

# Implementation of Inverse Neural Control To VSC Converter for Active and Reactive Power Flow

Freddy Alexander Forero R., Andrés Mauricio Molina M., José Guillermo Guarnizo M., and Harold Rene Chamorro V.

**Abstract**— In this paper is presented the implementation of a VSC (Voltage Source Converter), to be used in HVDC (High Voltage Direct Current) systems. The control is carried out of active and reactive power flow for the VSC, by an Inverse Neural Control, based on Multi layer Perceptron.

The non linearity nature presents learning problems in the Neural Network like poor identification for the VSC, when the Neural control is implemented in real time. This paper proposes a design for an Inverse Neural Control of the active and reactive power flow for the VSC converter, and it solves the learning problem through real time control for the VSC. Four neural controllers are used, which are training and implemented in parallel, activated just one in time, depending on the work region in the converter. The system is controlled in a -100W to 100W range of active power and -30 VAR to 30 VAR in reactive power.

**Index Terms**— VSC, Neural Control, active power, reactive power.

## I. INTRODUCTION

THE HVDC (High Voltage Direct Current) systems based on VSC (Voltage Source Converter) is a technique for the transmission and distribution of energy, where the active and reactive power present flexibility in the control strategies [1].

Some previously works have shown the advantages of the active and reactive power control for VSC converters, in special using Fuzzy control [2], Neural Control [3], and Classical control [4]. In case of Fuzzy control implemented in computational real time, the sampling time is insufficient, being converted to supervised neural control [5], identified the behavior of the fuzzy control [6].

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The VSC has the property of the flow controls active power, by means of the variation of the phase shift of coordination of the signal generated, with the signal of the net where the VSC is connected. And it controls the flow of reactive power by means of modulation index which relates the amplitude of the signal generated, it is named index of modulation. In this paper, a novel proposal for the control of active and reactive power flow is presented, by Inverse Neural Control, and implemented in Real Time using Matlab. For solving problems in the training of the Neural Control, it was proposed a structure where 4 specialized Neural Controllers were trained and used in parallel, where each one is activated given dynamics characteristics which are presented in the VSC.

In II is shown VSC theory, in III is presented the design of the VSC, in IV is shown the implementation of VSC, in V is presented the design and implementation of Inverse Neural Control, in VI are shown the results and finally in VII are shown the conclusions.

## II. VSC CONVERTER

The VSC's are composed by a 6-pulse bridge equipped by self-commutating switches as IGBT's which it have been used commonly in VSC-HVDC's systems [1], diodes connected in anti-parallel, a converter-reactor which it is the linkage between the VSC and the AC network or the passive load, DC capacitors that they have the function of energy storage, and shunt AC filters [1]. The basic structure of a VSC is shown in the Figure 1, where the system is feed by a regulate DC source.

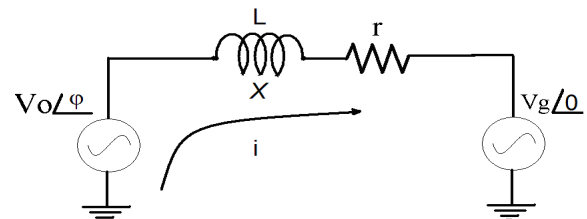


Figure 1. Equivalent circuit of an VSC viewed from the AC side.

The main function of a VSC is to convert the DC voltage that it could be obtained from different sources of generation (i.e. solar cells, wind farms together with a rectifier or an AC network interconnected through other VSC, among others), into an AC current. The polarity of the DC voltage is defined by the polarity of the diode bridge, the VSC valves can be

switched in any time by appropriate gate voltage. However it is important to take in account that whether a valve is switched on, then its complementary valve must have been switched off previously to avoid a short circuit in the arm [2]. The alternate switching of the valves connected to one phase module successively connects the AC terminal of the VSC to the central tab of the DC source. Therefore, a square wave AC voltage comprising two voltage levels is obtained:  $+V_{dc}/2$  and  $-V_{dc}/2$ . A VSC operating in this way is therefore referred to as a 2-level converter [2].

The expression that represents the output voltage in each phase of the converter is given by [10]:

$$V_{an}(t) = E \cdot [2 \cdot \delta(t) - 1] \quad (1)$$

Where  $E=V_{dc}/2$  is the voltage in the DC side of the converter in each pole,  $V_{an}$  is the output voltage in the phase **a** and  $\delta$  is the rate between the time in which the valve is switched on and the time of commutation  $T$ ,  $\delta(t)$  means that the time in which the valve is switched on is a function of the time.

To obtain a sinusoidal voltage  $V_{an}(t)$  in the output with a determinate frequency and a reduced amount of harmonics, it is necessary to use PWM (Pulse Width Modulation) techniques with a high switching frequency  $f_c$  in the 1-2kHz range [2], it will be the frequency of a triangular wave shape that modulates a sinusoidal wave to the frequency  $f_m$  which it will be the set frequency in the output controlled by  $\delta(t)$ . The wave shape of the converter AC voltage output can be controlled to be almost sinusoidal with the aid of small high frequency filters. Solving for  $\delta(t)$  in (1):

$$\delta(t) = \frac{1}{2} + \frac{1}{2} \cdot \frac{V_{an}(t)}{E} \quad (2)$$

To obtain the desired value  $V_{an}(t)=E_m \sin(\omega t + \varphi)$ , where  $E_m$  is the top value of tension,  $\omega$  is the angular set frequency and  $\varphi$  is the phase angle of the fundamental component of PWM with respect to the bus voltage, is required:

$$\delta(t) = \frac{1}{2} + \frac{1}{2} \cdot \frac{E_m \cdot \sin(\omega t + \varphi)}{E} \quad (3)$$

$$m = \frac{E_m}{E} \quad \text{and} \quad E_m \leq E$$

The outputs voltages in each phase -omitting the harmonics are:

$$\begin{aligned} V_{an} &= E \cdot m \cdot \sin(\omega t + \varphi) \\ V_{bn} &= E \cdot m \cdot \sin(\omega t + \varphi - 2\pi/3) \quad \text{and} \\ V_{cn} &= E \cdot m \cdot \sin(\omega t + \varphi + 2\pi/3) \end{aligned} \quad (4)$$

### III. DESIGN OF THE IMPLEMENTATION OF THE VSC

The design of a converter VSC corresponds to three parameters which are [12]:

- Inductance of commutation: In which the flow of powers between the VSC and the electrical network
- Filters DC: Ordered to maintain the VDC constant
- Filters AC: In loaded to filter the signal generated by the VSC, to obtain pure a sinusoidal signal.

#### A. General Specifications

The system must be in the capacity to interchange or to feed power a load it activates or passive with a value of 300 (VA), the warhead will be the public network AC which presents a voltage  $V_s=120V_{rms}$  to 60Hz by phase, therefore chooses  $E > \sqrt{2} \cdot V_s$ , where  $E=195$  V and therefore  $VDC = 390$  V.

The system design for S (three-phase) = 400(VA) with the objective to over-determine the proportions the system. Therefore the basic characteristics of design of the VSC will be:

$$S=400VA, m=0.9, E=195V, f_m=60Hz, f_c=1800Hz.$$

#### B. Selection of the commutation inductance.

The value of the inductance of commutation (reactor) in by unit this around 0.1 to 0.2 with the capacity of interchange of power of the converter [8][9]. The value of the inductance of commutation can be obtained from the impedance for phase that the VSC sees in his output which is:

$$Z_{Phase} = \frac{(V_{Phase})^2}{S_{Phase}} = \frac{\left(m \frac{E}{\sqrt{2}}\right)^2}{\frac{S_{Total}}{3}} = \frac{\left(0.9 \cdot \frac{195}{\sqrt{2}}\right)^2}{\frac{400}{3}} = 115.5 \quad (5)$$

To calculate the commutation inductance, as it were said in the previous paragraph is between 0.1 and 0.2, of the capacity of transference of power of the system, in this document it takes this value of 0.2, this is:

$$0.2 S_{Phase} = 0.2 (V_{Phase})^2 / Z_{Phase} \quad (6)$$

Then:

$$0.2 Z_{BASE} = 0.2 (V_{base})^2 / S_{base} \quad (7)$$

Where  $0.2 Z_{BASE} = XL$ .

Then  $XLA=XLB=XLC=0.2$  p.u. (per unit), in real values  $XLA = 0.2 * Z_{BASE} = 0.2 * 115.5 = 23.1 \Omega$  and the value of the inductance of commutation is:

$$L_A = XLA / (2\pi * f) \quad (8)$$

Where  $f$  is the frequency the electrical network.

Then  $XLA = (23.1) / (2\pi * 60) \approx 61$  mH.

Nominal reactive power  $Q$  to 60 Hertz of the reactance of the A phase is:

$$QXL_A = I_A^2 \cdot XL_A = (S_A / V_A)^2 \cdot XL_A = 26VAR. \quad (9)$$

Is considering the reagents of superior overtones,  $QXLA = QXLB = QXLC > 26VAR$ , this value allows the design of filters that reduce the value of the harmonic components [9].

### C. Design of filters AC

These filters are ordered to eliminate the overtones by above of 1800 Hertz, generated by the SPWM (Sinusoidal Pulse Width Modulation) modulation.

For the design of the tuned filters is due to consider that in  $\omega_1$ , capacitance C presents reactance:

$$X_C(\omega_1) = V^2/Q \quad (10)$$

in  $\omega_2$ , presents reactance:

$$X_C(\omega_1) = X_C(\omega_1) * \omega_1 / \omega_2 \quad (11)$$

and so that of the resonance in

$$\omega_2 L = X_C(\omega_1) * \omega_1 / \omega_2 \quad (12)$$

it allows to obtain[9]:

$$L = \frac{V^2}{Q} \cdot \frac{\omega_1}{\omega_2^2} \quad (13)$$

and

$$C = \frac{Q}{\omega_1 \cdot V^2} \quad (14)$$

Where Q is the reagent to compensate (26 VAR),  $\omega_1$  is the fundamental angular frequency to 60Hz,  $\omega_2$  is the angular frequency of harmonic, that it is wanted to eliminate for this case the one of 1800 Hz and its lateral ones [11]. Then is obtained  $L=1700 \mu\text{H}$  and  $C = 4.57 \mu\text{F}$

### D. Design of filters DC

Taking by pole 195VDC and 150W represented by  $R=V^2/P=253\Omega$ , frequencies near and greater to 1800Hz can be leaked, installing in each pole of exit DC of the rectifier a condenser C that fulfills  $RC \gg TC$ . Then  $C \gg (1/(1800*253))$  and is chosen  $C=47\mu\text{F}$  or superior [10].

## IV. THE IMPLEMENTATION OF THE VSC

In this implementation the value of the condensers of part DC is of 2 mF, greater to the calculated value of 47  $\mu\text{F}$ , expiring with the restriction that mention in the previous section, and the coil of the tuned filters is eliminated, since it presented great losses, even so total harmonic distortion does not surpass the 2% [12]. This implementation connects a computer where the powers and the Inverse Neural Control are calculated, by means of software Matlab®.

1. A rectifier of 2 diodes each one with a nominal current of 10 amperes
2. 2 condensers of 2 mF to 200V of work
3. The stage of this power composed by 6 IGBT's that they were shaping the three-phase bridge.
4. 3 coil of commutation for each phase of the VSC with values of inductance of 64 mH
5. 3 tuned filters consisted only a no polar condenser, since the inductance of the tuned filter was presenting significant losses.
6. The stage of generation of the SPWM is compose by for a PIC30F4011, that it possesses a module of generation of 6

pulses for the three-phase bridge, this microcontroller also tries the signal delivered by a card of acquisition of information, to generate the signal with a respective phase shift and index of modulation, also it tries the sign of a circuit to synchronize the signal generated by the VSC with the signal of the net.

7. The stage of power and control isolated by means of optocouplers of high frequency, to avoid damages in the stage of control for if there are damages in the stage of power.
8. A resistive load composed by 3 lamp chimneys of 120V/200W, to dissipate the power when the VSC receives it.
9. Sensors of voltage and current provided the information to calculate the respective powers. In the case of the voltage sensor it is a transformer laminated of 80mVA, with a relation of 20:1 Type EE20, and to sense the current a transformer in current way made by COILCRAFT CS2106L is used.
10. Card of data acquisition PCI 6024-E of National Instruments, as much as to collect data as to send them to the software of Matlab®.

The VSC converter developed has the following characteristics as far as the power flow: 100 W to -100 W by phase of active power, 30 VAR to -30 VAR of reactive power by phase. Hardware implementation is presented in the Figure 2.

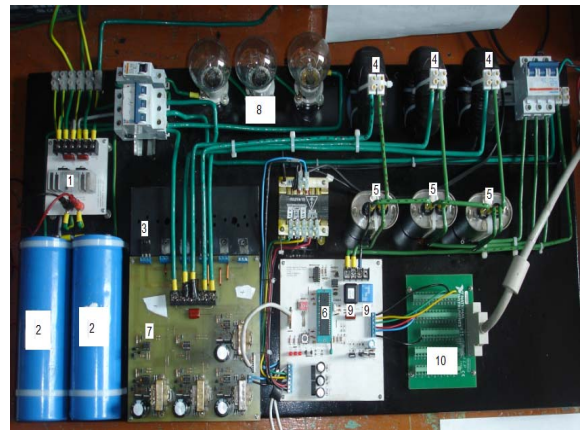


Figure 2. Prototype of a converter VSC

## V. IMPLEMENTATION OF THE NEURAL INVERSE CONTROL IN THE PROTOTYPE OF VSC

The architecture used for the control of the plant was Multilayer Perceptron. The algorithm of training was Levenberg-Marquardt [7].

Based on previously works presented in [4], some architecture is proposed for Neural Control implementation using NNARX [7], the data set was done by a sweep a different values of the active and reactive power of the VSC, for the training of the neural network. The first neural network corresponds to the control signal phase shift was trained with 5 neurons in the hide layer. The second neural network corresponds to the control signal modulation index was trained

by 3 neurons in the hide layer. The neural control scheme is shown in the Figure 3.

The input signs are active power with 5 delays, error of active power with 4 delays, reactive power with 5 delays, and error of reactive power with 4 delays in both neural networks.

The number of patterns used to train both neural networks was 10000 patterns (10 time units per 0.001 time units for sample time), the epochs of training were 150. This controller's result in the prototype of the VSC is observed in the Figure 4.

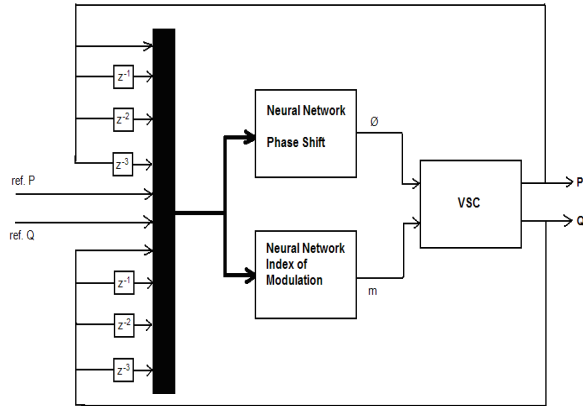


Figure 3. Scheme of Inverse Neural Control for an alone region of work in the prototype of the VSC

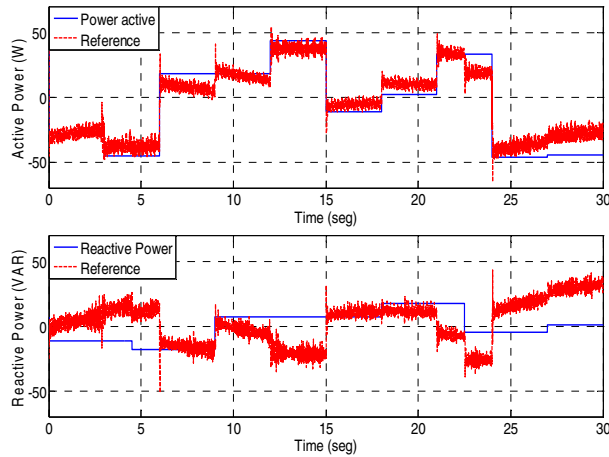


Figure 4. Power Control using first Neural Control.

It is observed that there is no control on the reactive power and a great offset in the active power.

When the data is analyzed, it was observed that in this prototype there are two characteristics which differentiate it from a common VSC:

1. The constant voltage or  $V_{dc}$  that feeds to this converter is not regulated, the consequences are that on having delivered power the  $V_{dc}$  it falls down, and on having received power the  $V_{dc}$  increases. For the second condition, it is placed a load resistive that consumes the power which is receiving for this one, and of this form to support the constant  $V_{dc}$ , but on having applied this, the

VSC behaves of very different form.

2. The  $V_{dc}$  does not provide all the needed power in order that the VSC works in certain regions.

For which the following step is made and it was to take information of the VSC, analyze them and generate a new controller. Of the analysis of information and of both previous characteristics of the prototype is concluded that one was not working with a system, but with several systems, with different characteristics and with his respective regions of work, both for phase shift and for index of modulation. To solve this problem the prototype proposed to work in four regions of work that are showed in the Figure 5, they are:

- Region 1: delivery of active power and delivery of reactive power.
- Region 2: delivery of active power and receipt of reactive power.
- Region 3: receipt of active power and delivery of reactive power.
- Region 4: receipt of active power and receipt of reactive power.

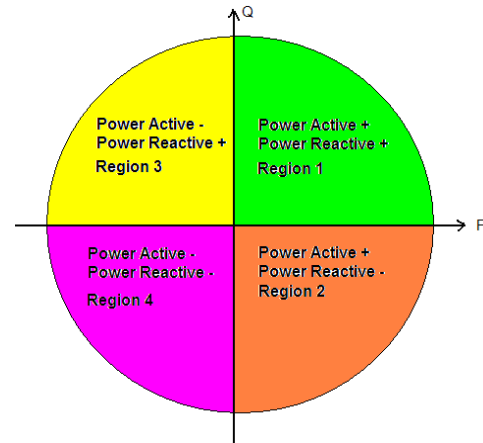


Figure 5. Regions of work of the prototype of the VSC

Due to the fact that the region of work of the VSC divided in four regions, for each of these four regions one was implemented an Inverse Neural Control.

The final model of the Inverse Neural Control for an alone region of work is similar to Figure 3, in which the VSC was divided. In all the four regions of work they operate on two Neural Networks for the control, one sends the sign of phase shift and other one sends the sign of index of modulation. It is to say that in whole they are eight Neural Networks, which possess the same input vector, it is composed for: reference of active power, active power with 3 delays, reference of reactive power, reactive power with 3 delays, for a input vector consisted of 10 inputs in whole.

## VI. RESULTS OF CONTROL NEURAL REGIONS

In all regions the number of patterns used for the training of the neural networks was 21429 patterns (30 units of time for

0.0014 units of time of sampling). So in all neural networks the inputs are: reference of active power, active power with 3 retards, reference of power reactivates and active power with 3 retards, like is shown in the Figure 5.

Region 1: Control of the positive active power and power reactivates positive. The neural network for phase shift has been trained with 5 neurons in the hidden layer, and neural network for modulation index has been trained with 2 neurons in the hidden layer. The number of times of training for the neural network of phase shift was of 200, the MSE (Mean Squared Error) of the training it converged at  $8.3 \times 10^{-6}$ . The number of times of training for the Neural Network of modulation index was of 50, the MSE of the training it converged at  $7.8 \times 10^{-9}$ .

This controller's result in the prototype of the VSC is shown in the Figure 6, some spurious pulses are observed, this is because the load to be active fluctuates, these are external disturbances to the plant, but the controller supports the reference.

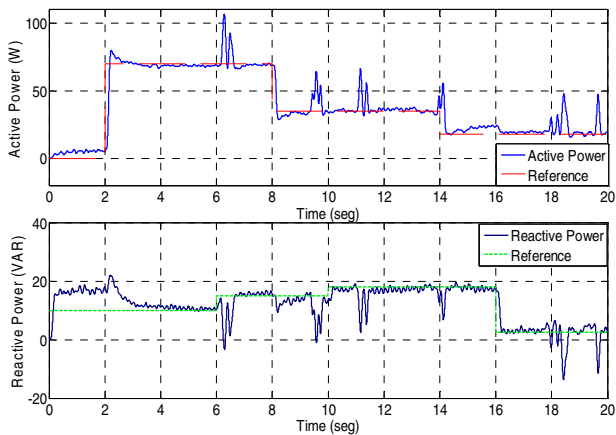


Figure 6. Power Control using Inverse Control Neural Region 1

Region 2: Control of the positive active power and power reactivates negative. The Neural Network for phase shift has been trained with 5 neurons in the hidden layer, and the Neural Network for modulation index it has been trained with 2 neurons in the hidden layer. The number of times of training for the Neural Network of phase shift was of 200, the MSE of the training it converged at  $7.4 \times 10^{-7}$ . The number of times of training for the Neural Network of modulation index was of 50, the MSE of the training it converged at  $6.7 \times 10^{-7}$ .

This controller's result in the prototype of the VSC is shown in the Figure 7, it is observed that the error is near of to 5%, spurious pulses are also presented by the fluctuation of the net, but again one sees that the controller takes the VSC to the reference.

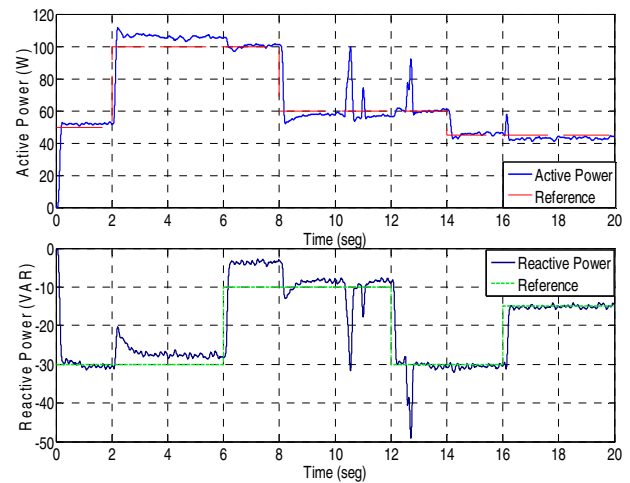


Figure 7. Power Control using Inverse Control Neural Region 2

Region 3: Control of the power active negative and power reactivates positive. The Neural Network for phase shift has been trained with 5 neurons in the hidden layer, and the Neural Network for modulation index has been trained with 2 neurons in the hidden layer. The number of times of training for the neural network of phase shift was of 250, the MSE of the training it converged at  $2 \times 10^{-7}$ . The number of times of training for the neural network of modulation index was of 50, the MSE of the training it converged at  $2.3 \times 10^{-7}$ . This controller's result in the prototype of the VSC is shown in the Figure 8. In this case more error is presented in stationary state in some work areas, in other areas it operates appropriately, the signals of power are but noisy since the load resistive is placed for the dissipation of the received active power, the characteristic spurious pulses of the fluctuations of the net are also observed.

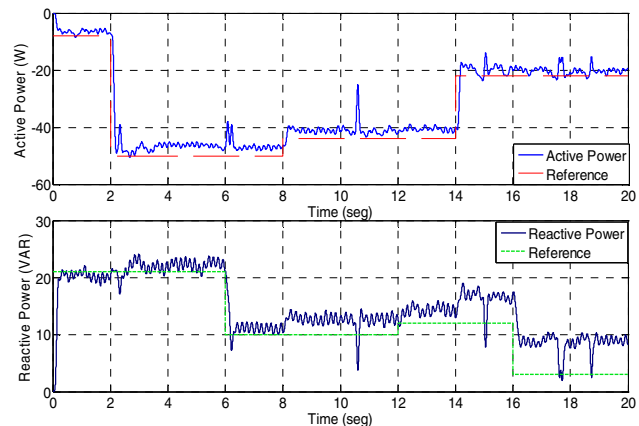
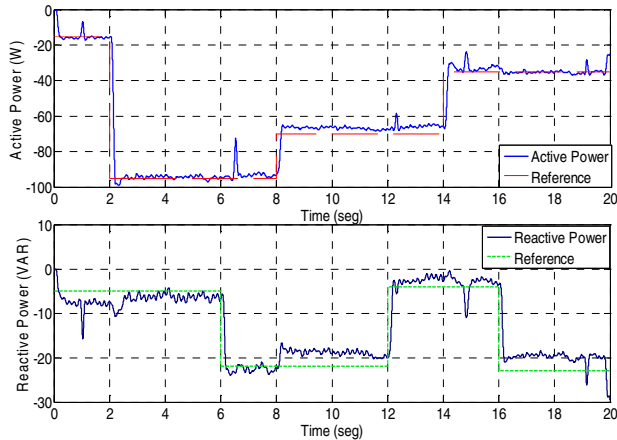


Figure 8. Power Control using Inverse Control Neural Region 3.

Region 4: Control of the power active negative and power reactivates negative. The Neural Network for phase shift has been trained with 5 neurons in the hidden layer, and the Neural Network for modulation index it has been trained with 2 neurons in the hidden layer. The number of times of training for the Neural Network of phase shift was of 240, the MSE of the training it converged at  $4.4 \times 10^{-5}$ . The number of times of training for the neural network of modulation index was of 50,

the MSE of the training it converged at  $1.1 \times 10^{-9}$ .

This controller's result in the prototype of the VSC is shown in the Figure 9. This is since the best controller that presents the best error in stationary state in an entire sweeping of powers they don't overcome 3%, the same as the previous one the signals of power are but noisy due to load that it is placed



to dissipate power.

Figure 9. Inverse Neural Control Region 4

## VII. CONCLUSIONS

One of the advantages of working with Neural Networks for control is that it works directly with the system, by which the variations in the time of this one are guarded in the information of the training, and they are born in mind at the moment of realizing the controller, giving hardness to the control. Other advantage for this propriety is not need mathematical model for the design of the control, in special for complexity system as VSC converter. For the case of the VSC, the control of the Active and the Reactive power flow lets more flexibility for the use in the HVDC systems, so, an Inverse Neural Control was used for this issue.

In some non linear systems as VSC converter, a classical Inverse Neural Control cannot identify completely the dynamics of the system, in this situation the control shown low performance. The control by regions present some alternative for specialize controllers by regions of work, in this case there allowed to develop an Inverse Neural Control of a VSC, which it has a different dynamics depending on the point of work where it is, and in addition it has the characteristic of which the controlled variables are coupling.

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