2 V_b \cos(\theta_b - \delta_2) \tag{37}$$

where V_a, V_b, V_1, V_2, θ_a, θ_b, δ_1, and δ_2 are the voltage and angles of the bus a, b, and HVDC link, respectively. B_1, B_2 and B_{SVC} are susceptance for the rectifier, inverter and SVC, respectively. G_1 and G_2 are the side conductance of the rectifier and inverter, respectively. P_1, P_2, P_a, P_b are the active powers of rectifier and inverter, buses a, and b, respectively. Finally, Q_a, Q_b, Q_{SVC}, Q_1, and Q_2 are the reactive powers for a, and b buses, the SVC reactive power and the rectifier and inverter sides of the model, respectively.

In (29) to (37) we see that the hybrid model is effective in active and reactive powers related to buses and lines. For example, in (30) B3 is used which is a combination of SVC and HVDC. These show a comprehensive hybrid model that can be generalized to larger networks, and this model can also be used in load flow and stability analysis, etc. To solve the Newton-Raphson power flow (38)-(44). The Newton-Raphson method is scientifically efficient due to quadratic convergence and high convergence velocity, which is obtained by extending the Taylor series [63]–[67].

$$[f(x)] = [J] \cdot [x] \tag{38}$$

The matrix [J] is the Jacobin matrix obtained by the partial derivatives of each function as shown in (29)-(37) relative to the variables:

$$x = \begin{bmatrix} \Delta\theta_a \\ \frac{\Delta V_a}{V_a} \\ \frac{\Delta B_{SVC}}{B_{SVC}} \\ \Delta\delta_1 \\ \frac{\Delta V_1}{V_1} \\ \Delta\delta_2 \end{bmatrix}, F(x) = \begin{bmatrix} \Delta P_a \\ \Delta Q_a \\ \Delta Q_{SVC} \\ \Delta P_1 \\ \Delta Q_1 \\ \Delta P_{HVDC} \end{bmatrix}, J = \begin{bmatrix} [J_1] & [J_2] \\ [J_3] & [J_4] \end{bmatrix} \tag{39}$$

$$J_1 = \begin{bmatrix} \frac{\partial P_a}{\partial \theta_a} & \frac{\partial P_a}{\partial V_a} V_a & 0 \\ \frac{\partial Q_a}{\partial \theta_a} & \frac{\partial Q_a}{\partial V_a} V_a & \frac{\partial Q_a}{\partial B_{SVC}} B_{SVC} \\ 0 & 0 & \frac{\partial Q_a}{\partial B_{SVC}} B_{SVC} \end{bmatrix} \tag{40}$$

$$J_2 = \begin{bmatrix} \frac{\partial P_a}{\partial \delta_1} & \frac{\partial P_a}{\partial V_1} V_1 & 0 \\ \frac{\partial Q_a}{\partial \delta_1} & \frac{\partial Q_a}{\partial V_1} V_1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{41}$$

$$J_3 = \begin{bmatrix} \frac{\partial P_1}{\partial \theta_a} & \frac{\partial P_1}{\partial V_a} V_a & 0 \\ \frac{\partial Q_1}{\partial \theta_a} & \frac{\partial Q_1}{\partial V_a} V_a & 0 \\ \frac{\partial P_{HVDC}}{\partial \theta_a} & \frac{\partial P_{HVDC}}{\partial V_a} V_a & 0 \end{bmatrix} \tag{42}$$

$$J_4 = \begin{bmatrix} \frac{\partial P_1}{\partial \delta_1} & \frac{\partial P_1}{\partial V_1} V_1 & 0 \\ \frac{\partial Q_1}{\partial \delta_1} & \frac{\partial Q_1}{\partial V_1} V_1 & 0 \\ \frac{\partial P_{HVDC}}{\partial \delta_1} & \frac{\partial P_{HVDC}}{\partial V_1} V_1 & \frac{\partial P_{HVDC}}{\partial \delta_2} \end{bmatrix} \tag{43}$$

Where in the above relations J, J_1, J_2, J_3, J_4 are the Jacobin matrix and its components and f(x) are the function of state variables and x are state variables in load flow equations and we have:

$$P_{HVDC} = P_1 - P_2 \tag{44}$$

Since the active power is set at the end of the rectifier in the HVDC line and the voltage range at bus b is kept constant, the equations of active and reactive power of the inverter are additional [9].

3. RESULTS AND DISCUSSION

We applied the model obtained in the previous section on a 5-bus test system according to Figure 7, where all the information about the buses and lines and the whole network was extracted from reference [38]. The information required for the test system is provided in Appendix. First, power flow was without adding FACTS devices, and then in this network, we added the SVC and HVDC devices individually to the network and observed the results. Finally, based on the SVC-HVDC model obtained in the previous section of this paper, all the both devices were added to the system and the results were recorded. In this paper, the focus was on load flow in buses on which the devices have a direct effect, such as buses 3 and 4 (Lake and Main), although they affect the whole network.
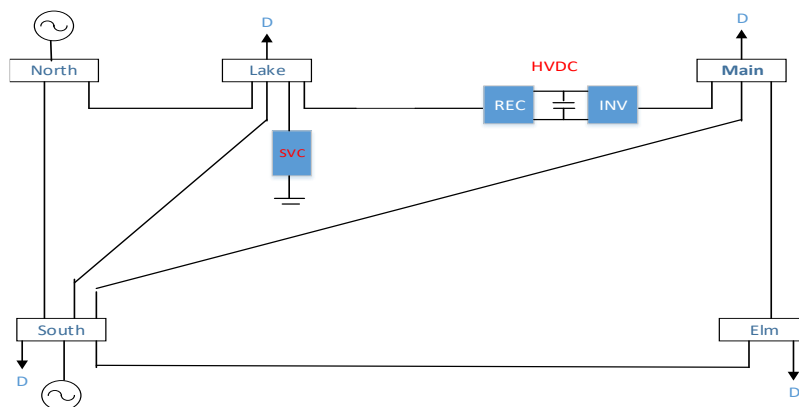

Figure 7. System test 5 buses with SVC-HVDC

In Figure 8, which shows voltage changes in the presence of various FACTS devices, the voltage state for stabilization at 1p.u. is presented. Using SVC, was better than the mode without FACTS devices and the mode of using HVDC, and in buses 3 and 4, it was 1p.u. closer. But the best state and voltage stabilization occurred in the case that the SVC-HVDC combination was used. Also, compared to the different references in Figure 9, the SVC-HVDC model has the best state of recovery and voltage stabilization. The best state for voltage improvement was the mode of using SVC in reference [9].
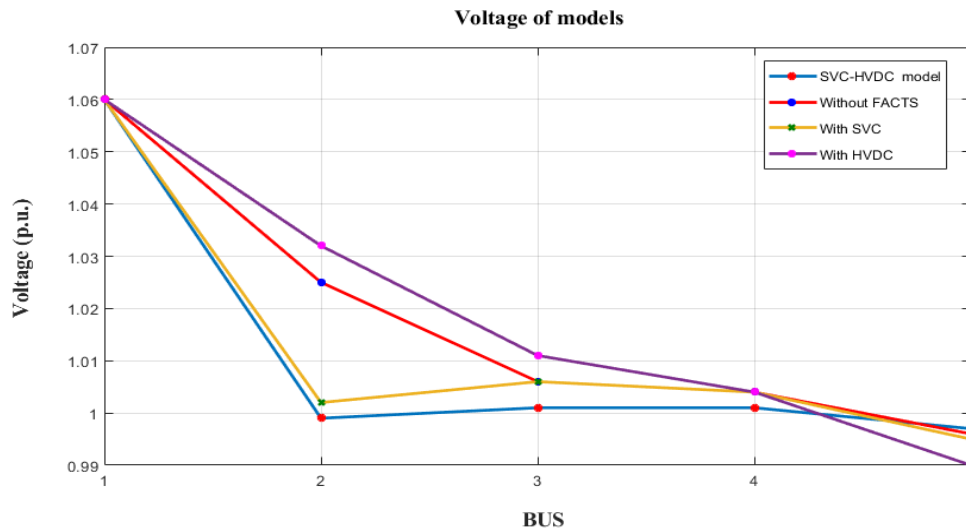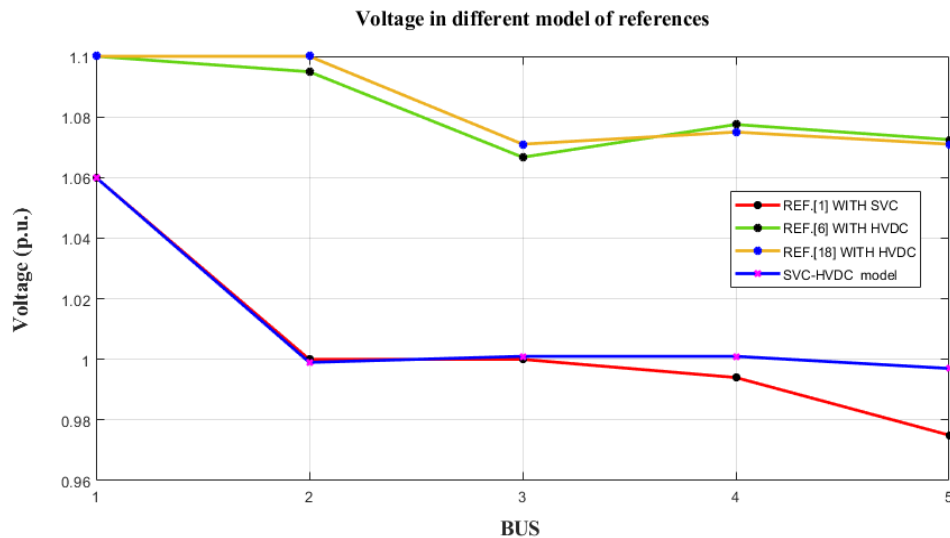

Figure 8. Voltage of models

Figure 9. Voltage in different model of references

In all diagrams and figures, PG1, PG2, P3-4 and P4-3 are the active powers produced by the North and South generators, and the active powers are between buses 3 and 4, respectively. In addition, QG1, QG2, Q3-4 and Q4-3 are the reactive powers generated by the North and South generators, and the reactive powers are between buses 3 and 4, respectively. By applying Newton-Raphson load flow in the final model and different models in Figure 10 and Figure 11 (by keeping the output of the South generator constant at 40 MW), an increase in active and reactive power between the buses used by the devices is noted, which is the best way to use SVC-HVDC. It is the most efficient model in compensating active and reactive power. In the final hybrid model, the generators are forced to produce more power, which is more costly for the system and is among the disadvantages of the system.
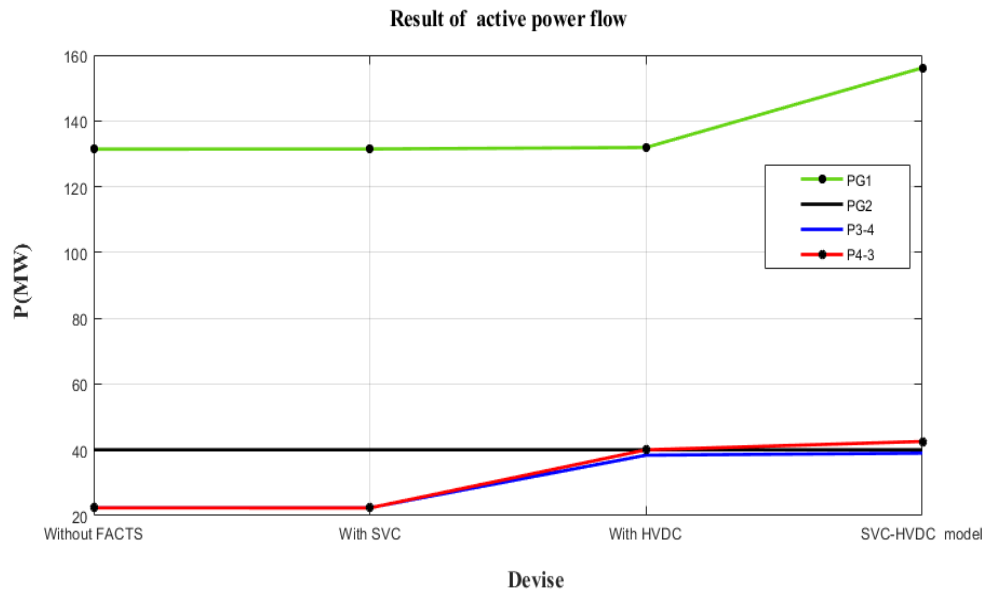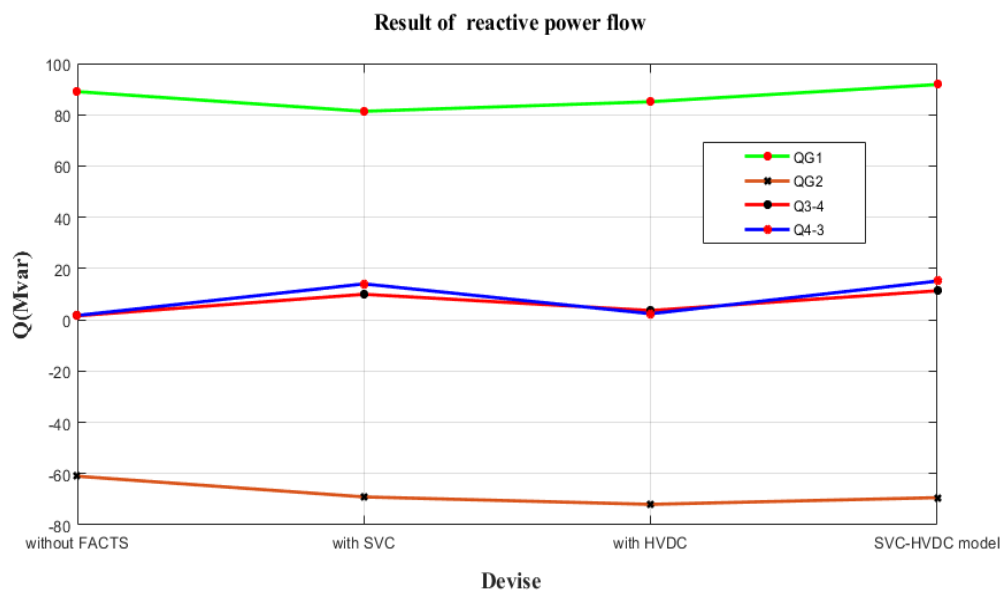
Figure 10. Result of active power flow

Figure 11. Result of reactive power flow

By comparing load flow in the models used in this paper and the different references in Figure 12 and Figure 13, we see a further spike in active and reactive power, which indicates the efficiency of the proposed SVC-HVDC hybrid model in the network. Comparing this model with the references in Figure 12 and Figure 13, it can be concluded that good compensation is obtained for the system. Besides, an increase in active and reactive power between the buses and lines, and at the same time, voltage stabilization in the Main and Lake Buses in this SVC-HVDC model were obtained. However, this paper examined a comprehensive model for the simultaneous effects of all the two types of devices for power flow and controlled the active and reactive power simultaneously, which had not been done in any of the previous studies [9], [23]–[25],[29]–[31], [33], [34], [40], [52], [54], [57],[68]–[70].
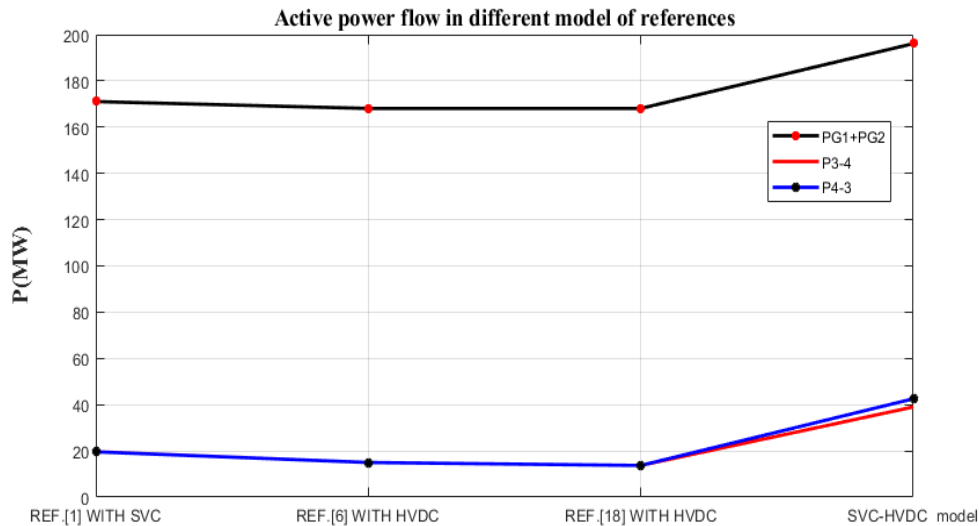
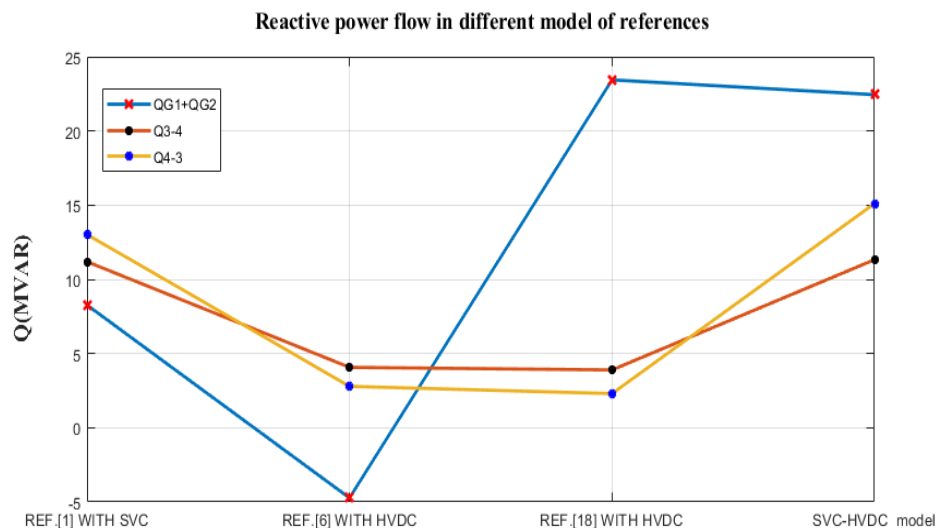Figure 12. Active power flow indifferent model of references

Figure 13. Reactive power flow indifferent model of references

4. CONCLUSION

In this paper, models for the use of different flexible alternating current transmission system (FACTS) devices were presented, and finally a hybrid model including static var compensator (SVC) as a parallel compensator and high voltage direct current (HVDC) link was modeled for simultaneous use in a 5-bus network and Newton-Raphson load flow. According to the results, the installation of several types of FACTS devices simultaneously with SVC-HVDC, by increasing the flexibility of the power network to achieve better results, improved the voltage profile and compensation to increase the active and reactive power in the network. In this model, we observed an increase in the power generation of generators, which increases the production cost in the network and is one of the disadvantages of the model. The results showed that the proposed method had good performance. This study obtained a suitable hybrid model for load flow studies that can be generalized to larger networks and this model can be used in stability discussion studies and other power system studies. Future studies are needed to examine the optimal load flow of this model and optimal placement of these devices in the network.

APPENDIX

The information required for the test system in Figure 6 and the range of selected parameters for the equipment is as:

SVC	BSVC0 = 0.02 BLO = -0.2 BHi = 0.2	V0 = 1.00	QSVC0 = -100 MVAr 100 MVAr
HVDC	Rdc = 0.00	V1' = 1.00 V2' = 1.00 VLO =0.9 VHi = 1.1	PHVDC0 = 0.4 MW 300 MW

Where B_{SVC0}, B_{LO}, B_{Hi}, V_0 and Q_{SVC0} are the initial values and upper and lower limits of the susceptance, the initial voltage and range of change of reactive power values in SVC, respectively. Also, $V_{1'}$, $V_{2'}$, V_{LO} and V_{Hi} are the initial voltage values on the rectifier and inverter side and their change amplitude, respectively. P_{HVDC0} the range of change of active power values is HVDC. The rest of the information related to buses, lines and generator information is available in reference [38].

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