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STATCOM's contribution to the improvement of voltage plan and power flow in an electrical transmission network

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Abstract

Flexible alternating current transmission systems are used since nearly four decades and present very good dynamic performances. The purpose of this work is to study the behaviour of a system where static compensator (STATCOM) is located at the midpoint of a long transmission line functioning in disturbed modes with various levels of load caused by tripping and then, reclosing of the incoming station breaker. The studied model and starting from the analysis of various alternatives will lead to the checking of the aptitude of the STATCOM to maintain the voltage plan and to improve the power flow in electro-energetic system which is the east region of Algerian 400 kV transmission network. The steady state performance of STATCOM's controller is analysed through computer simulations with MATLAB/Simulink program. The simulation results have demonstrated that STATCOM can be effectively applied in power transmission systems to solve the problems of poor dynamic performance and voltage regulation.

Keywords: STATCOM, reactive power, power flow, voltage plan, breaker automatic recloser.

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1. Introduction:

It has long been recognized that the steady-state transmittable power can be increased and the voltage profile along the line controlled by appropriate reactive shunt compensation. The purpose of this reactive compensation is to change the natural electrical characteristics of the transmission line to make it more compatible with the prevailing load demand. Thus, shunt connected, fixed or mechanically switched reactors are applied to minimize line overvoltage under light load conditions, and shunt connected, fixed or mechanically switched capacitors are applied to maintain voltage levels under heavy load conditions [1].

The traditional control methods of the networks (transformer with adjustable catches in load, compensators commutated by circuit breakers, modification of instructions of production and action on the generators field circuits) prove too slow and insufficient to answer the disturbances of the network effectively [2]. It will be necessary to supplement the action of these devices by the FACTS (Flexible Alternative Current Transmission systems) which allow a more effective exploitation of the networks by the action continues and fast on various parameters whose behavior of the voltage [3].

Several previous studies have dealt with this issue, with various orientations: the SMIB Single Machine Infinite Bus (SMIB) system [4], a generator-transmission line to supply various load-level systems was opted for in several studies [5,6]. In addition to reactive power compensation, the STATCOM associated with different control strategies can help to cushion distortion waves of current and voltage of a power system [7,8], the transits of power will be controlled better [9]. For this purpose, we targeted the behavior of the STATCOM established in a real functioning production transmission system [10] with various modes of load.

1. - Presentation of problematic and studied diagram modelisation:

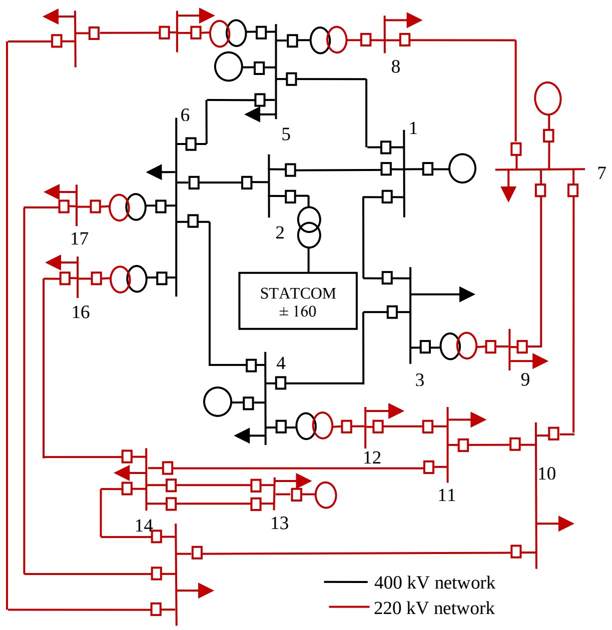


Fig.1 – Studied network.

So it was agreed to opt for the study scheme shown in **Fig.1** [10,13]. The data of the scheme of study are in appendix. This scheme represents the eastern area of Algerian APTS which we simplified at its maximum to make a test circuit. For this purpose we considered the 400 kV loop with a line 1-6 idea in which the STATCOM is placed in the middle. The 220 kV mesh network was simplified considering areas of high transit. Interconnections with Tunisia and other regions as well as the charges were represented by arrows starting from nodes 400 kV and 220 kV.

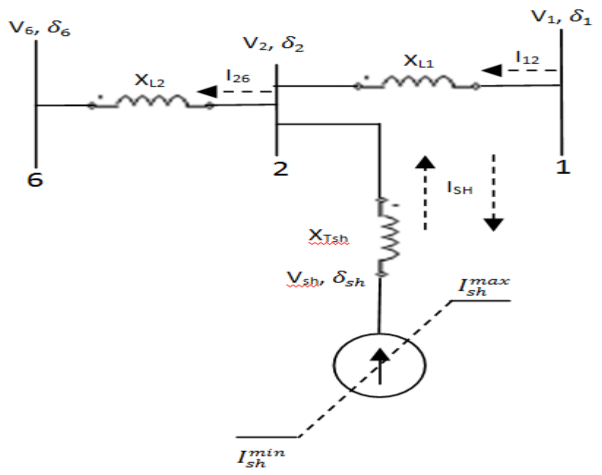


Fig.2 – STATCOM equivalent diagram.

The STATCOM placed on a transmission line via a reactance, which is the one of the coupling transformer, can be modeled in any mode as a shunt voltage source placed between two regions. To describe the STATCOM performance, a first-order differential equation is used :

$$\dot{I}_{sh} = \frac{1}{T_{sh}}(I_{sh}^{ref} - I_{sh}) \quad (1)$$

$$\dot{I}_{sh} = \frac{1}{T_{sh}}[K_{sh}(v_{ref} - v_2) - I_{sh}] \quad (2)$$

where I_{sh} is the reactive current exchanged with the network, v_{ref} is the voltage reference of the STATCOM regulator, K_{sh} and T_{sh} are respectively gain and time constant of the regulator.

$$I_{sh} = \frac{V_{sh} - V_2}{jX_{Tsh}} \quad (3)$$

for each line of the study scheme in Fig.1, we have to determine the primary and secondary parameters.

$$\gamma_0 = (Z_0 . Y_0)^{1/2} = \beta_0 + j\alpha_0 \quad (4)$$

Or if $r_0 \approx g_0 \approx 0$ $\quad \gamma_0 = j\alpha_0 = (jb_0 . jx_0)^{1/2} \quad (5)$

Where : γ_0 : electromagnetic wave factor.

α_0 : wave phase factor.
β_0 : attenuation wave factor.

Characteristic impedance become:

$$Zc = (Z_0/Y_0)^{1/2} = (x_0 / b_0)^{1/2} \tag{6}$$

To evaluate the distribution of the voltage in each point of the network and from the setting of the parameters of the reference node [14]:

$$U^*(l) = \cos(\alpha_0 l) + Q^*_2 \sin(\alpha_0 l) + j\, P^*_2 \sin(\alpha_0 l) \tag{7}$$

$$\text{With} \quad U^*(l) = U(l) / U_2 = k_u(l) = K_u(l)\, e^{j\delta} \tag{8}$$

$$k_u = U_1 / U_2 = (U_2 + \Delta U_p) / U_2 = 1 + \Delta U^*_p \tag{9}$$

Or

$$\Delta U^*_p = k_u - 1 \tag{10}$$

Where ΔU^*_p : voltage drop.
k_u : voltage deviation coefficient.

Starting from the same reasoning for the distribution of the voltage, it is to determine that of the reactive power to have the two parts of the balance U / Q [14].

$$Q^*_2 = [\, (K^2_u / \sin^2(\alpha_0 l)) - (P^*_2)^2\,]^{1/2} - Ctg\,(\alpha_0 l) \tag{11}$$

$$Q^*_{(x)} = (K^2_{u(x)} - 1)\,.\, Ctg\,(\alpha_0 x) - Q^*_2 \tag{12}$$

The mathematical model described above will be combined with the STATCOM control logic to give a formulation of the problem that will be discussed in the next sections.

2. Operating principle of STATCOM in power transmission system:

The control logic is based on a current control strategy using the two current components d-q decoupled from the alternating current of the STATCOM. The control system is implemented as shown in **Fig. 3**. A phase locked loop (PLL) that synchronizes with the positive sequence of the three-phase voltage at the connection point. The output of the PLL is the angle (θ) that allows to determine the direct and quadrature components of the AC voltage current. The external regulation loop includes the AC voltage regulator which supplies the reference current (Iqref) for the current regulator which is always in quadrature with the output voltage to control the reactive power exchanged.
The phase lock loop (PLL) system generates the basic timing signal which is the phase angle of the voltage of the transport network Vs, θ, and the selected gradient, k, determines the compensation behavior of the STATCOM. To improve the dynamic performance of the model, an additional control loop is added using the voltage of the DC capacitor.

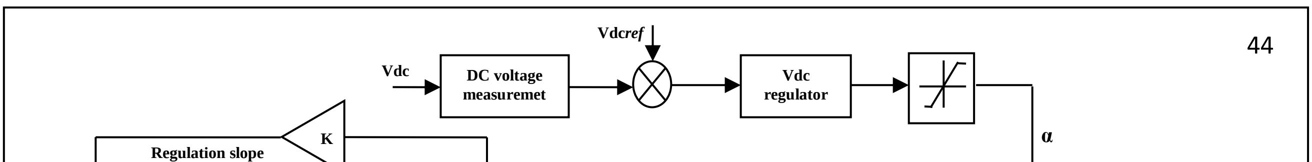


Fig. 3 : STATCOM control scheme

The charging voltage of the capacitor is determined as a function of the variation of the voltage across its terminals. This strategy consists in correcting the phase angle of the STATCOM voltage, θ*, by respecting the positive or negative sign of this variation [15, 16, 17].

The power exchanged with the connection point (Fig. 2) is written as follows:

$$S = V_2 . I_{sh}^* = \frac{V_2 .(V_{sh}^* - V_2^*)}{-jX_{Tsh}} \quad (13)$$

$$P_{sh} = \frac{V_2 . V_{sh}}{X_{Tsh}} \sin(\delta_2 - \delta_{sh}) \quad (14)$$

$$Q_{sh} = \frac{V_2^2}{X_{Tsh}} \left[\frac{\mathrm{V_{sh}}}{\mathrm{V_2}} \cos(\delta_2 - \delta_{sh}) - 1 \right] \quad (15)$$

If we consider the STATCOM without losses, hence $P_{sh}=0$ so that $\delta_2 = \delta_{sh}$. Therefore V_2 and V_{sh} are in phase, which gives $V_{shd} = V_{sh}$; $V_{shq} = 0$ and $I_{sh} = I_{shq} = \frac{V_{sh} - V_2}{jX_{Tsh}}$, hence:

$$Q_{sh} = V_{sh} \, . \, I_{shq} = \frac{V_{sh}^2}{X_{Tsh}} \left[1 - \frac{\mathrm{V_2}}{\mathrm{V_{sh}}} \right] \quad (16)$$

From equation (16), three possible operating modes of the STATCOM are defined:

- $V_2 = V_{sh}$ so $Q_{sh} = 0$: no power exchange.
- $V_{sh} > V_{sh}$ so $Q_{sh} > 0$: the STATCOM is in capacitive mode and the energy is supplied to the network.
- $V_{sh} < V_{sh}$ therefore $Q_{sh} < 0$: the STATCOM is in inductive mode and absorbs energy from network.

The effects of STATCOM compensation result as follows:

$$I_{12} = \frac{(X_{L2} + jX_{Tsh})V_1 - X_{L2}V_{sh} - jX_{Tsh}V_6}{X_{L1}X_{L2} + jX_{Tsh}(X_{L1} + X_{L2})} \quad (17)$$

$$I_{sh} = \frac{X_{L2}V_1-(X_{L1}+X_{L2})V_{sh}-X_{L1}V_6}{X_{L1}X_{L2}+jX_{Tsh}(X_{L1}+X_{L2})} \quad (18)$$

$$I_{26} = \frac{jX_{Tsh}V_1-X_{L1}V_{sh}-(X_{L2}+jX_{Tsh})V_6}{X_{L1}X_{L2}+jX_{Tsh}(X_{L1}+X_{L2})} \quad (19)$$

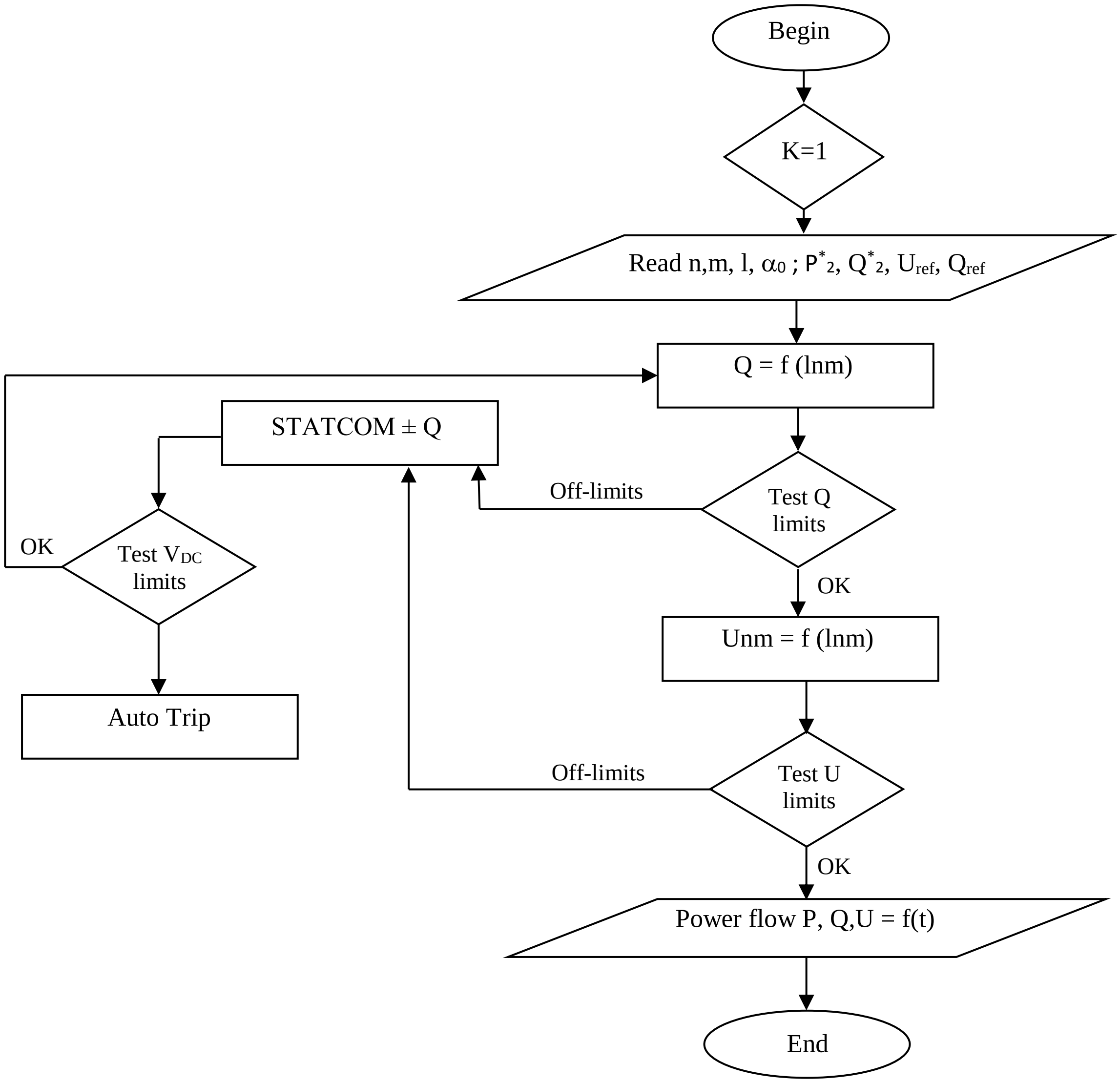


Fig. 4 Flowchart of the simulation process

The power provided by the node 1 is:

$$P_1 = Re\,[V_1 I_{12}^*] \;\; ; \;\; Q_1 = Im\,[V_1 I_{12}^*] \tag{20}$$

It is obvious that the reactive power supplied by node 1 decreases with the increase of the value of V_{sh} and hence with the degree of compensation of the STATCOM.

$$P_{sh} = Re\,[V_{sh} I_{sh}^*] \;\; ; \;\; Q_{sh} = Im\,[V_{sh} I_{sh}^*] \tag{21}$$

From what preceded, we have a model of the study scheme, it will have in the following section place to formulate the problem as shown in **Fig. 4** in order and those to try to have the best results.

3. Simulation results and discussion:

The simulation process of the study scheme involving the combination of STATCOM with the 400 kV loop of the East Algerian EPTS region in the Matlab Simulink environment takes into account the data given in the appendix and those in accordance with the block diagram of Fig. 4. With the power flow set, a 400 kV 2-6 line breaker tripping occurs followed by a fast reclosing. It is therefore subject to observe the behavior of the interconnected network in the case of operation of the automatic reclosers following fugitive faults. The results are shown in the graphs of the characteristic parameters of the power flow.

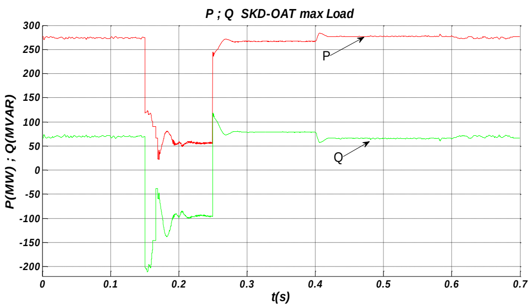


Fig. 5 : P,Q line 1-2

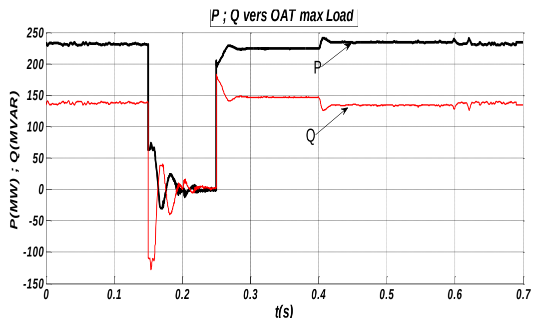


Fig. 6 : P,Q line 2-6

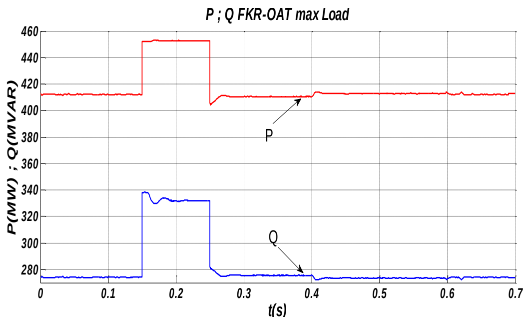


Fig. 7 : P,Q line 4-6

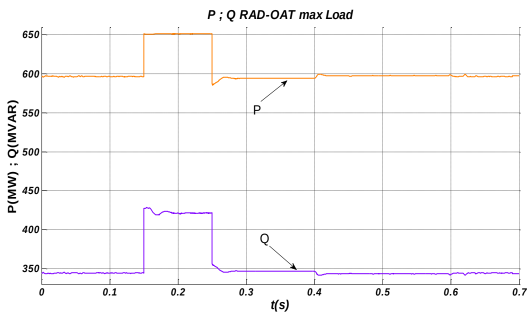
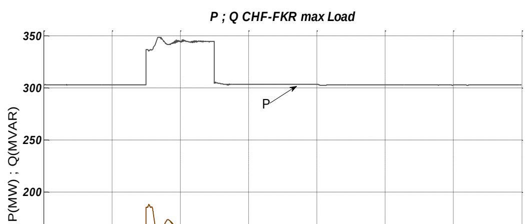


Fig. 8 : P,Q line 5-6



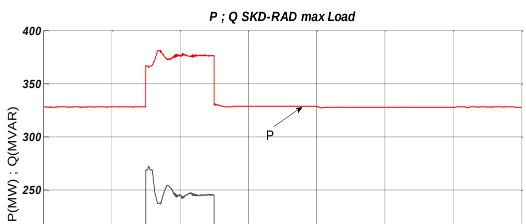


Fig. 9 : P,Q line 1-4

Fig. 10 : P,Q line 1-5

It can be seen that from the simulation results the effects of load rejection in a long transmission line. The STATCOM functioning in voltage regulation mode and in spite of its low power compared with those of the loads and the stations, showed very good performances in the damping of the abrupt voltage variations. The impact is very appreciable at the buses 2 and 6: the damping of the voltage rise borders the 7% [Fig. 12 and Fig. 13] and within 0.05s. The effect on the bus 1 is less intense since this last is rather far away from the end the line [Fig. 11]. The voltage in buses 4, 5 and 6 shown in [Fig. 14] are lower and do not leave the acceptable limits in spite of the additional transits of power generated by the discharge of the median line. From the power point of view, the most brutal constraint is observed with the line downstream STATCOM (line 2-6) where P passes from 250 MW to zero and Q from 140 to -125 MVAR [Fig. 5 and Fig. 6].

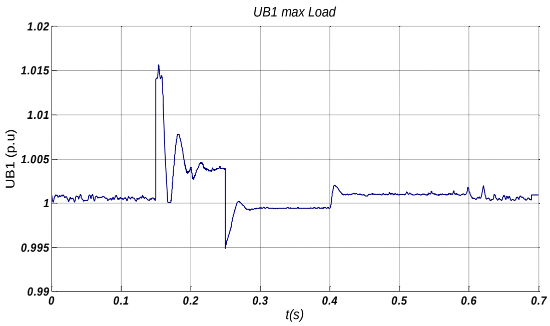


Fig. 11 : U bus 1

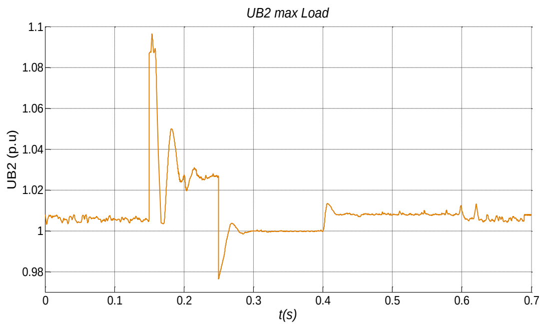
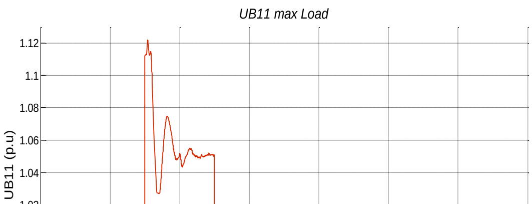


Fig. 12 : U bus 2



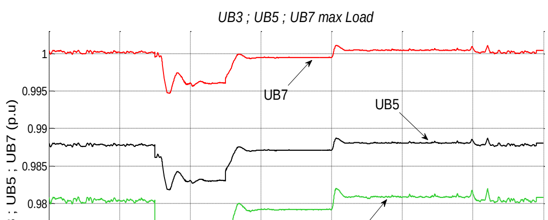


Fig. 13 : U bus 6 upstream

Fig. 14 : U bus 6 downstream breaker (red), U bus 5 (Black), Ubus 4 (green)

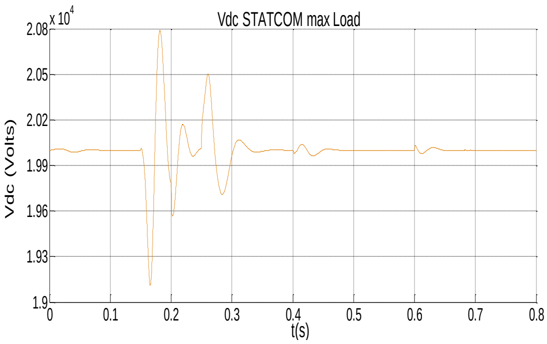


Fig. 15 : V_{DC} STATCOM

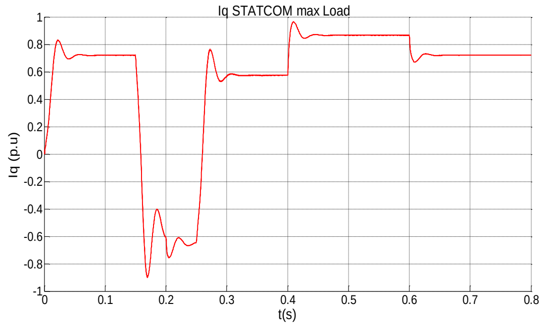


Fig. 16 : Iq STATCOM

The STATCOM makes well in relation to the capacitive effect of the line with vacuum.

Forwards discharged line is deviated towards the other lines thing which is visible on the P, Q graphs of lines 4-6; 5-6; 1-5 and 1-4 between 0.15 and 0.25s, i.e. between opening and reclosing of the circuit breaker upstream of bus 6. So the power flow to the load node12 were divided on the other lines (average 2x50MW) [see Fig. 7, 8, 9, 10] and station situated at node 6.

this disturbed mode affects also the STATCOM continues voltage [Fig. 15] where the introduction of the load is more severe than its rejection in term of variation of V_{DC}, the regulator action forces this last to function as an absorber thing which is well confirmed by the Iq graphs [Fig. 16] with the two load modes imposed by the action of the circuit breaker.

4. Conclusion:

In this paper, a three phase voltage source inverter STATCOM controller is successfully modeled. The steady state performance of the controller is analyzed through computer simulations with Matlab/Simulink program. The presented simulation has demonstrated that STATCOM can be effectively applied in power transmission systems to solve the problems of poor dynamic performance and voltage regulation. The STATCOM placed at the midpoint of a long transmission line functioning with abrupt disturbed mode, showed good performances which can secure us collapses of transmission systems and those by the damping of the abrupt voltage and forwarded powers variations. The study of the modes min and max of load emphasize the degrees of variations of different sizes characteristic of the studied network as well as the parameters from the STATCOM. Works in the same direction will be carried out in the goal to lead to modeling and the simulation of the behavior of the national transmission system associated with FACT systems.

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- **Appendices:**

The data of the studied system are presented. **Table 1** illustrates the linear parameters of the transmission lines and the maximum current of the current transformer of the span of the starting line. **Table 2** gives the parameters of generators coupled to generation nodes.

Table 1 : Parameters of lines for the studied network [18].

Bus-Bus	Un (kV)	L (km)	$R_{ij}(\Omega)$	$X_{ij}(\Omega)$	$I_{max}(A)$
1-2	400	200	5,83	66,9	2400
1-5	400	135	3,93	45,17	2400
1-3	400	40	1,17	13,38	2400
2-6	400	200	5,83	66,9	2400
3-4	400	150	4,37	50,19	2400
4-6	400	120	3,5	40,15	2400
5-6	400	80	2,33	26,77	2400
7-8	220	80	9.82	61.99	1600
7-9	220	40	1,79	14,4	1440
7-10	220	140	6,28	50,4	1440
10-11	220	55	4,49	20,5	1200
10-15	220	120	6,79	48	1200
11-12	220	7	0,31	2,38	1440
11-14	220	85	3,82	28,9	1440
13-14	220	65	2,92	22,1	1440
14-15	220	30	2,69	12,3	1200
14-16	220	52	4,67	21,32	1200
15-17	220	50	4,49	20,5	1200
15-18	220	78	7	31,98	1440
18-19	220	20	1,79	8.2	1440

Table 2 : parameters of the generators.

Node	1	4	5	7	13
MVA	1400	700	940	600	760
f	50	50	50	50	50
Q_{max}	750	370	500	320	400
Q_{min}	-600	-300	-400	-250	-320
X_d	1,85	2,53	1,85	1,86	2.38
X'_d	0,245	0,25	0,245	0,189	0,234
X''_d	0,22	0,19	0,22	0,156	0,177
X_q	1,78	2,36	1,78	1,70	2,21
X'_q	0,455	0,40	0,455	0,368	0,378
X''_q	0,22	0,20	0,22	0,21	0,189
T'_{d0}	6,7	10,12	6,7	7,66	10,8
T'_{q0}	0,58	0,93	0,58	0,975	0,987
H	-	1,288	-	-	-