Analysis and Operation of STATCOM in Unbalanced Systems

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Abstract – **This work shows a study of the STATCOM operating in unbalanced systems with negative sequence components. It describes the basic operation of the STATCOM and its control method. The simulation of a 48 pulse STATCOM based on the electromagnetic-transients program, ATP-EMTP, is presented to show its good performance under balanced conditions. Then, based on an analytical analysis it is shown how negative sequence components disturb the control method used in the STATCOM studied. At last, solutions to solve this problem are presented.**

Keywords: STATCOM, FACTS, reactive power, inverters for reactive power control, PWM control

I. INTRODUCTION

The STATCOM is a static compensator used to regulate voltage and to improve dynamic stability [1-3]. There are some variations of the STATCOM, but the composition of it is basically the same [4]. It is composed of inverters with a capacitor in its dc side, coupling transformers, and a control system. The inverters are, in conventional STATCOMs, switched with a single pulse per period and the transformers are connected in order to provide harmonic minimization. The equipment action is made through the continuous and quick control of capacitive or inductive reactive power. Its output voltage is a waveform composed of pulses that approaches a sinusoidal wave. To obtain voltage harmonic content, that clearly agrees with strict standards, without the necessity of filters, it is necessary at least a set of eight inverters and transformers to produce a 48-pulse voltage waveform. Fig.1 shows one example of such a STATCOM and Fig. 2 shows its voltage. However, there are examples with more complex transformer connection (e.g. [4]).

II. STATCOM CONTROL

The interaction between the AC system voltage and the inverter-composed voltage provides the control of the STATCOM var output [3,4]. When these two voltages are synchronized and have the same amplitude, the active and reactive power output are zero. Fig.2 (a) shows this situation. However, if the amplitude of the STATCOM voltage is smaller than that of the system voltage, it produces a current lagging the voltage by 90^o (see Fig.2 (b)), and the compensator behaves as an inductive load, which reactive value depends on the voltage amplitude. Making the STATCOM voltage higher than the AC system voltage the current will lead the voltage by 90^o,

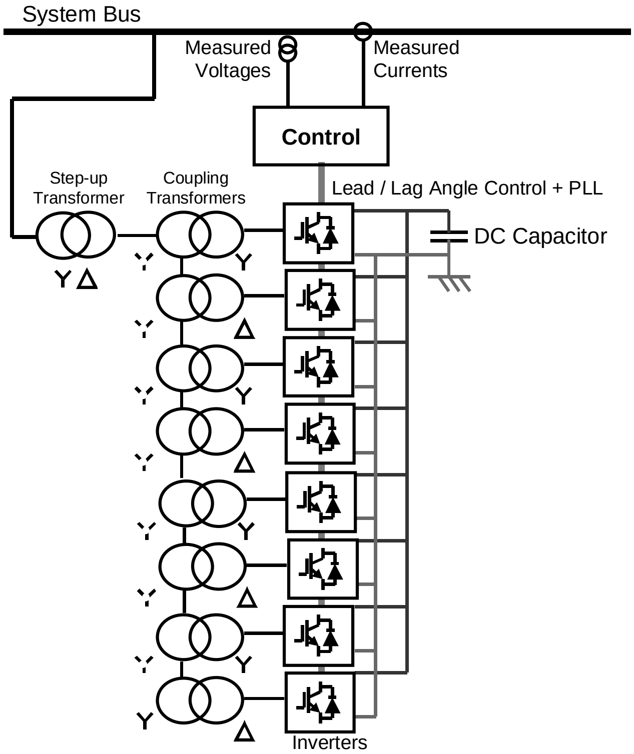

Fig. 1. 48-Pulses STATCOM diagram.

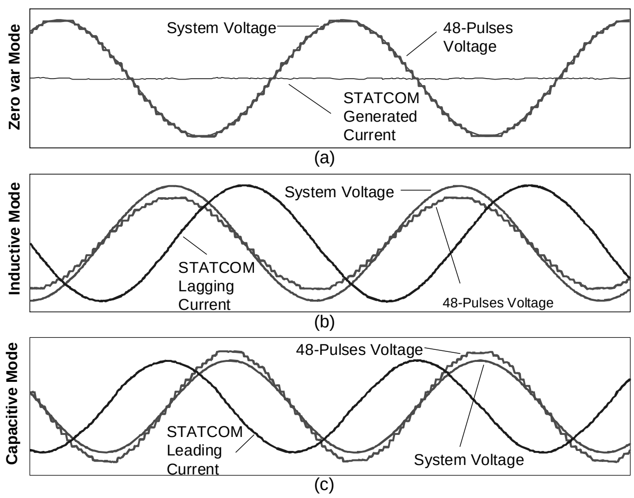

Fig. 2.STATCOM 48-pulses voltage and compensating current.

(see Fig.2(c)), and the compensator behaves as a variable capacitive load. As in the previous case, the reactive power depends on the voltage amplitude. This amplitude control is done through the control of the voltage on the dc capacitor. This voltage is related to the energy stored at the dc capacitor. By lagging or leading the STATCOM voltage, it is possible to charge or discharge the dc capacitor, as a consequence, change the value of the dc voltage and the STATCOM's operational characteristics. The control used for this model of STATCOM is a very simple one. It uses measurements of voltages and currents at the point where the STATCOM is connected to the AC system bus. These measured signals are worked in two ways as shown in Fig.3. In one way, the voltages are fed to the PLL *(phase locked loop)* block in order to detect the frequency and phase angle and to generate the synchronizing signal to the switching logic [5]. In the second way of the control, the voltage is fed together with the measured currents to the "Instantaneous Power Theory" block [6-8], in order to calculate the instantaneous imaginary power q. This imaginary power q is compared with a reference q^* and the error observed is fed to proportional-integral controller block. The proportional-integral controller outputs a signal that gives the leading or lagging phase angle δ necessary to adjust the voltage on the dc side capacitor, thus controlling the energy flow in or out of it. The leading or lagging signal δ is added to the PLL synchronism signal output and delivered to the switch logic control block.

III. MODEL SIMULATIONS

A model of a STATCOM, including its control, was simulated using the electromagnetic transients program, ATP-EMTP. The model simulated was a 48-pulses STATCOM, rated at 50MVA and 18kV. The transformers are wye-delta connected with 20% reactance. The dc side capacitance is 4045μF which corresponds to a capacitor time constant [9], or unit capacitance constant, UCC, [10], of 0.35ms. This STATCOM is connected to an 18kV AC system. Fig.4 shows the dc capacitor voltage, Fig.5 the instantaneous imaginary power q and Fig.6 the voltages and current responses for a changes from inductive to capacitive characteristics in the imaginary power reference. These figures show that this equipment has a good performance under balanced conditions, and that it is able to have quick transient response (about ½ cycle).

IV. PROBLEM IDENTIFICATION

A. Simulations with negative sequence components

Introducing a negative sequence component in the AC system voltages, it is possible to see that the STATCOM does not have the same performance as before. To show this fact, a simulation study was performed introducing negative sequence components of voltage, at 10% of the positive sequence rated value. This simulation is shown in Fig.7, where it is observed an increase of oscillations into

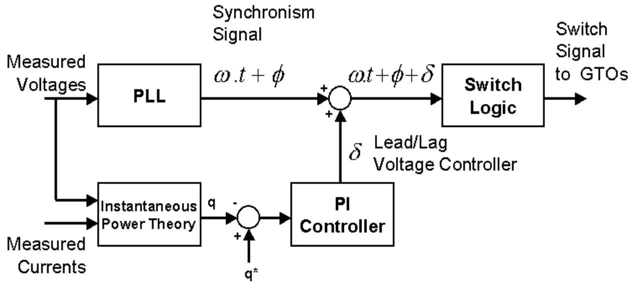

Fig. 3. Control diagram.

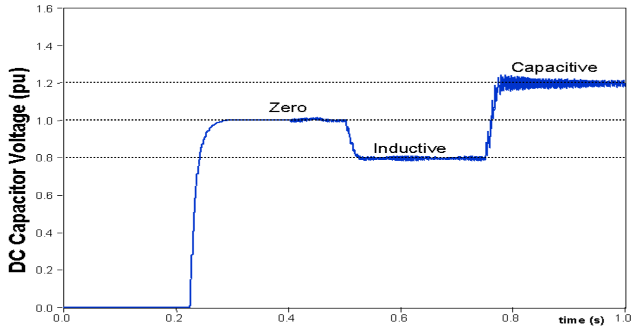

Fig.4. dc capacitor voltage (pu).

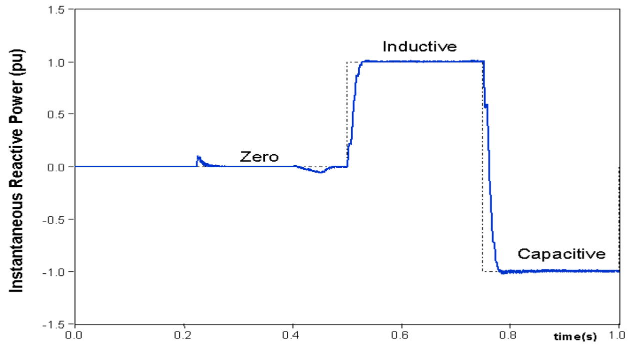

Fig.5. Instantaneous reactive power (pu).

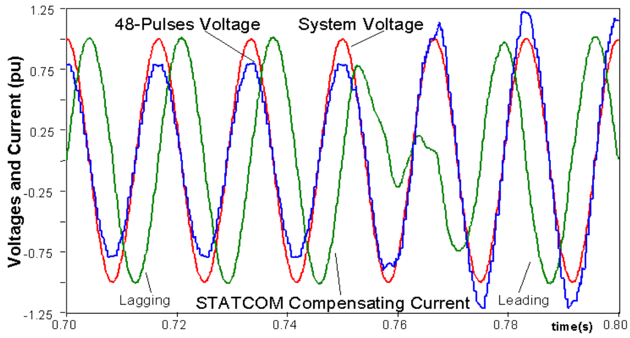

Fig.6. System and 48-pulses voltages (pu), compensating current (pu).

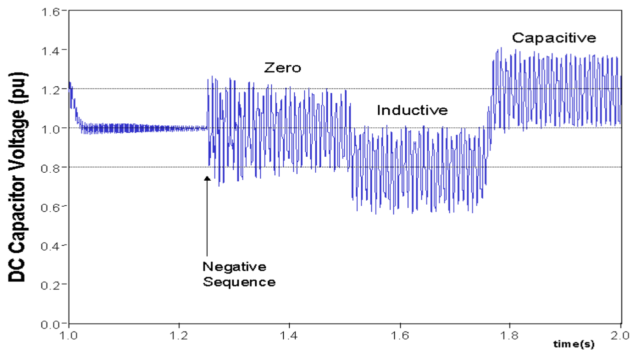

Fig.7. dc capacitor voltage (pu).

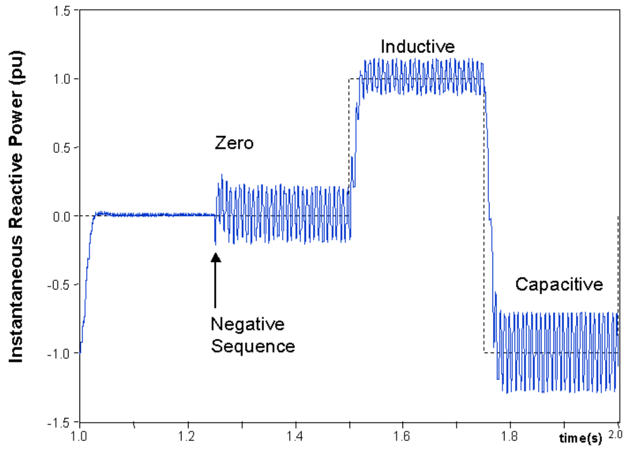

Fig.8. Instantaneous reactive power (pu).

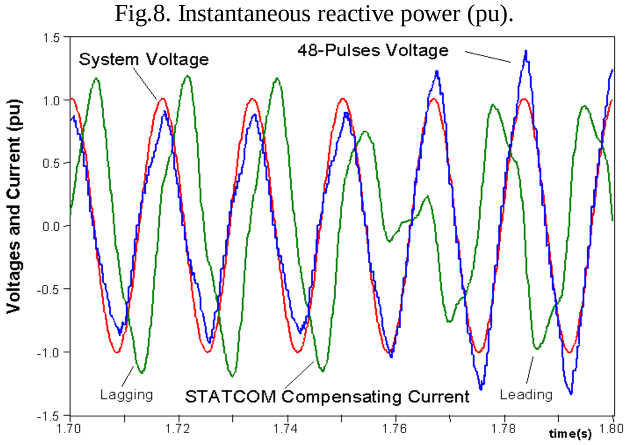

Fig.9. System and 48-pulses voltages (pu), compensating current (pu).

the dc voltage, when the negative sequence component is introduced at t = 1.25 seconds. In Fig.8, it is seen an increase of oscillations in the instantaneous imaginary power q. A higher distortion is observed in the 48-pulse voltage, shown in Fig. 9, as a result of the oscillations of the dc voltage. In Fig. 10, it is shown that when the system is unbalanced there is a 2nd order oscillation present in the dc capacitor voltage. This oscillation disturbs the 48-pulse voltage introducing 3rd and 5th order harmonics, shown in Fig.11. These harmonics are, consequently, propagated to the currents, as shown in Fig. 12, for the cases of inductive and capacitive compensation.

B. Power flow study with negative sequence components

A simplified system is made for the positive and negative components, shown in Fig.13, including the AC system voltage (V_s) and the STATCOM fundamental component of the generated voltage (V_i). These voltage sources are linked through an equivalent reactance. Based on this simplified model, it is possible to find the source of the problems due to unbalances caused by negative sequence components.

Considering first only positive sequence components, the active and the reactive power are given by:

$$P = \frac{V_{s+}.V_{i+}}{X_L}.\sin\delta \,, \qquad (1)$$

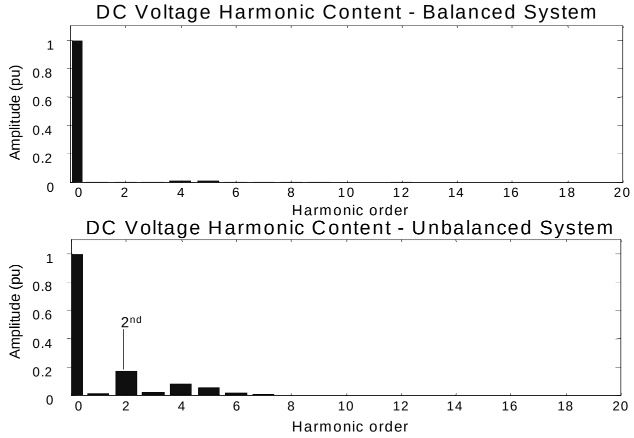

Fig. 10. DC Voltage harmonic content.

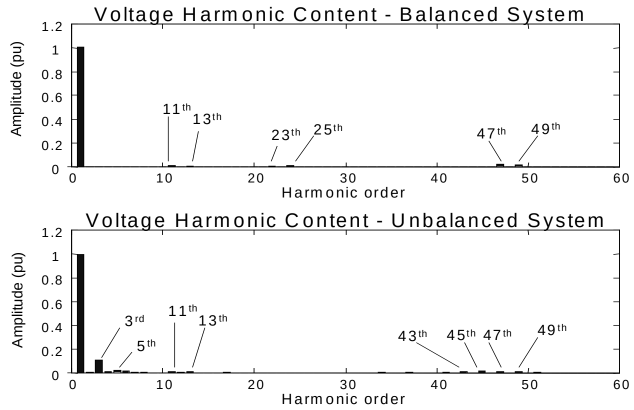

Fig. 11. 48-pulses voltage harmonic content.

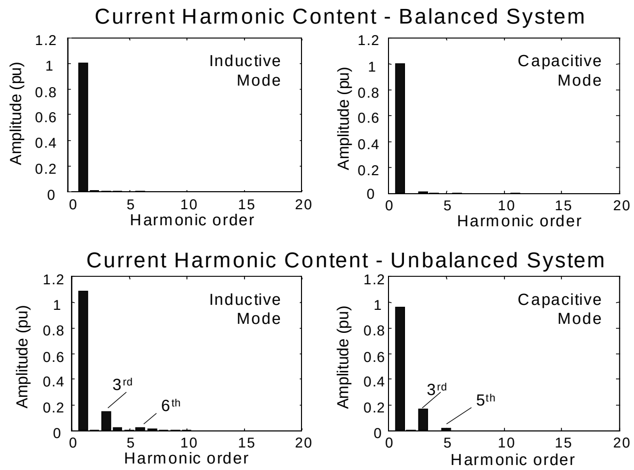

Fig. 12. Compensating current harmonic content.

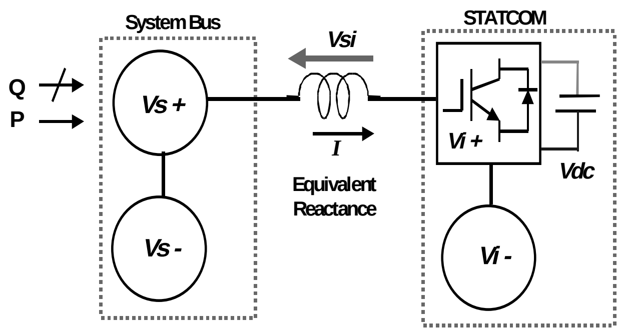

Fig. 13. Simplified system diagram with positive and negative sequence components.

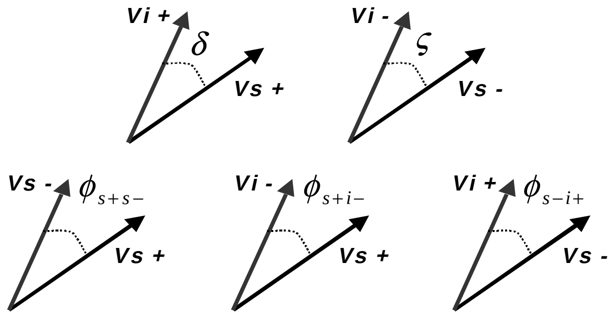

Fig. 14.Voltage angle relations.

$$Q = \frac{{V_{s+}}^2 - V_{s+}.V_{i+}.\cos\delta}{X_L}. \quad (2)$$

In (1) and (2), δ, is the angle between the positive sequence voltages in the AC system V_{s+} and in the STATCOM V_{i+}, as shown in Fig.14, X_L is the equivalent reactance considering that resistive losses are negligible. The STATCOM control can also be described through (1) and (2). If the angle δ is zero, the AC system and STATCOM voltages are in phase and there is only reactive power, and by variations in the phase angle δ, it is possible to allow an active power flow.

Considering the negative sequence components sources shown in Fig.13, and the angle relations shown in Fig.14, it is possible to write the power flow between the sources as:

$$P = \left\{ \begin{array}{l} + \dfrac{V_{s+}.V_{i+}}{X_L}.\sin\delta + \dfrac{V_{s-}.V_{i-}}{X_L}.\sin\zeta + \\ + \dfrac{V_{s+}.V_{i-}}{X_L}.\sin\phi_{s+i-} + \dfrac{V_{s-}.V_{i+}}{X_L}.\sin\phi_{s-i+} \end{array} \right\}, \quad (3)$$

$$Q = \left\{ \begin{array}{l} \dfrac{{V_{s+}}^2}{X_L} - \dfrac{V_{s+}.V_{i+}}{X_L}.\cos\delta + \\ + \dfrac{{V_{s-}}^2}{X_L} - \dfrac{V_{s-}.V_{i-}}{X_L}.\cos\zeta + \\ + 2.\dfrac{V_{s+}.V_{s-}}{X_L}.\cos\phi_{s+s-} + \\ - \dfrac{V_{s+}.V_{i-}}{X_L}.\cos\phi_{s+i-} - \dfrac{V_{s-}.V_{i+}}{X_L}.\cos\phi_{s-i+} \end{array} \right\}. \quad (4)$$

Equation (3) and (4) show that the inclusion of negative sequence components results in many more terms into the power flow equations. But, since there is not a negative sequence source in the STATCOM, (3) and (4) are reduced to (5) and (6):

$$P = \frac{V_{s+}.V_{i+}}{X_L}.\sin\delta + \frac{V_{s-}.V_{i+}}{X_L}.\sin\phi_{s-i+} \quad , \quad (5)$$

$$Q = \left\{ \begin{array}{l} \dfrac{{V_{s+}}^2}{X_L} - \dfrac{V_{s+}.V_{i+}}{X_L}.\cos\delta + \\ + \dfrac{{V_{s-}}^2}{X_L} + 2.\dfrac{V_{s+}.V_{s-}}{X_L}.\cos\phi_{s+s-} + \\ - \dfrac{V_{s-}.V_{i+}}{X_L}.\cos\phi_{s-i+} \end{array} \right\}. \quad (6)$$

For the case where only reactive power is desired, so the angle δ is zero, (5) and (6) become:

$$P = \frac{V_{s-}.V_{i+}}{X_L}.\sin\phi_{s-i+} \quad , \quad (7)$$

$$Q = \left\{ \begin{array}{l} \dfrac{{V_{s+}}^2}{X_L} - \dfrac{V_{s+}.V_{i+}}{X_L} + \\ + \dfrac{{V_{s-}}^2}{X_L} + 2.\dfrac{V_{s+}.V_{s-}}{X_L}.\cos\phi_{s+s-} + \\ - \dfrac{V_{s-}.V_{i+}}{X_L}.\cos\phi_{s-i+} \end{array} \right\}. \quad (8)$$

Since the phase angles between the positive and negative sources: $\phi_{s-i+}, \phi_{s+s-}, \phi_{s+i-}$, can be seen as functions of $2\omega t$, these results show that when negative sequence components are present, an uncontrolled power flow goes through the inverter direct to the dc capacitor causing oscillations in the STATCOM.

If the STATCOM could generate negative sequence components with the same amplitude, frequency and phase angle as the one that disturbs the system, the result would be ideally a reduction of the oscillations. Applying the necessary conditions to obtain the zero var compensation into (3) and (4) the results are:

$$P = \left\{ + \frac{V_{s+}.V_{i-}}{X_L}.\sin\phi_{s+i-} + \frac{V_{s-}.V_{i+}}{X_L}.\sin\phi_{s-i+} \right\}, \quad (9)$$

$$Q = \left\{ \begin{array}{l} 2.\dfrac{V_{s+}.V_{s-}}{X_L}.\cos\phi_{s+s-} + \\ - \dfrac{V_{s+}.V_{i-}}{X_L}.\cos\phi_{s+i-} - \dfrac{V_{s-}.V_{i+}}{X_L}.\cos\phi_{s-i+} \end{array} \right\}. \quad (10)$$

Equations (9) and (10) show the existence of a complex interaction between the positive and negative sequence voltage sources and based in these equations, it would be very difficult to obtain a control able to set the necessary conditions desired.

V. PROPOSED SOLUTION FOR THE PROBLEM

The equations have shown how negative sequence components disturb the operation of the STATCOM but it does not contribute to an easy control method. Moreover, it is not desirable to use the conventional methods applied to solve this problem caused by the negative sequence unbalances: power derating or STATCOM temporary disconnection [3].

If the negative sequence component appears only during transient period, high frequency switching PWM technique may be a solution. In this case, the control algorithm should be temporarily changed to the one that is shown in Fig.15. This PWM control is done measuring the system voltages and separating the positive components of them using the PLL and the instantaneous power theory [5]. These positive sequence component voltages are transformed to the $\alpha\beta 0$ reference frame by (11), and the results are used in (12) to obtain the compensating $\alpha\beta$ currents. Through (13) the reference currents are transformed back to the *abc* frame.

$$\begin{bmatrix} v_o \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}, \qquad (11)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \cdot \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \cdot \begin{bmatrix} p^* \\ q^* \end{bmatrix}, \qquad (12)$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}. \qquad (13)$$

In equation (12) it is introduced the references for the instantaneous active power (p*), in order to control the voltage over the dc capacitor, and the instantaneous imaginary power q*.

The PWM switching technique used is the adaptative current control. It compares the measured current with the reference currents and from that generates the gate signals to the switches.

A. Simulations with PWM adaptative current control

To test this possibility an extra inverter was introduced into the STATCOM system as shown in Fig. 16.

The feasibility of the proposed technique was tested connecting an extra inverter in parallel to the conventional STATCOM shown in Fig.16. Naturally, in actual systems it will not be possible to add an inverter just for PWM control, due to high costs. However, it is possible to develop a PWM control using the existent inverter structure of the proposed STATCOM.

This inverter worked with the control shown in Fig. 15 and was linked to bus system through a 1:1, wye-wye connected transformer with a 10% reactance. A negative sequence detector was implemented in order to switch the STATCOM controls from multipulse to PWM when needed. The references for the PWM control, as shown in Fig. 15, are the instantaneous reactive power and the dc

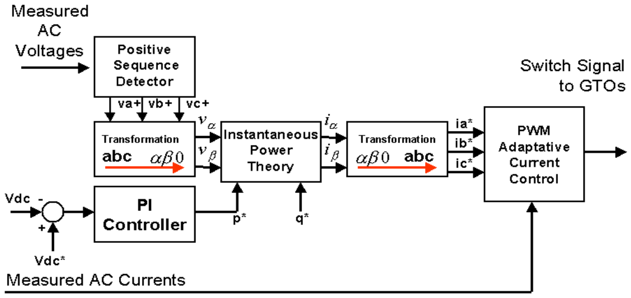

Fig. 15. Instantaneous power theory control diagram.

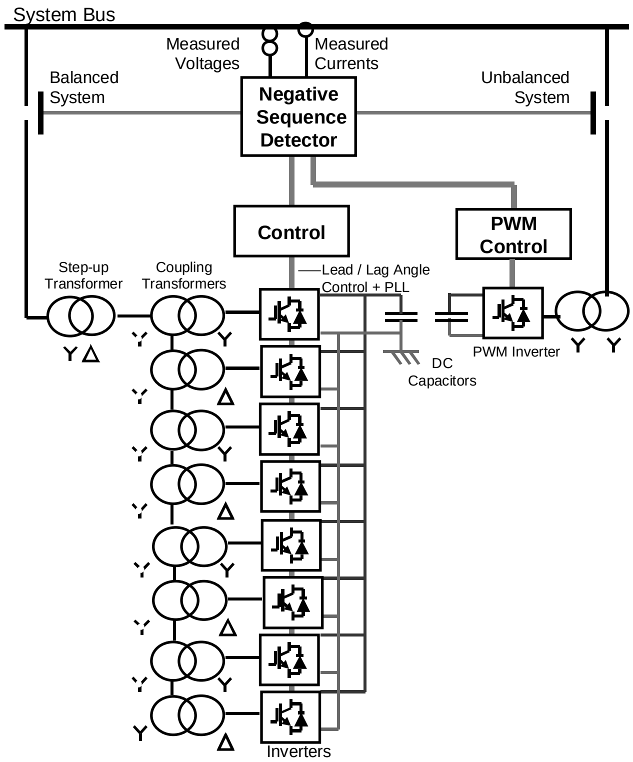

Fig. 16. STATCOM with PWM negative sequence control.

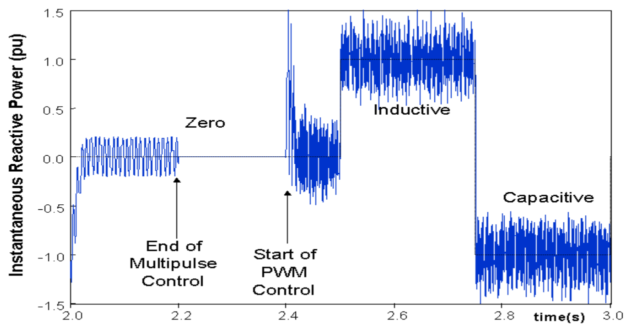

Fig.17. Instantaneous reactive power (pu).

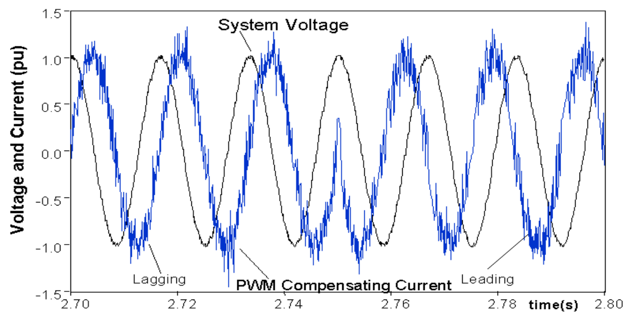

Fig.18. System voltage and compensating current (pu).

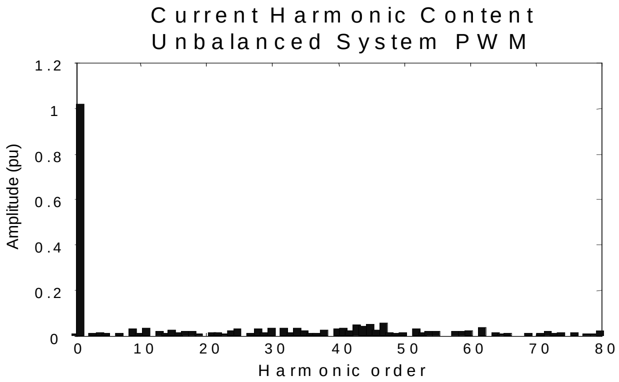

Fig. 19. Current harmonic content.

voltage over the capacitor. A limited switching frequency of 8kHz was imposed through the control logic. This high frequency limit is not practical for actual high power equipment. In this case the frequency would be limited at a lower frequency. In this test the capacitance used was of 250μF and 50kV.

The results for the instantaneous reactive power in Fig. 17, and for the compensating currents, in Fig.18, show that the dynamic performance of the PWM control is much faster than that of the multipulse. Also, as it can be seen in Fig.19, the PWM control introduces many low amplitude high order harmonics, which should be filtered.

Although there are high frequency components in the voltage and instantaneous imaginary (reactive) power their “average” values are quite good showing better behavior of the PWM control than the conventional control in presence of negative sequence components.

VI. CONCLUSION

The studies have shown that the STATCOM has a good performance under balanced conditions but using the conventional control methods it is subjected to oscillations when negative sequence components are present in the AC system. The bad performance of the STATCOM is due to uncontrolled active power flow at 2ω resulting in quick variations of the dc voltage capacitor voltage. The use of PWM technique brings better “average” voltage, current and power behaviors results, however it has a problem: the switching losses may be relatively high. Therefore, this technique may be interesting if used during transient conditions when unbalances may appear. The study will continue to analyze ways of introducing the PWM control in the conventional structure of STATCOM, without the need of an extra high power inverter. The basic objective is to avoid the necessity of high oversizing of the STATCOM power ratings or to disconnect it form the system until the unbalances can be tolerated.

VII. ACKNOWLEDGEMENT

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