Uluslararası İleri Doğa Bilimleri ve Mühendislik Araştırmaları Dergisi
Sayı 8, S. 1-10, 5, 2024

Araştırma Makalesi

International Journal of Advanced Natural Sciences and Engineering Researches
Volume 8, pp. 1-10, 5, 2024

Research Article

https://as-proceeding.com/index.php/ijanser
ISSN: 2980-0811

Impacts Static Inverters on the Performance of UPFC Systems

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(Received: 20 April 2024, Accepted: 08 June 2024)

(2nd International Conference on Scientific and Innovative Studies ICSIS 2024, April 18-19, 2024)

ATIF/REFERENCE: Boukarana, L., Fellag, S. A. & Habi, I. (2024). Impacts Static Inverters on the Performance of UPFC Systems. *International Journal of Advanced Natural Sciences and Engineering Researches*, 8(5), 1-10.

Abstract **–** Recent developments in power grids have made it increasingly difficult to ensure reliable control of energy transfers in highly interconnected networks using traditional low-speed response devices such as phase shifters, shunt or series compensators. As a result, there have been recent studies on a new generation of 'FACTS' control devices that utilize new controllable components for both opening and closing. This article presents the contribution of the Unified Power Flow Controller (UPFC) to improve the control of active and reactive power transmission in an electrical network. The study focuses on increasing and controlling power flow, followed by the presentation of simulation results in the Matlab/Simulink environment.

Keywords – Compensation, Electronics of Power, Reactive Power, FACTS, Electrical Supply Networks.

I. INTRODUCTION

The FACTS concept encompasses all power electronics-based devices that enhance power grid operation. These systems, which use static switches, operate at higher speeds than conventional electromechanical systems. They can also regulate power flow in networks, increase transport capacity, and maintain network stability.

II. STRUCTURE AND OPERATING PRINCIPLE

The Unified Power Flow Controller (UPFC) enables control of both active power and line voltage. It can perform the functions of other FACTS devices, including voltage regulation, energy flow distribution, stability improvement, and attenuation of power oscillations [1], [2].

Figure 1 shows that inverter 1 is used through the DC link to provide the active power required for inverter 2. In addition, it performs the function of compensating for reactive energy by supplying or absorbing power, regardless of active power, to the network. Inverter 2 injects voltage Vb and supplies the active and reactive powers required for series compensation.

The UPFC offers significant advantages due to its flexibility in controlling voltage, transport angle, and line impedance through a single device consisting of only two three-phase voltage inverters. It can also switch between these functions instantly by changing the control of its inverters, allowing it to handle network faults or modifications by temporarily prioritizing one of the functions.

In the mixed operation of the UPFC, this device can combine the other control modes at a time.

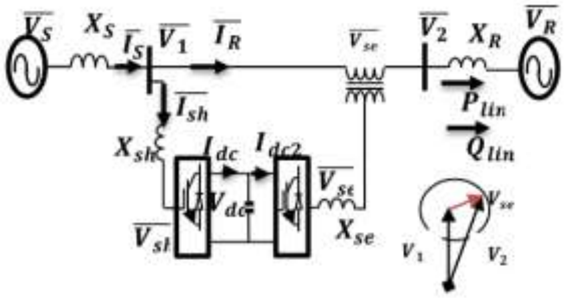

Fig. 1 Diagram of bottom of the UPFC

In all four cases, control of the powers is achieved by adding a voltage (V_{se}) in series with the line. This voltage can be adjusted in both module ($V_{semin} \leq V_{se} \leq V_{semax}$) and phase ($0 \leq \delta_{se} \leq 360°$) relative to the voltage at the connection point [6]. The ability to adjust the voltage at the module and phase levels enables us to modify the effective voltage at those levels, thereby allowing for static modification of the transmitted active and reactive powers.

The voltage is controlled by injecting the voltage of the series part in phase or antiphase with respect to V_1, affecting only the amplitude of V_2 (see Fig. 2a).

The diagram in Figure 2.b illustrates the impedance control mode of the line. The voltage V_{se}, which is equal to V_C, is shifted by an angle of 90 degrees either in advance or backward from the line current I_R. As a result, the voltage V_{se} increases or decreases the total voltage across the line impedance.

The regulation of the phase (Fig. 2c) can be achieved by injecting the voltage $Vse=V\sigma$ at an angular relation with V_1. As a result, the resulting tension V_2 has the same amplitude as tension V_1, but with a phase angle shifted by a desired angle σ.

The voltage V_{se} of the other three trios can be controlled individually to synthesize the phaser, with ΔV_0, V_C, and $V\sigma$ being controlled.

The phaser is given by $Vse = \Delta V_0 + V_C + V\sigma$, as shown in Fig. 2.d [2], [4], [5].

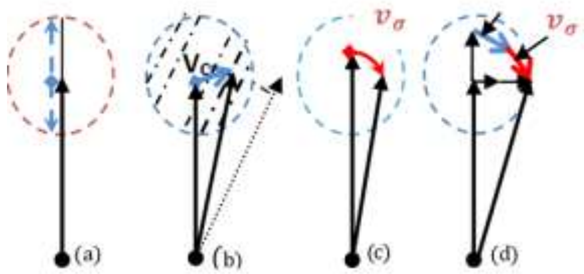

Fig. 2 Diagram of phase of the UPFC

III. Analysis and control of the UPFC

Theoretically, the UPFC should be treated as a multi-variable system because the two series and parallel inverters are connected on one side to the transmission line and on the other side to the DC circuit.

A. *Control OF THE shunt part*

From the figure.1, the mathematical formulations of the voltages V_S, V_1 are given by the system of following equation [3], [4]:

$$\begin{cases} \overline{V_s} = \overline{V_1} + jX_S\overline{I_s} \\ \overline{V_1} = \overline{V_{pq}} + jX_R\overline{I_R} + \overline{V_R} \end{cases} \quad (1)$$

If we orient the axis d on the tension$\overline{V_1}$, we can rewrite the previous two-phase formulations in the d_q mark as follows:

$$\begin{cases} V_{Sd} = V_{1d} + L_S \frac{dI_{Sd}}{dt} - X_S I_{Sq} \\ V_{Sq} = L_S \frac{dI_{Sq}}{dt} - X_S I_{Sd} \end{cases} \quad (2)$$

$$\begin{cases} V_{1d} = V_{sed} + L_R \frac{dI_{Rd}}{dt} - X_R I_{Rq} + V_{Rd} \\ 0 = V_{seq} + L_R \frac{dI_{Rq}}{dt} - X_R I_{Rd} + V_{Rq} \end{cases} \quad (3)$$

The set (2) indicates that to maintain the direct component of the voltage $\overline{V_1}$ (V_{1d}) constant it is necessary to set the reactive component of the current $\overline{I_S}$ (I_{Sq}) invariant during the [5], [6]. Knowing that:

$$\overline{I_S} = \overline{I_R} + \overline{I_{sh}} \quad (4)$$

Using the Park transformation equation (4) becomes:

$$\begin{cases} I_{Sd} = I_{Rd} + I_{Shd} \\ I_{Sq} = I_{Rq} + I_{Shq} \end{cases} \quad (5)$$

So, to maintain the quadrature component I_{Sq} invariant where the reactive component of the current I_{Rq}varies according to the needs of the load, we must satisfy the following condition [1] [5]:

$$\Delta I_{Rq} + \Delta I_{shq} = 0 \quad (6)$$

From Equation (6), it is concluded that the control of the voltage at the connection point(V_1), is carried out by controlling the current absorbed or generated by the shunt inverter of the UPFC.

In the same figure, the formulation of the active powers is given as follows:

$$P_S + P_{se} - P_{sh} = P_{lin} \quad (7)$$

$$\overline{V_s} * \overline{I_s} = \overline{V_1} * \overline{I_{sh}} + \overline{V_{se}} * \overline{I_R} + \overline{V_R} * \overline{I_R} \quad (8)$$

To maintain the voltage across capacitor C at a constant value, the following constraint must be imposed:

$$\overline{V_1} * \overline{I_{sh}} + \overline{V_{se}} * \overline{I_R} = P_{dc} \quad \Longrightarrow P_{se} + P_{sh} \approx 0 \quad (9)$$

Where P_{dc} represent losses joule of the UPFC

$$\overline{V_s} \cdot \overline{I_s} = P_{lin} + P_{dc} \quad (10)$$

$$P_{lin} = \overline{V_2} \cdot \overline{I_R} \quad (11)$$

By the transformation of Park d_q and by the use of equation (10), we obtain:

$$\begin{cases} V_{1d}.I_{shd} = I_{dc2} V_{dc} \\ V_{1d}.I_{sd} = P_S \end{cases} \quad (12)$$

This relation (12), is justified by the criterion of the conservation of active powers in the converter between the continuous side and the alternative side.
We also have: $\overline{V_{se}} \cdot \overline{I_1} = -I_{dc2}V_{dc}$
So, to satisfy the balance of the active powers of the UPFC, I_{shd} must vary with the current I_{dc}. Then, for the control of the voltage across the capacitor, we use the direct component of the current injected by the shunt inverter I_{shd} this command is performed in order to satisfy the exchange of active energy between the series and shunt inverter [6], [7]. Figure.3 shows the identification scheme of the reference current of the shunt part.

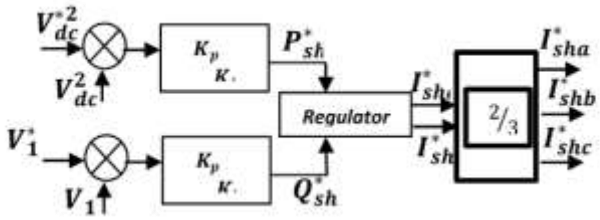

Fig. 3 – Identification of the reference current of the shunt part.

B. ***Control of the serial part***

The purpose of this part is to control the output voltages of the series inverter to act on the active and reactive powers transmitted in the transmission line.
From equation (11) and from figure (1) we can write:

$$P_{lin} = [\overline{V_S} - jwL_s(\overline{I_R} + \overline{I_{sh}}) - \overline{V_{se}}].\left(-\frac{\overline{V_R}}{jwL_R}\right) \quad (13)$$

In this case we assume that: $\Delta\overline{V_S}\ et\ \Delta\overline{V_R} \approx 0$ (Change in a light way)
So the variation of the active power transmitted P_lin is given in the system (d-q) as follows:

$$\Delta P_{lin} = \frac{\Delta V_{sed}V_{Rq} - V_{Rd}}{wL_R}\left[wL_S(\Delta I_{Rd} + \Delta I_{shd}) + \Delta V_{seq}\right] \quad (14)$$

Equation (14) indicates that the variation of the transmitted active power is dependent on several parameters, in this case the control of the active power P_{lin} is carried out by controlling the reactive component of the voltage (V_{se}) V_{seq}
On the other hand, the formulation of the reactive power of the circuit of (Fig.1) is given as follows:

$$Q_S = Q_{sh} + Q_{se} \quad (15)$$

So:

$$\overline{I_S} * \overline{V_S} = \overline{I_{sh}} * \overline{V_1} + \overline{I_R} * \overline{V_{se}} + \overline{I_R} * \overline{V_2} \quad (16)$$

By the transformation of Park can write:

$$I_{sd}V_{sq} - I_{sq}V_{sd} = I_{shd}V_{1q} - I_{shq}V_{1d} + I_{Rd}V_{seq} - I_{Rq}V_{sed} + Q_{lin} \quad (17)$$

According to the previous study and the equation (17), the control of the reactive power Q_{lin} is carried out by Controlling the active component of the voltage injected by the SSSC (V_{sed})

With:

$$\begin{cases} V_{sed}^* = V_{Rd} - V_{1d} - (R_{se} + R_L)I_{Rd}^* + (X_{se} + X_L)I_{Rq}^* \\ V_{seq}^* = V_{Rq} - V_{1q} - (R_{se} + R_L)I_{Rq}^* + (X_{se} + X_L)I_{Rd}^* \end{cases} \quad (18)$$

Figure.4 shows the identification scheme of the reference current of the serial part.

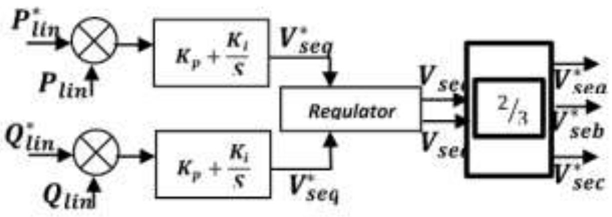

Fig. 4 Identification of the reference current of the serial part.

IV. SIMULATION RESULTS

The network consists of a 400 KV generator with a nominal power of 3000MVA, connected to the infinite network by the transformer T and a 500Km transmission line modulated in π for each 100Km.

The transformer Tsh is used to lower the mains voltage (400 KV) to 34 KV (STATCOM shunt converter input voltage). Tse serves on the one hand to isolate the SSSC series converter to the mains voltage (400 KV) and on the other hand to adapt the output voltage of this converter (20 KV) to the voltage injected in series.

Simulation of the electricity network without compensation.

In this part, we will present the behavior of the electrical network, without compensation system, for different operating points, relating to different values of the transmitted active and reactive powers:

at t = 0s; a load of (30MW, 30MVRA) is applied at t = 0.5s; the load is increased to (70MW, 50MVAR), at t = 1.5s; the charge is further increased to (95MW, 65MVAR) at t = 2s; the load is reduced to (65MW, 30MVAR), and finally to t = 2.5s; the load is reduced to (25MW, 15MVAR).

The purpose of this part is to watch the need for a compensation device.

For this we will show the results of simulations and especially: the active and reactive powers transmitted by the line, line currents and line voltages.

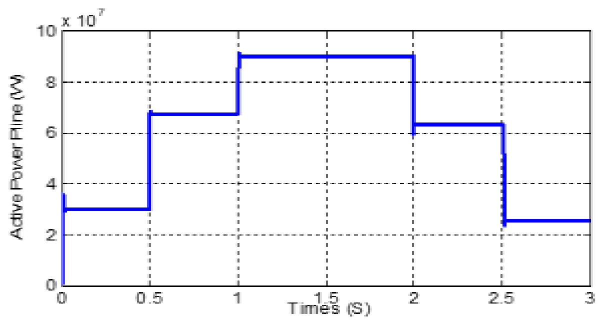

Fig. 5 Active power of the line without compensation.

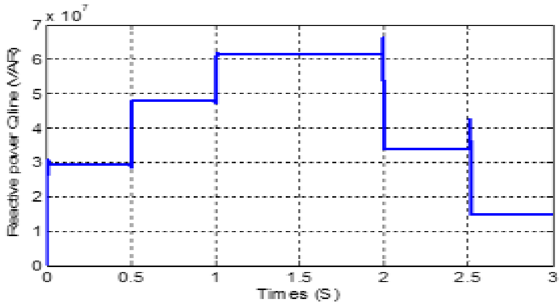

Fig. 6 Reactive power of the line without compensation.

Figure (6) shows the fluctuations of the reactive power transmitted by the line, which results in a non-unit power factor and therefore: the voltage drops and the reduction of the transit capacity of the lines.

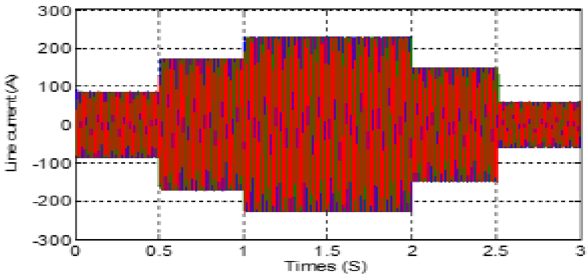

Fig. 7 Current of the line

Figure (7) shows that the currents follow the profile of the active power.

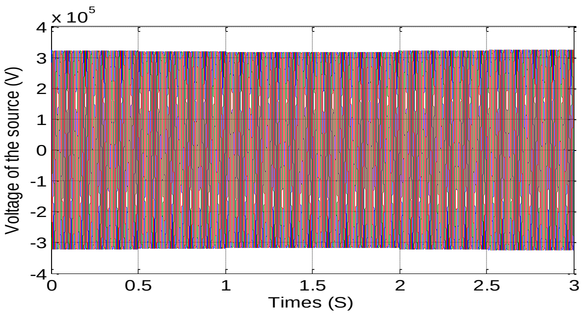

Fig. 8 Voltage of the source

By cons figure (8); shows the fluctuations of the voltage of the line and especially the voltage drops, which forces the company operating the electricity network to use a compensation system for:

- Maintain a constant network voltage,
- operate with a unit power factor, and increase the transit capacity of the line.

A. *Impact of STATCOM on the control of the electricity network*

In this part we will show the importance of the STATCOM, for the control of the voltage and the compensation of the reactive power of the lines.

For the same variations of the active powers, described in the screen, we will analyze the impact of the STATCOM on the control of the electrical network and especially:

- The compensation of the reactive power.
- And the control of the tension of the lines.

- **The characteristics of the line**

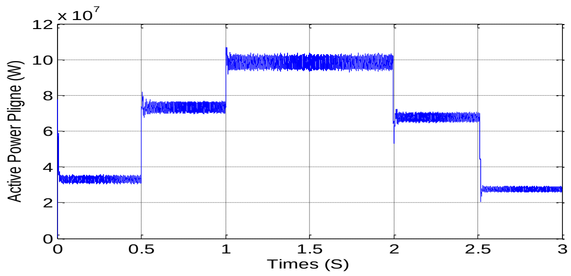

Fig. 9 Active power of the line.

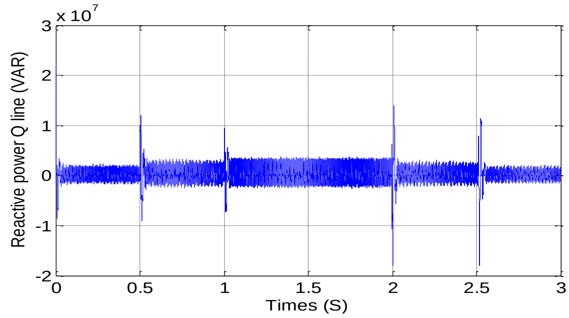

Fig. 10 Reactive power of the line

We find that:
The reactive power transmitted by the lines figure (10) oscillates around zero, which shows a very good compensation for this energy and gives the possibility of operating with a unit power factor.

- **The characteristics of STATCOM**

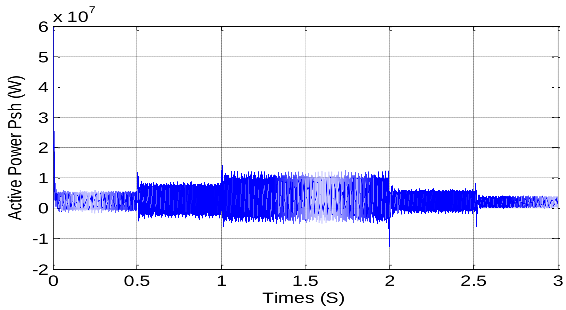

Fig. 11 The active power injected by the STATCOM.

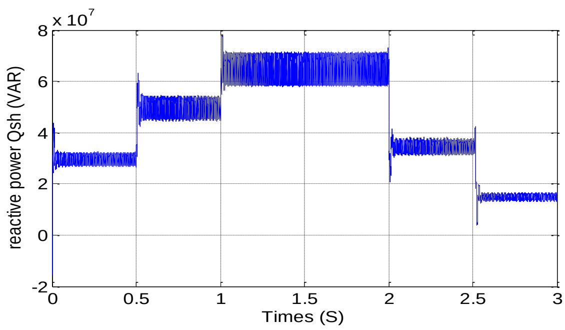

Fig. 12 The reactive power injected by the STATCOM.

From the simulation results, we can see that:

- The active power exchanged with the STATCOM, Figure (11) is relatively very low (theoretically zero) and only represents the transformer level losses (Tsh), semiconductor switches and connection cables.

- On the other hand, the STATCOM injects capacitive reactive power figure (12), to compensate for the inductive reactive power of the lines.

- **The characteristics of the STATCOM command**

In this part we are interested in the control of the DC bus voltage and the current control.
We can note that:

- The active component of the current (Id-ch), Figure (13) perfectly follows its reference which remains almost zero, which allows an effective control of the active power injected by the STATCOM (Psh ≈ 0).
- On the other hand the reactive component, allows a dynamic control of the reactive powers injected by the STATCOM, in order to effectively compensate the lines.
- There is a very good decoupling currents, powers: active and reactive and thus the decoupled watt var method is valid.
- The Figure (14) shows the good control of the DC bus voltage, which remains constant, despite the variations of the loads, which indicates the robustness of its control and the good choice & regulators.

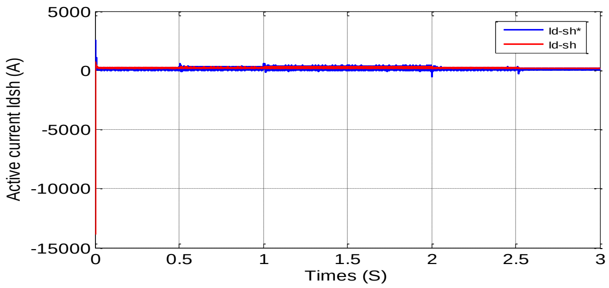

Fig. 13 The active current and its reference injected by the STATCOM.

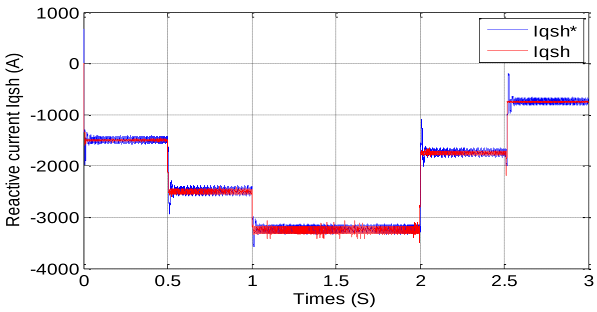

Fig. 14 The reactive current and its reference injected by the STATCOM.

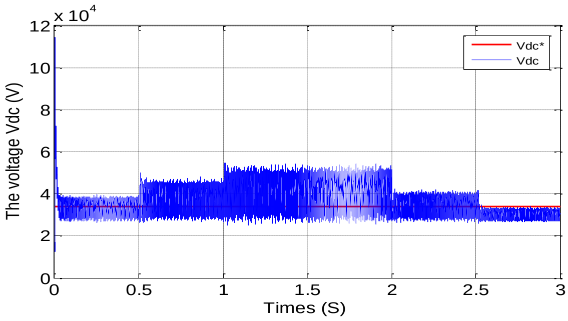

Fig. 15 The voltage at the terminal of the capacitor.

B. ***Impact of the SSSC series compensator on the control of the electricity network***

In this part, we are interested in the control of the power flow in the line and the possibility of increasing the capacity of transit lines.

- **Characteristics of the tensions**

Figure (16) shows the evolution of the voltage injected by the SSSC, by controlling the flow of power transmitted by the line.

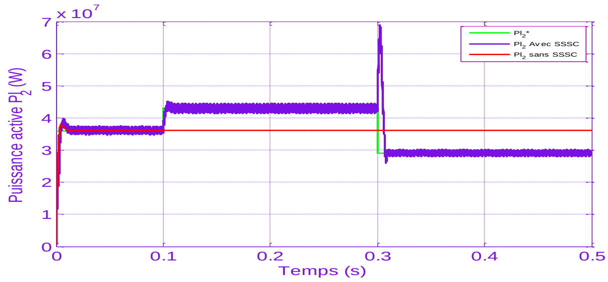

Fig.16. The voltage injected by the SSSC

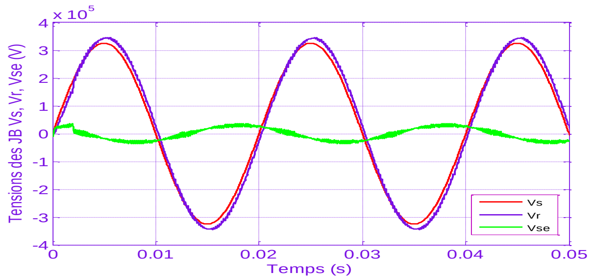

Fig.16. The different voltages Vs, Vr and Vse.

Figure (16) shows the different voltages in our electrical network:

- **Vs:** The voltage at the beginning of the line.
- **Vr:** The tension at the end of the line.
- **Vse**: The voltage injected by the SSSC.

It can be seen that the voltage injected with a voltage is in quadrature with the voltages of the line.

When the SSSC injects a voltage in series with the line, it makes it possible to modify the reactance of the line, and consequently it can control the capacity of transit of the line, as well as the flow of the powers: active and reactive.

C. ***Control of the power flow***

It can be seen that the SSSC can effectively control the flow of active and reactive powers in the transmission line.

Without the SSSC the power flow remains constant, on the other hand when SSSC is introduced, the power flow can be controlled by injecting a voltage in series with the line, which results in a modification of the reactance of the power supply. ci and therefore one controls the capacity of transit of the line between 80% and 120% of its initial capacity.

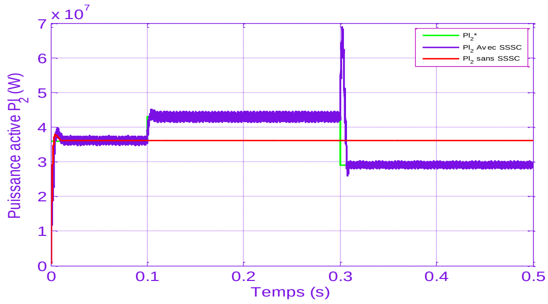

Fig.17 The active power injected by the SSSC.

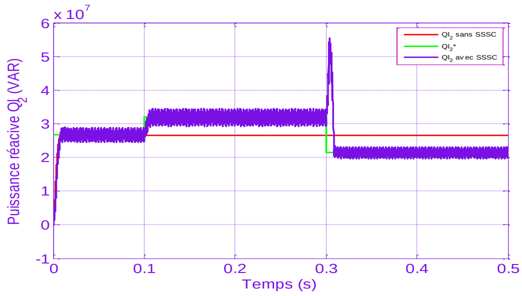

Fig.18 The reactive power injected by the SSSC.

V. CONCLUSION

In this paper we presented the impact of the series and parallel compensators, on the control of the power flow and the voltage of the line.

The STATCOM injects capacitive reactive power to compensate for the inductive reactive power of the lines.

The SSSC injects a voltage in series with the line, it allows to modify the reactance of the line, and consequently it can control the capacity of transit of the line, as well as the flow of the powers: active and reactive.

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