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Enhancement of power flow using FACTS systems

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Abstract

In this paper, both standard IEEE test systems 57-bus and Algerian 59-bus are considered. To enhance the power flow of these two considerable networks in terms of voltage profile and reduce the real and reactive total transmission losses, the inclusion of flexible alternating current transmission systems (FACTS) devices is one of the best solutions. For this, a static synchronous compensator (STATCOM) is proposed. Our code is written in the MATLAB computing environment, based on finding the weakest buses in the network, and placing one or two STATCOMs in an appropriate place; in the next step, there would be recalculation of the power flow again. The results of power flow compared with the popular MATPOWER software environment show the exactitude of our code calculation, and the enhancement of voltage profile, especially in buses where STATCOM is placed. Furthermore, the reduction of real and reactive losses shows the effectiveness of the FACTS device proposed.

Keywords: FACTS, STATCOM, MATLAB, MATPOWER.

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Nomenclature

V_{vR}, STATCOM voltage magnitude

$\mathrm{X}_{\mathrm{nAC}}$ AC network state variables

R_{nF}, controller state variable

δ_{vR}, STATCOM voltage angle

V_k, voltage magnitude at bus k

θ_k, voltage angle at bus k

P_{vR}, STATCOM active power

Q_{vR}, STATCOM reactive power

P_k, active power at bus k

Q_k, reactive power at bus k

1. Introduction

Continuously satisfying the electrical power contracted by consumers is a great challenge that engineering faces and which modern electrical power systems aim to solve when several operational policies are to be observed. Some of these policies are the nodal voltage magnitudes must be kept within narrow boundaries, and the total real and reactive losses must be kept as low as possible [1].

Many attempts were made to find possible ways to enhancement of the voltage profile and reduction of transmission losses of a network. To satisfy these two crucial goals, flexible alternative current transmission system (FACTS) devices are found to be the most suitable and appropriate solution that works near the steady stability limit [2, 3]. Placing FACTS devices appropriately in the power system and paying attention to their size is what guarantees the complete goal.

A static compensator or static synchronous compensator (STATCOM) can be defined as one of the FACTS device members. It is composed of a voltage source converter and is shunt connected to the network. Once a DC capacitor creates the voltage source, the STATCOM can work at exchanging reactive power with the network [5]. STATCOM can also be used to improve the voltage profile and reduce losses in a network.

This paper aims at solving the problem of voltage collapse, keeping it between narrow boundaries, and reducing both total real and reactive losses throughout by installing STATCOM in the weakest buses. The standard IEEE 57-bus and Algerian 59-bus test systems are used to seek and test the performance of the intended device.

1. FACTS Modelling

1.1. Building of Jacobian Matrix Including FACTS Controllers

Due to its simplicity, uncomplicatedness and strong convergence, the Newton–Raphson method is the most useful and preferable method for calculation of the highest networks power flow [6, 7]. This approach uses iteration to solve the following set of non-linear algebraic equations:

$$\begin{cases} f_1(x_1, x_2, \ldots, x_n) = 0 \\ f_2(x_1, x_2, \ldots, x_n) = 0 \\ \quad\quad . \\ \quad\quad . \\ f_n(x_1, x_2, \ldots, x_n) = 0 \end{cases}$$

, or $F(X) = 0$ (1) where ‘F’ represents the set of ‘*n*’ non-linear equations, and ‘X’ is the vector of ‘*n*’ unknown state variables.

Furthermore, the state variables describing FACTS devices and those describing the power network are combined in one single frame of reference to get a unified, iterative solution through the Newton–Raphson method [8–10]. The aforementioned approach mingles the alternating current (AC) network and power system controller state variables in a single system of simultaneous equations

$$\begin{cases} f(X_{nAC}, R_{nF}) = 0 \\ g(X_{nAC}, R_{nF}) = 0 \end{cases} \tag{2}$$

where X_{nAC} represents the AC network state variables, so-called nodal voltage magnitudes and phase angles, and R_{nF} stands for the power system controller state variables.

The extension in the dimensions of the Jacobian, compared with the case when there are no FACTS devices, is proportional to the number and kind of such devices. Figure 1 illustrates the structure of the modified Jacobian matrix [1].

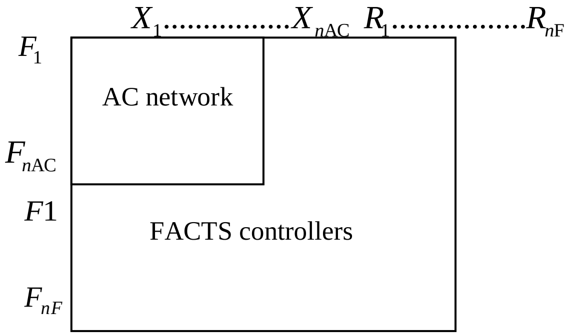

Figure 1. DFIM supplied by two PWM inverters

1.2. Model of STATCOM

For the purpose of positive sequence power flow analysis, a well-represented STATCOM through a synchronous voltage source with maximum and minimum voltage magnitude limits is needed. This synchronous source is made up of the fundamental Fourier series component of the switched voltage waveform at the AC converter terminal of STATCOM [11, 12].

The bus at which the STATCOM is connected is represented as a PV bus, which may change to a PQ bus in the event of limits being violated. Here, the absorbed or produced reactive power will correspond to the violated limit. Figure 2 shows the STATCOM equivalent circuit that is used to derive the mathematical model of the controller [1].

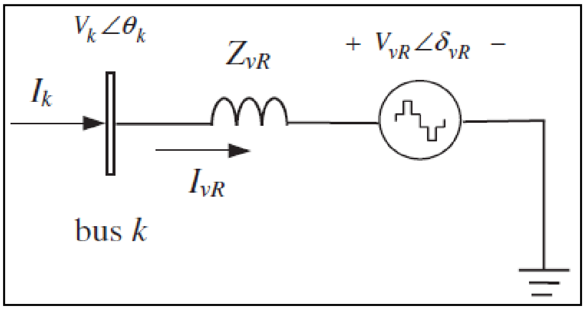

Figure 2. Static compensator (STATCOM) equivalent circuit [1]

The power flow equations for the STATCOM are derived below from first principles and assuming the following voltage source representation:

$$E_{vR} = V_{vR}(cos\,\delta_{vR} + j\sin\delta_{vR}) \tag{3}$$

Based on the shunt connection shown in Figure 2, the following may be written:

$$S_{vR} = V_{vR} I^*{}_{vR} = V_{vR} Y^*{}_{vR} (V^*{}_{vR} - V^*{}_k) \tag{4}$$

After performing some complex operations, the following active and reactive power equations are obtained for the converter and bus *k*, respectively:

$$\left\{ \begin{aligned} P_{vR} &= V_{vR}{}^2 G_{vR} + V_{vR} V_k \left[G_{vR} \cos\left(\delta_{vR} - \theta_k\right) + B_{vR} \sin\left(\delta_{vR} - \theta_k\right) \right] && (5) \\ Q_{vR} &= -V_{vR}{}^2 B_{vR} + V_{vR} V_k \left[G_{vR} \sin\left(\delta_{vR} - \theta_k\right) - B_{vR} \cos\left(\delta_{vR} - \theta_k\right) \right] && (6) \end{aligned} \right.$$

$$\left\{ \begin{aligned} P_k &= V_k{}^2 G_{vR} + V_k V_{vR} \left[G_{vR} \cos\left(\theta_k - \delta_{vR}\right) + B_{vR} \sin\left(\theta_k - \delta_{vR}\right) \right] && (7) \\ Q_k &= -V_k{}^2 B_{vR} + V_k V_{vR} \left[G_{vR} \sin\left(\theta_k - \delta_{vR}\right) - B_{vR} \cos\left(\theta_k - \delta_{vR}\right) \right] && (8) \end{aligned} \right.$$

Using these power equations, the linearised STATCOM model is given below, where the voltage magnitude V_{vR} and phase angle δ_{vR} are taken to be the state variables

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \\ \Delta P_{vR} \\ \Delta Q_{vR} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_k}{\partial \theta_k} & \frac{\partial P_k}{\partial V_k} V_k & \frac{\partial P_k}{\partial \delta_{vR}} & \frac{\partial P_k}{\partial V_{vR}} V_{vR} \\ \frac{\partial Q_k}{\partial \theta_k} & \frac{\partial Q_k}{\partial V_k} V_k & \frac{\partial Q_k}{\partial \delta_{vR}} & \frac{\partial Q_k}{\partial V_{vR}} V_{vR} \\ \frac{\partial P_{vR}}{\partial \theta_k} & \frac{\partial P_{vR}}{\partial V_k} V_k & \frac{\partial P_{vR}}{\partial \delta_{vR}} & \frac{\partial P_{vR}}{\partial V_{vR}} V_{vR} \\ \frac{\partial Q_{vR}}{\partial \theta_k} & \frac{\partial Q_{vR}}{\partial V_k} V_k & \frac{\partial Q_{vR}}{\partial \delta_{vR}} & \frac{\partial Q_{vR}}{\partial V_{vR}} V_{vR} \end{bmatrix} \begin{bmatrix} \Delta \theta_k \\ \frac{\Delta V_k}{V_k} \\ \Delta \delta_{vR} \\ \frac{\Delta V_{vR}}{V_{vR}} \end{bmatrix} \tag{9}$$

2. Application and Results

In order to illustrate the effectiveness of the proposed STATCOM device, it has been tested on the IEEE 57- and Algerian 59-bus test systems. The upper and lower boundaries of voltage magnitude of both networks are considered as 1.1 and 0.95 pu, respectively. The developed program code is written in the MATLAB computing environment and applied on a 2.10-GHz personal computer with 2-GB RAM. The performance of STATCOM was verified in terms of minimising the total real and reactive losses $\boldsymbol{P_{loss}}$ and $\boldsymbol{Q_{loss}}$, and voltage deviation $\boldsymbol{\Delta V}$ in each bus *k*, where

$$\boldsymbol{\Delta V} = |\boldsymbol{V_{ref}} - \boldsymbol{V_k}| \tag{10}$$

In order to achieve a very important enhancement of voltage profile, we take the reference value as 1 pu. Therefore, Eq. (10) becomes

$$\Delta V = |1 - V_k| \tag{11}$$

In the PF problem, two cases in terms of the number of STATCOMs are considered, namely,

- Case 1: Only one STATCOM
- Case 2: Two identical STATCOMs

2.1. IEEE 57-Bus Test System

In order to evaluate the effectiveness and robustness of the proposed STATCOM controller, a wider test system consisting of 57 buses with and without STATCOM is considered to solve the PF problem. This system consists of seven generators, 42 loads of 1250.8 MW and 336.4 MVar, three shunt capacitors at buses 18, 25 and 53, 80 branches, 17 transformers with off-nominal tap ratio at lines (4–18, 4–18, 21–20, 24–25, 24–25, 24–26, 7–29,34–32, 11–41, 15–45, 14–46, 10–51, 13–49, 11–43, 40–56, 39–57 and 9–55). In addition, the detailed line, bus data and generator data are given in [13].

2.1.1. Case 1: One STATCOM Only

The first case investigated in this paper consists of minimising the total real and reactive losses, and voltage deviation at all buses throughout using only one STATCOM. The STATCOM parameters are taken from [14] and are tabulated in Table 1. Note that these parameters are retaken for all the remaining sections.

Table 1. STATCOM parameters

Upper voltage limit $V_{vR}{}^{max}$	1.10 pu
Lower voltage limit $V_{vR}{}^{min}$	0.9 pu
Upper phase angle limit $\delta_{vR}{}^{max}$	0°
Lower phase angle limit $\delta_{vR}{}^{min}$	−20°
Resistance of equivalent STATCOM converter R_{vR}	0.01 pu
Reactance of equivalent STATCOM converter X_{vR}	0.1 pu
Upper reactive power limit of STATCOM $Q_{vR}{}^{max}$	0.5 pu
Lower reactive power limit of STATCOM $Q_{vR}{}^{min}$	−0.5 pu

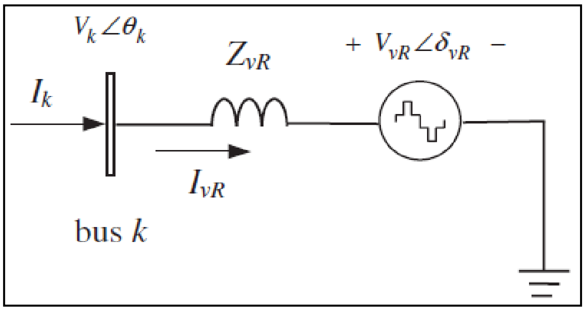

Figure 3. System voltage profile improvement with one STATCOM compared without FACTS

Figure 3 depicts the voltage magnitude of all the 57 buses without and with STATCOM. It can be seen that when no FACTS devices are installed in the network, the voltage magnitudes of buses 31 and 33 are 0.936 and 0.948 pu, respectively, and consequently they overstep the lower boundary of 0.95 pu. After calculation of voltage deviation in the violated buses, the code considers the most violated between them as the weakest bus in the network and places it in STATCOM. It is clear from the figure that the voltage magnitude in bus 31 where STATCOM is installed is at the reference value 1 pu. We also notice from this figure that the voltage profile has been greatly improved, especially in the buses relatively near to the STATCOM bus, namely, 30, 31, 32 33, 34, 35, 36 and 37, as shown in Table 2.

Table 2. Enhancement of voltage magnitudes of buses near to STATCOM

Bus	Voltage magnitude without FACTS	Voltage profile with STATCOM
30	0.963	1.008
31	0.936	1.000
32	0.950	0.992
33	0.948	0.990
34	0.959	0.972
35	0.966	0.977
36	0.976	0.985
37	0.985	0.993

Furthermore, the installation of STATCOM at bus 31, with −0.0641 pu of reactive power, provides the minimum of total real power losses of 27.527 MW compared with 27.864 MW without FACTS. Percentage wise, this reduction is equivalent to 1.21%. Similarly, the total reactive losses are minimized from 121.67 to 120.46 MVar at 1%.

2.1.2. Case 2: Two Identical STATCOMs

In this case study, two identical STATCOMs are coordinated in order to minimize better the total losses and voltage deviation. The voltage magnitude curve associated with the 57 buses is presented as seen in Figure 4. It appears from this figure that in the presence of two STATCOMs, the enhancement of voltage profile is better compared to the only one STATCOM case. We can summarize from Table 3 the voltage magnitude of STATCOM buses 31 and 33, and the nearest buses to the FACTS area. It is also worth mentioning that in this region, the enhancement of voltage profile is clearly noted in the same buses of the only one STATCOM case, but with greater improvement in buses 32, 33, 34, 35, 36 and 37; for example, the voltage deviation in bus 32 is 0.05 pu without FACTS, and it decreases to become 0.008 pu with one STATCOM, but in the presence of two STATCOMs, ΔV reaches 0.001 pu, which shows the number of FACTS effects in the improvement of the voltage profile.

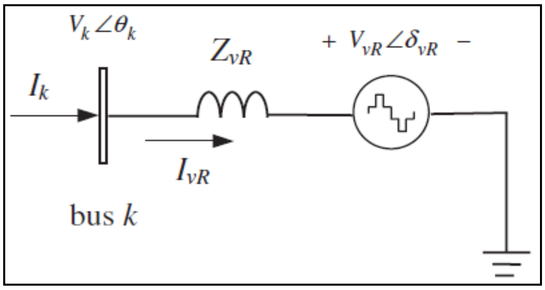

Figure 4. System voltage profile improvement with two STATCOMs compared without FACTS and case 1

Table 3. Enhancement of voltage magnitudes of buses near to the FACTS area (case 2)

Bus	Voltage magnitude without FACTS	Voltage profile with STATCOM	Voltage profile with two (case 2) STATCOMs
30	0.963	1.008	1.008
31	0.936	1.000	1.000
32	0.950	0.992	1.001
33	0.948	0.990	1.000
34	0.959	0.972	0.974
35	0.966	0.977	0.979
36	0.976	0.985	0.986
37	0.985	0.993	0.994

Otherwise, the code calculates the appropriate reactive power of −0.051 and −0.0194 pu for each STATCOM installed in buses 31 and 33, respectively. Hence, the total real and reactive losses are more minimized compared with the first case, which convinces us of the importance of installing more FACTS devices in large-scale power systems. The total losses values and the percentage reduction are given in Table 4.

Table 4. Total losses reduction in different cases

	Without FACTS	With 1 STATCOM	With 2 STATCOMs	Reduction (%)
Ploss (MW)	27.864	27.527	27.461	1.21; 1.44; 0.23
Qloss (MVar)	121.67	120.46	120.29	1; 1.13; 0.13

Note that the percentage reduction values are successively between case 1 and initial case (without FACTS); case 2 and initial case; case 2 and case1.

2.2. Algerian 59-Bus Test System

In order to provide a more practical aspect to our work, we repeat the same cases studied in the previous section, but applied on the Algerian 59-bus test system. This network is composed of 59 buses, 10 generators, 36 loads of 684.10 MW and 311.6 MVar and 83 branches [15, 16]. It is worth mentioning that generator no. 5 at bus 13 is not in service [17]. The line data, bus data and generator data are given in [17].

2.2.1. Case 1: One STATCOM Only

It would be worth to recall that the STATCOM parameters remain the same as in Table 1 for all the sections. From Figure 5, it is easy to see that there are a lot of buses that violate the lower voltage limit, namely, 8, 14, 17, 35, 36, 43, 47 and 48, which present that more than 13% of the system buses have a voltage collapse. Hence, the most voltage deviation is marked in bus 36 with 0.168 pu, which makes it the most suitable placement for the STATCOM device.

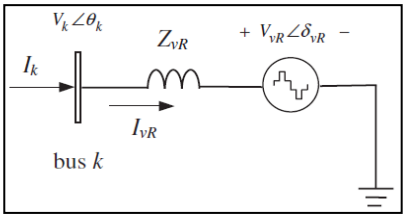

Figure 5. System voltage profile improvement with one STATCOM of the Algerian 59 bus test system

Table 5. Enhancement of voltage magnitudes of buses near to STATCOM for the Algerian network

Bus	Voltage magnitude without FACTS	Voltage profile with STATCOM
8	0.938	0.938
14	0.932	0.932
17	0.946	0.946
35	0.935	0.936
36	0.832	1.000
43	0.934	0.983
47	0.947	0.947
48	0.833	0.833

On subject of total losses, our code finds the appropriate value of the STATCOM reactive power of −0.1857 pu to possibly minimise the total real and reactive losses. Compared with the basic case (i.e. without FACTS), we can see that the total real loss is reduced from 29.141 to 28.878 pu. Percentage wise, this reduction is nearly equivalent to 1%. Otherwise, the total reactive loss is also reduced from 97.61 to 96.64 pu with a percentage of 1%.

2.2.2. Case 2: Two Identical STATCOMs

The same as in Section 3.1.2, two identical STATCOMs are considered, but applied on the Algerian test system. Taking into account both the objectives of enhancement of voltage profile and minimising total losses, our code finds buses 36 and 47 as the most suitable placements for the two STATCOMs. Hence, the voltage magnitude curve of the 59 buses is shown in Figure 6, wherein we can easily see the improvement in voltage profile compared with case 1 and without FACTS, especially near the FACTS area, namely, buses 7, 43, 47, 49, 52 and 56. Table 6 shows the voltage magnitude values of the STATCOMs area buses in the basic case, cases 1 and 2.

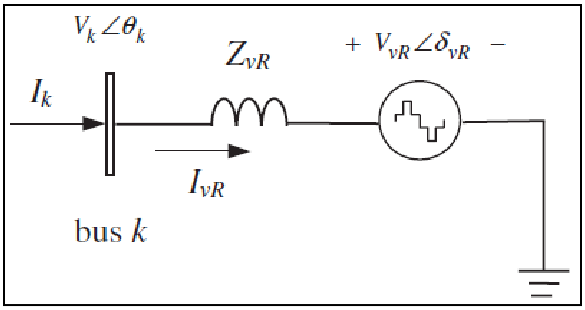

Figure 6. Voltage profile improvement with two STATCOMs compared without FACTS and case 1 for the Algerian network

Table 6. Enhancement of voltage profile of buses near to the STATCOMs area (case 2)

Bus	Voltage magnitude without FACTS	Voltage profile with STATCOM	Voltage profile with two (2) STATCOMs
7	0.981	0.981	0.992
36	0.832	1.000	1.000
47	0.947	0.947	1.000
49	0.953	0.953	0.971
52	0.968	0.993	0.993
56	0.957	0.957	0.974

The appropriate reactive powers of STATCOMs installed in buses 36 and 47 calculated by the code are, respectively, −0.1857 and −0.1160 pu. Thus, the total real and reactive losses are more minimized compared with case 1, which is positive proof for the great necessity for installing more FACTS devices in the large-scale power systems. The details are given in Table 7, showing the total real and reactive losses and the percentage reduction.

Table 7. Total real and reactive losses in different cases for the Algerian test system

	Without FACTS	With 1 STATCOM	With 2 STATCOMs	Reduction (%)
Ploss (MW)	29.141	28.878	28.480	0.9; 2.27; 1.38
Qloss (MVar)	97.61	96.64	95.52	1; 2.14; 1.15

3. Conclusion

In this paper, we have introduced the popular FACTS devices to solve the PF problem, that is, the STATCOM. This electronic compensator is connected parallel to the specific bus of a power system in which its primary goal is to enhance the reactive power compensation, which adjusts the reactive power and voltage magnitude of the power system network. STATCOM has been integrated and tested in large-scale networks, such as the standard IEEE 57-bus and the Algerian 59-bus test systems, for two cases in terms of the number of STATCOMs: in the first case, only one STATCOM is considered, while in the second case, two STATCOMs are coordinated to work simultaneously in order to enhance the voltage profile and minimise the total real and reactive losses. The obtained results show the effectiveness and robustness of the proposed STATCOM device. Finally, as a future work we propose to introduce other FACTS devices like UPFC and HVDC, taking into account the case of single or multiple types.

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