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An Approach to Obtain an 84-Pulse VSC Three-Phase Voltage with Low THD

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Abstract

This paper analyses the structure of an 12-pulse 7 level 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. The device performance, proven on a lab prototype, allows verifying 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. W ith 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 and experimental results are provided to show the proposal appropriateness.

Index Terms—***Voltage Source Converter, STATCOM, Flexible AC Transmission systems.***

Introduction:

The static synchronous compensator (statcom) is one of the most useful FACTS devices, since it can synthesize the reactive power from small storing elements. When it is operated with in the linear region, it is seen by the system as a synchronous voltage source. By the regulation of the statcom’s output voltage magnitude, the reactive power exchange between the device and transmission system may be controlled to improve the power system voltage profile. Since the statcom may cause interface on the system’s fundamental sine wave at frequencies that are multiples of 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) pulse width modulation. 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. Here it describes a strategy to generate the 84-pulse VSC, assembled with the combination of one twelve –pulse converter with a seven level converter. A reinjection transformer is needed which is able to work properly with in a wide range of its turns ratio.

Power electronic based converters and controllers are extensively used for different types of domestic, agricultural and industrial applications. Ac-to-dc converters also called as rectifiers are widely used for the dc voltage and power control e.g. charging of batteries in inverters, UPS, cell-phones and speed control of dc motors etc. [10-12]. Dc-to-ac converters also called as inverters are commonly used to supply ac power fed from dc sources such as solar panels or batteries. The most famous device that applies this technology is Uninterruptible Power Supplies (UPS) [13-14]. It is also used in programmable ac power supplies and power conditioners [15].

STATCOM:

STATCOM or Static Synchronous Compensator is a shunt device, which uses force-commutated power electronics (i.e. GTO, IGBT) to control power flow and improve transient stability on electrical power networks. It is also a member of the so-called Flexible AC Transmission System (FACTS) devices. The STATCOM basically performs the same function as the static var compensators but with some advantages.
The term Static Synchronous Compensator is derived from its capabilities and operating principle, which are similar to those of rotating synchronous compensators (i.e. generators), but with relatively faster operation.

TYPES OF CONVERTERS:

A HVDC system requires an electronic converter for its ability of converting electrical energy from ac-dc or vice versa. There are basically two configuration types of three-phase converters possible for this conversion process. They are as follows
1. Current Source Converter (CSC),
2. Voltage Source Converter (VSC).

During the period (about) 1950-1990s, HVDC systems used the CSC configuration almost exclusively. The traditional CSC utilized the mercury-arc valve from the early 1950s to the mid-1970s, and thereafter, the thyristor valve as its fundamental switching device. From about 1990 onwards, the alternative VSC became economically viable due to the availability of new self-commutating high-power switches (such as GTOs and IGBTs) and the computing power of DSPs to generate the appropriate firing patterns. Modern HVDC transmission systems can utilize either the traditional Current Source Converter (CSC) or the Voltage Source Converter (VSC) as the basic conversion workhorse.

Current Source Converter (CSC):

In a Current Source Converter, the DC current is kept constant with a small ripple using a large inductor, thus forming a current source on the DC side. The direction of power flow through a CSC is determined by the polarity of the DC voltage while the direction of current flow remains the same.

Self-commutated Voltage Source Converters are more flexible than the more conventional Current Source Converter since they allow controlling active and reactive power independently.

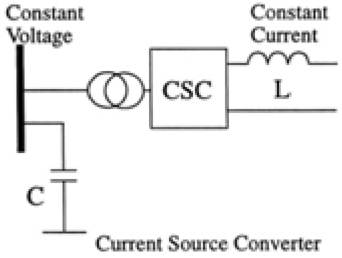

Figure 1

Voltage Source Converters (VSC):

Voltage Source Converters operating with the specified vector control strategy can perform independent control of active/reactive power at both ends. This ability of VSC makes it suitable for connection to weak AC networks, i.e. without local voltage sources. For power reversal, the DC voltage polarity remains the same for VSC based transmission system and the power transfer depends only on the direction of the DC current.

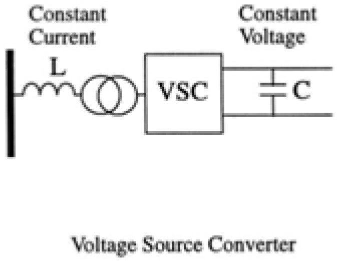

Figure 2

The commercial availability of high-power and high-voltage GTO and IGBT valves in the 1990’s offered the viable operation of VSCs in HVDC schemes. In essence, the impact of a VSC on the ac system can be approximated to be as the sum of a conventional CSC and SVC in parallel, but with the added flexibility of secure commutation.Different kinds of Pulse Width Modulation (PWM) techniques can be employed to operate the VSC in inverter mode to provide a sinusoidal output to the ac system. The advantages of the VSC are:

- Rapid control of active as well as reactive power,
- It provides a high level of power quality,
- Minimal environmental impact, and
- Ability to connect to weak ac networks, or even dead networks.

The technology lends itself to the following types of applications:

- Low power (less than 250 MW) HVDC transmission (commercially referred to as “HVDC Light”),
- VAR Computation (SVC and STATCOM), and
- Active Filters.

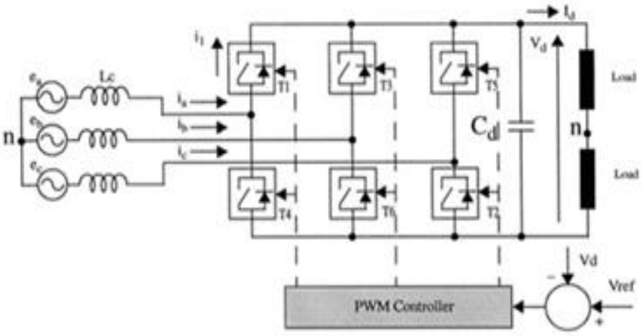

Figure 3 VSC operating principles

VSCs utilize self-commutating switches (e.g. GTOs, IGBTs) which can be turned-on or off at will. This is in contrast to the conventional CSCs which operate with line-commutated thyristorswitches. Commutation in a force commutated VSC valve can occur many times per cycle,whereas in a line commutated CSC it can happen only once per cycle. This feature allows the voltage/current in a VSC to be modulated to produce a nearly sinusoidal output and control the power factor as well. Furthermore, power reversal in a VSC can be made with either current or voltage reversal at the dc side. In contrast, with a CSC, power reversal can occur only with voltage reversal.

REINJECTION CONFIGURATION:

There are three main strategies to build a Voltage Source Converter (VSC):
(i) The multipulse;
(ii) The multilevel;
(iii) The pulse width modulation (PWM)

MULTI PULSE CONFIGURATION:

In the multipulse strategy, the period of the signal is broken down into equal sized parts in relation to the pulse number. The switches are triggered once per cycle at the fundamental frequency, and the amplitude on each pulse is controlled mainly by the output magnetic stage. The more pulses produces the less output Total Harmonic Distortion (THD). In the multilevel strategy, the DC source has to be broken down into parts of equal amplitude (x), given rise to a 2x-1 levels signal. Switches commute once per cycle at the fundamental frequency. The THD depends on the amount of DC sources or divisions available in the DC link. On the other hand, the PWM technique uses fast commutations to reach a low THD. The faster commutations are, the lower THD. However, it is limited due to the commutation speed of the switches and requires always an output filter coupled to the grid. This research deals with a combination of the first two strategies with emphasis on the use of multipulse configuration in order to reach the minimum total harmonic distortion.

There is a difference on the twelve-pulse converter used in this work, respect to the standard twelve-pulse converter. The DC source is not common to both six-pulse modules. In this proposition, a positive multipulse signal between the main terminals of the first six-pulse converter and another positive multipulse signal with opposite phase between the main terminals of the second six-pulse converter are connected. In order to have a neutral point, the

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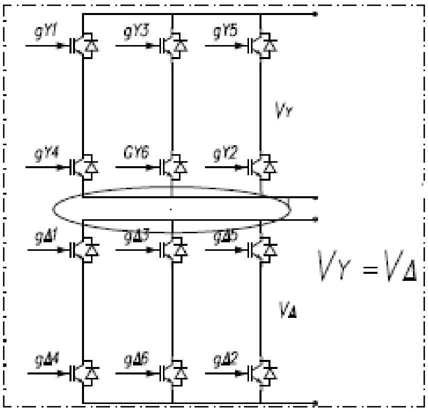
negative of the first converter is connected to the positive of the second converter, as presented on Fig. 4

Each branch in the six-pulse converters must generate electrical signals with 120° of displacement between them; the upper switch is conducting while the lower one is open and vice versa (180° voltage source operation).

TRADITIONAL SCHEME



REINJECTION SCHEME

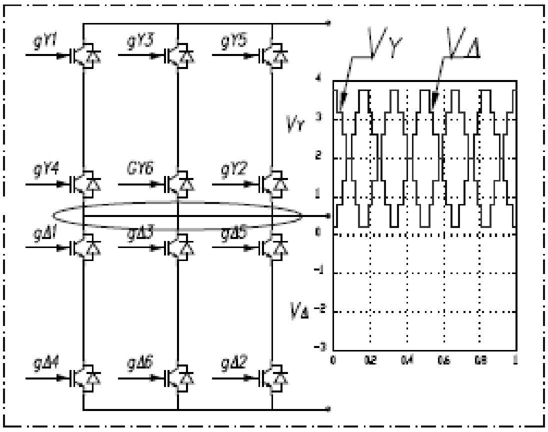


Figure 4 Traditional and reinjection scheme

A 30° displacement in the firing sequence of both converters must be considered. Transformer's turn ratios are 1:1 and 1:3 on the YY and YΔ transformers, respectively. In order to operate the VSC in special applications such as airports or hospitals, an 84 level voltage signal is proposed, generated through a 7 level auxiliary circuit operating as a re-injection scheme.

MULTI LEVEL CONFIGURATION:

A voltage level of three is considered to be the smallest number in multilevel converter topologies. Due to the bi-directional switches, the multilevel VSC can work in both rectifier and inverter modes. This is why most of the time it is referred to as a converter instead of an inverter in this dissertation. A multilevel converter can switch either its input or output nodes (or both) between multiple (more than two) levels of voltage or current. As the number of levels reaches infinity, the output THD approaches zero. The number of the achievable voltage levels, however, is limited by voltage-imbalance problems, voltage clamping requirements, circuit layout and packaging constraints complexity of the controller, and, of course, capital and maintenance costs. Three different major multilevel converter structures have been applied in industrial applications: cascaded H-bridges converter with separate dc sources, diode clamped, and flying capacitors. The multilevel inverter structures are the main focus of discussion in this chapter; however, the illustrated structures can be implemented for rectifying operation as well. Although each type of multilevel converters share the advantages of multilevel voltage source inverters, they may be suitable for specific application due to their structures and drawbacks.

In a multilevel VSI, the dc-link voltage Vdc is obtained from any equipment which can yield stable dc source. Series connected capacitors constitute energy tank for the inverter providing some nodes to which multilevel inverter can be connected. Primarily, the series connected capacitors will be assumed to be any voltage sources of the same value. Each capacitor voltage Vic is given by Vic=Vdc/ (n-1), where n denotes the number of level.

Fig. 5 shows a schematic diagram of one phase leg of inverters with different number of levels, for which the action of the power semiconductors is represented by an ideal switch with several positions. A two-level inverter generates an output voltage with two values (levels) with respect to the negative terminal of the capacitor, while the three-level inverter generates three voltages, ¬and so on.

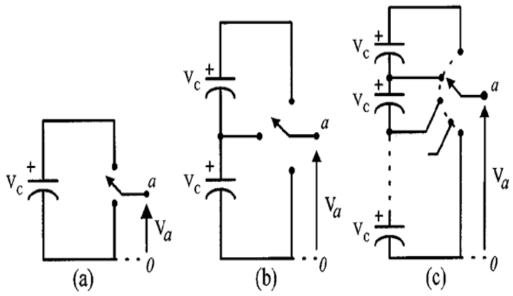


Fig. 5: One phase leg of an inverter with (a) two levels, (b) three levels, and (c) n levels.

The increase of the world energy demand has entailed the investment of huge amounts of resources, economical and human, to develop new technologies capable to produce, transmit and convert all needed electric power. In addition, the dependence on fossil fuels and the progressive increase of its cost lead to appearance of new cheaper and cleaner energy resources not related to fossil fuels. In ultimate decades, renewable energy resources have been the focus for researchers, and different families of power converters have been designed to integrate these types of supplies into the distribution grid.

Beside the generation, electric power transmission needs high-power power electronic systems to assure conversion and the energy quality. Static converters such are high-voltage dc (HVDC), static synchronous compensator (STATCOM) and flexible alternating current transmission system (FACTS) are becoming standard part of the high-voltage grid in addition to traditional transformers and power lines. Last but not least, numerous industry applications, such as for example textile and paper industry, steel mills, electric and hybrid electric vehicles, ship propulsion, railway traction, ‘more-electric’ aircraft, etc., require utilization of variable speed electric drives. As far as the variable speed operation of electric drives is concerned, this is nowadays invariably achieved by supplying the machine, regardless of the type, from a power electronic converter.

PWM Pattern Generation Techniques:

Three widely used PWM modulation techniques for following the current reference template are described here:

Periodical Sampling (PS): This method employs a clock of fixed frequency to control the power switches of the VSC. An error signal, generated from a measurement of theline and reference currents, is used to modulate the clock frequency and generate the PWM pattern using a comparator and D-type flip-flop. The minimum time between switching is limited by the clock frequency.

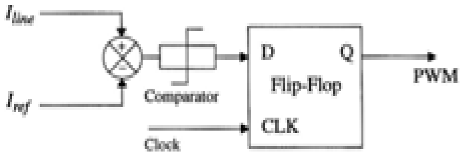


Fig:6 periodic sampling Technique for PWM pattern generation

Hysteresis Band (HB): The hysteresis Band technique modulates the conveter switches when the error between the line Iline and Iref exceeds by a fixed magnitude of Iref .In this case,the switching frequency is not fixed and varies as a function of the Iref magnitude ,the hysteresis band h and the inductance in the load.

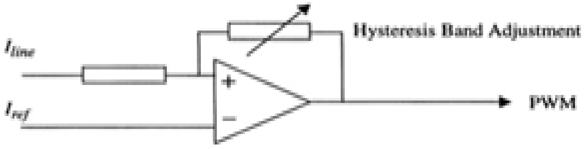


Fig:7 Hysteresis band (HB) technique for PWM pattern generation

Triangular Carrier (TC) Technique: The TC method compares the error between the Iline nad Iref with a fixed frequency fixed amplitude triangular carrier wave.A PI regulator provides the static and dynamic properties to the feedback loop.This method is more complex than the other two methods in its implementation since the gains of the PI controller need to be selected.

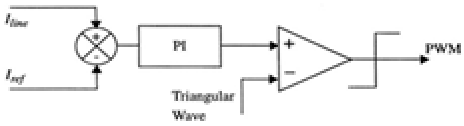


Fig:8 Triangular carrier wave technique for PWM pattern generation

PWM WITH BIPOLAR VOLTAGE SWITCHING

In this PWM scheme diagonally opposite switches from two legs of the converter are switched together as switch pairs 1 and 2 respectively. With this type of PWM switching the output voltage waveform of the leg is identical to the output of the basic one-leg inverter which is determined by comparision of a sinewave and a triangular wave.In it can be observed that the output voltage switches between +Vd and –Vd voltage level.That is the reason why this type of switching is called PWM with bipolar voltage switching.

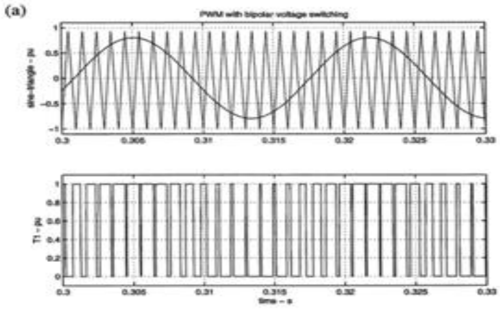


Figure 9 PWM with bipolar voltage switching

PWM with unipolar voltage switching:

In this PWM scheme with unipolar voltage switching the switches in the two legs of the full bridge inverter are not switched simultaneously as in the previous PWM scheme. Here the legs of the full bridge inverter are controlled separately. As shown in fig the comparison of Vcontrlwith the triangular waveform results in the logic signals to control the switches T1 and T3.In this type of PWM scheme when a switching occurs the output voltage changes between zero and +Vd or between zero –Vd voltage levels.For this reason this type of PWM scheme is called PWM with in a unipolar voltage switching scheme described earlier .This scheme has the advantage of 'effectively' doubling the switching frequency as far as the ouput harmonics are connected compared to the bipolar voltage switching scheme.Also the voltage jumps in the output voltage at each switching are reduced to Vd as compared to 2Vd in the previous scheme.

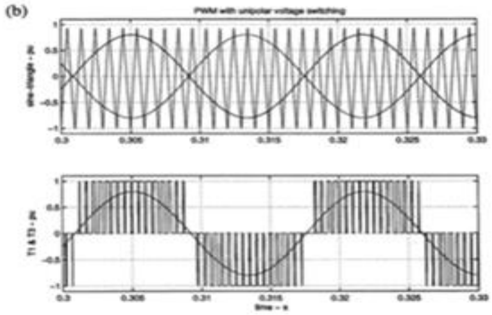


Figure 10 PWM with unipolar voltage switching

84-PULSE VSC TOPOLOGY

84-pulse VSC Configuration:

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. Such topology results through modifying the DC input on the conventional double bridge twelve-pulses shunt converters through a multi-level auxiliary with an injection transformer. In this strategy a asymmetric seven-level array for the auxiliary circuit is used ad reinjection scheme. 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). 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 is common to the three phases reducing the number of extra components. The figure below 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 Vy or VΔ ; 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 Ui by

$$V_Y = V_{DC} + U_i$$
$$V_\Delta = V_{DC} - U_i$$

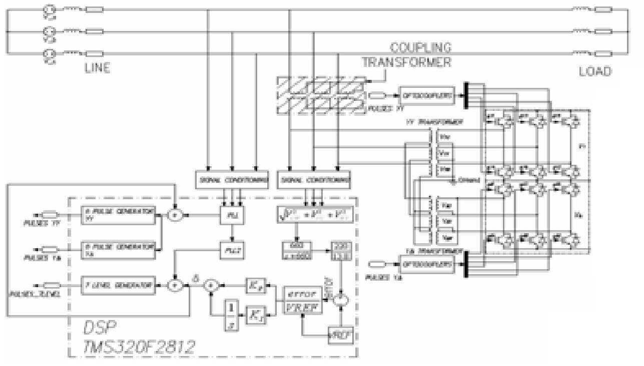


Figure 11: 84-pulse generator circuit

The injection voltage is determined by the seven-level inverter ratio. By switching pattern and the injection transformer turns ratio. By using voltages Vy and VΔ as inputs to the six pulse converter a cleaner VSC's output voltage.The below waveform of seven level and six pulse signals and transformer ratio exhibits the followed strategy to build VYU and VΔU 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 YΔ TRANSFORMER and adding their corresponding signals the 84-pulse line- to- neutral signal VU emerges.VU is an odd symmetric signal so that Fourier even terms are zero.

84-pulse signal value VU depends on injection transformer turns a, which is determined so as to minimize the total harmonic distortion (THD). The minimization of THD yields the parameter a,In this topic 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.

Through our proposition, the resultant THD allows its use even in applications with stringent quality requirements; it exhibits less dependence to variations in the transformers turns 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.

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 2 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 IGBT.

Basic unit of a converter station in a conventional HVDC system is the six-pulse bridge converter or called Graetz Bridge. The structure of the bridge is shown in the Figure

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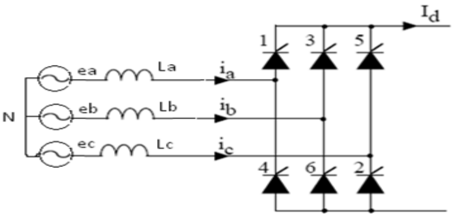


Figure 12 Graetz Bridge Circuit

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. This signal will be the period for the seven-level generator which will changes its state.

The 7-level version of the proposed topology is shown in Fig.13, where another dc supply, and two auxiliary switches, Q7 and Q8, are added while keeping the four main switches, Q1~Q4, unchanged.

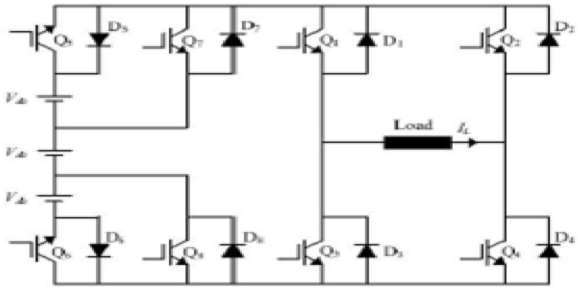


Figure 13 The 7-level inverter of new topology

SIMULINK RESULTS:

Case 1: Evaluation of proposed 84-pulse VSC for StatCom:

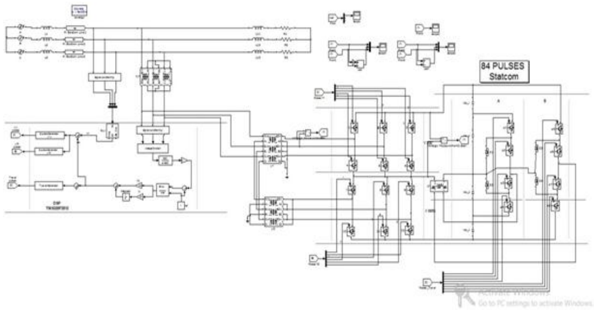


Figure 14: Matlab/Simulink Model of Proposed 84-pulse VSC for StatCom

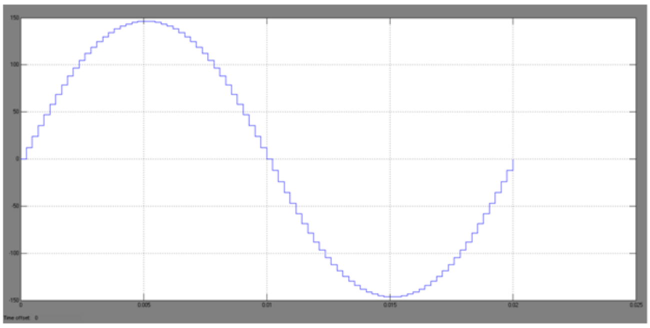


Figure 15: 84-pulse out put voltage for StatCom

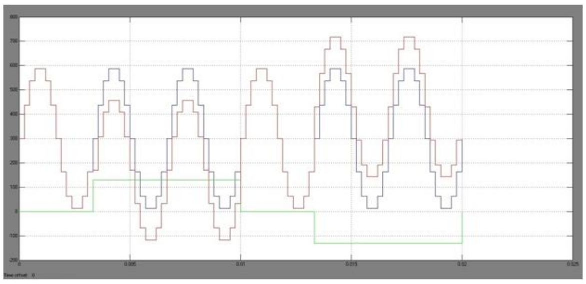
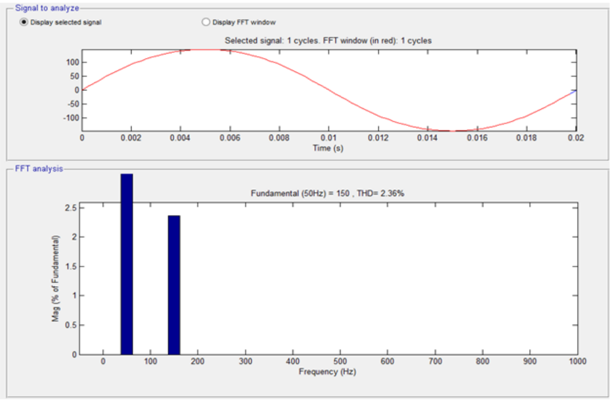


Figure 16: Output of 84-pulse VSC for StatCom



Selected signal: 1 cycles. FFT window (in red): 1 cycles

Fundamental (50Hz) = 150 , THD= 2.36%

Figure 17: Total Harmonic Distortion for 84-pulse VSC for StatCom

Case 2: Evaluation of proposed 84-pulse VSC for SSSC

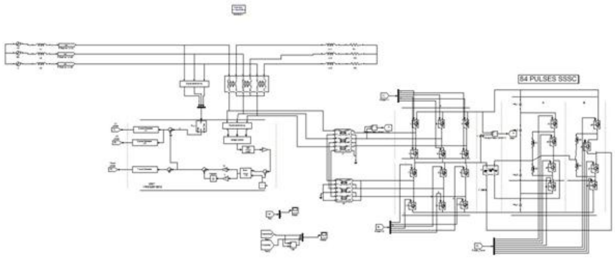


Figure 18: Matlab/Simulink Model of Proposed 84-pulse VSC for SSSC

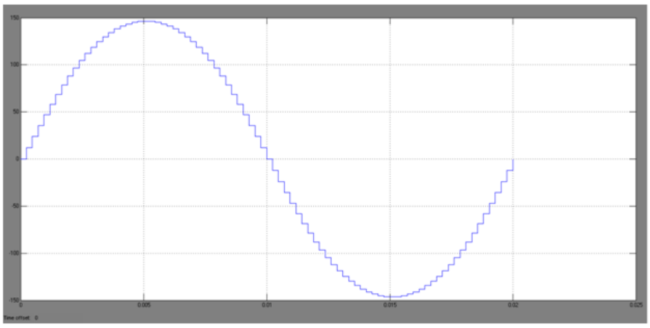


Figure 19: 84-pulse out put voltage for SSSC

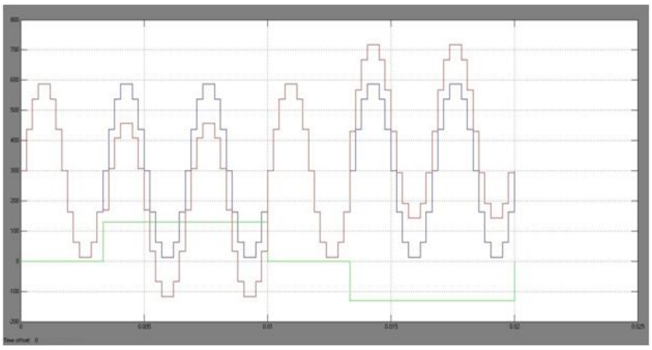


Figure 20: Output of 84-pulse VSC for SSSC

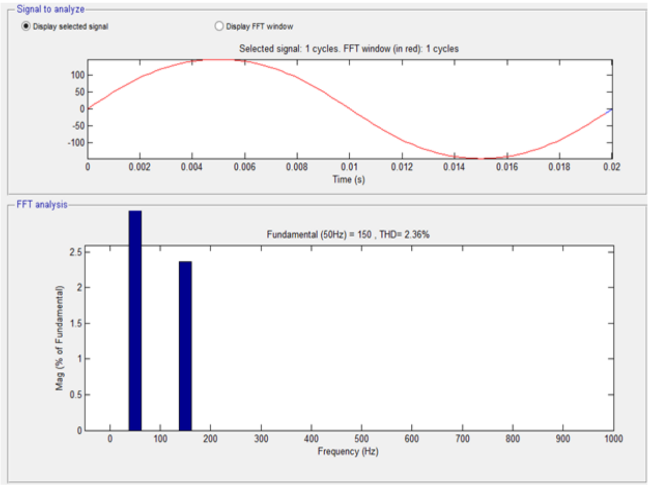


Figure 21: Total Harmonic Distortion for 84-pulse VSC for SSSC

CONCLUSION:

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 todetect the phase of the fundamental voltage synchronizes the firing signals in all switches within a sample cycle.

The THD of output voltage in voltage source converter is low for 84-pulse converter for STATCOM and SSSC.

FUTURE SCOPE:

The control technique for multilevel power converters can be further simplified and generalized to different levels and other class of power converters and inverters. The levels of multilevel configuration can be increased and further improvements in terms of performance and power quality issues can be broadly studied and could be implemented with hardware circuits. The same cascaded multilevel inverter configuration can be installed for other applications like UPFC & UPQC system and performance can be studied for larger AC systems.

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