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Multi Level DC Voltage Reinjection for Especial Applications using STATCOM

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ABSTRACT

A new concept, the multi level voltage/current reinjection is described in this paper. A voltage source converter is proposed, in which the multi-step output voltage waveform is achieved by the reinjection of different DC voltage levels via the common neutral point of the converter bridges an 84-pulse voltage source converter (VSC), assembled by combining one twelve-pulse VSC, in conjunction with an asymmetric single phase seven-level converter plus an injection transformer. With this arrangement, the VSC output's total harmonic distortion in voltages is reduced, allowing it to be used in especial applications or as the basement of flexible A.C. transmission systems (FACTS) devices. The proposed strategy allows savings in the number of employed switches. Simulations results are provided to show the proposal appropriateness.

Key words: **FACTS devices, Multi pulse converters, StatCom, Voltage source converters (VSC).**

1. INTRODUCTION

A static synchronous compensator (STATCOM) is a regulating device used on alternating current electricity transmission networks. It is based on a power electronics voltage-source converter and can act as either a source or sink of reactive AC power to an electricity network. If connected to a source of power it can also provide active AC power. It is a member of the FACTS family devices. By regulation of the StatCom's output voltage magnitude, the reactive power exchange between the device and the transmission system maybe controlled to improve the power system voltage profile [4,5, 6, 7, 8].

Since the StatCom may cause interference on the system's fundamental sine wave at frequencies that are multiples of the fundamental one, especial care should be taken to ensure not to pollute the system to prevent further harmonic issues. In general, there are three feasible strategies to assemble a VSC:(*i*) the multi-pulse; (*ii*) the multi-level; (*iii*) and the pulse width modulation (PWM) [9, 10].

Strong efforts have been made in order to reach minimum harmonic distortion in the VSC's output voltage. A strategy to build an 84-pulse equivalent output voltage waveform, which employs a twelve-pulse along with an eight-level reinjection converter is presented in [10]. However, the cost for this is 26 extra switch devices and 7 DC voltage sources (capacitors).This array makes the control task difficult because of the amount of gate signals needed, and it is prone to unbalance, due to the large chain of capacitors. Multi-Level Voltage Reinjection (MLVR) H-bridge conversion is another option to generate 84 pulses, which requires the use of 5 additional DC voltage sources and 12 switches, as opposed to the conventional 12-pulse converter. It may be easily utilized to attain more levels on the reinjection by adding H-bridges in series [11].

This paper describes a strategy to generate the 84-pulse VSC, assembled with the combination of one 12-pulse converter with a seven-level converter, as well as one reinjection transformer to attain the required performance. The extra components are: 8 switches, 4 DC voltage sources, and 4 diodes for the seven-level converter. A reinjection transformer is needed, which is able to work properly within a wide range of its turn ratio. This constitutes an attractive array in terms of costs. In high-voltage applications, the voltage will generally be higher than the switches' and diodes' ratings at the current technology. Therefore, each symbol in the following diagrams may represent a chain of series-connected switches with auxiliary components [11].

2. 84-PULSE VSC TOPOLOGY

Numerous methods have been investigated to increase the number of pulses in the multi-pulse converters' output. The simplest one is by increasing the number of six-pulse converters and the corresponding transformers (4 six-pulses converter results in 24-pulse, 8 six-pulse converter results in 48-pulses operation, and so forth). The harmonic cancellation is carried out by the transformer secondary windings' arrangement. The weakness of this method is the large size and high cost due to the increased number of bridges and transformers. In order to overcome such difficulty, an auxiliary circuit in the DC link side has been proposed for reinjection [12]. Such topology results through modifying the DC input on the conventional double bridge twelve-pulses shunt converters through a multi-level auxiliary circuit with an injection transformer [13]. In this paper, an asymmetric 7-levelarray for the auxiliary circuit is used as a reinjection scheme, Fig.1.

The conventional double bridge twelve-pulse operation is assembled by connecting two identical three-phase bridges to three-phase transformers in a parallel VSC configuration. Each branch in the six-pulse converter must have a displacement of 120° among them. The upper switch is conducting while the lower one is open and vice versa (180°voltage source operation) [14]. A 30° displacement in the firing sequence of both converters should be considered. Transformer's turn ratios are 1:1 and 1: 3 on the YY and YΔ transformers, respectively. By injecting additional DC pulses via the three-phase bridges' neutral point, an effect of pulse spreading is attained. The auxiliary circuit is common to the three phases, reducing the number of extra components. The configuration description to provide pulse multiplication is detailed in [9, 10, 12, 15, 16, 21]. In Fig. 1, A-B illustrates the auxiliary seven-level inverter utilized as a reinjection circuit. To apply the seven-level inverter output voltage to feed the standard twelve-pulse converter, special care should be taken to not inject negative voltage into V_Y or V_Δ notice the inclusion of the injection transformer between both arrays. Thus, voltages at the six-pulse converter inputs can be regulated by adjusting the injection voltage *U i* by:

$$V_{Y} = V_{dc} + U I \quad (1)$$

$$V_{\Delta} = V_{dc} - U I \quad (2)$$

The injection voltage is determined by the seven-level inverter switching pattern and the injection transformer turns ratio. By using voltages V_Y and V_Δ as inputs to the six-pulse converters, a cleaner VSC's output voltage comes about. Fig.4 (a&b) exhibits the followed strategy to build V_{YU} and $V_{\Delta U}$ as the interaction of the seven-level output and the corresponding six-pulse signals. Through the 1:1 ratio for the *YY* TRANSFORMER,1:√3 for the YΔ TRANSFORMER, and adding their corresponding output signals, the 84-pulse line-to-neutral signal *VU* emerges (Fig.5a). The corresponding harmonic spectrum is depicted in Fig. 5b, illustrated on a linear scale, while the one presented in Fig. 4 is displayed in decibels.*VU* is an odd symmetric signal, so that the Fourier's even terms are zero. Thus,

$$V_U(t) = \sum_{n=1}^{\infty} V_{U_{2n-1}} \sin\left((2n-1)\omega t\right) \quad (3)$$

$$V_{U_{2n-1}} = \frac{4V}{3\pi(2n-1)}\left(A_{2n-1} + aB_{2n-1}\right) \quad (4)$$

$$A_{2n-1} = 2 + 2\cos\left(\frac{1}{3}\pi(2n-1)\right) + 2\sqrt{3}\cos\left(\frac{1}{6}\pi(2n-1)\right) \quad (5)$$

$$B_{2n-1} = \sum_{i=0}^{20} Coeff_i \cos\left(\frac{i}{42}\pi(2n-1)\right) \quad (6)$$

where

$$Coeff = \begin{Bmatrix} -3, & 1, & 1, & 1, & 1, & 1, & 1,\ldots \\ -3\sqrt{3}, & \sqrt{3}-1, & \sqrt{3}-1, & \sqrt{3}-1, & \sqrt{3}-1, & \sqrt{3}-1, & \sqrt{3}-1,\ldots \\ -3, & -\sqrt{3}+2, & -\sqrt{3}+2, & -\sqrt{3}+2, & -\sqrt{3}+2, & -\sqrt{3}+2, & -\sqrt{3}+2 \end{Bmatrix} \quad \ldots(7)$$

In (4), ***a*** is the reinjection transformer turns ratio.

The 84-pulse signal value (*VU*) depends on the injection transformer turns ratio *a*, which is determined so as to minimize the total harmonic distortion (THD), which is defined by [9, 17]:

$$THD_{VU} = \sqrt{\frac{\sum_{n=2}^{\infty} V_{Un}^2}{V_{U1}^2}} \quad (8)$$

The minimization of THD yields the parameter *a*. In this paper such estimation has been made through MATLAB for a value *n* = 7200, with increments of *a* = 0.0001. With these parameters, the minimum THD becomes 2.358% with *a* = 0.5609 , value employed in previous figures. According to the IEEE Std. 519, the distortion limits indicate that the llowed THD voltage is 10% in dedicated ystems,5% in general systems, and 3% for special applications as hospitals and airports [17]. Table 1 presents the voltage's minimum THD generated by several multi-pulse configurations. Through our proposition, the resultant THD allows its use even in applications

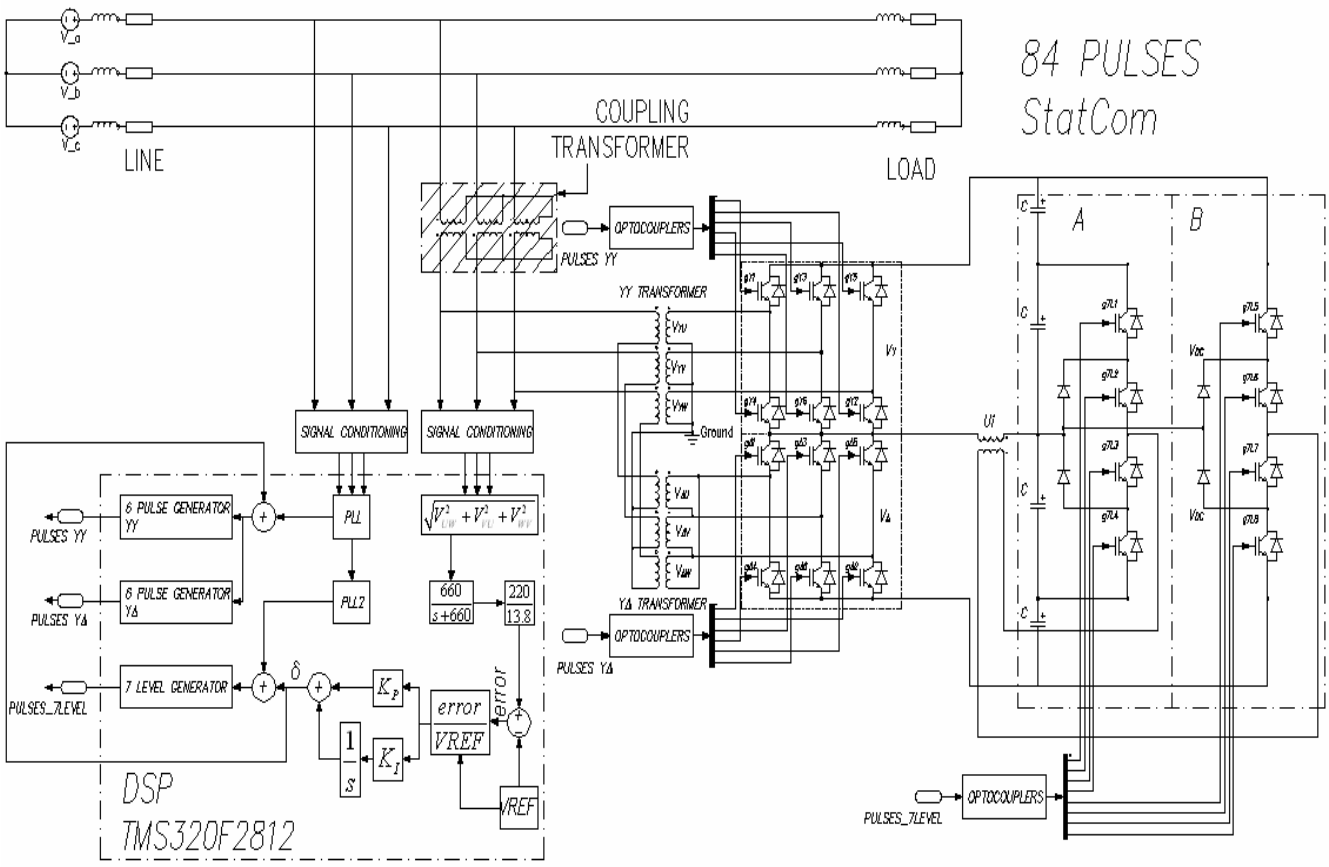

Fig. 1. *84-pulse StatCom structure*

with stringent quality requirements; it exhibits less dependence to variations in the transformer's turn ratio *a*, which can have a variation until 12.5%to reach a maximum THD lower than 3%. This means that it does not need a strict reinjection transformer turn ratio in order to get the THD for stringent conditions.

Table 1 *Minimum THD reached through VSC multi-pulses-based*

Number of pulses	THD (%)
12	15.22
24	7.38
48	3.8
60	3.159
84	2.358

Fig. 2 illustrates the THD dependence respect to variations in the reinjection transformer's turn ratio ***a***

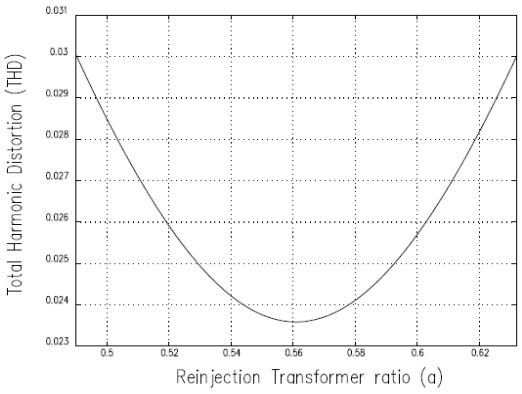

Fig. 2 *THD dependence respect to the reinjection transformer turns ratio a*

3. OPEN LOOP STATCOM STRUCTURE

The connection of the improved VSC to the system requires aspects to be considered. This section deals with such details within an open loop context.

3.1. Phase-Locked-Loop (PLL)

The Synchronizing Circuit is responsible for determining the system frequency and the phase-angle of the controlled AC bus fundamental positive sequence voltage [18]. The Phase-Locked-Loop (PLL) utilizes the Stationary Reference Frame in order to reduce the computational cost, and helps to improve the system's dynamic performance [19]. The digital PLL is an algorithm able to detect the phase of the fundamental voltage, through the synchronization of the output signal to the frequency and phase of the input one, without requiring a zero crossing subroutine at the input voltage, or to generate an internal reference signal for the input current [20]. The proposed strategy employs a $-\tan^{-1}(\quad)$ function added to a correction value determined by the signs of α and β, Fig.3.

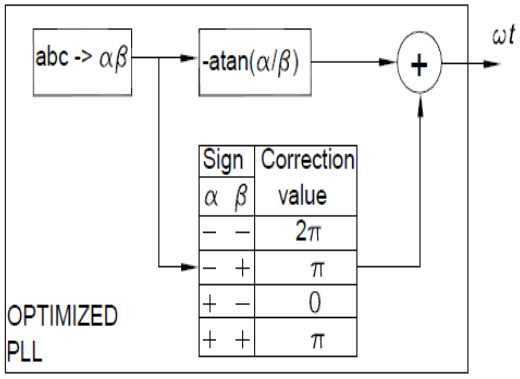

Fig .3 Optimized PLL scheme.

3.2. Six-Pulse Generator

The second block is the six-pulse generator, responsible for generating the pulse sequence to fire the three-phase IGBT array. It consists of an array of six-pulse spaced 60° each other. The IGBT will operate at full 180° for the *on* period and 180° for the *off* period. Any disturbance on the frequency will be captured by the synchronizing block, preventing malfunctioning. The falling border in the synchronizing block output signal is added to a series of six 60° spaced signals. The modulus operator with the 2π argument gives the needed *on* sequence that will be sent to the gate opto-coupler block, which will feed each six-pulse converter. The *off* sequence turns out on a similar way but waiting 180° to keep the same *on* and *off* duration in each IGBT.

3.3. Seven-Level Pulse Generator

To operate the seven-level inverter, six times the frequency of the six-pulse generator must be ensured. This is achieved by monitoring the falling border in the novel PLL output signal, using it along with the modulus operator with the 3 argument. This signal will be the period for the seven-level generator which will change its state each π/ 42 rad.

4. SIMULATION RESULTS

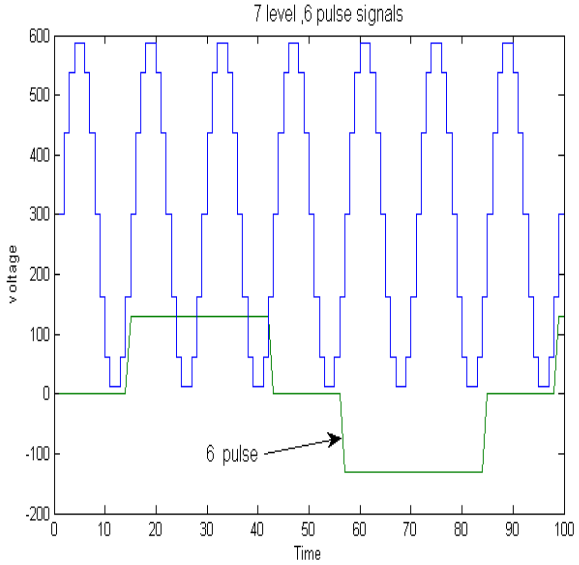

Fig.4(a) *Mixing seven-level, six-pulse signals to attain* V_{YU}

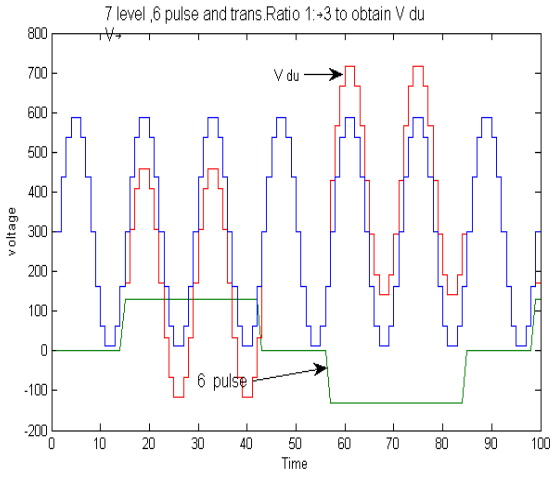

Fig .4(b) *Mixing seven-level, six-pulse signals, and transformer's ratios to attain* $V_{\Delta U}$

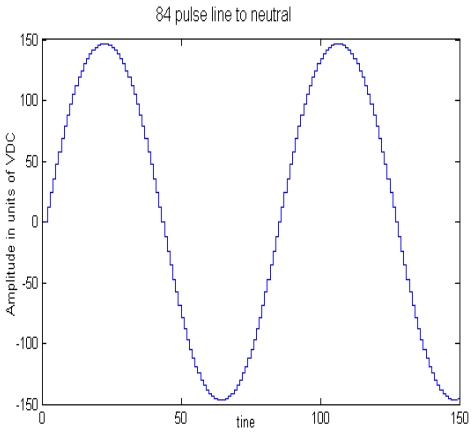

Fig.5(a) *84-pulse line to neutral output voltage*

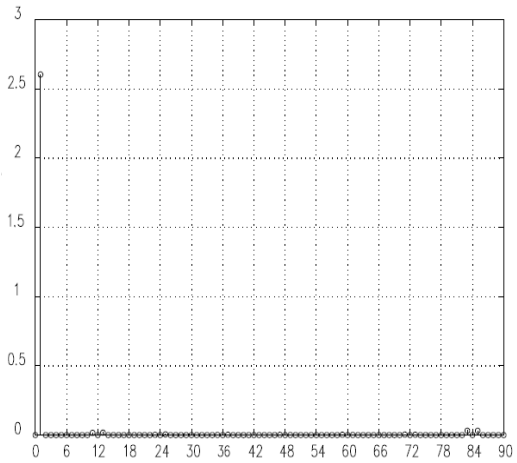

Fig.5(b) *harmonic content*

V. CONCLUSIONS

This paper describes the strategy to obtain an 84-pulse VSC three-phase voltage with the associated low THD, by combining one twelve-pulse converter plus a seven-level converter. The device performance, proven on a lab prototype, allows to verify the harmonic content of the resultant voltage signal. The exhibited low THD, permits the system to be used in especial applications or as basement of FACTS devices. The three-phase digital PLL used to detect the phase of the fundamental voltage, synchronizes the firing signals in all switches within a sample cycle.

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