Mitigation of Resonance Problems between Power Systems and STATCOM Using Electronic Phase Shifting Voltage Source Inverters

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***Abstract* - This paper presents a phase control scheme to cancel low order harmonics and to minimize total harmonic distortion of ac output voltages of STATCOM based on *quasi*-multipulse Voltage Source Inverter (VSI). *Quasi*-multipulse VSI is a multilevel inverter formed by the series connection of 6-pulses VSIs. The proposed scheme can be used to reduce a specific harmonic generated by the *quasi*-multipulse VSI in such a way to avoid some resonance phenomena between the VSI and power systems. Digital simulation results obtained with an Alternative Transients Program (ATP/EMTP) are used to test and compare the performance of the *quasi*-multipulse VSI with and without the proposed scheme technique.**

Keywords – STATCOM, Reactive power compensators, VSI, Resonance phenomena.

I. Introduction

One of the most attractive applications of Voltage Source Inverters (VSIs) in power systems involves FACTS (*Flexible AC Transmission Systems*) compensators [1]. Gyugyi [2] was the pioneer to suggest several possible uses of Solid-state Voltage Sources (SVS) based on VSIs operating as shunt and series reactive power compensators. The basic idea of these compensation techniques is to use self-commutated VSIs to synthesize synchronous ac voltage to be connected in parallel and in series with ac transmission lines. In this scenario, when multipulse VSI are shunt connected to a power system, to improve the system voltage regulation or to supply reactive power in parallel, it is called STATCOM (*STATic synchronous COMpensator*).

Although VSIs can generate controllable ac voltages in its ac terminals, they have the disadvantage of generating harmonics due to the switching operation of the inverters. These harmonics can cause distortions in the power systems voltages and currents. Thus, passive filters should be connected at the VSIs terminals to mitigate these effects. Unfortunately the design of passive filters is not easy because the harmonic content of the inverters is highly influenced by the system impedance.

The objective of this paper is to describe the fundamentals of operation of a STATCOM based on a *quasi*-multipulse VSI using the Electromagnetic Transient Program (EMTP) simulation package. The compensator characteristics and the mechanisms for which the harmonic are minimized to avoid resonance problems are also discussed.

II. VSI Fundamentals

There are many kinds of VSI circuits based on different operation principles. Nowadays, the application of self-commutated dc/ac converters in high power systems has been possible thanks to the development of large capacity self-commutated semiconductor devices (GTOs, IGBTs, IGCTs, etc). Fig. 1 shows a three-phase bridge VSI with a dc capacitor connected at its dc terminals. This type of converter is expected to have better performance than line-commutated converters, which need external ac voltages source and reactive power supply.

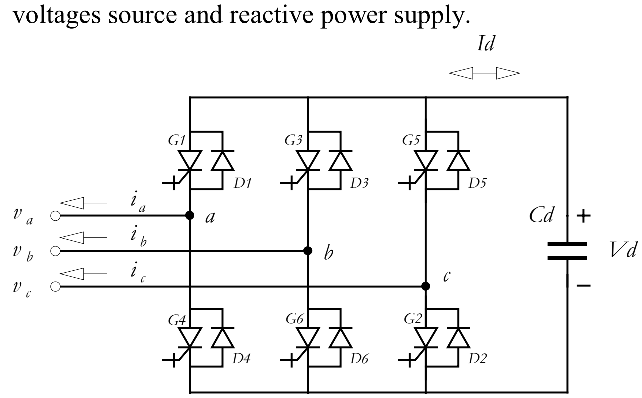

Fig. 1: Three-phase VSI circuit diagram.

The branches of the inverter shown in Fig. 1 are composed by GTOs, with diodes connected in antiparallel. These self-commutated switches can be turned-on and turned-off by gate pulses to generate three independent ac voltages on VSI output terminals. In high power applications, two modulation strategies have been used to control the magnitude and the frequency of the VSI output voltages.

The VSI-PAM (Pulse Amplitude Modulation), in the most simple operation mode, each semiconductor switch connects and disconnects the ac terminal alternatively to positive and negative poles of the dc source once in a half-cycle, producing an ac rectangular wave as shown in Fig. 2(a). Since the inverter has six self-commutated switches, during a fundamental frequency period, six turn-on and turn-off signals are sent to the inverter's GTOs. Thus, this kind of inverter is also called in the literature, as 6-pulse VSI.

In the VSI-PWM (Pulse Width Modulation), the semiconductor switches connect and disconnect the ac terminals alternatively to positive and negative dc source terminals several times per half-cycle as shown in Fig. 2(b). Note that the pulse width can be changed to obtain a regulated fundamental frequency ac voltage. Both voltage waveforms plotted bellow were obtained assuming a large dc VSI capacitor to assure a voltage without any dc ripple.

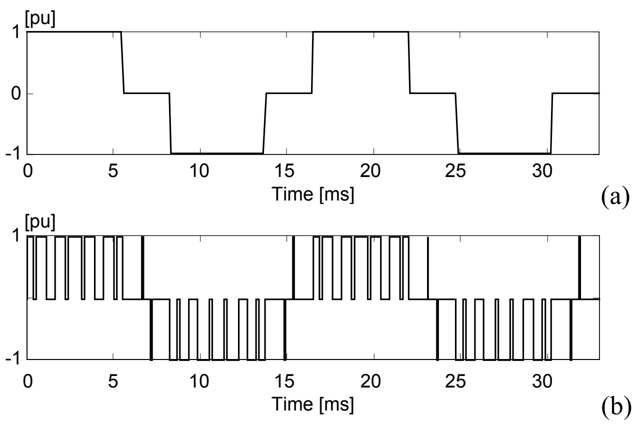

Fig. 2: (a) Line-to-line 6 pulse VSI voltage waveform; (b) Line-to-line VSI- PWM voltage waveform.

In spite of the better performance of high frequency PWM techniques, which is widely used in industrial applications such as ASD (*Adjustable Speed Drives*), in high power applications the VSI switching frequency is usually taken lower than 600 *Hz* to reduce the losses. This frequency limitation in the PWM converter worsens its harmonic content, making it close to the case of PAM-VSI.

Based on previous considerations, there is a high tendency to use PAM to control VSI for power systems applications. In the next section, it will be shown how some 6-pulse VSIs could have their outputs combined to reduce the harmonic distortion of the output voltages.

III. *QUASI* MULTIPULSE VSI

Multipulse schemes involve multiple parallel or series connection of PAM-VSI so that the harmonics generated by one converter are canceled by the harmonics produced by the others [3]. Several STATCOM prototypes based on 24-pulses VSI or higher have been reported in literature [4]-[6]. The main disadvantage of a multipulse VSI is the complicated magnetic structure necessary to obtain output voltages and currents with low harmonic distortion.

These magnetic structures are zigzag transformers with fractional turns ratio, used to connect many 6-pulse converters in series. The complexity of these phase shifting transformers increases as the number of pulses of the VSI increases and when practical transformer imperfections such as magnetizing currents and losses are included. However, similar voltage and current waveforms could be obtained by using a *quasi*-multipulse inverter [7],[8].

One approach to obtain a *quasi*-multipulse VSI is to use 6-pulses converters connected through Y-Y and Y-Δ transformers. Fig. 3 shows an example of *quasi* 24-pulses VSI formed by four 6-pulses VSIs or two pair of 12-pulses VSIs connected in series.

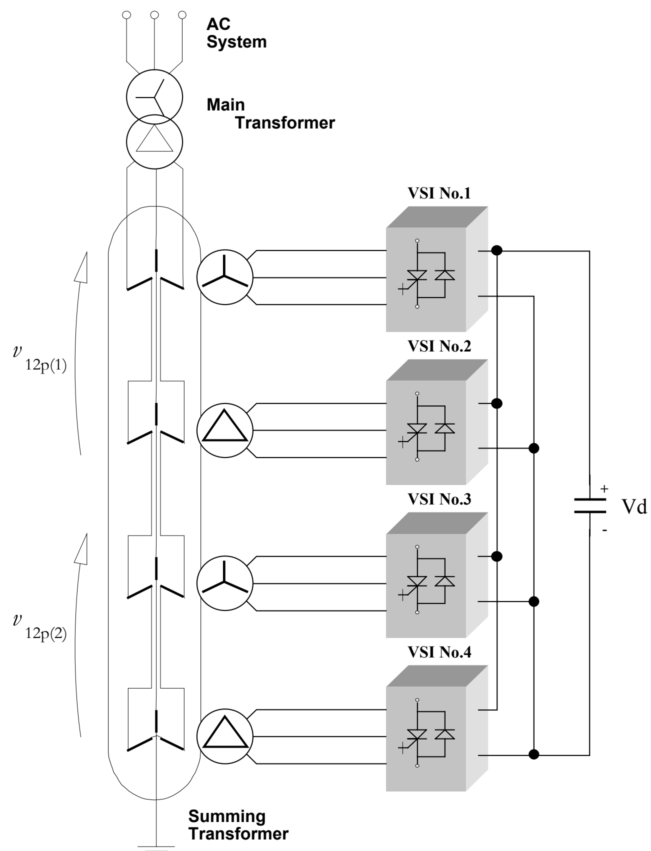

Fig. 3: A *quasi* 24-pulse VSI circuit diagram.

Expanding the output voltages of each 12-pulse VSI in its Fourier series the following expressions are obtained for phase "*a*":

$$v_{a12(1)} = \frac{4V_d}{\pi}\Big[\cos(\omega t+\delta_1) - \frac{1}{11}\cos[11(\omega t+\delta_1)] + \frac{1}{13}\cos[13(\omega t+\delta_1)] - \frac{1}{23}\cos[23(\omega t+\delta_1)] + \frac{1}{25}\cos[25(\omega t+\delta_1)] - \ldots\Big], \quad (1)$$

and,

$$v_{a12(2)} = \frac{4V_d}{\pi}\Big[\cos(\omega t+\delta_2) - \frac{1}{11}\cos[11(\omega t+\delta_2)] + \frac{1}{13}\cos[13(\omega t+\delta_2)] - \frac{1}{23}\cos[23(\omega t+\delta_2)] + \frac{1}{25}\cos[25(\omega t+\delta_2)] - \ldots\Big], \quad (2)$$

where, V_d is the average dc voltage of the VSI (V); ω is the system fundamental angular frequency (rad/s); δ_1 and δ_2 are the electronic angles (rad) of the first and the second 12-pulses VSI, respectively.

From (1) and (2), if the fundamental output voltage of the first pair of converters is leading by 7.5º (+π/24 *rad*) and the second pair of converters is lagging by 7.5º (-π/24 *rad*), the output voltage will have the eleventh and thirteenth harmonics amplitude attenuated. Fig. 4 shows the phase-to-neutral output voltage for the phase "*a*" of the *quasi* 24-pulses VSI. Here, also a large dc capacitor was considered connected to the VSI terminals to assure a 1 *pu* of dc voltage without any ripple. Fig. 5 presents the harmonic spectrum of the synthesized staircase voltage obtained using a FFT (*Fast Fourier Transform*) algorithm. Fig. 6 (a) and (b) show the mechanism how the 11th and 13th harmonics are minimized.

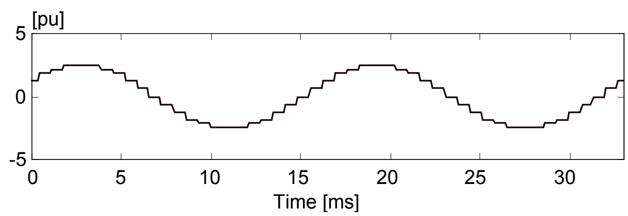

Fig. 4: Phase-to-neutral output voltage of *quasi*- 24 pulses VSI.

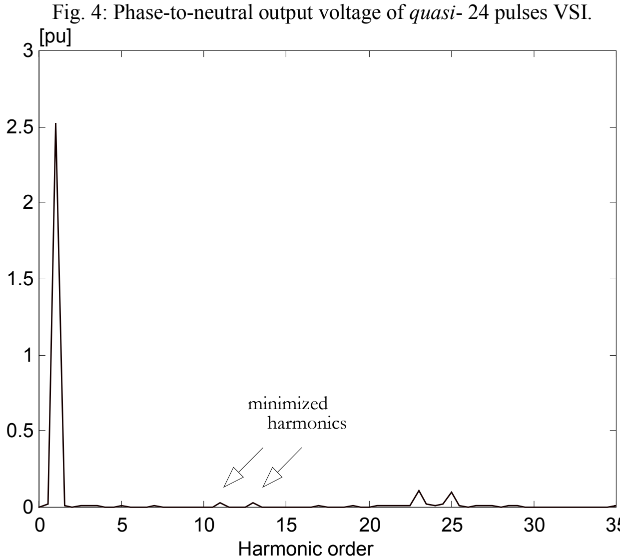

Fig. 5: Harmonic spectrum of phase-to-neutral output voltage of *quasi*- 24 pulses VSI for δ_1 = +7.5º (+π/24 *rad*) and δ_2 = -7.5º (-π/24 *rad*) respectively.

With this simple technique we cannot eliminate the 11th and 13th harmonics simultaneously. However, based on (1) and (2), if the electronics phase angles of the two 12-pulses VSIs are taken δ_1 = +8.18º (+π/22 *rad*) and δ_2 = -8.18º (-π/22 *rad*) respectively, the 11th harmonic is eliminated while the 13th harmonic has its amplitude attenuated without the connection of any passive filter. This behavior is shown in Fig. 7. This technique can be also used to eliminate the 23rd or the 25th harmonics or minimized both, but in this case the 11th and the 13th will be not attenuated. Table 1 shows the optimum phase difference between the two 12-pulse VSIs and their effects over the lower harmonic generated by the *quasi*-multipulse inverter.

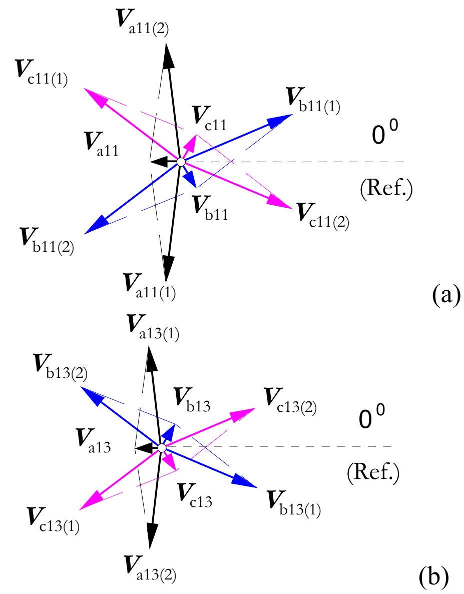

Fig. 6: Phasor diagram of *quasi* 24-pulses VSI output harmonics: (a) 11th harmonic and (b) 13th harmonic.

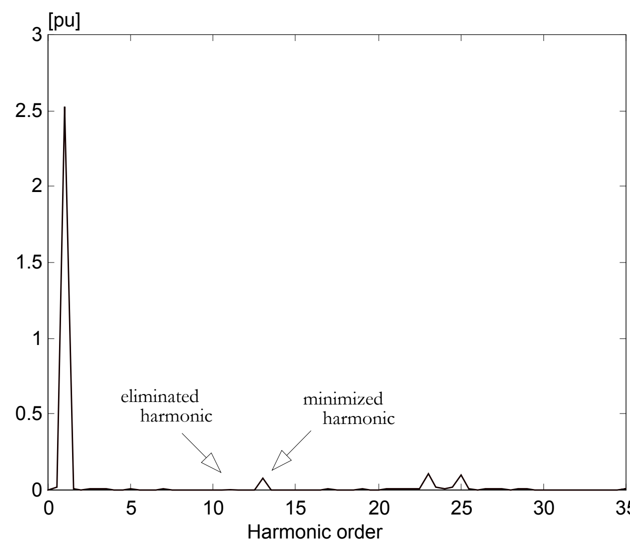

Fig. 7: Harmonic spectrum of phase-to-neutral output voltage of *quasi*- 24 pulses VSI for δ_1 = +8.18º (+π/22 *rad*) and δ_2 = -8.18º (-π/22 *rad*), respectively.

This electronic phase shifting scheme is the basis to avoid any resonance problem between the STATCOM and power system in an economic and easy way, as it will be shown in the next section.

Table 1: Normalized harmonic amplitude (V_n / V_1) [*pu*].

(δ_1 - δ_2) [*rad*]	Harmonic order			
	11th	13th	23rd	25th
π/11	0.0$^{(*)}$	0.0219	0.0435	0.0368
π/12	0.0120	0.0099	0.0427	0.0400
π/13	0.0219	0.0$^{(*)}$	0.0410	0.0400
π/23	0.0666	0.0487	0.0$^{(*)}$	0.0055
π/24	0.0685	0.0508	0.0029	0.0026
π/25	0.0702	0.0528	0.0055	0.0$^{(*)}$

$^{(*)}$ *eliminated harmonic*

IV. Studied Resonance Problem

Fig. 8 shows the single-line diagram of a STATCOM based on a quasi 24-pulses VSI, with a capacitor C_d connected in its dc side. The VSIs are connected at the 230 *kV* bus through a main transformer and four Y-Y and Y-Δ units form the summing transformer as shown in Fig. 3.

As explained before, the objective of this work is the investigation and the solution of some resonance problems between the VSI and an electrical system. Thereby a transmission line with variable length is used to connect the proposed compensator to an equivalent power system.

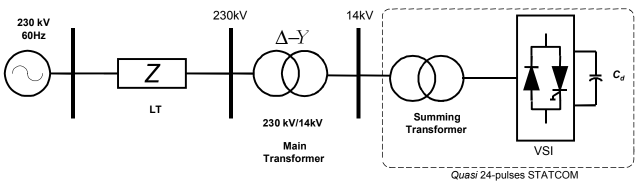

Fig. 8: Single-line diagram of STATCOM based on a *quasi* 24-pulses VSI.

Since the STATCOM operates as a *var* controller, the reactive energy flow in the system shown in Fig. 8 will mainly depend on the difference between the magnitude of the inverter output voltage ($\boldsymbol{V_I}$) and ac source voltage ($\boldsymbol{V_S}$). Considering the ac source $\boldsymbol{V_S}$ as reference, if $V_I > V_S$, the inverter reactive power will be capacitive ($Q > 0$). Otherwise, if $V_I < V_S$, the inverter reactive power will be inductive ($Q < 0$). Detailed description of the STATCOM control strategy can be found in [4]-[9].

However the three-phase output voltages of the *quasi*-multipulse STATCOM are similar to that shown in Fig. 4. In other words¸ the three-phase output voltages have the eleventh, thirteenth, twenty-third, twenty-fifth and so on harmonics. Therefore if the electrical system, where the STATCOM is connected, has low impedance at a harmonic frequency, as example the 25th harmonic, high harmonics currents will arise between the power system and STATCOM.

A. Digital Simulation

The STATCOM in Fig. 8 is connected at the sending–end side of a 152 *km* transmission line with parameters given in Table 2. The length of this line was chosen in consequence of the low equivalent impedance at the STATCOM output terminals for 1500 *Hz* (25th order harmonic component for a 60 Hz system). Fig. 9 shows the frequency response for the main transformer plus transmission line impedance. Note that the low system impedance coincides with the 25th harmonic generated by the *quasi* 24-pulses VSI for $\delta_1 = +7.5º$ ($+\pi/24$ *rad*) and $\delta_2 = -7.5º$ ($-\pi/24$ *rad*), respectively. Consequently, a high level of 25th harmonic current flow into the system from STATCOM and the phase-to-neutral voltage at the transformer terminals becomes distorted as shown in Fig. 10.

Table 2: Transmission line parameters.

#	R (Ω/km)	L (mH/km)	C ($\mu F/km$)
Zero seq.	0.4629	4.3362	0.00577
Pos. seq.	0.0976	1.3785	0.00844

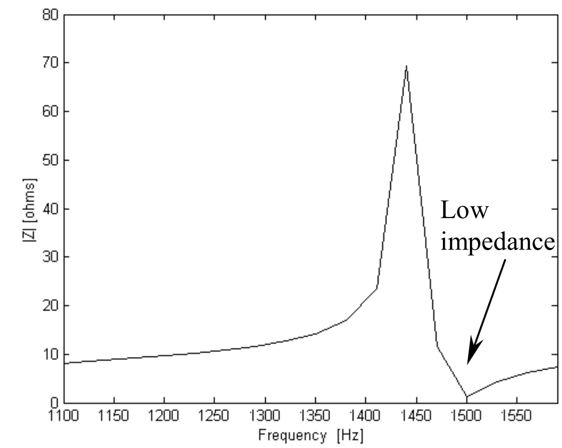

Fig. 9: Frequency response of the system impedance (line+tranformer).

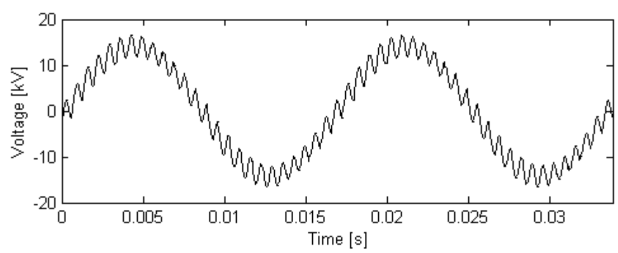

Fig. 10: Phase-to-neutral voltage measured at high voltage transformer side for $\delta_1 = +7.5º$ ($+\pi/24$ *rad*) and $\delta_2 = -7.5º$ ($-\pi/24$ *rad*).

The harmonic resonance between the STATCOM and the power system causes the voltage distortion shown in Fig. 10 and it is described in details in [9]. To avoid this problem it is necessary to use passive filters or design a STATCOM with higher number of pulses, as example 48-pulse STATCOM [4]-[7]. On the other hand, a cheaper solution is obtained adjusting the electronic phase angles in such a way as to eliminate the undesired harmonic at the *quasi*-multipulse inverter.

As shown in Table 1, adjusting the electronic phase shifting angles of each 12-pulses VSI to $\delta_1 = +3.6º$ ($+\pi/50$ *rad*) and $\delta_2 = -3.6º$ ($-\pi/50$ *rad*) respectively, the twenty-fifth harmonic at the STATCOM output voltage is eliminated and the twenty-third harmonic is minimized. Fig. 11 shows the new system phase-to-neutral voltage after the implementation of the proposed scheme. Fig. 12 shows the comparison of harmonic content for the system voltage with and without the proposed control scheme. Table 3 shows the measured 23rd and 25th harmonics amplitude for the *quasi* 24-pulse STATCOM with ($\delta = \pi/12$ *rad*) and without ($\delta = \pi/25$ *rad*) the proposed control scheme.

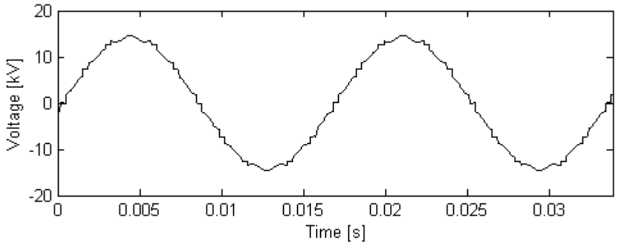

Fig. 11: Phase-to-neutral voltage measured at high voltage transformer side for $\delta_1 = +3.6°$ ($+\pi/50$ *rad*) and $\delta_2 = -3.6°$ ($-\pi/50$ *rad*).

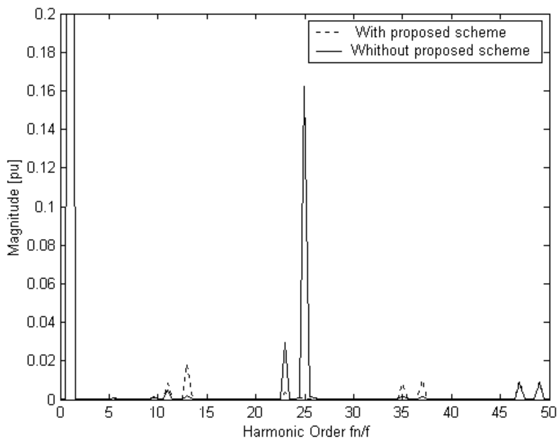

Fig. 12: Harmonic spectrum of phase-to-neutral voltage with and without the proposed scheme.

Table 3: Harmonic amplitude.

$(\delta_1 - \delta_2)$ [*rad*]	Harmonic order	
	23^{rd}	25^{th}
$\pi/12$	0.02844	0.16330
$\pi/25$	0.00377	0.00023

V. Conclusions

This paper presented and discussed the basic concepts of a *quasi* 24-pulses VSI and its operation as a *Static Synchronous Compensator* (STATCOM). The *quasi*-multipulse VSI can synthesize staircase ac voltages with a minimized harmonic content using simple transformers configuration.

It was shown a simple scheme to avoid resonance problems between the converter and a power system at a specific frequency. The electronic control of each the output voltage phase angle permits to eliminate or to minimize a specific harmonic generated by *quasi*-24 pulses VSI. The EMTP was used to model and illustrate the operation of the proposed control scheme.

VI. References

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