A Power Electronic Transformer (PET) fed Nine-level H-Bridge Inverter for Large Induction Motor Drives

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***Abstract*- This paper is devoted to the investigation of a 500 HP induction machine drive based on a nine-level 4.16 kV H-bridge inverter. Previous work in the area of controlling H-Bridge inverters at such power levels report enhancement in the performance of a conventional staircase modulation technique by employing optimization of switching angles to minimize voltage distortion. However, the dc link voltages of each level are typically held constant. Such a control scheme enables elimination of a maximum of three dominant harmonics (5^{th}, 7^{th} & 11^{th}) to synthesize a given fundamental voltage with a nine-level waveform. Moreover, at lower modulation depths, the nine-level operation degenerates into seven or even fewer levels. This restricts the number of harmonics that can be eliminated to two (5^{th} & 7^{th}) or less. An alternative strategy to produce a required fundamental voltage with a nine-level waveform by controlling the dc bus voltages is presented in this paper. This control scheme enables elimination of four dominant harmonics (5^{th}, 7^{th}, 11^{th} & 13^{th}) over the entire range of operation. The required dc link voltage control is achieved by employing active power electronic transformers for isolation, thereby supplying varying ac voltage to the front-end rectifiers. Operating principles, spectral structure and design consideration are discussed. Computer simulations backed up by experimental results are presented in the paper.**

I. Introduction

Multilevel power conversion has been receiving increasing attention in the past few years for high power applications [1]. Numerous topologies have been introduced and studied extensively for utility and drive applications in the recent literature. These converters are suitable in high voltage and high power applications due to their ability to synthesize waveforms with better harmonic spectrum and attain higher voltages with a limited maximum device rating.

Of particular interest is the topology, which employs series connection of single-phase inverters, popularly known as the H-bridge multilevel inverter [2]. In this approach, a number of full bridge single-phase inverters with dedicated dc bus capacitors are connected together in series to form a high voltage inverter for each phase of the system. This approach, being modular, offers simpler implementation when compared to other classes of multilevel inverters and has been successfully employed in high power drives [3]-[5]. For the 4.16 kV / 500 HP induction machine drive system under investigation, it is proposed to use a nine-level inverter as shown in Figure 1.

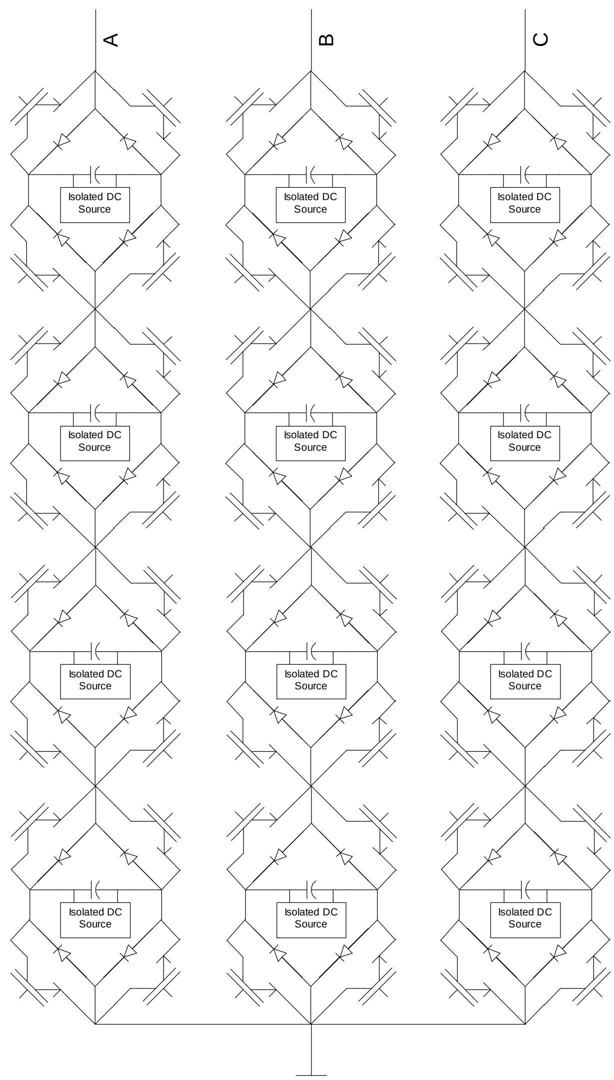


Figure 1. Simplified schematic of a nine-level inverter.

As shown in Figure 1, the nine-level inverter under consideration is composed of four full-bridge single-phase inverters in series. Each small inverter cell is supplied from a dedicated dc bus derived from an isolated source. In a commercial industrial drive [6], the output voltage of the multilevel inverter is controlled by Pulse Width Modulation (PWM) techniques, wherein each cell synthesizes a quarter of the required total fundamental voltage. Such a scheme ensures that all the devices in the entire multilevel inverter are stressed equally and uniformly under all operating conditions. However, these PWM techniques often employ high switching frequencies, typically in the order of few kHz. By this reason it is difficult to adopt such strategies for large capacity drives (> 500 HP), where the switching frequency of the semiconductor devices is limited to few hundred Hz. Multilevel inverter drives rated for such power levels are normally controlled by extensions of six-step waveforms, popularly termed as staircase modulation [7].

Previous work in this area reports enhancement in the performance of a conventional staircase modulation technique by employing optimization of switching angles to minimize voltage distortion [7]. However, the dc link voltages of each level are typically held constant. As will be described shortly, such a control scheme enables elimination of a maximum of three dominant harmonics (5^{th}, 7^{th} & 11^{th}) to synthesize a given fundamental voltage with a nine-level waveform. Moreover, at lower modulation depths, the nine-level operation degenerates into seven or even fewer levels. This restricts the number of harmonics that can be eliminated to two (5^{th} & 7^{th}) or less. An alternative strategy to produce a required fundamental voltage with a nine-level waveform by controlling the dc bus voltages is presented in this paper. This control scheme enables elimination of four dominant harmonics (5^{th}, 7^{th}, 11^{th} & 13^{th}) over the entire range of operation. The required dc link voltage control is achieved by employing active Power Electronic Transformers (PET) for isolation, thereby supplying varying ac voltage to the front-end rectifiers. In addition to improving the spectral quality of the output voltage, this approach also serves to reduce the size of isolation transformer which is an indispensable component in H-bridge multilevel power conversion systems. This is due to the fact that the PET employs ac-ac switched mode power converter to realize a chopped ac link, thereby decreasing the required magnetic core size for voltage transformation and isolation.

The following section presents a brief mathematical analysis of nine-level waveform synthesis. A comparative evaluation of the options to realize a nine-level waveform for the application under consideration and the concept of a PET fed multilevel inverter is presented in Section III. Experimental results establishing the efficacy of this approach are given in Section IV. The paper concludes with a short summary describing merits and demerits of the proposed approach.

II. Analysis Of Nine-level Waveform Synthesis

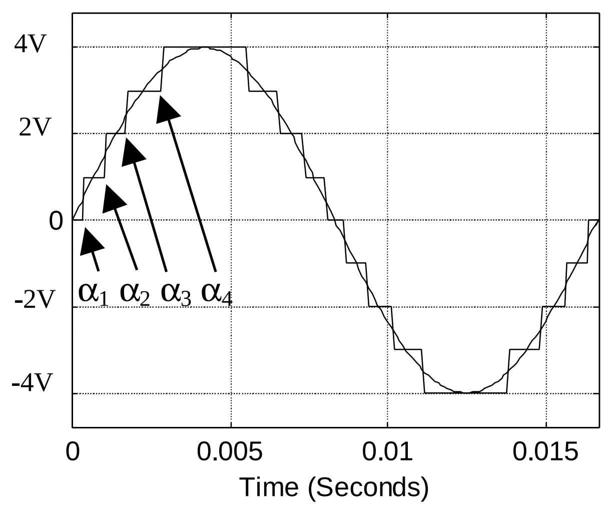


Figure 2. Baseline staircase waveform synthesized by the nine-level inverter.

One can synthesize a simple nine-level staircase waveform with the candidate H-bridge inverter topology as shown in Figure 2. Previous work in the area of devising control methodologies for such inverters stipulates optimization of switching angles of the individual inverters (α_i) for a given modulation depth M, so as to minimize a set of dominant harmonics in the output [8]. To obtain an optimization cost function, the Fourier coefficients of the output voltage can be derived as follows

$$H(n) = V\frac{4}{\pi}\frac{1}{n}[\cos(n\alpha_1)+\cos(n\alpha_2)+\cos(n\alpha_3)+\cos(n\alpha_4)] \quad (1)$$

where n is the harmonic number.

It may be verified that if all the switching angles are set to zero, the output falls back to a conventional two-level waveform and the fundamental voltage in this case is

$$H_{max}(1) = 4V\frac{4}{\pi} \quad (2)$$

Since conventional modulation strategies employ a fixed dc link voltage, one has four degrees of freedom (four α_i's). This means that one can control four independent parameters simultaneously. It can be calculated that the maximum attainable fundamental voltage with elimination of first four harmonics viz. 5^{th}, 7^{th}, 11^{th} and 13^{th}, is 92% of $H_{max}(1)$. For lower values of fundamental voltage, it is required to solve equations (3)-(6) for switching angles to eliminate the 5^{th}, 7^{th} and 11^{th} harmonics. It may be noted that 5^{th}, 7^{th} and 11^{th} are the most dominant harmonics since the even harmonics are cancelled because of the half wave symmetry and triplen harmonics are rejected in a three-phase three-wire system.

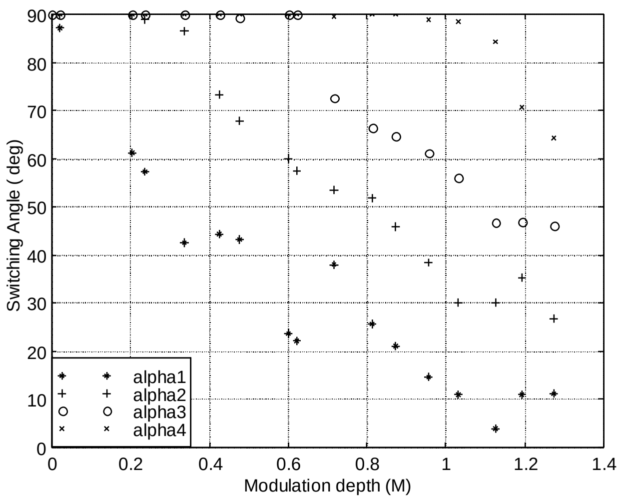


Figure 3. Switching angles as a function of modulation depth with the conventional optimization of a nine-level waveform.

$$H(1) = 4V * M \quad (3)$$

$$H(5) = 0 \quad (4)$$

$$H(7) = 0 \quad (5)$$

$$H(11) = 0 \quad (6)$$

A plot of the switching angles versus modulation depth to eliminate 5^{th}, 7^{th} and 11^{th} harmonics is presented in Figure 3. It may be observed that as the modulation depth approaches $4/\pi$, the switching angles approach zero which results in a conventional six-step inverter waveform. So also, as one decreases the modulation depth, the switching angles approach 90^{o} one by one, which means, the phase leg voltage converts from nine-level to seven-level to five-level and eventually to three-level mode. This also implies that one can only eliminate 5^{th} and 7^{th} harmonics in seven-level region, only 5^{th} harmonic in five-level mode and none when a three-level waveform is synthesized. Representative phase leg voltage waveforms for modulation depths M = 1 and M = 0.5 are shown in Figures 4(a) and 5(a). Figures 4(b) and 5(b) verify the fact that 5^{th}, 7^{th} and 11^{th} harmonics are eliminated in the former case where a nine-level waveform is synthesized while only 5^{th} harmonic is eliminated in the latter case since it is just a five-level waveform.

This paper investigates the possibilities of maintaining nine-level waveform under all conditions, thereby eliminating a complete set of all four harmonics at all operating points. This is made possible by regulating the dc bus voltages, thereby adding an additional degree of freedom in control parameters. Revisiting equation (1), since one has five degrees of freedom (four α_i's and V), one can control five independent parameters simultaneously. Thus, it is possible to eliminate four harmonics (5^{th}, 7^{th}, 11^{th} & 13^{th}) to synthesize a given fundamental voltage by solving equations (7)-(11).

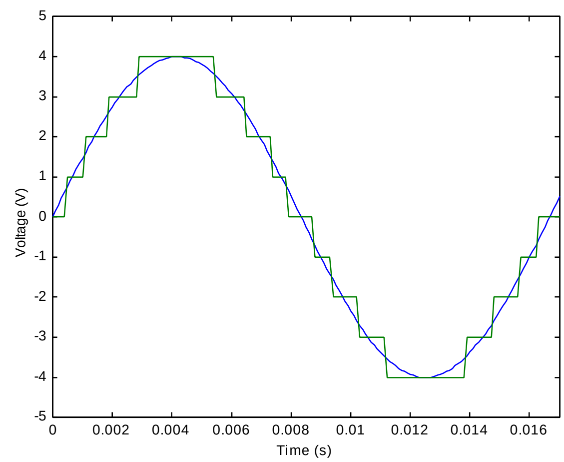
$$H(1) = 4V * M \quad (7)$$

$$H(5) = 0 \quad (8)$$

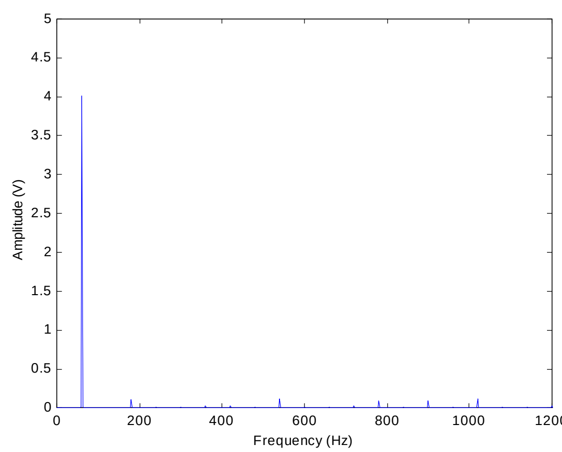
$$H(7) = 0 \quad (9)$$

$$H(11) = 0 \quad (10)$$

$$H(13) = 0 \quad (11)$$

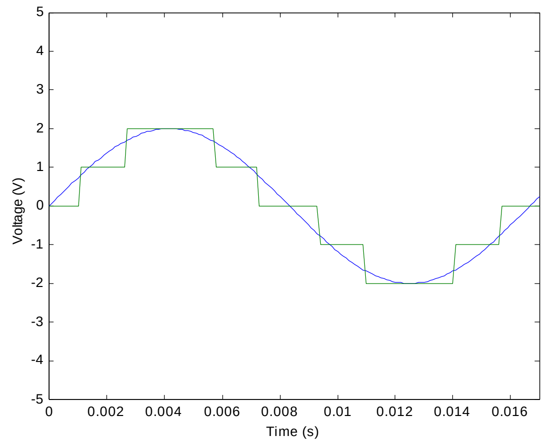


(a) Phase leg voltage waveform.

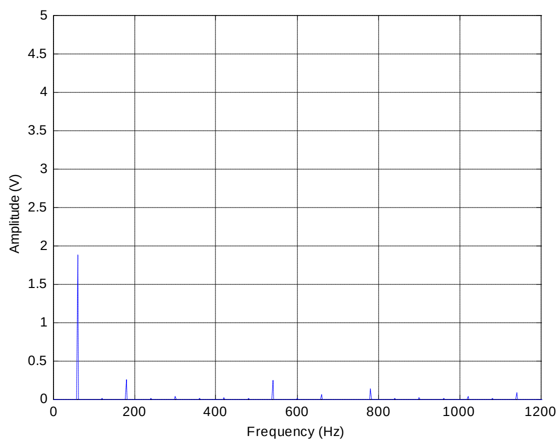


(b) Phase leg voltage spectrum.

Figure 4. *Phase leg voltage obtained with the conventional nine-level inverter (employing fixed dc link voltages) for M = 1.*



(a) Phase leg voltage waveform.



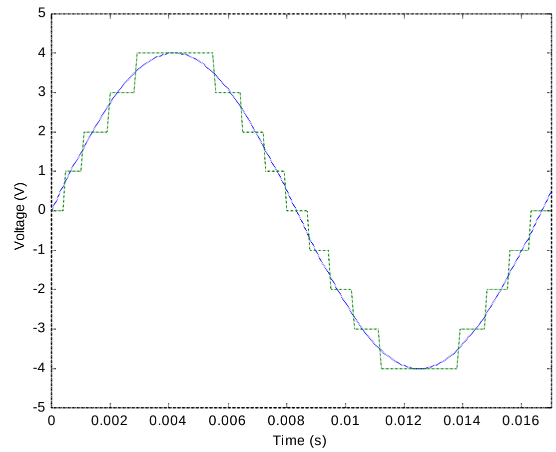
(b) Phase leg voltage spectrum.

Figure 5. *Phase leg voltage obtained with the conventional nine-level inverter (employing fixed dc link voltages) for M = 0.5.*

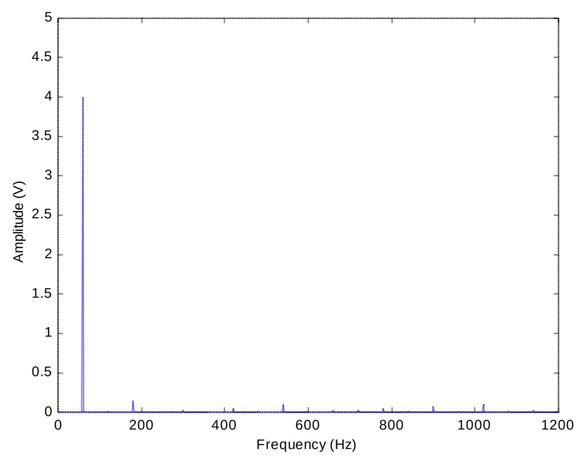
The values of switching angles to eliminate four harmonics are given in Table 1. These values are fixed and used for all operating points. The required fundamental voltage is obtained by varying the dc link voltage. Representative phase leg voltage waveforms for modulation depths M = 1 and M = 0.5 are shown in Figures 6(a) and 7(a). As may be verified from Figures 6(b) and 7(b), all, 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonics are eliminated in both cases since both are nine-level waveforms (commanded fundamental voltage is synthesized by suitably adjusting the dc link voltage). On comparison of Figures 6(a) and 7(a) with Figures 4(a) and 5(a), one may expect substantial decrement in the voltage distortion in the entire operating region by virtue of maintaining nine-level profile according to the proposed approach.

Table 1: Switching angles to optimize a nine-level waveform at M = 1.

Angle	α_1	α_2	α_3	α_4
(degrees)	8.9980	23.6129	41.1689	60.7003



(a) Phase leg voltage waveform.



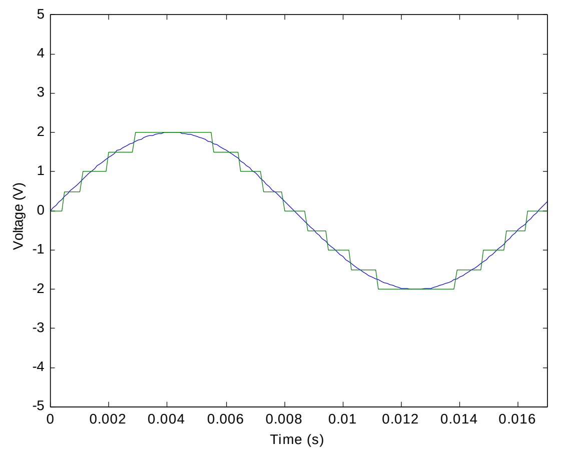
(b) Phase leg voltage spectrum.

Figure 6. Phase leg voltage obtained with the proposed nine-level inverter (employing variable dc link voltages i.e. dc link voltages in latter case are half of that of this case) for M = 1.

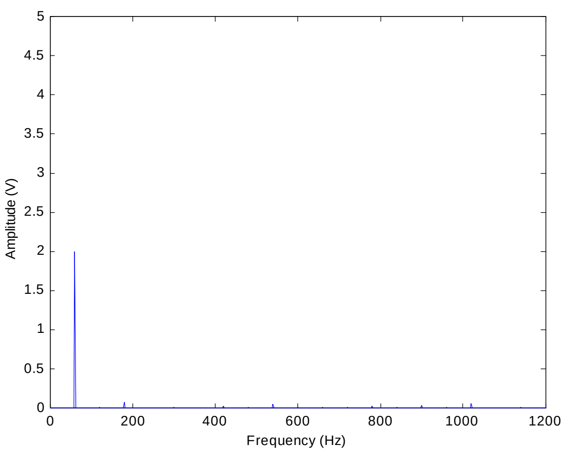
III. PET FED NINE-LEVEL INVERTER

There are several possible ways to achieve the required control of dc link voltages. A popular choice is to employ dc choppers at individual dc links thus gaining independent control of each dc bus voltage [9]. Not only is this approach cumbersome, but also it is not practical to use a dc-dc converter at the voltage and power levels under consideration. An alternative method of gaining control on dc link voltage is to use thyristor controlled rectifiers.

However, the dynamic response of such a system is poor owing to the limited switching capability of thyristors.



(a) Phase leg voltage waveform.



(b) Phase leg voltage spectrum.

Figure 7. Phase leg voltage obtained with the proposed nine-level inverter (employing variable dc link voltages i.e. dc link voltages in this case are half of that of former case) for M = 0.5.

Hence it is proposed to use a Power Electronic Transformer (PET), which can actively control the ac voltage to be fed to the rectifiers at the front end [10]. A PET is built around an isolated ac-ac switched mode power converter. The topology of choice is a flyback converter, which employs minimal number of switches and reactive elements. The voltage transformation ratio is a simple function of duty cycle and one can use a feedback control to actively regulate the output voltage.

It should be noted that, it is equally applicable to employ solid-state transformers based on high frequency link conversion [11], [12]. By virtue of active control of semiconductor switches in the frequency converters, it is possible to have an active control on the voltage to be fed for rectification. However, as compared to PET technology, these schemes involve more than twice as many devices, without a reciprocal reduction in the size of magnetic components or increment in the overall efficiency. A more detailed discussion of various forms of switched mode ac transformers may be found in [10].

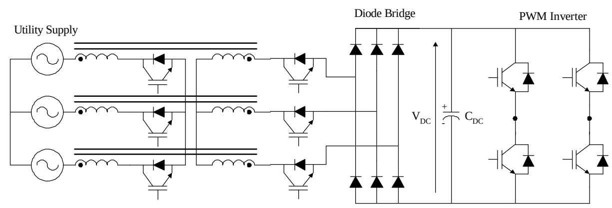


Figure 8. Simplified schematic of a PET with a rectifier and one modular H-bridge inverter.

A simplified schematic of the power circuit for PET fed single-phase inverter is illustrated in Figure 8. The PET is supplied from a three-phase 480V power source. The output voltage of the PET is controlled through the duty ratio, which is enslaved to the dc bus voltage regulation. The input current waveforms can be maintained to be at unity power factor through appropriate control. A simplified schematic of the power circuit of the entire system is shown in Figure 9. As may be seen from this figure, the proposed system consists of four cells as depicted in Figure 8 in each phase. A simplified control schematic is shown in Figure 10. The required fundamental output voltage command is translated into the dc link voltage command in an open loop fashion. The dc link voltage is actively regulated through a feedback control employing duty ratio of the PET as the control parameter.

IV. Experimental Results

A prototype H-Bridge inverter module with a PET-fed rectifier was built to verify the operation of the concept. The PET rectifier was rated at 10 kW, designed to operate from a 230 V ac line. Figure 11 illustrates the waveforms obtained from the experimental prototype converter. The inverter switching angles were chosen in this case to eliminate the triplen harmonics. The control system was built using a TI320C240 based digital signal processing system.

Figure 12 shows the spectrum of the output voltage of the inverter, illustrating the characteristic spectrum containing the 5th, 7th, 11th and 13th harmonics. Realization of the complete unit with multiple converter cells is under way and the results will be reported in the future.

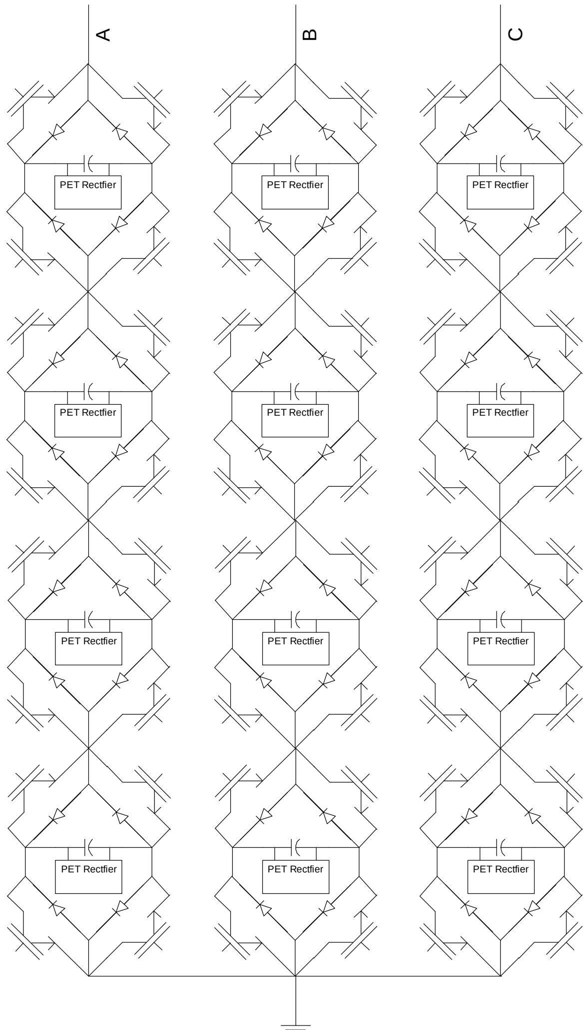


Figure 9. Simplified schematic of a PET fed nine-level inverter.

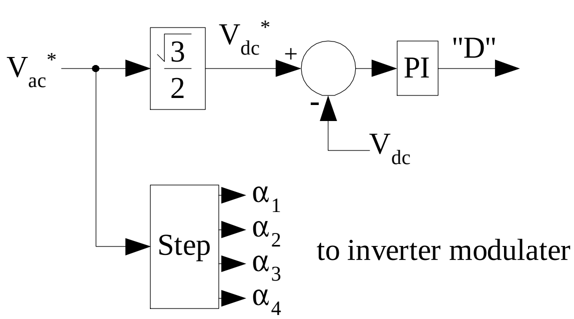


Figure 10. Simplified control schematic for the PET.

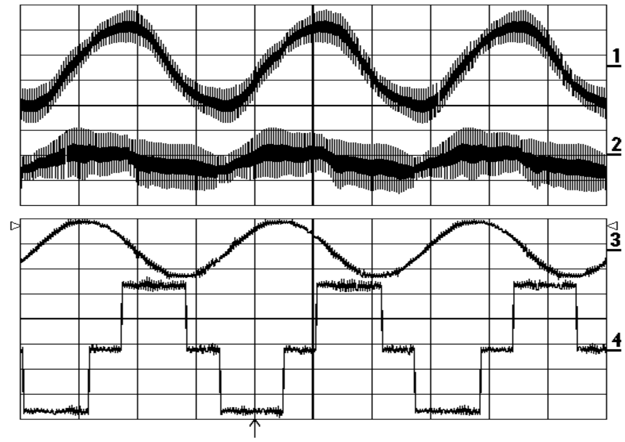


Figure 11: Waveforms of (1) PET current, (2) PET voltage, (3) Rectifier input voltage and (4) Inverter output voltage of a PET-fed H-Bridge inverter.

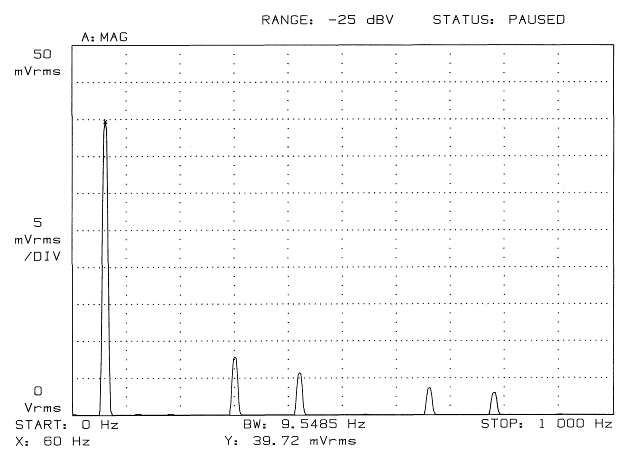


Figure 12: Inverter output voltage spectrum of a PET-fed H-Bridge inverter where the triplen harmonics have been eliminated.

CONCLUSIONS

This paper has presented an approach for realization of multilevel inverters with variable dc link voltages to track the modulation depth of the output waveforms. This allows the realization of spectrally optimized waveforms at the output at all modulation depths, uniformly. This is possible because all the inherent number of levels provided by the converter structure are used for waveform synthesis at all modulation levels.

The use of high frequency switched mode ac-ac converter based power electronic transformer allows reduction of transformer size and provides the isolated dc sources for each distinct level of the multilevel H bridge converter.

The field of switched mode ac-ac power conversion involving no frequency change represents an important field of application of power electronic systems. This paper presents an application of the approach to the area of industrial drives.

ACKNOWLEDGMENT

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