An Experimental Study of the Unbalance Compensation by Voltage Source Inverter Based STATCOM

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ABSTRACT

This work presents an experimental study of the unbalance compensation caused by the high speed railway substations in the high-voltage power grid with a shunt voltage source inverter based STATCOM. This experimental study is realized on a reduced scale prototype. The Control of inverter is implemented in a DSP card. The practical results presented in this paper are shown the performance of unbalance compensation by VSI_STATCOM in static and dynamic regime.

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1. INTRODUCTION

The high speed railway sub-stations connected between two phases of the high-voltage power grid are considered pollution loads, disrupting power grids. The major problem of these sub-stations is the unbalance [1]. The compensation of this unbalance by current injection technique is treated in theoretical viewpoint by simulation [2]. This work presents the experimental validation of control laws for the unbalance compensation. A reduced scale prototype model is presented in this paper, then we proceed to size the necessary elements in order to realize the experimental test, and finally we will compare the practical results with and without compensation by voltage source invertyer based STATCOM (VSI_STATCOM) in static and dynamic regime.

2. NOTATION

The notation used throughout the paper is stated below.

Indexes:

a, b, c : Phase index power grid side ; **a',b',c'** : Phase index inverter AC side; + : Positive sequence index ; - : Negative sequence index; **d** : d-axis component for current or voltage (Park transformation) ; **q** : q-axis component for current or voltage (Park transformation) ; **α** : α-axis component for current or voltage (Clark transformation) ; **β** : β-axis component for current or voltage (Clark transformation)
.C : Set-point of the injected current ;**.ref** : Reference of the injected current and DC voltage ;

Constants & Quantities:

t : Time ; **p** : Laplace transformation operator ; $\mathbf{V_r}$: Phase-ground voltage in the power grid side (autotransformer's secondary) ; $\mathbf{V_O}$: Phase-ground voltage in the inverter AC side ; $\mathbf{I^-}$: Negative sequence

of the current consumed by the single-phase load ; $\mathbf{I_{inj}}$: Injected current for unbalance compensation ; $\mathbf{I_L}$: Current consumed by the single-phase load ; $\boldsymbol{\omega_r}$: Power grid pulsation ($\boldsymbol{\omega_r = 2.\pi.f_r}$ **and** $\mathbf{f_r = 50Hz}$) ; **L** : Filtering inductance; **r** : Amplitude ratio of the PWM control ($\mathbf{r = V_{réf.max} / V_{p.max}}$) ; $\mathbf{V_{p.max}}$: Amplitude of PWM carrier ; $\mathbf{V_{réf.max}}$: Amplitude of PWM sinusoidal reference ; $\mathbf{V_{DC}}$: DC bus Voltage; $\mathbf{f_d}$: Switching frequency ; $\boldsymbol{\delta I_{inj}(\%)}$: Ripple rate of the injected current ; **a** : Fortescue transformation operator $\mathbf{a=e^{j(2\pi/3)}}$; **C** : Clark transformation matrix ; **C'** : Matrix for determining the instantaneous power in α-β frame ; **p(t) and q(t)** : Active and reactive instantaneous power into the power grid side (autotransformer's secondary) ; $\mathbf{p_{dc}}$: Instantaneous power in the DC side ; $\mathbf{p_{dc.corrected}}$: Corrected instantaneous power in the DC side; $\mathbf{K_v}$: Voltage controller gain; $\boldsymbol{\tau_v}$:Time constant of the voltage controller; $\mathbf{P_K}$: Park transformation matrix ; **θ** : Park transformation operator ; **x** : Modulating signal corrected ; **PWM** :Pulse-width modulation signal
$\mathbf{K_I}$: Current controller gain ; $\boldsymbol{\tau_I}$: Time constant of the current controller

3. PRESENTATION OF THE EXPERIMENTAL PROTOTYPE

This reduced scale prototype (Figure 1) is realized in order to validate the unbalance compensation by the current injection technique, using the voltage source inverter based shunt STATCOM. It is composed of:

- A variable single phase resistive load, connected between two phases of low voltage power grid. This load is equivalent to a high speed railway substation to generate a current unbalance.
- Three-phase autotransformer of an autonomous post in electrotechnical laboratory, protected by differential circuit breaker, this autotransformer supplies the single phase load between two phases. The current unbalance caused by the single phase load, leads to a voltage unbalance, via the network impedances at the load connection point (autotransformer's secondary).
- A voltage source inverter (low voltage) of Semikron manufacturer whose PWM control is accessible. This inverter contains a DC capacitor equivalent to an energy storage circuit; the initial charging by a DC voltage source is realized by the switch S2; its discharge is realized by the switch S1 and the resistor Rdc.
- Three single-phase filter inductance in order to filter the current injected at the autotransformer's secondary.
- A small control panel which contains a coupling contactor to the autotransformer's secondary and overload relay for protecting the shunt STATCOM against over-current due to overload.
- A DSP card (ref : CP 1104) in order to ensure the control of the injected current, the control of DC bus voltage, and generating the PWM signals. This card is equipped by an interface circuit board in order to realize an isolation between control part and power system.
- Currents sensors with gain (b_i) and Voltages sensors with gain (b_v) in order to transmit the values of these real quantities to the DSP card.

The disturbances existing in the high-voltage power grid are not considered in this low-voltage reduced scale prototype.

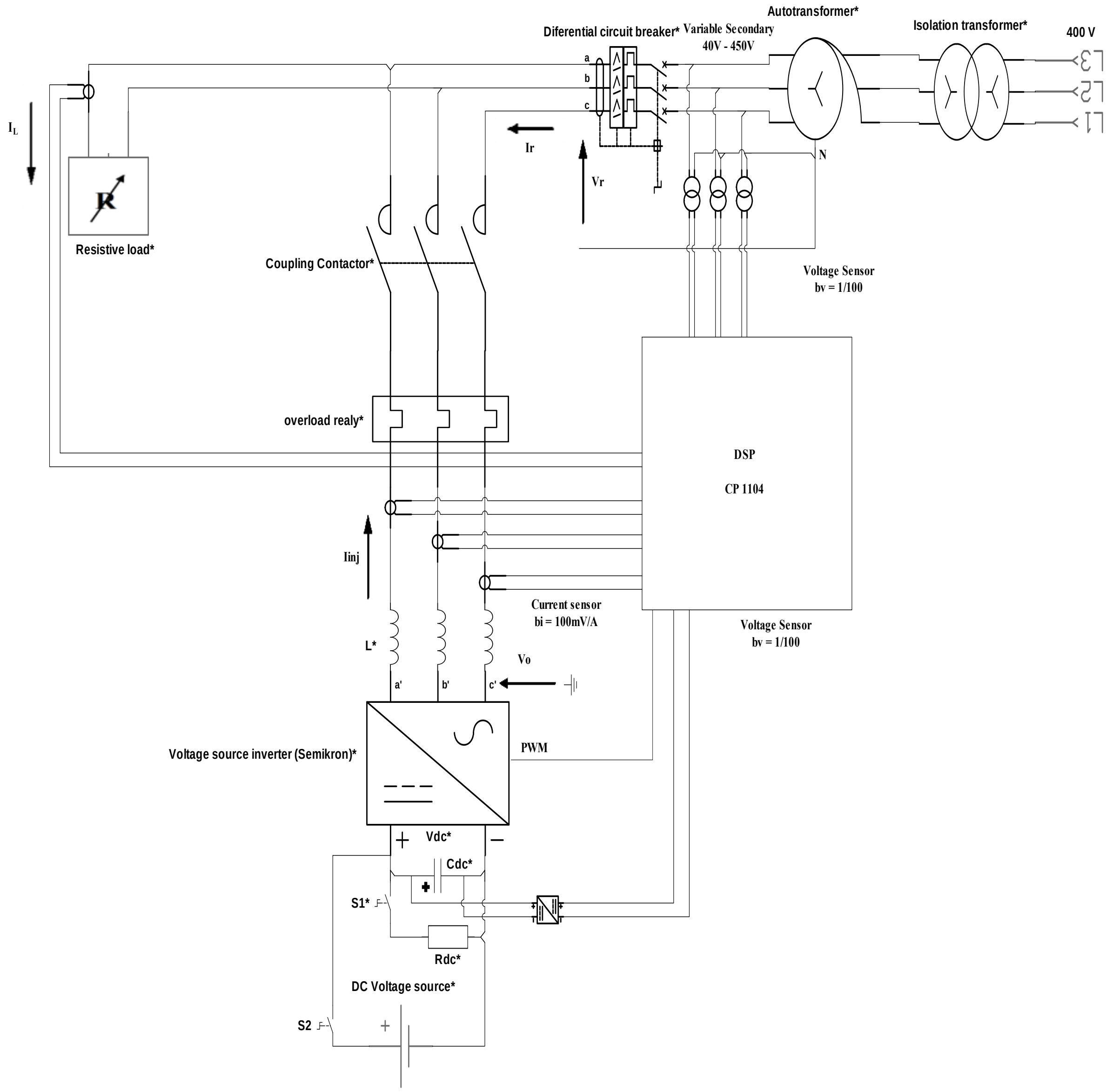

Figure 1. Reduced scale prototype of voltage source inverter based shunt STATCOM

4. TECHNICAL CHARACTERISTICS OF REDUCED SCALE PROTOTYPE

a. Three-Phase Voltage Source PWM Inverter (Figure 2)

The voltage source inverter is important in the structure of shunt STATCOM because it represents a three-phase voltage source which imposes an AC voltage at the output from a DC voltage. The control of this voltage allows to impose the injected current by the voltage difference ($V_O(t) - V_r(t)$) across the filter inductor.

This inverter is equipped with a control interface composed by the driver circuits in order to ensure the IGBT switching, PD3 rectifier in order to ensure the DC voltage source, the capacitor DC link bank, and two cooling fans.

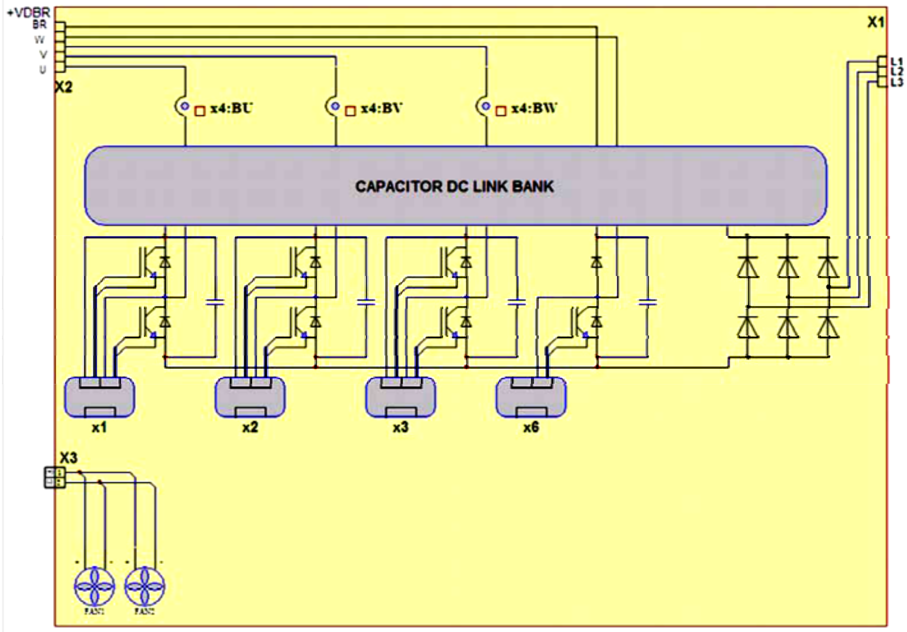

Figure 2. Power structure of the inverter

b. Filtering Inductor

The inductance, used for filtering the injected current into the power grid, is a laminated magnetic circuit inductor with a static resistance R.

c. Autotransformer of Autonomous Post

It is a three-phase autotransformer with star connection and with galvanic isolation. For reasons of security and sizing optimization, the composed secondary voltage is adjusted at $\sqrt{3}.\mathbf{V_r = 80\ V}$.

d. Single-Phase Load

It is a variable single phase resistive load, which consumes a variable power [**50VA; 530VA**] with a fixed voltage of **80V**. The load creates a current unbalance and a voltage unbalance in the autotransformer's secondary. This unbalance will be compensated by the voltage source inverter based shunt STATCOM.

e. DSP Card (ref : CLP1104)

The DSP card controls the injected current into the power grid, and the DC bus voltage. Control loops realized by Simulink blocks will be translated automatically in C language by the DSP card software. This program will generate the PWM signals controlling the current and keeping the DC bus voltage constant.

5. SIZING PROTOTYPE PARAMETERS

5.1. Power Circuit

5.1.1 Injected Current

The current injected by the inverter depends on the negative sequence of the current consumed by the single-phase load according to the following complex equation (1) [2]:

$$\overline{I^-} = \overline{I_{inj}} = \frac{\sqrt{3}}{3}\overline{I_L}e^{j\frac{\pi}{6}} \quad (1)$$

The rms value of the current injected by the inverter is variable between [**0,36A; 3,825A**].

5.1.2 DC Bus Voltage

If we neglect the voltage harmonics in the inverter AC side to the fundamental and the static resistance (R) of the self to the inductive reactance, the complex equation that relates the injected current at this voltage is [3] :

$$\overline{V_O} = \left(L\omega_r e^{-j\frac{\pi}{2}}.\overline{I_{inj}}\right) + \overline{V}_r \quad (2)$$

For a three-phase sinus-triangle PWM inverter, the DC bus voltage is depending on the power grid voltage, and the maximum voltage drop in the filtering inductor:

$$V_{DC} \geq \frac{2\sqrt{2}}{r}\max\left\{\left|\left(L\omega_r e^{-j\frac{\pi}{2}}.\overline{I_{inj.max}}\right) + \overline{V}_r\right|\right\} \quad (3)$$

5.1.3 Ripple Rate of the Injected Current

The equation that relates the ripple rate of injected current with the value of the filtering inductance is defined in the article [4]:

$$L \geq \frac{100 * V_{DC.réf}}{\sqrt{2}.12.f_d.\delta I_{inj}(\%).I_{inj}} \quad (4)$$

According to this equation, we deduce the expression of current ripple rate:

$$\delta I_{inj}(\%) \geq \frac{100 * V_{DC.réf}}{\sqrt{2}.12.f_d.L.I_{inj}} \quad (5)$$

5.2. Control Part

5.2.1 Calculating the Set-Point of Injected Current

The shunt STATCOM must inject the negative sequence of the current consumed by the single-phase load in the power grid connection point (autotransformer's secondary). According to equation (1) and knowing that the injected currents have a negative sequence order, the block diagram for the set-point generation of the injected currents into the three phases power grid is presented in figure 3 [2].

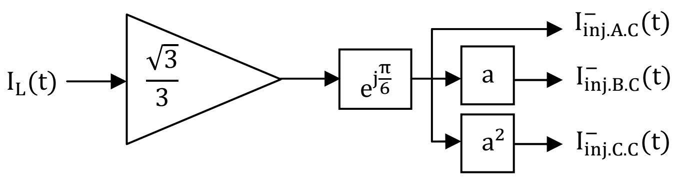

Figure 3. Obtaining the set-point currents to be injected

5.2.2 DC Bus Voltage Control (figure 4)

The DC bus voltage $\mathbf{V_{DC}}$ across the capacitor must be maintained at a fixed value ($\mathbf{V_{DC.ref}}$). The main cause which affects the stability of this voltage is the power losses in the compensator (power switch, filtering inductor). Control of the average voltage across the capacitor must be realized by determining the reference currents that maintain $\mathbf{V_{DC}}$ constant, from the set-point current to be injected. For generating the reference currents maintained $\mathbf{V_{DC}}$ constant, we are based on the instantaneous power method with the Clark transformation (α-β) [5]. This transformation is applied to the power grid voltage $\mathbf{V_r}$, and the negative sequence of the injected current $\mathbf{I_{inj}^-}$.

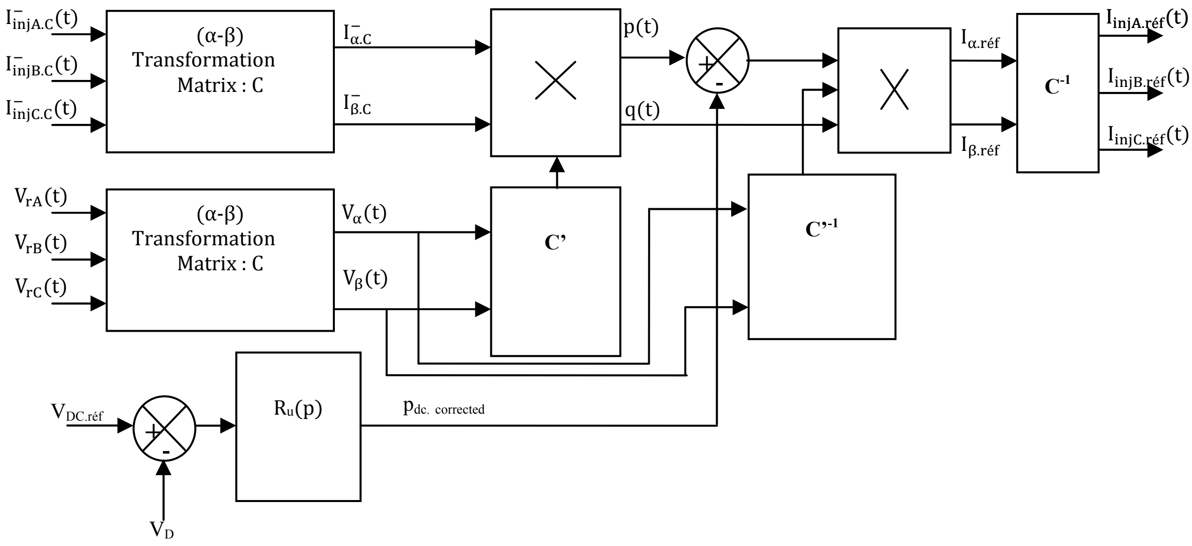

Figure 4. Diagram control blocks of the voltage VDC

With:

$$C = \frac{1}{\sqrt{3}}\begin{bmatrix} 0 & \frac{\sqrt{3}}{\sqrt{2}} & \frac{-\sqrt{3}}{\sqrt{2}} \\ \sqrt{2} & \frac{-1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} \end{bmatrix} \qquad \text{And} \qquad C' = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix}$$

5.2.3 DC Bus Voltage Controller

In order to keep the $\mathbf{V_{DC}}$ constant, it is necessary that the voltage controller creates an instantaneous power which corrects the value of the injected current reference. The $\mathbf{R_u(p)}$ controller is a proportional with delay, the transfer function is [5] :

$$R_u(p) = \frac{K_v}{1+\tau_v p} \tag{6}$$

5.2.4 Control of the Injected Currents in the d-q Frame (figure 5 and 7) :

The current control loop imposes the value of the currents injected by the shunt STATCOM. The choice of the current controller is based on the control objectives and the output filter order. The current control in the control part is realized by a comparison of the real injected current with the reference currents that maintain $\mathbf{V_{DC}}$ constant. This control is realized in the d-q frame for both current injected sequences (positive sequence and negative sequence) [6]. The generation of three-phase PWM control signals from the corrected modulating signals is shown in figure 6.

With:

$$P_k^+ = \frac{1}{3}\begin{bmatrix} 2\sin(\theta) & 2\sin\left(\theta - \frac{2\pi}{3}\right) & 2\sin\left(\theta + \frac{2\pi}{3}\right) \\ 2\cos(\theta) & 2\cos\left(\theta - \frac{2\pi}{3}\right) & 2\cos\left(\theta + \frac{2\pi}{3}\right) \\ 1 & 1 & 1 \end{bmatrix}$$

$$P_k^- = \frac{1}{3}\begin{bmatrix} 2\sin(-\theta) & 2\sin\left(-\theta - \frac{2\pi}{3}\right) & 2\sin\left(-\theta + \frac{2\pi}{3}\right) \\ 2\cos(-\theta) & 2\cos\left(-\theta - \frac{2\pi}{3}\right) & 2\cos\left(-\theta + \frac{2\pi}{3}\right) \\ 1 & 1 & 1 \end{bmatrix}$$

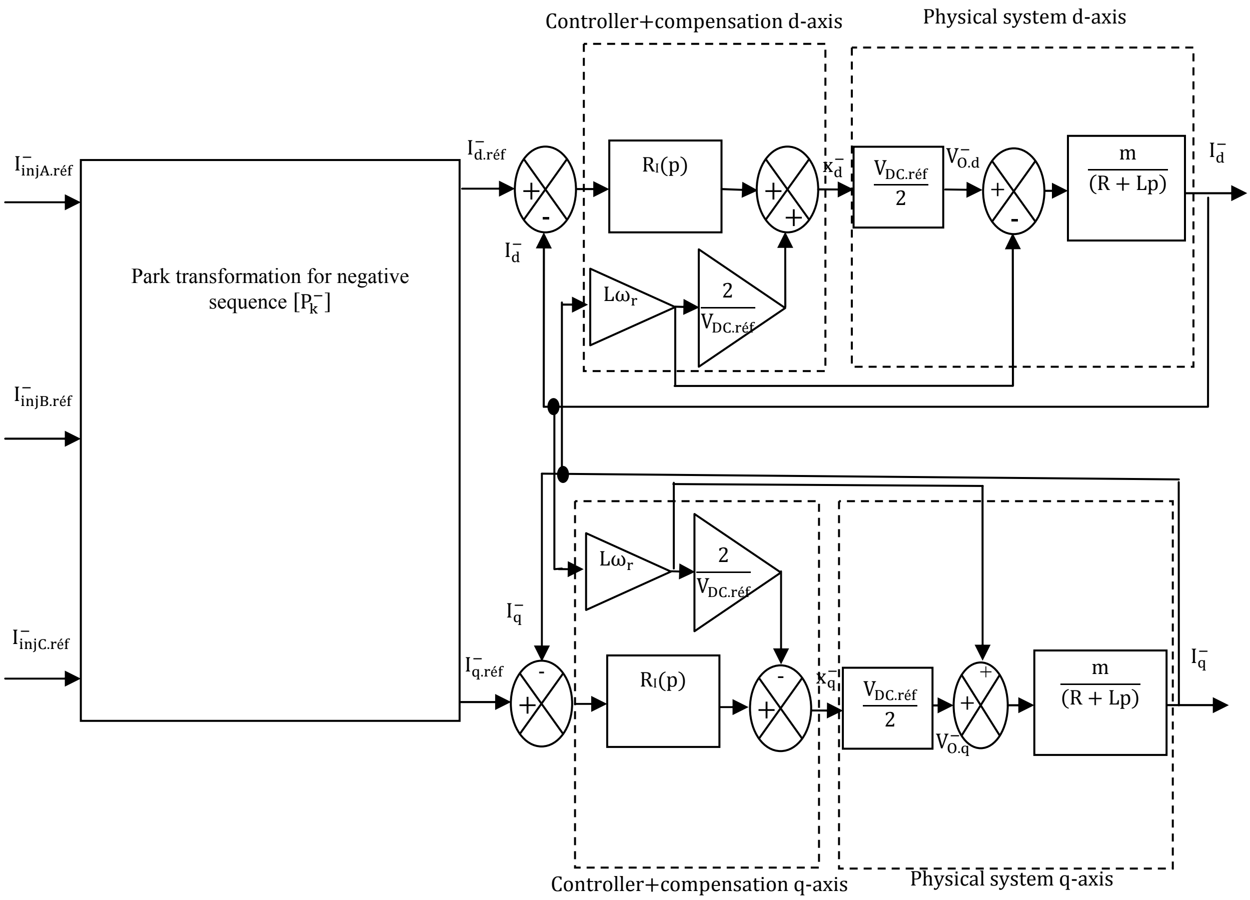

Figure 5. Diagram control blocks of the injected current negative sequence

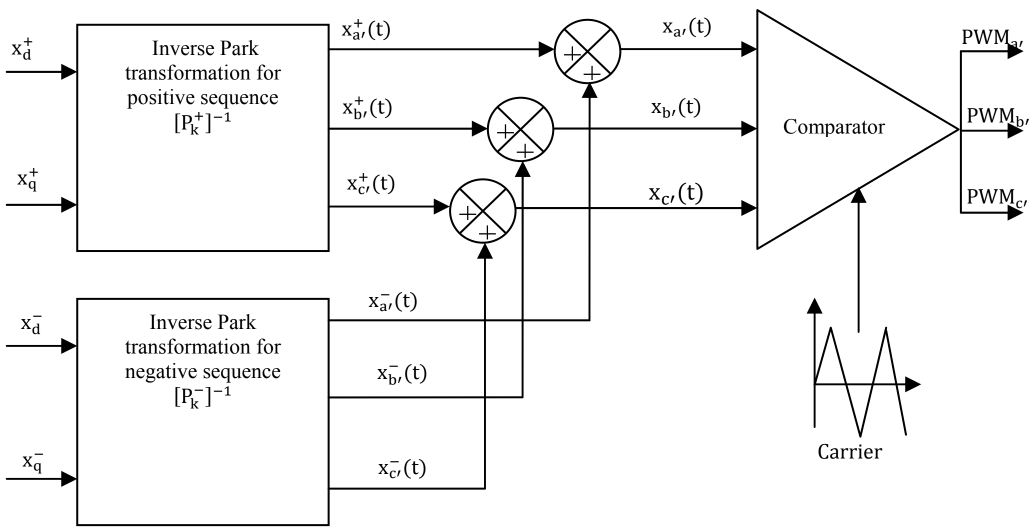

Figure 6. Generation of tree-phases PWM signals

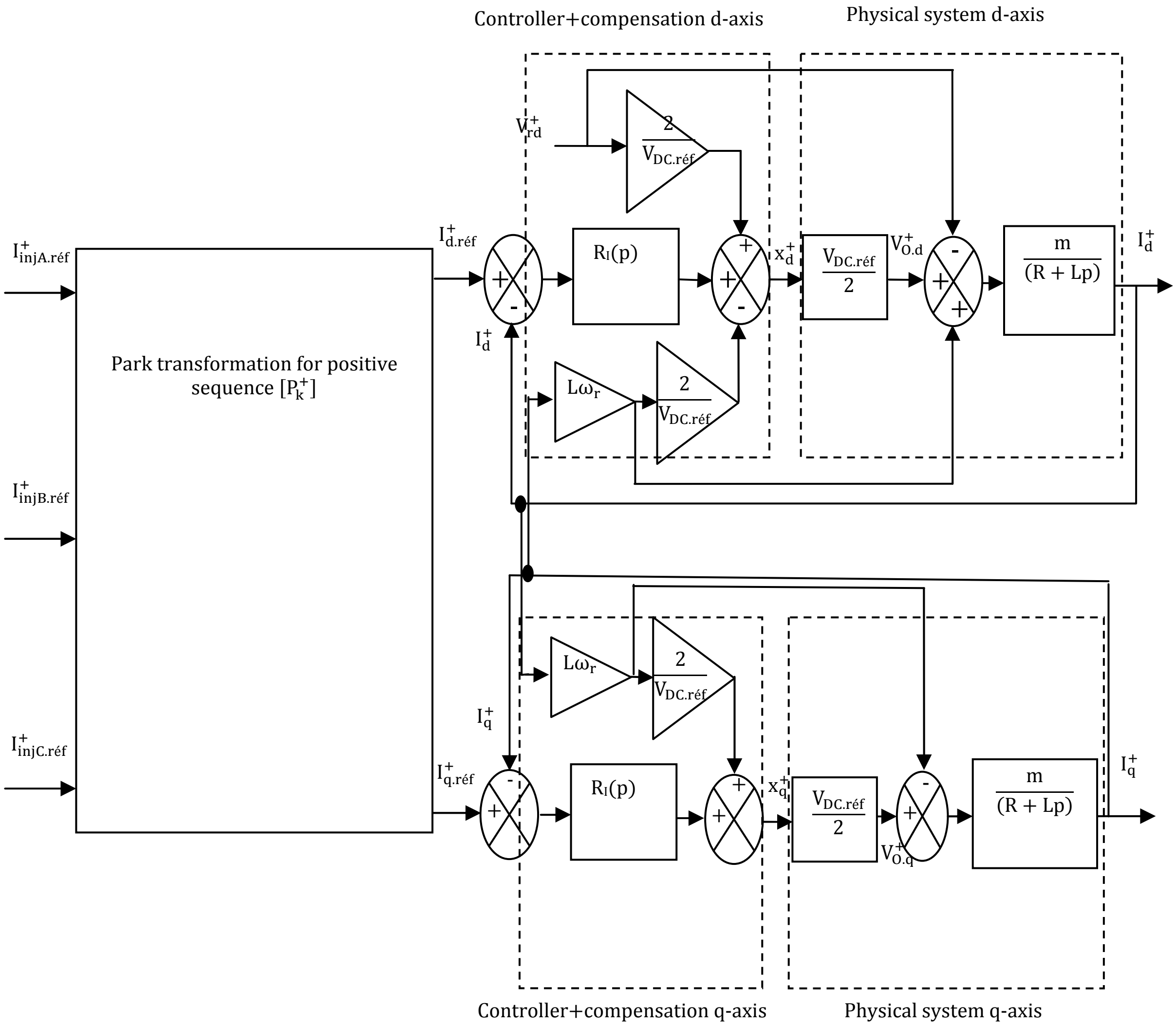

Figure 7. Diagram control blocks of the injected current positive sequence

5.2.5 Injected current Controller

The injected current reference is variable depending on the power consumed by the single-phase load. So in order to improve the performance of this control, we use a mixed PI controller $\mathbf{R_I(p)}$. Its transfer function is:

$$R_I(p) = K_I \frac{1+\tau_I p}{\tau_I p} \quad (7)$$

This controller allows to cancel the static error and to reduce the dynamic error.

6. EXPERIMENTAL RESULTS

We present in this part the results obtained with and without compensation by current injection in static and dynamic regime. The voltage unbalance factor ($\mathbf{T_{iv}(\%)}$), the voltage total harmonic distortion ($\mathbf{THD_v(\%)}$), and the DC bus voltage are acquired by oscilloscope and plotted using MATLAB tools. This experimental test is realized through the following parameters:

Table 1. Power circuit parameters

Power circuit	
Parameter	**Value**
Line-line power grid voltage (autotransformer's secondary)	80V
Reference of the DC bus voltage $\mathbf{V}_{\mathbf{DC.réf}}$	300V
Variable single-phase resistive load	Apparent power $\mathbf{S}_{\mathbf{L}}$ with supply by 80V [50VA→530VA]
DC Capacitor	6mF
Filtering inductor	30mH/0.4Ω

Table 2. Control part parameters

Control part	
Parameter	**Value**
Carrier frequency	5KHz
Gain of current sensor	100mV/A
Gain of voltage sensor	1/100
Gain of voltage controller $\mathbf{K}_{\mathbf{v}}$	95.47
time constant of the voltage controller $\boldsymbol{\tau}_{\mathbf{v}}$	9,43ms
Gain of current controller $\mathbf{K}_{\mathbf{I}}$	10
time constant of the current controller $\boldsymbol{\tau}_{\mathbf{I}}$	75ms

➢ **Static Regime**

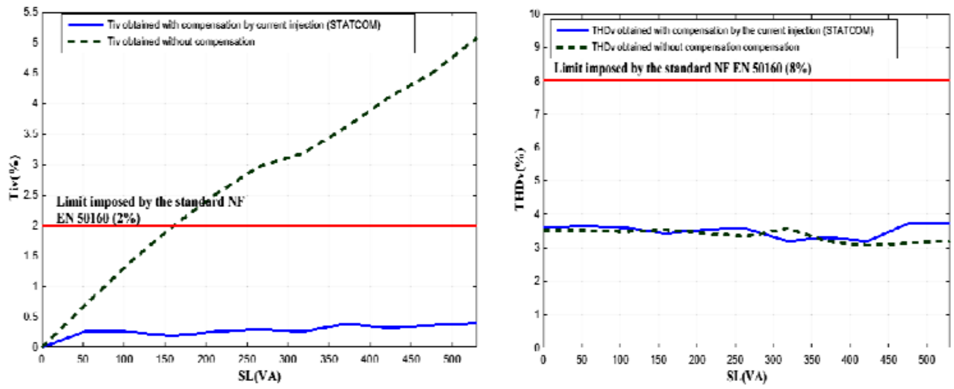

Figure 8. Voltage unbalance factor $\mathbf{T}_{\mathbf{iv}}$ and voltage total harmonic distortion $\mathbf{THD}_{\mathbf{v}}$ in function of the load power ($\mathbf{S}_{\mathbf{L}}$)

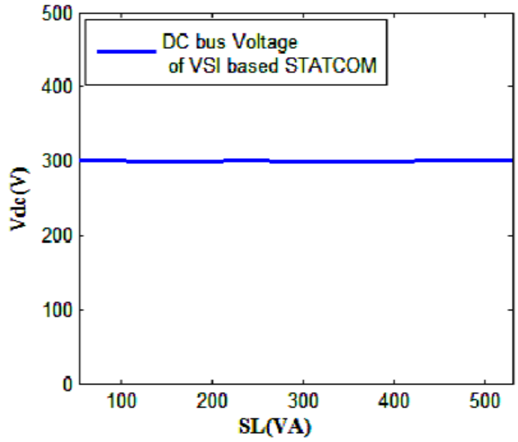

Figure 9. DC bus voltage V_{DC} in function of the load power ($\mathbf{S}_{\mathbf{L}}$)

➢ Dynamic Regime

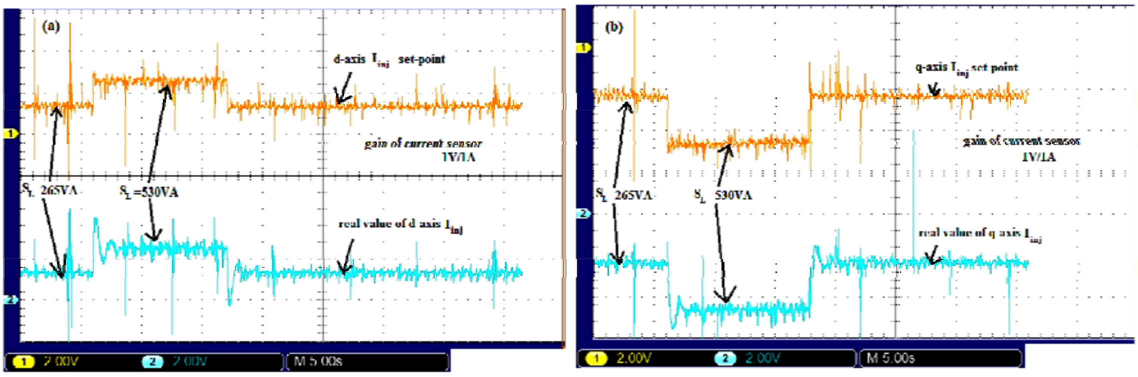

Figure 10. Step response of the injected current in the dq-frame (a : d-axis, b : q-axis)

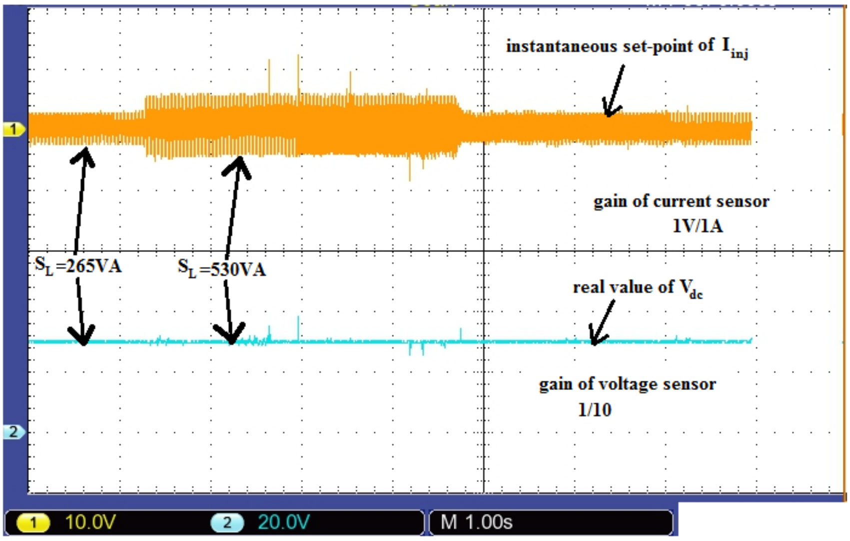

Figure 11. DC bus Voltage in function of injected current set-point change

Figure 12. Experimental banc picture

7. CONCLUSION

We conclude that the unbalance compensation by current injection with VSI_STATCOM allows to obtain the best results independently of the power level consumed by the single-phase load SL. The voltage unbalance factor is kept around the value tolerated by the standard (**T_{iv}<2%**), the current injection does not have an influence on the voltage total harmonic distortion, and for any power level of single-phase load, the injected current keeping the sinusoidal waveform. The DC bus voltage is constant near its reference value for all values of the power consumed by single-phase load.

In the dynamic regime, the step response of the injected current in the dq-frame shows that, the current control loop allows mastering the stability, the accuracy, and the response time, in order to follow the change set-point.

This experimental study with reduced scale prototype (low-voltage) allows us to check the validity of the system and the control technique in laboratory with safety and controllable way before implantation in large scale (high-voltage).

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