Optimal Power Flow using FACTS Devices in Electrical Network with Wind Generator

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Abstract: *Wind power is a means of producing efficient, effective and sustainable. In terms of electricity generation, it is one of the streams cleaner, safer and faster to implement and also renewable. But the increase in wind power has an increasing impact on the electricity grid because of the difficulty in predicting the production, the limited capacity of the network, the risk of unwanted disconnections wind farms and degradation of electricity quality.*
This paper presents a solution to the optimal active power dispatch problem following the arrival of wind generators on the electrical network. The use of FACTS devices, such as thyristor controlled series compensators (TCSC); the power system can be operated in such a way that the total power production cost is minimized. The Static Compensator (STATCOM) will be also used to improve the power quality of wind generation by maintaining the voltage level.

Key words: *Wind power, STATCOM, TCSC, Newton Raphson algorithm, Voltage control, Economic dispatch.*

1. Introduction

During the last decades, an increase in electricity demand and environmental concern resulted in fast growth of power production from renewable sources. Wind power is one of the most efficient alternatives. Due to rapid development of wind turbine technology and increasing size of wind farms, wind power plays a significant part in the power production in some countries.

The problem of economic dispatch of a network of production and transportation of energy has always been an intensely studied topic in the history of electricity. Numerous publications on this subject are a clear proof. The complexity of the optimization problem of the flow of power, especially in an environment of the free electricity market, with the emergence of new constraints on emissions of pollutant gases and the use of renewable energy sources, that have it is necessary to use accurate methods of solution given the inflexibility of traditional methods incorporating various constraints.

Numerous publications on this subject are an evident proof. The author in [1] presents a new approach to determine the power that can be extracted from a wind farm for a given wind speed, while dispatching the rest of the system to have minimum cost. The work presented in [2] characterizes the stochastic wind power via probability distribution function and cumulative distribution function; analyzes the integrated cost of wind power in the context of dynamic economic dispatch. In [3], the authors propose a new simulation method that can fully assess the impacts of large-scale wind power on system operations from cost, reliability, and environmental perspectives.

Several other studies have addressed the problem of optimal power distribution using flexible compensators only [4-8] or with only the presence of the wind power into the power network, in this paper a different view is adapted to solving the problem of power flow dispatching with the presence of wind generator in the network and at the same time the use of Flexible AC Transmission Systems 'FACTS' as compensators.

The introduction of FACTS in power networks, is considered as, a key element in research and in the development of tomorrow's networks. These devices are solutions that enable network operators to increase the power capacity of existing equipment, while maintaining or improving the operating margins necessary for grid stability. This increases the amount of power delivered to the load centers with minimal impact on the environment, with projects much faster to implement and capital expenditure reduced compared to alternatives such as the construction of new transmission lines or new means of production.

The aim of this work is firstly; find the optimal locations of TCSC devices for optimal distribution of power in an electrical network with the integration of wind generator. This device installed in series in the line will allow to control the power flow in the network and to compensate the inductive voltage drop by inserting a capacitive voltage. Indeed, when several parallel paths lead to the same node, the control of the reactance of the line, allows forcing the power flow in lines underutilized and thus reducing the burden of overloaded lines or near their thermal limits. Secondly, the impact of inserting the wind generator in the grid is not negligible and leads the voltage control problem. Compensation is proposed by installing STATCOM device for voltage control by the control of reactive power at the connection point of the wind generator. Both devices TCSC and STATCOM are adjusted to achieve an optimal level of compensation within the constraints of power and voltage, to maximize the power flow in an electrical network with wind generator for the economic power distribution and voltage stability.

2. Economic dispatch considering line losses

The power losses in the transmission lines will vary depending on the distribution of power between the station and the load. Economic dispatch with loss takes into account the network topography. To penalize stations that produce power whose transit causes significant losses, their incremental cost is multiplied by a penalty factor. The physical justification of this penalty factor is explained by the fact that, because of the losses, it may be more interesting to produce more expensive near the place of consumption that far and cheaper. The economic dispatch with loss is an iterative process that must converge to the optimal solution [9]. If the power losses are considered constants, they must be evaluated and included in the request.

The total power demanded Pd is related to the total power generated in addition to the losses in the lines by the following relation:

$$P_D + P_L - \sum_{i=1}^{n} P_{Gi} = 0 \qquad (1)$$

It must also be ensured that the power generated by each station remains within the limits imposed which are modeled by the following inequality equations:

$$\begin{cases} P_{Gi} \le P_{Max\,i} \Longrightarrow P_{Gi} - P_{Max\,i} \le 0 \\ P_{Min\,i} \le P_{Gi} \Longrightarrow P_{Min\,i} - P_{Gi} \le 0 \end{cases} \quad (2)$$

P_{Gi}: The power generated by the station i.
P_D: The total power required.
$P_{Max\ i}$: The maximum power generated by the station i.
$P_{Min\ i}$: The minimum power generated by the station i.
n: number of the centrals.

The cost associated with the total power generated is given by:

$$C_T = \sum_{i=1}^{n} C_i(P_{Gi}) \quad (3)$$

It is this feature that will minimize costs to achieve optimal operation.
Two approaches are used primarily for economic dispatching solution with losses; the first is the development of a mathematical expression of loss in function of the output powers of each production unit. The second approach is to use the equations of optimum power flow.

2.a. Economic dispatch with losses in terms of generated power:

In real networks, the electrical generators are located near the electric charge, while the transmission losses become important.

Considering the diagram of Fig.1, we obtain the expression:

$$P_L = 3.(R_{L1}.|I_{L1}|^2 + R_{L2}.|I_{L2}|^2 + + R_{L3}.|I_{L3}|^2) \quad (4)$$

Knowing that the currents in the three lines may be expressed as:

$$\begin{cases} |I_{L1}| = \frac{P_{G1}}{\sqrt{3}.V_{G1}.cos\varphi_{G1}} \\ |I_{L2}| = \frac{P_{G2}}{\sqrt{3}.V_{G2}.cos\varphi_{G2}} \\ |I_{L3}| = \frac{P_{G3}}{\sqrt{3}.V_{G3}.cos\varphi_{G3}} \end{cases} \quad (5)$$

The general expression of the losses in terms of generating power is obtained by replacing the current in expression (4):

$$P_L = A.P_{G1}^2 + B.P_{G2}^2 + C.(P_{G1} + P_{G2}) \quad (6)$$

with,

$$\begin{cases} A = \frac{R_{L1}}{V_{G1}^2.cos^2\varphi_{G1}} + \frac{R_{L3}}{V_{G3}^2.cos^2\varphi_{G3}} \\ B = \frac{R_{L2}}{V_{G2}^2.cos^2\varphi_{G2}} + \frac{R_{L3}}{V_{G3}^2.cos^2\varphi_{G3}} \\ C = 2.\left(\frac{R_{L3}}{V_{G3}^2.cos^2\varphi_{G3}}\right) \end{cases}$$

The general expression given by:

$$P_L = B_{11}.P_{G1}^2 + 2.B_{12}.P_{G1}.P_{G2} + B_{22}. \quad (7)$$

In general, we obtain the general expression of the following losses:

$$P_L = \sum_{i=1}^{n} \sum_{j=1}^{n} P_{Gi}\,.B_{ij}.P_{Gj} \quad (8)$$

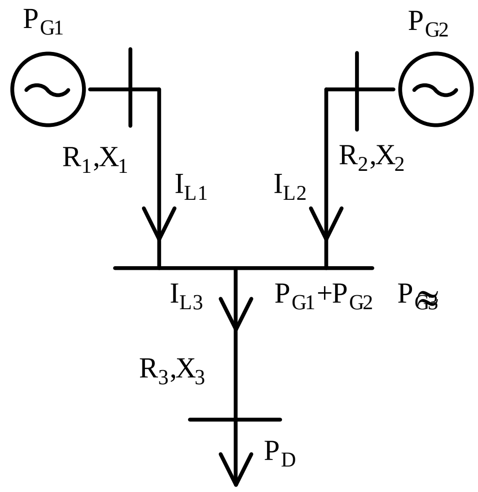


Fig. 1: Line with three generators

2.b. Economic dispatch solution by Lagrange's method

It is considered that P_L can be expressed in terms of P_{Gi}, the Lagrangian is then given by:

$$L = C_T + \lambda.(P_D + P_L - \sum_{i=1}^{n} P_{Gi}) \quad (9)$$

The derived of expression (9) with respect to P_{Gi} and λ :

$$\begin{cases} \frac{dL}{dP_{Gi}} = \frac{dC_i}{dP_{Gi}} - \lambda\left(1 - \frac{dP_L}{dP_{Gi}}\right) = 0 \\ \frac{dL}{d\lambda} = 0 \quad \Longrightarrow \quad P_D + P_L - \sum_{i=1}^{n} P_{Gi} = 0 \end{cases} \quad (10)$$

With $\frac{dL}{dP_{Gi}}$ is called incremental loss.

From expression (10), $\frac{dL}{dP_{Gi}} = 0$ implies that:

$$\frac{dC_i}{dP_{Gi}} = \lambda\left(1 - \frac{dP_L}{dG_i}\right) \quad (11)$$

The derived of expression (8) from P_{Gi} and replacing in equation (11), we have:

$$\begin{cases} \frac{dC_i}{dP_{Gi}} = \lambda(1 - 2.\sum_{j=1}^{n} B_{ij} \,.\, P_{Gj}) \\ \qquad \text{for} \quad P_{Gi} = P_{Gj} \end{cases} \quad (12)$$

3. Modeling of TCSC

The TCSC is a serial device which allows the control of the active energy flowing in a transmission line and this by the introduction of a variable reactance in series with the impedance of the line.

This system uses fixed value capacitors placed in parallel over the inductors controlled by a variable current thyristor, in order to make the adjustment of the capacitive or inductive compensation, respectively, beyond and below the resonant frequency [10]. The diagram of a TCSC is described in Fig.2.

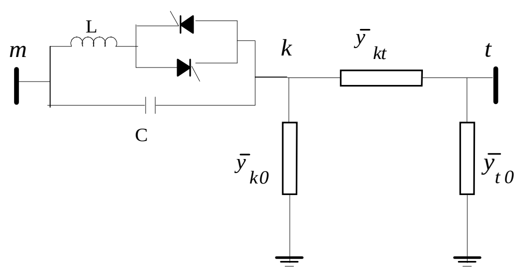


Fig. 2: Inserting the TCSC in line

Several mathematical models of the TCSC steady state proposed in the literature.

The electrical characteristics of the devices are translated and replaced by powers injected. Another method is to model the TCSC as variable reactance whose values depend on the firing angle of the thyristors. This device allows a continuous control of the reactance offered by the TCSC.

The fundamental expression of the TCSC impedance, as a function of the firing angle of thyristor, is given by the following expression [11-13]:

$$X_{TCSC} = -X_C + K_1\{2(\pi - \alpha_{TCSC}) + \sin(2(\pi - \alpha_{TCSC}))\} - K_2 \cos^2(\pi - \alpha_{TCSC}) \times \{\overline{\omega} \cdot \tan(\overline{\omega} \cdot (\pi - \alpha_{TCSC})) - \tan(\pi - \alpha_{TCSC})\} \quad (13)$$

where,

$$\begin{cases} X_{LC} = \frac{X_C \cdot X_L}{X_C - X_L} \\ K_1 = \frac{X_C + X_{LC}}{\pi} \\ K_2 = \frac{4 \cdot X_{LC}^2}{\pi \cdot X_L} \\ \overline{\omega} = \sqrt{\left(\frac{X_L}{X_C}\right)} \end{cases}$$

With $X_C = \frac{1}{C\omega}$ the reactance of the bank and capacity $X_L = L\omega$ is the reactance of the linear inductor. α_{TCSC} is the firing angle after the passage through zero of the voltage across the capacitor.

With, $\overline{\omega} = \frac{\omega_0}{\omega}$, $\omega_0 = \frac{1}{\sqrt{LC}}$ and $\omega = 2\pi f$

The equations of active and reactive powers of TCSC at node k are given by:

$$\begin{cases} P_k = V_k \cdot V_m \cdot B_{km} \cdot \sin(\theta_k - \theta_m) \\ Q_k = -V_k^2 \cdot B_{kk} - V_k \cdot V_m \cdot \cos(\theta_k - \theta_m) \end{cases} \quad (14)$$

Where, $B_{kk} = -B_{km} = -\frac{1}{X_{TCSC}}$, For equations at node m; k is exchanged by the index m in equations (14). In the case where the TCSC control the active power flowing from node k at node m to a specified value, the set of power flow equations is:

$$\begin{bmatrix} \Delta P_k \\ \Delta P_m \\ \Delta Q_k \\ \Delta Q_m \\ \vdots \\ \vdots \\ \Delta P_{km}^{\alpha_{TCSC}} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_k}{\partial \delta_k} & \frac{\partial P_k}{\partial \delta_m} & \frac{\partial P_k}{\partial V_k} & \frac{\partial P_k}{\partial V_m} & \frac{\partial P_k}{\partial \alpha_{TCSC}} \\ \frac{\partial P_m}{\partial \delta_k} & \frac{\partial P_m}{\partial \delta_m} & \frac{\partial P_m}{\partial V_k} & \frac{\partial P_m}{\partial V_m} & \frac{\partial P_m}{\partial \alpha_{TCSC}} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{\partial P_{km}^{\alpha_{TCSC}}}{\partial \delta_k} & \frac{\partial P_{km}^{\alpha_{TCSC}}}{\partial \delta_m} & \frac{\partial P_{km}^{\alpha_{TCSC}}}{\partial V_k} & \frac{\partial P_{km}^{\alpha_{TCSC}}}{\partial V_m} & \frac{\partial P_{km}^{\alpha_{TCSC}}}{\partial \alpha_{TCSC}} \end{bmatrix} \begin{bmatrix} \Delta \delta_k \\ \Delta \delta_m \\ \Delta V_k \\ \Delta V_m \\ \Delta \alpha_{TCSC} \end{bmatrix} \quad (15)$$

where, $\Delta P_{km}^{\alpha_{TCSC}}$, is given by :

$$\Delta P_{km}^{\alpha_{TCSC}} = P_{km}^{reg} - P_{km}^{\alpha_{TCSC,cal}} \quad (16)$$

It is the error on the active power transited to the module TCSC, $\Delta\alpha_{\ TCSC}$ is given by:

$$\Delta\alpha_{TCSC} = \alpha_{TCSC}^{(i+1)} - \alpha_{TCSC}^{(i)} \quad (17)$$

Which is the incremental change in the firing angle of TCSC to the ith iteration, and $\Delta P_{km}^{\alpha_{TCSC,cal}}$ is calculated power using the equation 14. The Jacobian elements for the series reactance as a function of the firing angle α_{TCSC} are given as follows:

$$\frac{\partial P_k}{\partial \alpha_{TCSC}} = P_k \cdot B_{TCSC} \cdot \frac{\partial X_{TCSC}}{\partial \alpha_{TCSC}} \quad (18)$$

$$\frac{\partial Q_k}{\partial \alpha_{TCSC}} = Q_k \cdot B_{TCSC} \cdot \frac{\partial X_{TCSC}}{\partial \alpha_{TCSC}} \quad (19)$$

$$\frac{\partial B_{TCSC}}{\partial \alpha_{TCSC}} = B_{TCSC}^2 \cdot \frac{\partial X_{TCSC}}{\partial \alpha_{TCSC}} \quad (20)$$

With,

$$\frac{\partial X_{TCSC}}{\partial \alpha_{TCSC}} = -2K_1[1+\cos(2\alpha_{TCSC})] + C_2\sin(2\alpha_{TCSC}) + \left[\overline{\omega}\tan\left(\overline{\omega}(\pi-\alpha_{TCSC})\right) - \tan(\alpha_{TCSC})\right] + K_2\left(\overline{\omega}^2 \frac{\cos^2(\pi-\alpha_{TCSC})}{\cos^2(\overline{\omega}\cdot(\pi-\alpha_{TCSC}))} - 1\right) \quad (21)$$

4. Modeling of STATCOM

A STATCOM is a voltage source converter VSC connected in parallel to an AC network (transmission or distribution), in general, through a step down transformer.

If the voltage amplitude of the VSC is adjusted in order that it is higher than the network's voltage, reactive power is supplied and the voltage increases to the connection point. Similarly, if the VSC voltage is set to a value lower than the network's voltage, reactive power is absorbed by the VSC and the voltage at the connection point is reduced.

The operating range of the STATCOM is substantially symmetrical, which means that it can supply or absorb reactive power quantities almost identical [14,15].

Fig.3 shows the equivalent circuit of STATCOM connected to a node k: *(a)* Static Compensator and *(b)* Equivalent circuit.

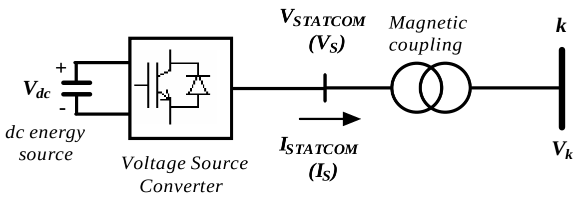


Fig. 3.a: Static compensator

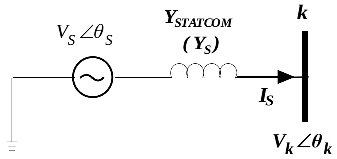


Fig. 3.b: Equivalent circuit of STATCOM

The exchange of reactive power is affected by controlling the output voltage of the inverter V_S, which is in phase with the line voltage V.

The operation may be described as follows:

- ✓ If the voltage $V_S < V$, the current flowing in the inductor is phase shifted by $-\frac{\pi}{2}$ relative to the voltage V which gives an inductive current (Fig.4.a).

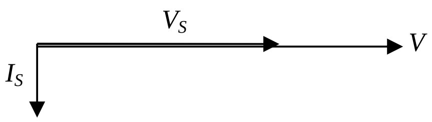


Fig. 4.a: Inductive current

- ✓ If the voltage $V_S > V$, the current flowing in the inductor is phase shifted by $+\frac{\pi}{2}$ relative to the voltage V which gives a capacitive current (Fig.4.b).

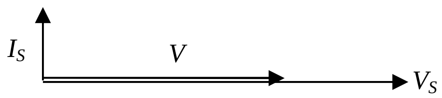


Fig. 4.b: Capacitive current

- ✓ If the voltage $V_S = V$, the current flowing in the inductor is zero and therefore there is no exchange of energy.

The node where the STATCOM is connected is considered as a PV node, which can change to a PQ node when the limits are exceeded. In such cases, the reactive power supplied or absorbed will correspond to the violated limits.

The STATCOM is represented as a voltage source for a full range of operation, a support mechanism for a voltage more robust.

The equations of the power flow of STATCOM are developed below from first principles, assuming the representation of the voltage and power as follows:

$$\bar{V}_s = V_s(\cos\delta_s + j\sin\delta_s) \qquad (22)$$

Based on the shunt connection shown in Fig.3.b, the following can be written:

$$\bar{S}_s = \bar{V}_s \cdot \bar{I}_s^* = \bar{V}_s \cdot \bar{Y}_s^* \cdot (\bar{V}_s^* - \bar{V}_k^*) \qquad (23)$$

After execution of some complex operations, the equations of active and reactive power are obtained for the converter and the node k, respectively:

$$\begin{cases} P_s = V_s^2 G_s + V_s V_k [G_s \cos(\delta_s - \theta_k) + B_s \sin(\delta_s - \theta_k)] \\ Q_s = -V_s^2 B_s + V_s V_k [G_s \sin(\delta_s - \theta_k) - B_s \cos(\delta_s - \theta_k)] \end{cases} \qquad (24)$$

and

$$\begin{cases} P_k = V_k^2 G_s + V_k V_s [G_s \cos(\theta_k - \delta_s) + B_s \sin(\theta_k - \delta_s)] \\ Q_k = -V_k^2 B_s + V_k V_s [G_s \sin(\theta_k - \delta_s) - B_s \cos(\theta_k - \delta_s)] \end{cases} \qquad (25)$$

Using these equations, the model of STATCOM is obtained, where the voltage magnitude *Vs* and the phase angle *δs* are supposedly state variables:

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \\ \Delta P_s \\ \Delta Q_s \end{bmatrix} = \begin{bmatrix} \frac{\partial P_k}{\partial \theta_k} & \frac{\partial P_k}{\partial V_k} V_k & \frac{\partial P_k}{\partial \delta_s} & \frac{\partial P_k}{\partial V_s} V_s \\ \frac{\partial Q_k}{\partial \theta_k} & \frac{\partial Q_k}{\partial V_k} V_k & \frac{\partial Q_k}{\partial \delta_s} & \frac{\partial Q_k}{\partial V_s} V_s \\ \frac{\partial P_s}{\partial \theta_k} & \frac{\partial P_s}{\partial V_k} V_k & \frac{\partial P_s}{\partial \delta_s} & \frac{\partial P_s}{\partial V_s} V_s \\ \frac{\partial Q_s}{\partial \theta_k} & \frac{\partial Q_s}{\partial V_k} V_k & \frac{\partial Q_s}{\partial \delta_s} & \frac{\partial Q_s}{\partial V_s} V_s \end{bmatrix} \cdot \begin{bmatrix} \Delta \theta_k \\ \frac{\Delta V_k}{V_k} \\ \Delta \delta_s \\ \frac{\Delta V_s}{V_s} \end{bmatrix} \qquad (26)$$

5. Numerical result

The transmission network, which will serve as the basis for this study is the IEEE 26 bus bars network. The electrical network of Fig.5 consists of 6 generators (for bus bars 1, 2, 3, 4.5, and 26) injecting their powers to a system supplying 23 loads across 46 lines.

Node 1 with the constant voltage of 1.025∠0° is considered assessment node. The network generation data are shown in Table 1, and the branch impedance, loads and other necessary data are given in [16].

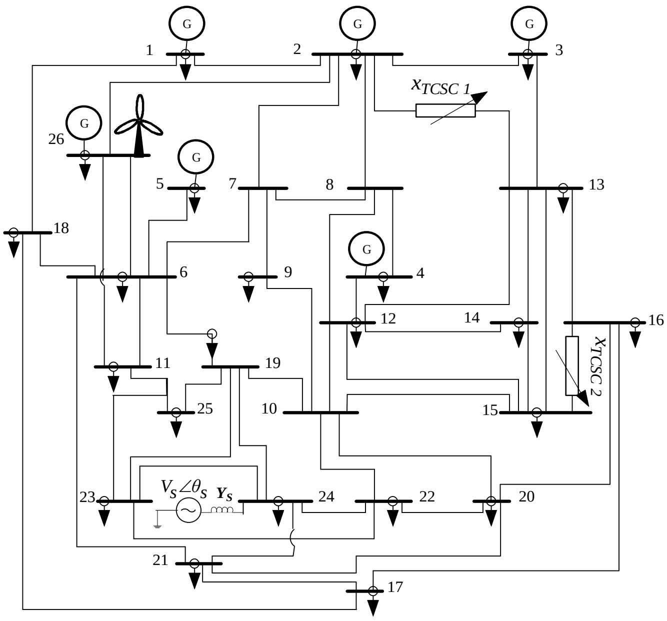


Fig. 5: IEEE 26 bus bars network

Table 1. IEEE 26-bus system generation data

Bus no.	P_G^{min}(MW)	P_G^{max}(MW)	Cost coefficients a	b	C
1	100	500	240	7	0.0070
2	50	200	200	10	0.0095
3	80	300	220	8.5	0.0090
4	50	150	200	11	0.0090
5	50	200	220	10.5	0.0080
26	50	120	190	12	0.0075

The results are obtained for five cases of the network state:

- ✓ Electrical network study without the presence of wind generator and FACTS;
- ✓ Insertion of TCSC to reduce losses in the lines (without wind generator);
- ✓ Integration of wind generator at IEEE 26 buses (without FACTS);
- ✓ Integration of the STATCOM for voltage regulation;
- ✓ Insertion of TCSC to reduce losses in the lines (with a wind generator and STATCOM).

5.1. Electrical network without wind generator and FACTS

A power flow calculation by the Newton-Raphson method is performed to assess the Busbar magnitude voltages and power lines flowing through the lines then evaluate power losses. The results are presented in Figs.6 and 7.

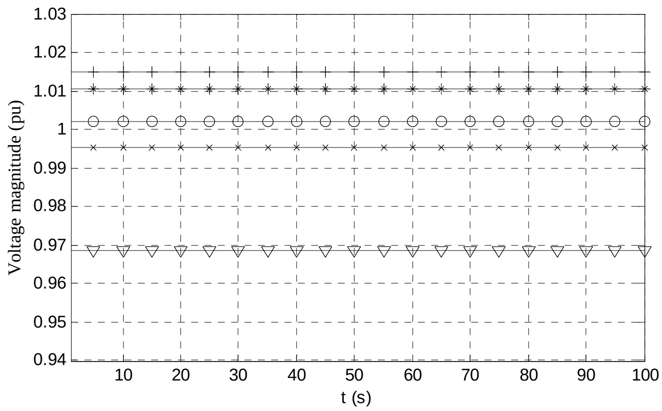


Fig. 6: Voltage magnitude at buses 6(+), 11(*), 20(x), 24(v) and 26(o) before integration of wind generator

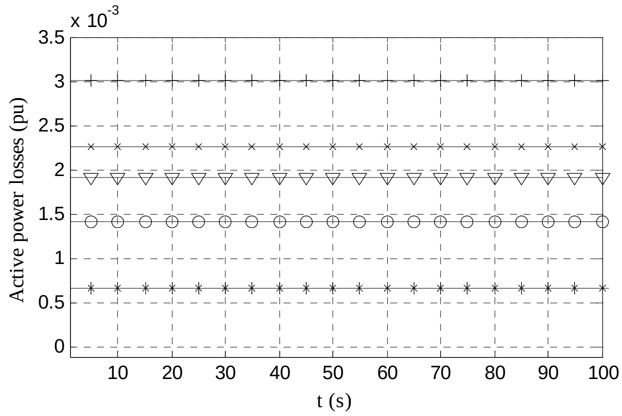


Fig. 7: Active power losses on the lines 17(*), 27(o), 33(x), 36(v) and 45(+) before integration of wind generator

5.2. Insertion of TCSC to reduce losses in the lines (without wind generator)

To show the importance from the presence of TCSC controller in the power system, power flow calculation without wind generator is initially done by installing a first TCSC controller then a second to find the optimal parameters of the controllers, that is to say, the firing angles α_{TCSC} and reactance X_{TCSC} for optimal operation of the network with minimum active power losses.

5.2.1. Power flow Calculation in the network with a single TCSC

A first controller TCSC1 is installed in the 33th (between the buses 15 and 16) whose parameters are chosen as:

Capacitive reactance X_{C1} = 0.02 pu
Inductive reactance X_{L1} = 0.007 pu
Initial value α_{TCSC1}= 142°
(α_{TCSC1_min} = 130° and α_{TCSC1_max} = 180°)

A power flow calculation was carried out to assess the network state after insertion of the TCSC1. The firing angle is considered as a state variable to be determined by the calculation. This convergence is obtained at the 7th iteration, with a firing angle of α_{TCSC1}=146.63° equivalent to a reactance controller X_{TCSC1}=-0.00273pu, therefore, a compensation of 53% of the line.

5.2.2. Power flow Calculation in a network with two TCSC

To increase the transport capacity of the network studied, a second controller TCSC2 is inserted in the network whose the calculation parameters are the same as the first case.

The first TCSC1 is kept in the same location in line (15-16) with the same characteristics and the second is inserted in line (2-13). Recalculation of the power flow is done by changing the location of the second TCSC2 to find the optimal gives minimum losses, convergence is obtained after the 18th iteration with the following results:

- ✓ For the first $TCSC_1$, reactance X_{TCSC1}= -0.0248 pu, for a firing angle α_{TCSC1} = 149.97°, compensation of the 33th line is about 48.5%.
- ✓ For the second $TCSC_2$, reactance X_{TCSC2} = -0078 pu, for a firing angle α_{TCSC2} = 132.49°, compensation of the 6th line is about 80%.

Figs.8 and 9, show the evolution of the magnitude voltages at buses 6, 11, 24 and 26, as well as the power losses in lines 6, 33, 36 and 45 according to the time after insertion of the two TCSC in lines. The simulation results clearly show the interest of these controllers in reducing the voltage drop due to the change in the impedance of the two lines that increases the amplitude of the voltage at busbars as well as power losses in the lines decrease.

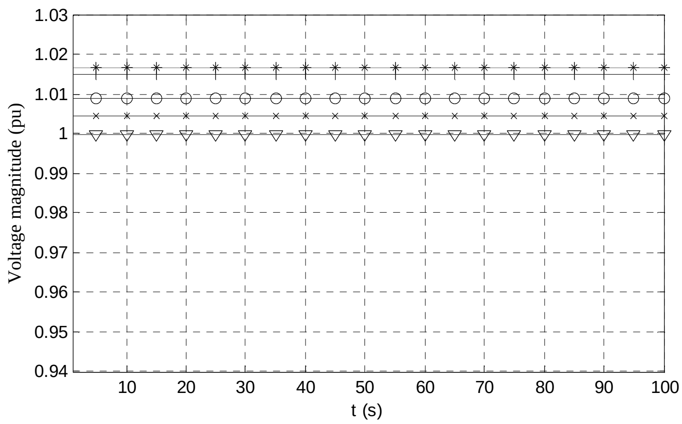
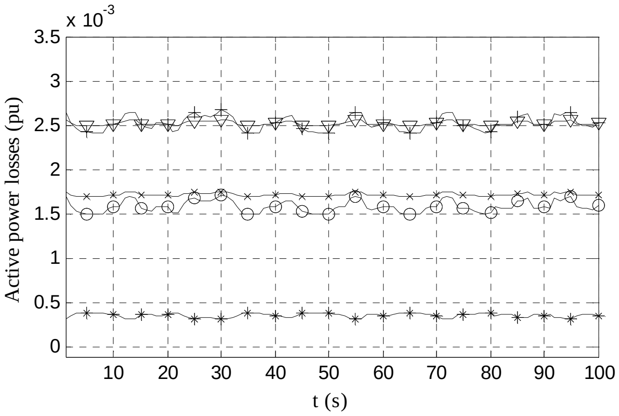


Fig. 8: Voltage magnitude at buses 6(+), 11(*), 20(x), 24(v) and 26(o) with two TCSC before integration of wind generator



9: Active power losses on the lines 17(*), 27(o), 33(x), 36(v) and 45(+) with two TCSC before integration of wind generator

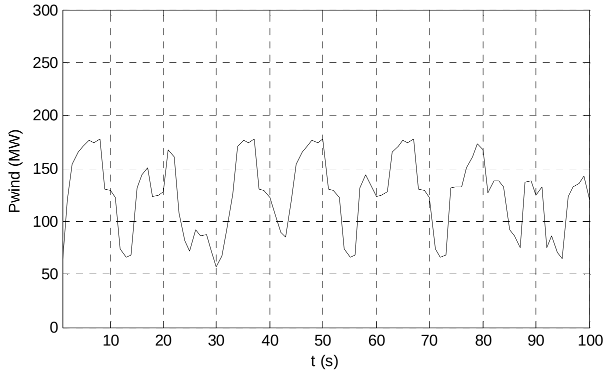


Fig. 10: Active power injected by the wind generator

5.3. Integration of wind generator

The wind generator is installed on the busbar 26, the power injected into the network is in the form shown in Fig.10. A power flow calculation is carried out to evaluate the voltage magnitude variations and power losses in the lines as shown in Figs.11 and 12.

The power injected by wind 'P_{wind}' causes disturbances of the voltage busbars, so in this case, the introduction of regulation device is necessary.

5.4. Integration of the STATCOM for voltage regulation

The STATCOM is introduced as a state variable in power flow and combined with the nodal voltage magnitudes and angles of the power network for iterative solutions [16], i.e, to find reactive power necessary for, either to compensate the hollow voltage or to decrease this value in order to obtain a stable voltage.

Noting that the parameters of the STATCOM are the inductor reactance of 10 pu, the voltage is initially set at 1.00 pu.

Figs.13 and 14 present respectively, the evolution of the voltage magnitudes at buses 6, 11, 20, 24 and 26 and the evolution of the active power losses on the lines 17, 27, 33, 36 and 45 under to the evolution of the active power delivered by the wind generator.

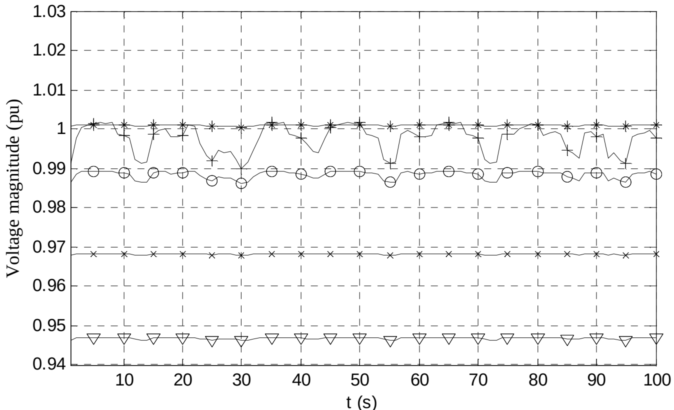


Fig. 11: Voltage magnitude at buses 6(+), 11(*), 20(x), 24(v) and 26(o) after integration of wind generator.

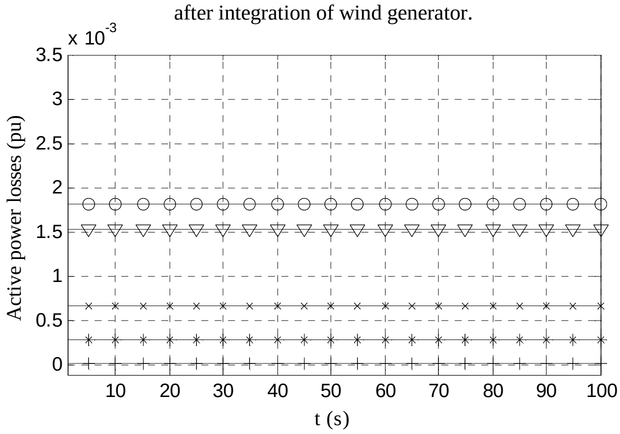


Fig. 12: Active power losses on the lines 17(*), 27(o), 33(x), 36(v) and 45(+) after integration of wind generator

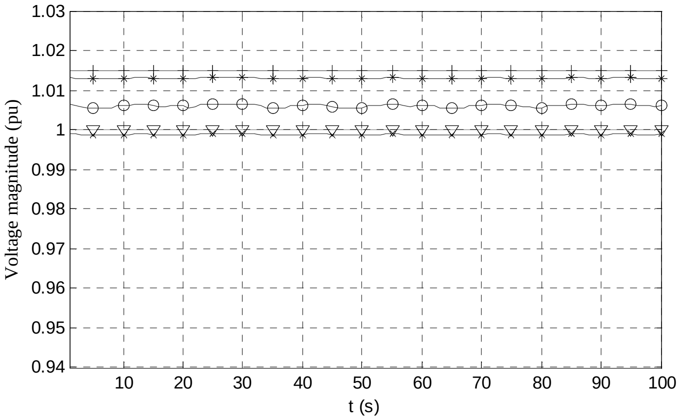


Fig. 13: Voltage magnitude at buses 6(+), 11(*), 20(x), 24(v) and 26(o) after integration of wind generator and STATCOM

Fig.13 shows that the nodal voltage at busbar which is connected to the compensator and the others buses, have more stable paces, although the variation of power injected by the wind generator, and that by injecting or absorbing the active power by STATCOM, to compensate the voltage disturbances if it exceeds or less than the desired voltage magnitude.
The results showed a better behavior with regard to the voltage support on the load bus bar and the voltage drop within the limits 5%.

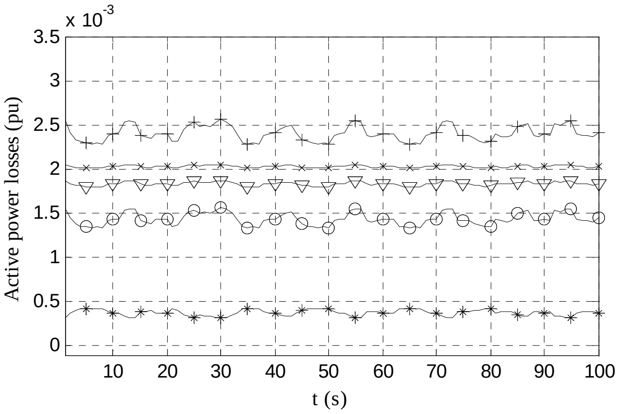


Fig. 14: Active power losses on the lines 17(*), 27(o), 33(x), 36(v) and 45(+) after integration of wind generator and STATCOM

5.5. Insertion of TCSC to reduce losses in the lines

In this section, influence of the presence of TCSC is illustrated. By design, the TCSC are intended to control the power transfer in the lines. It is this characteristic that must be observed, inserting them into the network to optimal locations already found in section 5.2. Figs.15 and 16 allow seeing the influence of TCSC on voltage busbars and verifying their performance and effectiveness in controlling the power transit, therefore reducing active power losses in the network.

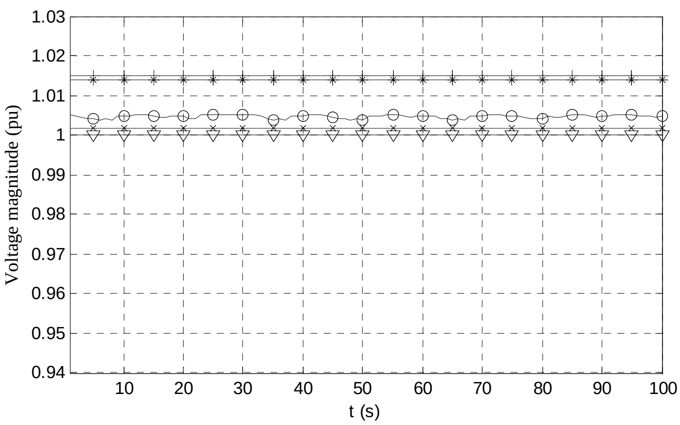


Fig. 15: Voltage magnitude at buses 6(+), 11(*), 20(x), 24(v) and 26(o) after integration of wind generator, STATCOM and TCSC

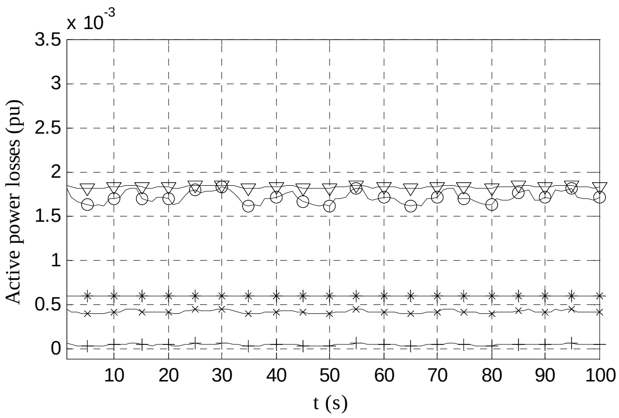


Fig. 16: Active power losses on the lines 17(*), 27(o), 33(x), 36(v) and 45(+) after integration of wind generator, STATCOM and TCSC

The solution of economic dispatch with losses is obtained from calculating the power flow by classical Newton-Raphson method taking into account the network topology and calculating for each case studied previously total active losses of all lines. The optimal values of power generated, the fuel costs and the generation cost (λ) for the different cases studied are given in Table 2. In the calculations assuming that the cost of wind generation is zero compared to the production of conventional power plants as the primary source of which is the wind is free.

Loss reduction affects the power produced by the generator in both the absence and presence of the wind turbine. From Table 2, optimal powers are lower compared to those before insertion of TCSC and STATCOM without exceeding the minimum and maximum limits, thus reducing the cost of production as well as about the incremental cost.

Simulation results permit to verify in the Table2, the capabilities of TCSC to control the active power transit through the lines and STATCOM to regulate the voltage at the busbars of the network studied. The TCSC is inserted in optimal locations to achieve the minimum active losses by calculating the power flow, which resulted in a minimum production cost. By comparing the results of all the cases studied, there was a total satisfaction of all security constraints including active power generators in the presence of wind generation source although it is fluctuating form.

6. Conclusion

The work presented in this paper deal with three areas of research. The first relates to the problem of optimizing the power flow in an electrical network for economic power distribution, the second is due to the impact of inserting the wind power generation in the grid on the busbar voltages and power flows in the lines and the third axis representing FACTS devices that are considered optimal solutions to power transit problems and control voltages.

In this context, the aim of the optimization is to make the best use of network capacity. FACTS devices namely TCSC and STATCOM are installed in the grid to maximize the power served to consumers, and regulate the voltage after the insertion of the wind generator while respecting safety constraints. These devices are adjusted to achieve an optimal level of compensation under the constraints of power and voltage. They led to more economical solutions in cases where the power is set to a specified value.

The optimal integration of the TCSC controller in the line (15-15) and (2-13) has that the total losses in the electrical network have dropped dramatically compared to the initial state, which has led to a generation cost and lower total cost. The integration of the STATCOM for voltage regulation that has different disturbances affecting the busbar voltages are compensated, which allowed its conservation within permissible limits, even if distortion of the voltage after a significant fluctuations in wind power injected.

The simulation results were used to evaluate and compare the cost values of power generation with and without FACTS controllers, satisfying the constraints imposed by the power electrical network and taking into account the losses. The insertion of FACTS provides a huge economic gain, increased reliability and reduced losses, thus reducing fuel consumption. This decrease in production implies a contribution to preserving the environment by reducing pollution and greenhouse gases.

Table 2. Economic dispatch results

Variables	Min	Max	without wind generator	with wind generator	with wind generator and STATCOM	with wind generator STATCOM and TCSC
P_{G1}(MW)	100	500	453.91	428.23	428.02	427.48
P_{G2}(MW)	50	200	176.57	157.64	157.49	157.15
P_{G3}(MW)	80	300	269.71	249.74	249.57	249.15
P_{G4}(MW)	50	150	130.82	110.85	110.68	110.26
P_{G5}(MW)	50	200	178.42	155.95	155.77	155.30
P_{G26}(MW)	50	120	79.69	58.54	58.37	57.92
incremental cost λ (\$/MWh)			13.35	12.99	12.99	12.98
Cost (\$/h)			15630	13942	13928	13893
Losses (MW)			12.56	13.33	12.27	9.57

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