



IJRASET

International Journal For Research in
Applied Science and Engineering Technology



INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 4 Issue: III Month of publication: March 2016

DOI:

www.ijraset.com

Call:  08813907089

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Harmonic Distortion Elimination for STATCOM Application Using SHE-PWM Cascaded Multilevel Inverter

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Abstract—A novel multilevel selective harmonic elimination pulse-width modulation (MSHE-PWM) technique for transformer static synchronous compensator STATCOM system using cascaded H-bridge inverter (CHI) is proposed. MSHE-PWM method optimizes both the dc voltage levels and the switching angles, helping more harmonics to be eliminated without affecting the structure of the inverter circuit. The converter is operated by maintaining the switching frequency of a converter to a minimum value using a technique called (SHE-PWM). Rapid growth and development in the field of power semiconductor devices resulted in production of high efficiency dc to dc converters with a relatively high-voltage capacity and for simplicity, a buck dc to dc converter is considered in this project. The simulation study is tested in MATLAB to understand the performance of the proposed scheme

Index terms — Power quality problems, harmonics, pulse width modulation (PWM), selective harmonic elimination (SHE).

I. INTRODUCTION

The application of FACTS controllers, such as static compensator (STATCOM) and static synchronous series compensator (SSSC), is growing in power systems. This is due to their capacity to stabilize the transmission systems and to improve power quality (PQ) in distribution systems. STATCOM is universally accepted as a reliable reactive power controller replacing legacy var compensators, like Thyristors-switched capacitor (TSC) and thyristor-controlled reactor (TCR). This device offers reactive power compensation, dynamic power oscillation damping, flicker attenuation, voltage regulation and so on.

Usually for high power applications, var compensation is achieved using multilevel inverters. These inverters consist of a enormous number of dc sources which are generally realized by capacitors. Hence, the converters draw a small quantity of active power to maintain dc voltage for capacitors and to compensate the losses in the converter. However, due to discrepancy in transmission and switching losses of the switching devices, the capacitors voltages are unbalanced. Matching these voltages is an important research task in multilevel inverters. Among the three legacy multilevel inverter topologies, cascade H-bridge is the most popular for static var compensation. However, the above said topology requires additional number of dc capacitors. The control of individual dc-link voltage of the capacitors is very difficult. Static var compensation by cascading conventional multilevel/two level inverters is an smart solution for high power applications. The topology consists of standard multilevel/two level inverters connected back to back through open end windings of a three phase transformer. Such topologies are popular in high-power drives.

One of the benefits of this topology is by maintaining asymmetric voltages at the dc links of the inverters, the number of stages in the output voltage waveform can be improved. A three level inverters and two level inverters are connected on either side of the transformer low-voltage winding. The dc link voltages are sustained by separate converters. In three-level operation is obtained by using standard two-level inverters. The dc link voltage balances among the inverters is affected by the reactive power supplied to the grid.

II. ELECTRIC POWER QUALITY AND CLASSIFICATION OF PQ PROBLEMS, IMPACTS AND IMPROVEMENTS

Power quality has gained more importance in the power industry. Everybody does not agree with the use of the term power quality, but they do accept that it has become a important aspect of power delivery especially in 1990s. There is a lot of difference about what power quality actually incorporates. Other sources use similar but slightly different terminology like quality of power supply or voltage quality. The power quality is seriously disturbed due to the widely use of nonlinear loads and

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various faults in power system. This kind of devices are sensitive to small changes of power quality, a short time change on PQ can cause great economic losses. Because of the two reasons mentioned above, no matter for the power business, equipment manufacturers or for electric power customers, power quality problems had become an issue of increasing interest. Under the situation of the deregulation of power industry and competitive market, as the main character of goods, power quality will affect the price of power directly in near future. In most of the industries voltage sag/swell and harmonics are the common problems encountered in the industrial processes.

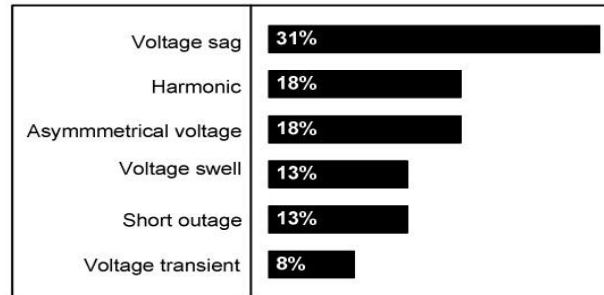


Fig.1. Percentage occurrences of PQ disturbances in equipment interruptions

This thesis takes into account the most common power quality problems such as voltage sags/swells and current harmonics as shown in Figure 2. Together they account for high percentage of the power quality disturbances affecting most commercial and industrial customers.

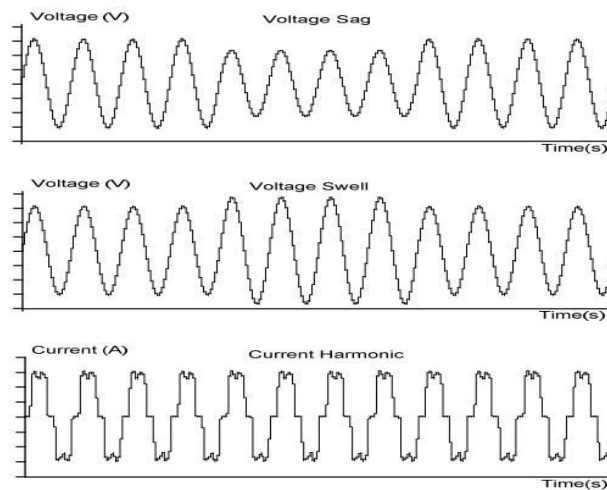


Fig.2. Most type of power quality problems

For the purpose of this thesis, we shall describe power quality problems as: “Any power problem that results in failure of customer equipment, establishes itself as an economic burden to the user, or produces negative impacts.” The AC and DC modifiable speed drives used on board container cranes are significant contributors to total harmonic current and voltage alteration. But SCR phase control creates the desirable average power factor; DC SCR drives work at less than this. Adding, line notching occurs when SCR’s commutate, creating transient peak recovery voltages that can be 4 times the normal line voltage depending upon the system impedance and the size of the drives. The severity of these power system conflicts varies with the speed of the drive.

III. HARMONICS AND ITS EFFECTS

A. Harmonics

The typical meaning for a harmonic is “a sinusoidal component of a periodic wave or quantity having a frequency that is an integral of the fundamental frequency”. Some references refer to “clean” or “pure” power as those without any harmonics. But such sanitary waveforms typically only exist in a laboratory. Harmonics have been around for an extended time and will stay to do so. In fact, musicians have been aware of such since the invention of the first string or woodwind instrument. Electrical generators attempt to

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produce electric power where the voltage waveform has only one frequency associated with it, the frequency. In North America, this frequency is 60 Hz, or cycles per second. In European countries and rest of the world, this frequency is usually 50 Hz. Aircraft often uses 400 Hz as the fundamental frequency. At a frequency of 60 Hz, this means that sixty times a second, the voltage waveform increases to a maximum positive value, then decreases to zero, further reducing to a maximum negative value, and then back to zero.

B. Effects of Harmonics

The presence of harmonics does not say that the factory or office cannot run properly. Like other power quality, it depends on the stiffness of the distribution system and the susceptibility of the equipment. As shown below, there are various types of equipment that can have mis-operations or failures due to high harmonic voltage and current levels.

In addition, a factory may be the source of high harmonics but able to run properly. This harmonic contamination is often taken back to the electric distribution system, and may effect facilities on the same system which are more vulnerable.

Some characteristic types of equipment susceptible to harmonic pollution include: - Disproportionate neutral current, causing overheated neutrals. The odd triplen harmonics in three phase wye circuits are actually stabilizer in the neutral. This is since the harmonic number multiplied by the 120 degree phase shift between the phases is a integer multiple of 360 degrees. This sets the harmonics from each of the three phase legs in phase with each other in the neutral, as pictured below

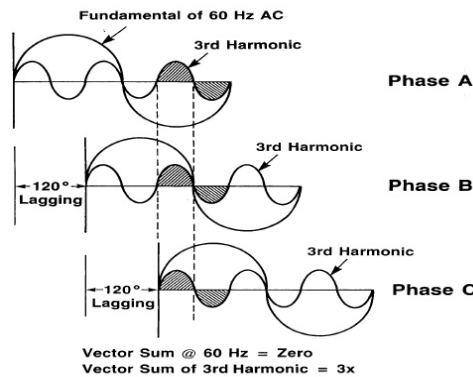


Fig.3. Harmonics in 3 phase output

Table 1- Harmonic sequencing value

HARMONIC	FUND	2ND	3RD	4TH	5TH	6TH	7TH	ETC
SEQUENCE	+	-	0	+	-	0	+

Harmonic Sequencing Ideals in Balanced Systems operation of protective devices, including false tripping of relays and miscarriage of a UPS system to transfer properly, especially if controls incorporate zero-crossing sensing circuits. Failure from shaft currents through non-insulated bearings of electric motors. - Blown-fuses on PF correction caps, due to high voltage and currents from line impedance. Mis-operation or failure of electronic equipment- If there are harmonics in the range of frequency 1 to 30Hz, the result on lighting is called flicker. This is especially true at 8.8Hz, where the eye of human is most sensitive, and just 0.5% variation in the voltage is noticeable with some types of lighting.

IV. HARMONICS ELIMINATION TECHNIQUES

FOR HARMONIC ELIMINATION WE USE COMBINATION OF TWO TECHNIQUES:-

A. Pulse Width Modulation Technique

The dawn of the transformerless multilevel inverter topology has brought out several pulse width modulation (PWM) techniques as a method to control the switching effect of the active devices in each of the various voltage levels in the inverter device. The most effective technique of controlling the output voltage is to incorporate pulse width modulation (PWM control) inside the inverters. In this technique, a fixed DC input voltage is supplied to the inverter and a organized AC output voltage is achieved by adjusting the

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on and off periods of the devices. Voltage type PWM inverters have been employed widely to such as power supplies and motor drivers. This is because: (1) these inverters are well adjusted to high-speed self-turn-off switching devices that, as solid-state power converters, are made with recently developed advanced circuits and (2) they are functioned stably and can be controlled well.

B. Multilevel Power Converters

Numerous industrial applications have started to necessitate higher power apparatus in recent years. Some medium voltage drives and utilities require medium voltage and megawatt power level. For a medium voltage grid, it is hard to connect only a power semiconductor switch directly. As a result, a multilevel power converter structure has been introduced as a substitute in high power and medium voltage situations. A multilevel converter not only attains high power ratings, but also permits the use of reusable energy sources. Renewable energy sources can be easily interfaced to a multilevel converter system in employment of high power application. The idea of multilevel converters has been presented since early 70's. The word multilevel began with the three-level converter. Successively, numerous multilevel converter topologies have been established. However, the elementary concept of a multilevel converter to accomplish higher power is to custom a series of power switches with several lower voltage dc sources to execute the power conversion by blending a staircase voltage waveform. Capacitors, batteries, and reusable energy voltage sources can be employed as the multiple dc voltage sources. The power switches combine these numerous dc sources to attain high voltage at the output. Though, the rated voltage of the power semiconductor switches relies only upon the rating of the dc voltage sources to which they are connected.

A multilevel converter has several benefits over a legacy two-level converter that uses high switching frequency pulse width modulation (PWM).

Unluckily, multilevel converters have some disadvantages. One particular disadvantage is the greater number of power semiconductor switches required. Though lower voltage rated switches can be utilized in a multilevel converter, each switch needs a related gate drive circuit. This will make the overall system to be more expensive and complex. Plentiful multilevel converter has been suggested during the last two decades. Contemporary research has engaged novel converter topologies and distinctive modulation schemes. Moreover, three different major multilevel converter structures have been reported in the works. A cascaded H-bridges converter with separate dc sources, diode clamped i.e., neutral clamped), and flying capacitors i.e., capacitor clamped. Moreover, abundant modulation techniques and control paradigms have been industrialized for multilevel converters like sinusoidal pulse width modulation (SPWM), selective harmonic elimination technique (SHE-PWM), space vector modulation technique (SVM), and others. In addition, many multilevel converter applications concentrates on industrial medium level voltage motor drives, utility interface for renewable energy systems (FACTS) flexible AC transmission system, and traction drive systems.

C. Multilevel Power Converter Structures

As previously stated, three different major multilevel converter structures have been applied in industrial applications: cascaded H-bridges converter with isolated dc sources, diode clamped, and flying capacitors. Before continuing discussion in this topic, it should be observed that the term multilevel converter is utilized to refer to a power electronic circuit that could function in an inverter or rectifier mode. The multilevel inverter structures are the focus of in this chapter; however, the illustrated structures can be applied for rectifying operation as well.

D. Cascaded H-Bridges

A single-phase assembly of an m-level cascaded inverter is illustrated in Figure 31.1. Each separate dc source (SDCS) is linked to a single-phase full-bridge, or H-bridge, inverter. Each inverter level can generate three different voltage outputs, +Vdc, 0, and -Vdc by linking the dc source to the ac output by different combinations of the four switches, S1, S2, S3, and S4. To get +Vdc, switches S1 and S4 are turned on, whereas -Vdc can be obtained by powering on switches S2 and S3. By powering on S1 and S2 or S3 and S4, the output voltage is 0.

The ac outputs of each of the different full-bridge inverter levels are connected in series such that the synthesized voltage waveform is the sum of the inverter outputs. The number of output phase voltage levels m in a cascade inverter is defined by $m = 2s + 1$, where s is the number of separate dc sources. An example phase voltage waveform for an 11-level cascaded H-bridge inverter with 5 SDCSs and 5 full bridges.

The phase voltage $v_{an} = v_{a1} + v_{a2} + v_{a3} + v_{a4} + v_{a5}$. For a stepped waveform such as the one depicted in Figure with s steps, the Fourier Transform for this waveform:

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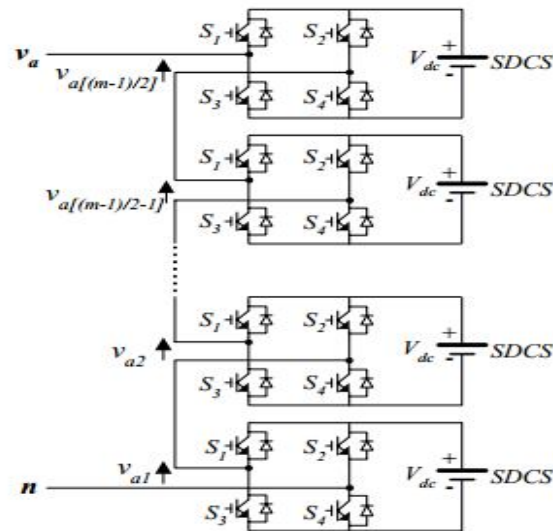


Fig.4. Cascaded H-Bridge

V. EXISTING CB-PWM SYSTEM

Electricity reconstructing envisions the transmission system as flexible, reliable and open to all exchanges no matter where the providers and consumers of energy are located. Today, however the transmission system cannot fully support such diverse and open exchange. Desirable market transactions today are quite different from those envisioned when the transmission system was designed executing them may stress the limits of safe operation.

The risks posed by such transactions may not be accepted in time to prevent major system emergencies. It is also increasingly common for one transaction to interface with the safe execution of others, producing “congestion” in the system. Mitigating congestion is technically difficult and poses new administrative challenges when the paths are long enough to span regions that have not had to coordinate such operations in the past. In addition, the technical infrastructure required to manage operations reliably may be overcome by the sheer volume of data and information concerning system conditions, transactions, and events.

These problems can be remedied in part by physical reinforcements to the transmission system, sometimes through new construction but increasingly through broader use of improved hardware technologies. However, the greater strategic need is for indirect reinforcements to the general infrastructure for grid operations and planning. It is at this level that transmission needs are recognized options for countering those needs are assessed and a balance is achieved between new transmission assets and new operating methods. Timely development and deployment of requisite technology is a major element throughout this process. But requisite technology is not exclusively new technology. There is today a backlog of prototype technologies that can be adapted to power system applications, given the incentive and the means to do so Progress in transmission system reinforcements has for many years been hampered by yet another aspect of electricity restructuring. This process is far from complete and it has greatly weakened the essential dialog between technology developers and technology users.

Development of new technology must be closely linked to its actual deployment for operational use. Together both actions should reflect, serve and keep pace with the evolving infrastructure needs of transmission organizations. The present level of uncertainty precludes this once orderly process.

A. Modulation Techniques

The modulation technique is an important role in a STATCOM control system as it has a high impact on its compensation objects, transient as well as steady-state presentations. Therefore, several pulse-width modulation (PWM) techniques have been examined, projected, and documented in the literature; including carrier-based PWM (CB-PWM), multilevel space vector modulation (SVM) and stair case modulation, and selective harmonic elimination PWM (SHE-PWM). CB-PWM is by far the simplest technique to generate the required multilevel pulses through the intersection of a fundamental reference waveform with the dedicated disposition carrier.

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There are three well-known disposition methods, specifically alternative phase disposition, in phase disposition (IPD), and phase opposite disposition (POD). Comparative evaluations of these methods based on total harmonic distortion (THD) for multilevel inverter topologies with number of levels, switching frequencies, and modulation indices have been reported in several articles. Zero sequence injected IPD CB-PWM, or else known as the switch frequency optimal PWM technique, with marginal THD enhancement is presented to further enhance the THD performance in lower modulation with extra switching instants. Despite its simplicity, the CB-PWM technique does not offer any direct manipulation over the harmonic contents and also exhibits high-switching losses due to high switching frequencies; making its service into high-power applications is a big problem where high-losses are intolerable. SVM, on the other hand, can be used to manipulate harmonics at low-modulation indices and maintain desired performance characteristics of multilevel inverter in low-switching frequencies. Though efforts have been made to extend the operation of multilevel inverters under SVM into the over modulation region, however, as the number of levels increases, the number of inverter's states also severely increases resulting in difficulty to compute the duty cycles, selecting the proper switching states, and to determine the sector in which the reference vector lies in.

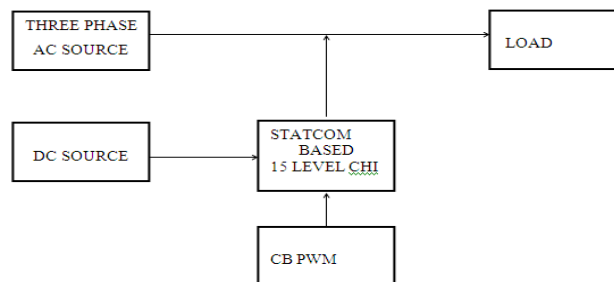


Fig.5. Existing CB-PWM Block Diagram

Further efforts to eliminate these problems have been attempted to simplify the computation and control. However, as the number of level decreases, the error in terms of the generated vectors with respect to the reference will be higher and, hence, producing an increase in current ripple, which affect the capacitor lifetime.

VI. PROPOSED SYSTEM – SELECTIVE HARMONIC ELIMINATION (SHE)

Selective Harmonic Elimination (SHE) has been a study topic since the early 1960's, first examined in and developed into an established form in during the 1970's is a long established method of generating pulse width modulation (PWM) with low baseband distortion.

Formerly, it was useful mainly for inverters with naturally low switching frequency due to high power or slow switching devices. Conventional sine-triangle PWM essentially eliminates baseband harmonics for frequency ratio of around 10:1 or greater, so it is arguable that SHE is unnecessary. However, recently Selective Harmonic Elimination (SHE) has received new consideration for several reasons. Next, these angles are kept in a look up table to be read in real time.

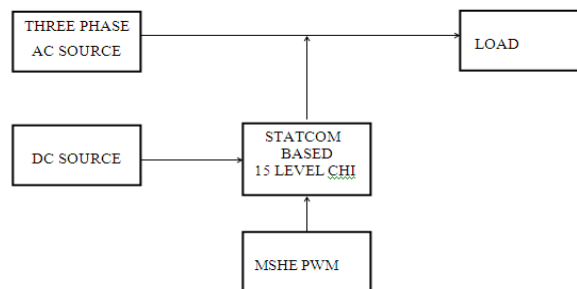


Fig.6. Proposed SHE PWM block diagram

Selective Harmonic Elimination (SHE) provides several benefits compared to traditional modulation methods including acceptable performance along low switching frequency to fundamental frequency ratios, direct control over output waveform

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harmonics, and the capability to leave triple harmonics unrestrained to take advantage of circuit topology in three phase systems. First, digital application has become common. Next, it has been shown that there are many solutions to the selective harmonic elimination (she) issue that were formerly unknown. Each solution has different frequency content above the baseband, which provides possibilities for flattening the high -frequency spectrum for noise suppression or optimizing efficiency. Third, some applications, even though the availability of high -speed switches, have low switching-to-fundamental ratios. One sample is high-speed motor drives, useful for reducing mass in applications like electric vehicles. These main advantages make SHE a possible alternative to other methods of modulation in applications such as ground power systems, dual frequency induction heating. Selective harmonic elimination (SHE) is normally a two-step digital process. First, the switching angles are calibrated offline, for several depths of modulation, by solving many nonlinear equations concurrently. Next, these angles are kept in a look up table to be read in real time. Much prior work has concentrated on the first step because of its computational troubles. One possibility is to replace the Fourier series preparation with another orthonormal set based on Walsh functions . The resulting equations are more tractable due to the resemblances between the rectangular Walsh function and the desired wave-form. Another way of approach is based on block-pulse functions is presented.

It is observed that the switching angles obtained conventionally can be represented as constant -sampled PWM where two phase-shifted modulating waves and a —pulse position modulation technique attained near -ideal eradication. Another approximate method is where mirror surplus

harmonics are employed. This includes solving multilevel elimination by considering reduced harmonic elimination waveforms in each switching level. In general-harmonic-families elimination concept simplifies a transcendental system to algebraic functional issues by nullifying entire harmonic families. A multilevel SHE-PWM is an off-line (pre-calculated) non carrier based PWM technique. In this system the basic square wave output is "cut" several times, which are acquired by appropriate off-line calculations. Fig. 7. shows a generalized symmetric quarter-wave stepped voltage waveform synthesized by a $(2m+1)$ -level inverter, where "m" is the number of switching angles.

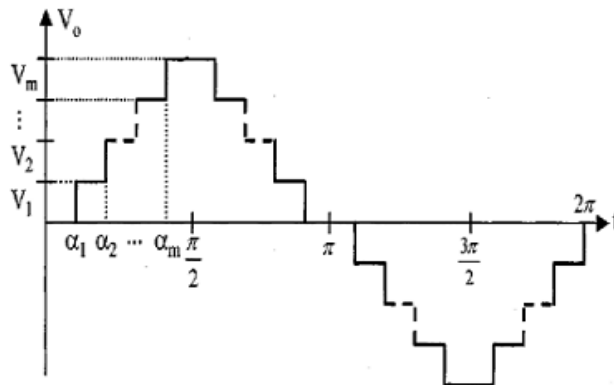


Fig.7. Generalized stepped voltage waveform

By using Fourier series analysis, the amplitude of an odd n^{th} harmonic of the stepped waveform can be expressed as expression given below, while the amplitudes of all even harmonics are zero.

$$h_n = \frac{4}{n\pi} \sum_{k=1}^m [V_k \cos(n\alpha_k)]$$

Where V_k is K^{th} level of dc voltage, n is odd harmonic order, m is the number of switching angles, and α_k is the m^{th} switching angle. The formulation of the SHE-PWM problem and acquisition of the solutions for seven-level waveform has been studied . The above equation can be further expressed as (2) for the fundamental frequency component and in (3) for the higher order harmonics. Where N_1 is the number of switching between the zero and the first level, N_2 is the number of switching between the first and the second levels, N_3 is the number of switching between the second and the third levels in the quarter period of the waveform, M is the modulation index, and α_i is the i^{th} switching within the quarter period of the waveform. The additional restriction imposed is

$$0 \leq M \leq 3$$

and

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$$0 < \alpha_1 < \alpha_2 < \alpha_3 < \dots < \alpha_N < \pi / 2$$

and the amplitude of the fundamental component is

$$v_1 = \frac{4M}{\pi} v_{dc}$$

To minimize harmonic distortion and to accomplish adjustable amplitude of the fundamental component, up to m-1 harmonic subjects can be disinterested from the voltage waveform. In general, the most significant low-frequency harmonics are chosen for eradication by suitably selecting angles among different level inverters, and high-frequency harmonic components can be easily eradicated by employing additional filter circuits. To keep the number of eliminated harmonics at a constant level, all the switching angles should be less than $\pi/2$

VII. SIMULATION

A. 15 Level With STATCOM Using SHE-PWM

The proposed system was modeled and simulated using MATLAB Simulink as shown below STATCOM is added in transmission line to Compensate Reactive Power. Here we are using SHE-PWM controller for harmonic reduction. Multilevel inverter to reduce the harmonics.

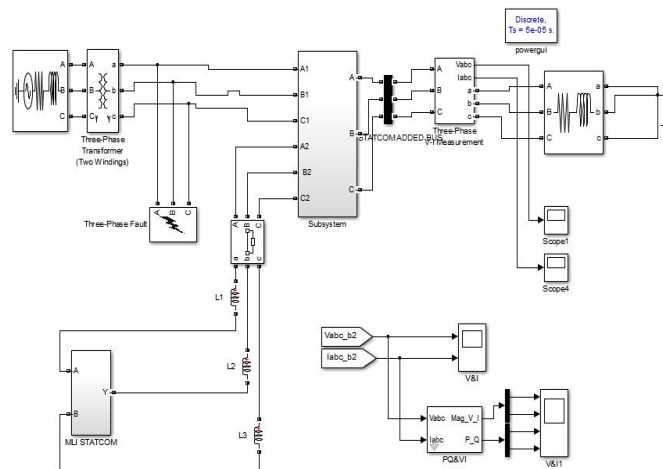


Fig.8. 15 Level Multilevel inverter using SHE- PWM Controller

B. SHE-PWM Controller

SHE-PWM method is used to optimize harmonic stepped waveform for multi-level inverters. Normally Pulse-width modulation (PWM) is a modulation technique used to encode a message into a pulsing signal. Here we are using SHE-PWM for selective Harmonic Elimination.

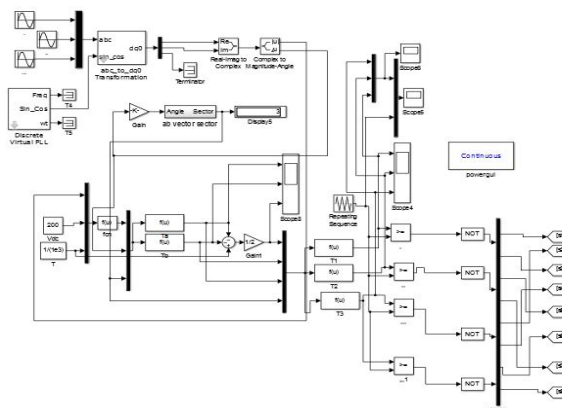


Fig.9. SHE -PWM Controller

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VIII. SIMULATION RESULTS

The simulation result for 15 levels SHE-PWM is shown in figure 10. the voltage level increase the harmonics reduced simultaneously. The harmonic elimination output is shown in fig 13. The THD percentage of harmonic order is 2.89%

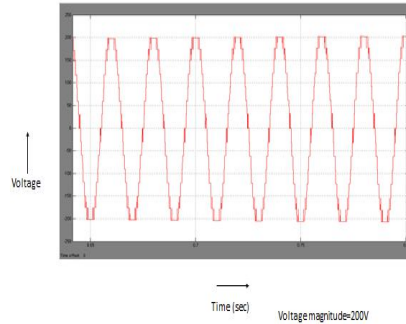


Fig.10. 15 Level SHE-PWM Outputs

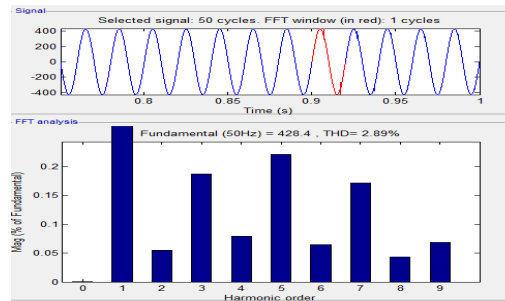


Fig.13. Simulation results of 15 level SHE-PWM technique

Table 2- THD comparison between CB-PWM and SHE-PWM

Harmonic Order	Magnitude percentage of frequency	THD value of CB PWM	Magnitude percentage of frequency	THD value of SHE PWM
1	4.5	19.60%	0.25	2.89%
3	1.25		0.17	
5	1.75		0.2	
7	2.25		0.15	
9	1.25		0.1	

Table.3- Overall THD output

	CB PWM	SHE PWM
THD %	19.60%	2.89%

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IX. CONCLUSION

In this project the comparative analysis of the CB PWM and SHE-PWM scheme for the control of multilevel inverter is performed. The CB PWM method used in multilevel inverters is more harmonics compared to SHE-PWM method. In this paper, the THD analysis and FFT analysis of fifteen-level inverter is done based on CB PWM and SHE-PWM strategy in order to control the output voltage of the considered inverter. Variable dc-voltage sources were obtained through a simple dc to dc converter, where the improvement and the rapid development in power semiconductors devices and advanced materials promised high effectiveness dc to dc conversion systems. Although only buck converter was considered in this project, however, other topologies can be equally applied and this will be investigated in future works for potential maximization of the system efficiency and performance.

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