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ANALYSIS OF HARMONIC INJECTION TO THE MODULATION OF MULTI-LEVEL DIODE CLAMPED CONVERTER IN A NORMAL AND OVER MODULATION MODE

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Abstract

This paper explores the analysis of third and ninth harmonic injection to the modulation of a multi-level diode clamped converter (DCC) at a varying modulation index. The spectral distributions of the various multi-level waveforms obtained under normal modulation index of 0.8 and over modulation index of 1.15 were presented in this work. The contribution of this paper is rooted in the introduction of ninth harmonic component to higher-levels of diode clamped converters with reference to the existing third order harmonic injected modulation with detailed Simulink models of 3rd, 5th and 9th voltage levels. The analysis and results obtained from this work shows appreciable reduction in the magnitudes of harmonic distortion values thus ensuring optimum and efficient devices performance.

Keywords: harmonic injected modulation, spectral analysis, pulse width modulation, diode clamped converter, modulation

1. Introduction

The concepts of multi- carrier pulse-width modulation (PWM) techniques have significantly gained a wide spread application in most industrial drive applications and power lines compensator devices (FACTS-DEVICES) as well as utility interfaced power appliances. Undoubtedly, most PWM techniques such as the sinusoidal PWM technique, staircase PWM technique and sub-harmonic PWM are prone to harmonics thus causing undue voltage distortion of the output voltage which in turn generates heat loss in most industrial drive appliances [1].

In order to achieve a better and efficient D.C bus voltage utilization at high modulation indices with reduced harmonic and reduced heat losses, the modulating or the reference signal is injected with a third or a ninth harmonic component with a magnitude of the fundamental component being approximately 15% more than the normal sinusoidal PWM [2].

2. Principles of Harmonic Injected Modulation Technique

Harmonic Injected modulation technique implies the process which involves the injection of a specified harmonic (third or ninth harmonic) into a modulating signal (sine or cosine wave) and the result obtained is sampled or is compared with multi-carrier signals usually triangular waves to produce output pulses with variable widths [3].

Conventionally, an n-level converter always has n-level output phase voltage, 2n-1 output line voltage and n-1 triangular carrier signals with the same frequency Fc and the same peak-peak amplitude Ac which are usually placed in a way that their frequency bands are close. The reference or the modulating waveform (sinusoidal wave) has peak-peak amplitude Am and a frequency of Fm which is centered in the middle of the carrier wave. This reference wave is continuously compared with each of the triangular carrier signals until the following conditions are achieved. If the modulating waveform (reference sinusoidal waveform) is greater than the carrier signal, then the active switching device corresponding to that carrier is

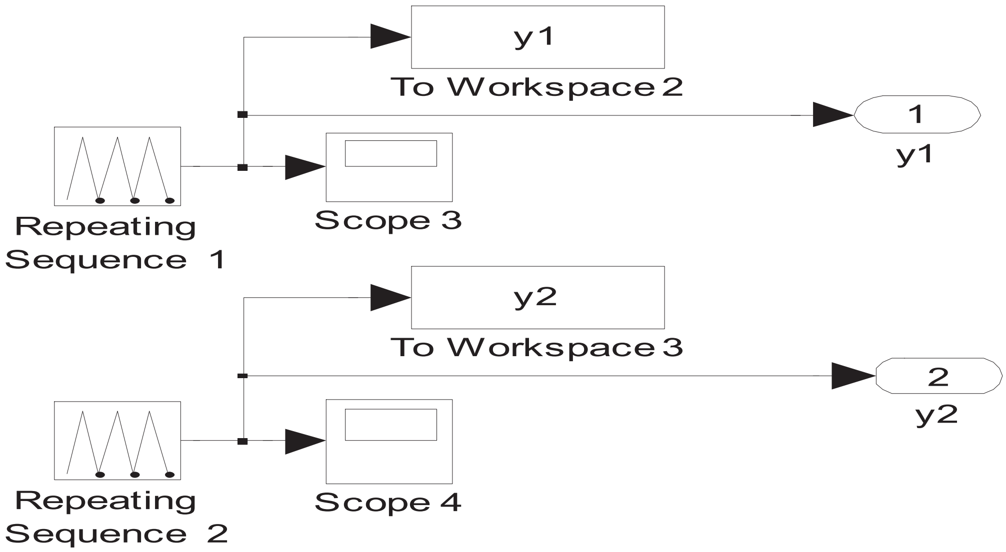

Figure 1: Simulink block model of 3-level Triangular carrier signals.

switched on. Conversely, if the reference waveform is less than the carrier signal, then the active switching device corresponding to that carrier signal is turned off [3]. The multi-carriers Simulink models for the n-level inverter are shown in figures 1 to 3.

3. Simulink Modeling of Multi-Level DCC With 3rd And 9th Harmonic Injected Modulation

The injected 3rd order harmonic has the following equations for the modeling: The three phase reference voltage equation and the injected 3rd harmonic modulating equation given in (1) to (6) [4].

$$V_a = mi \times \cos \omega t \quad (1)$$

$$V_{a3} = \frac{-mi}{6} \times \cos 3\omega t \quad (2)$$

$$V_b = mi \times \cos\left(\omega t - \frac{2\pi}{3}\right) \quad (3)$$

$$V_{b3} = \frac{-mi}{6} \times \cos 3\omega t \quad (4)$$

$$V_c = mi \times \cos\left(\omega t - \frac{4\pi}{3}\right) \quad (5)$$

$$V_{c3} = \frac{-mi}{6} \times \cos 3\omega t \quad (6)$$

Similarly, the equations used for modeling the 9th order harmonic are given in (7) to (12):

$$V_a = mi \times \cos \omega t \quad (7)$$

$$V_{a9} = \frac{-mi}{36} \times \cos 9\omega t \quad (8)$$

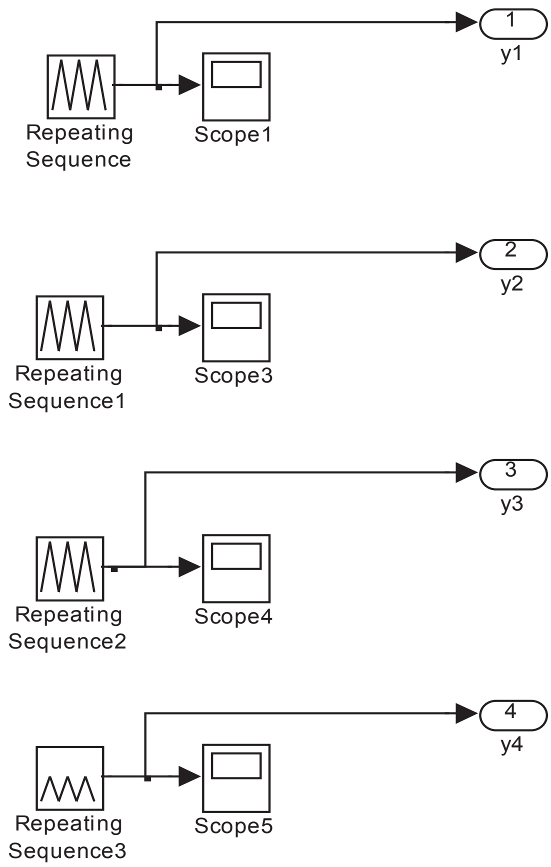

Figure 2: Simulink block model of 5-level Triangular carrier Signal.

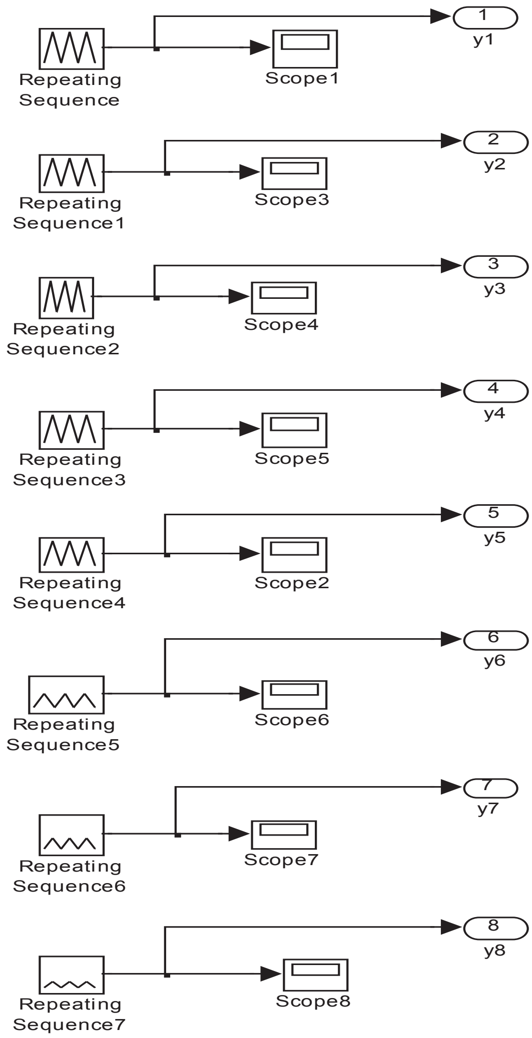

Figure 3: Simulink block model of 9-level Triangular carrier signals.

$$V_b = mi \times \cos\left(\omega t - \frac{2\pi}{3}\right) \quad (9)$$

$$V_{b9} = \frac{-mi}{36} \times \cos 9\omega t \quad (10)$$

$$V_c = mi \times \cos\left(\omega t - \frac{4\pi}{3}\right) \quad (11)$$

$$V_{c9} = \frac{-mi}{36} \times \cos 9\omega t \quad (12)$$

Where mi stands for the modulation index. The Simulink block diagram for the 3rd and 9th harmonic modulation are presented in Figs: 4-5 respectively while the actual 3, 5 and 9-level inverter Simulink models are shown in Figs: 6-8.

The waveforms representing the direct sampling of the multi-carrier signals with the injected harmonics are presented in Fig 9-11 for the above discussed multi-level DCC.

4. Simulation Results for the 3rd and 9th Harmonic Injected Modulation of Multi Level DCC at Modulation Index of 0.8 and 1.15

The results obtained from the simulation of 3, 5 and 9-level DCC with 3rd and 9th harmonic injected modulation at a varying modulation index of 0.8 and 1.15 are shown in Figs. 13 -24 with inverter load of $R = 45\Omega$ and $L = 30$mH.

Reference [5] did a similar work as the one proposed herein, but it dwells more on 3rd and 9th harmonic injections using two level voltage models with modified sine wave as its voltage source under modulation index less than unity only. Also, the analysis of quality factor as a function of modulation index was carried out in the referred article. Similarly, [6] presented a generalized concept of nth harmonic injection for five-phase inverter using space vector pulse width modulation (SVPWM) and harmonic injection components in the order of 3rd, 5th and 7th harmonic order. The spectral display shown in the referred article was in the order of 20Hz up to 200Hz. But in this proposed paper, an attempt has been made to go further by presenting the simulation models of 3rd, 5th and 9th voltage levels under modulation index less than unity and over modulation mode using modified cosine wave as our voltage source. Consequently, this proposed paper was limited to three-phase inverter while the THD and spectral results of those voltage levels were presented under modulation index of 0.8 showing the line voltages, phase voltages and phase currents under the fundamental frequency of 50 Hz up to 250 Hz.

5. The Spectral Distribution for the Normal Modulation

The spectral distribution for the normal modulation was realized with the aid of the discrete total harmonic distortion block obtained from the discrete measurement block in the SimPower extra under the Simulink sub-library. The values of total harmonic distortion for the 3, 5 and 9-level DCC are shown in table 1.0. This total harmonic distortion is mathematically calculated by the following relation [7]:

$$THD = \frac{\sqrt{\sum_{n=3,5,7}^{\infty} V_n^2}}{V_0} \quad (13)$$

Where THD = total harmonic distortion, V_n = the root mean square value of the n^{th} harmonic component. V_0 = root mean square of the fundamental component which can either be current or voltage.

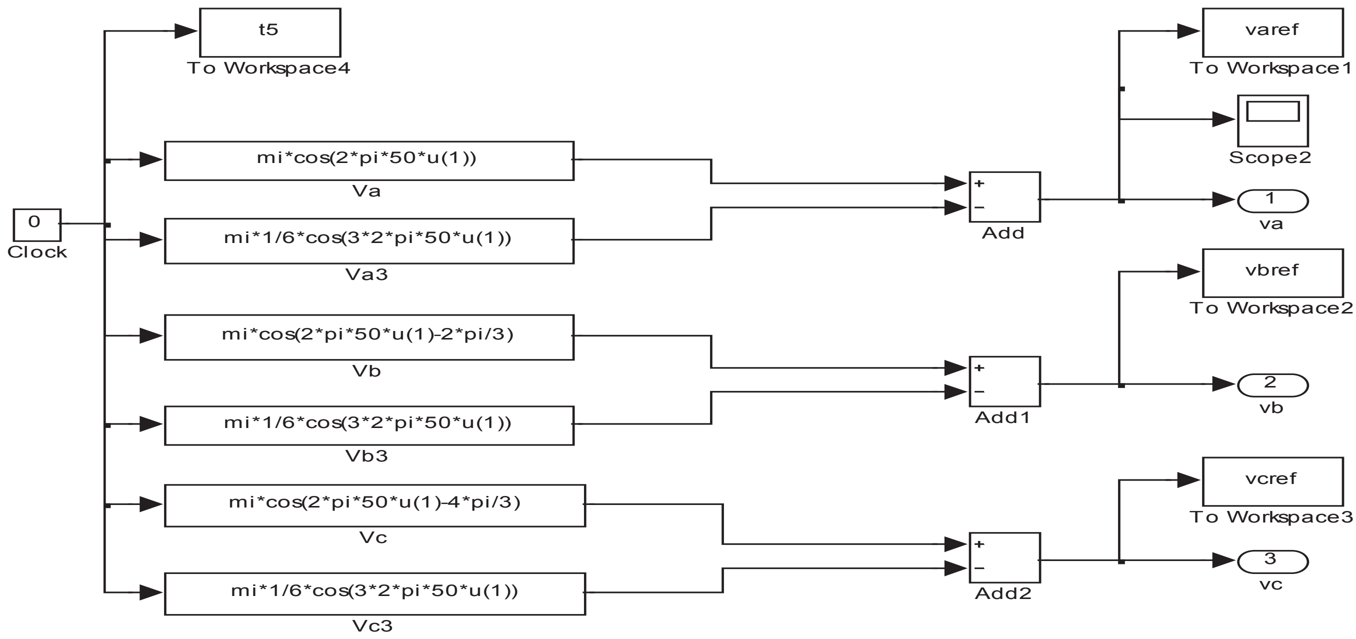

Figure 4: Simulink block diagram of 3rd harmonic injected reference voltage.

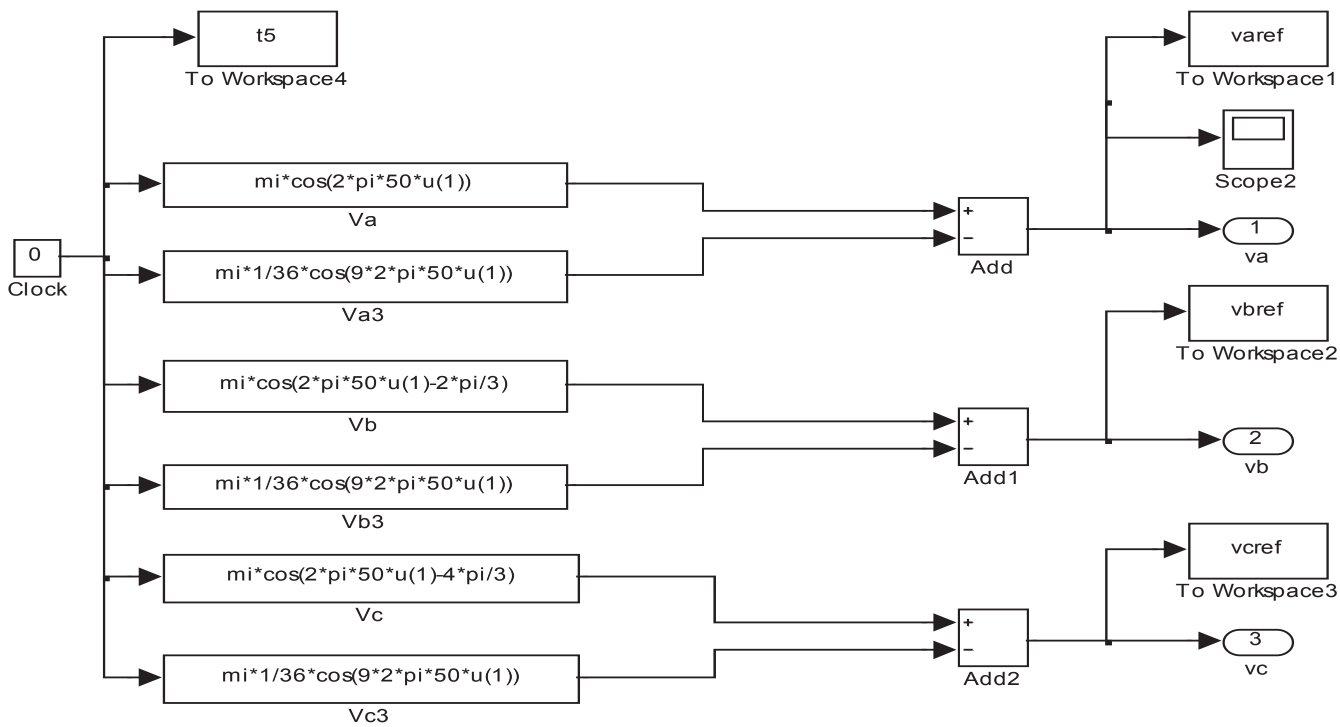

Figure 5: Simulink block diagram of 9th harmonic injected reference voltage.

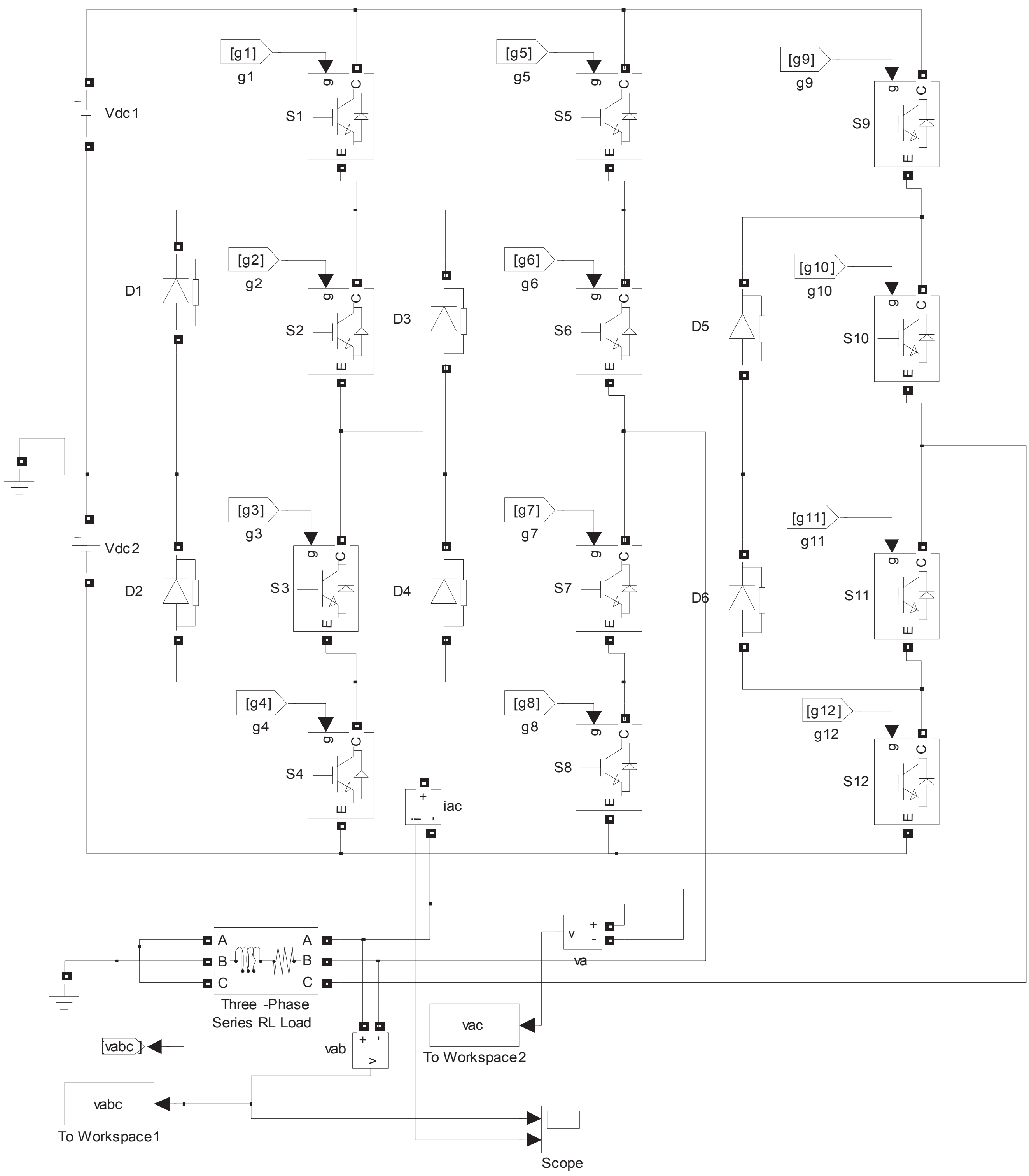

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Figure 6: Circuit diagram of three-level voltage source inverter.

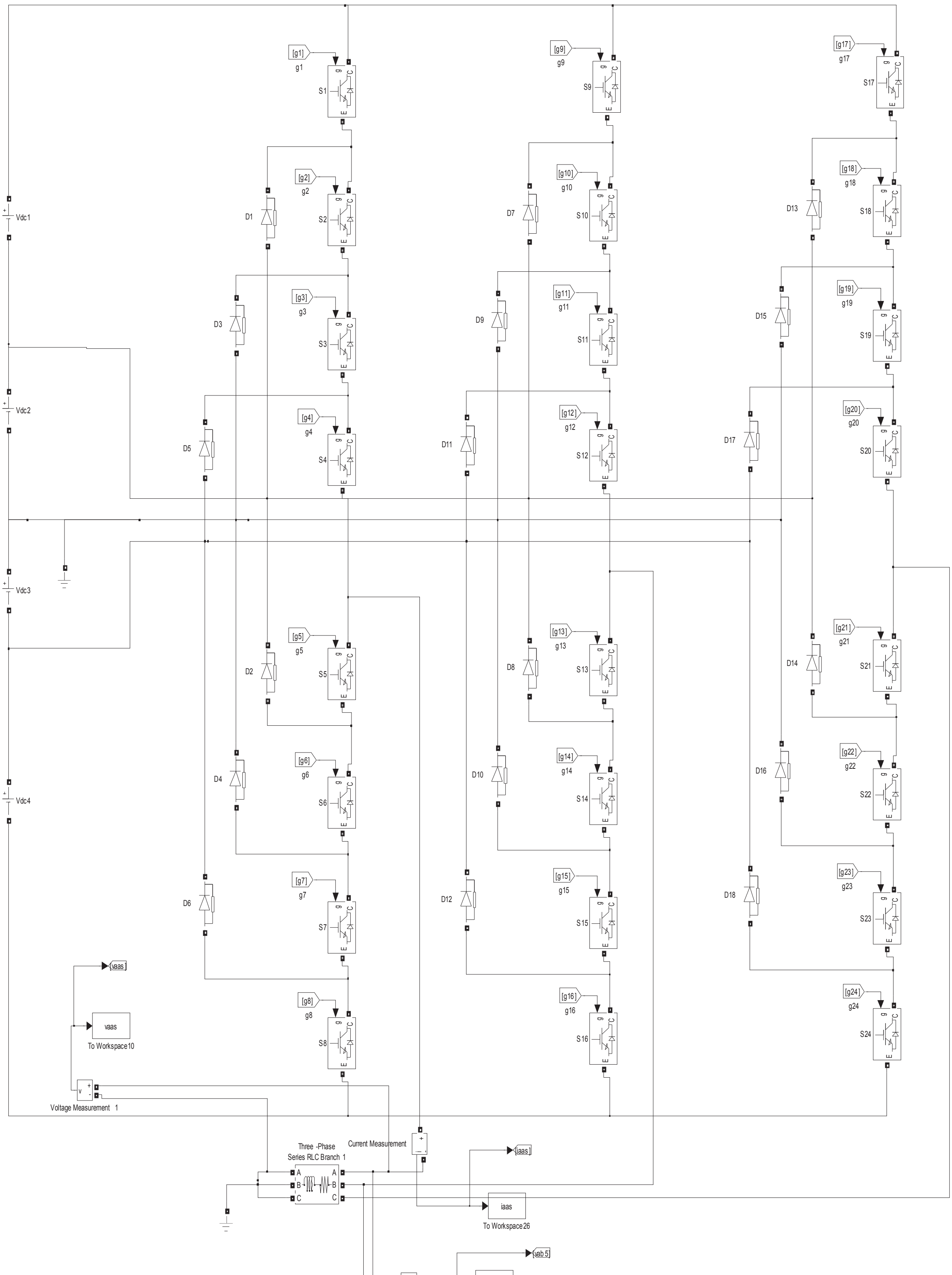

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Figure 7: Circuit diagram of five-level voltage source inverter.

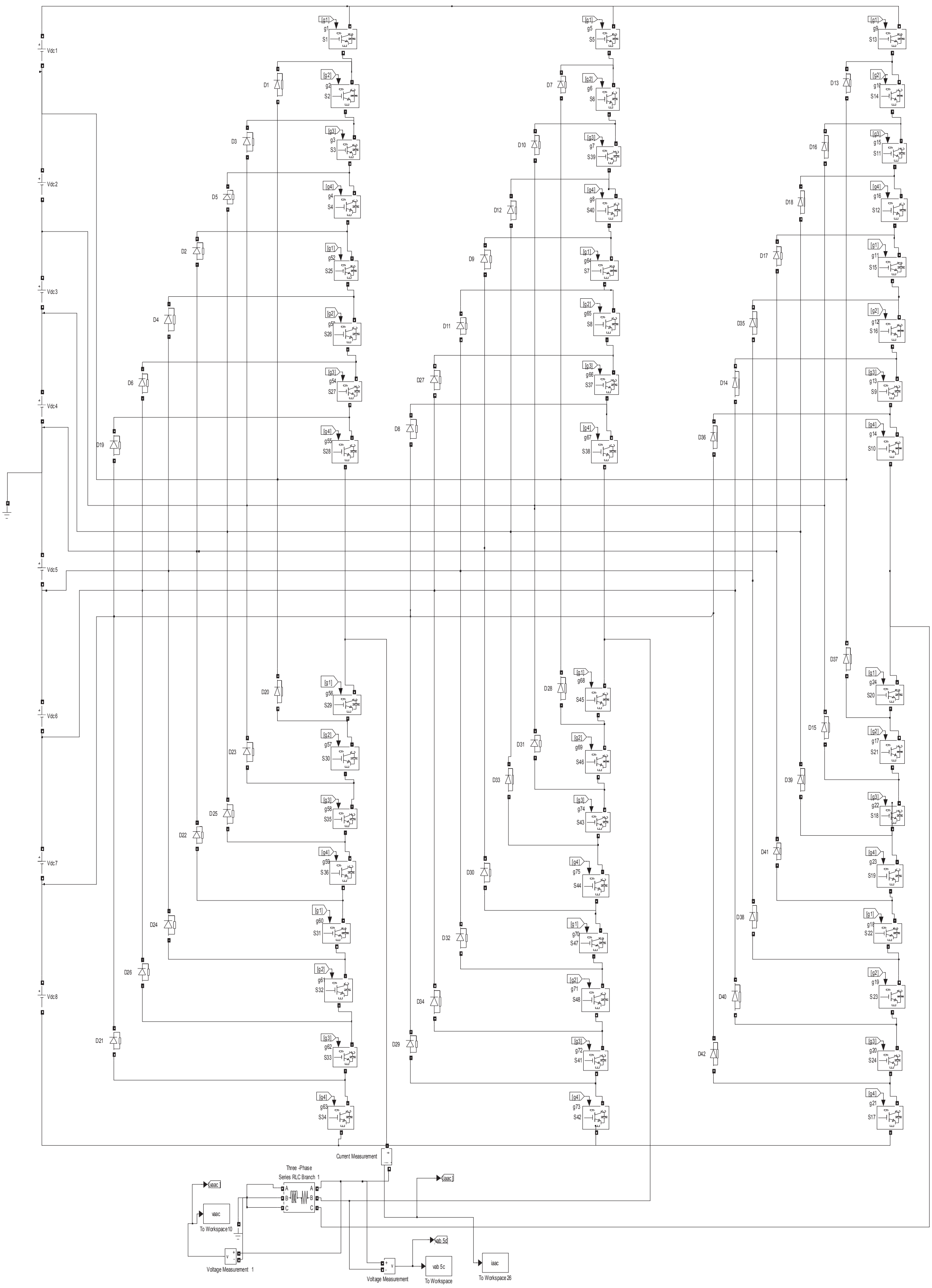

Figure 8: Circuit diagram of nine-level voltage source inverter.

Table 1: Regression, Anova and correlation analysis.

THD for 3 level DCC with 3rd Harmonic injection at 0.8 modulation index	**THD for 5 level DCC with 3rd Harmonic injected modulation at 0.8 modulation index**	**THD for 9 level DCC with 3rd Harmonic injected modulation at 0.8 modulation index**
Phase current = 21%	Phase current = 16.56%	Phase current = 12.56%
Phase voltage = 56.82%	Phase voltage = 34.68%	Phase voltage = 22.85%
Line voltage = 34.68%	Line voltage = 17.90%	Line voltage = 10.91%
THD for 3 level DCC with 9th Harmonic injected modulation at 0.8 modulation index	**THD for 5 level DCC with 9th Harmonic injected modulation at 0.8 modulation index**	**THD for 9 level with 9th Harmonic injected modulation at 0.8 modulation index**
Phase current = 18.97%	Phase current = 15.96%	Phase current = 11.03%
Phase voltage = 49.84%	Phase voltage = 29.84%	Phase voltage = 18.49%
Line voltage = 31.71%	Line voltage = 14.68%	Line voltage = 7.86%

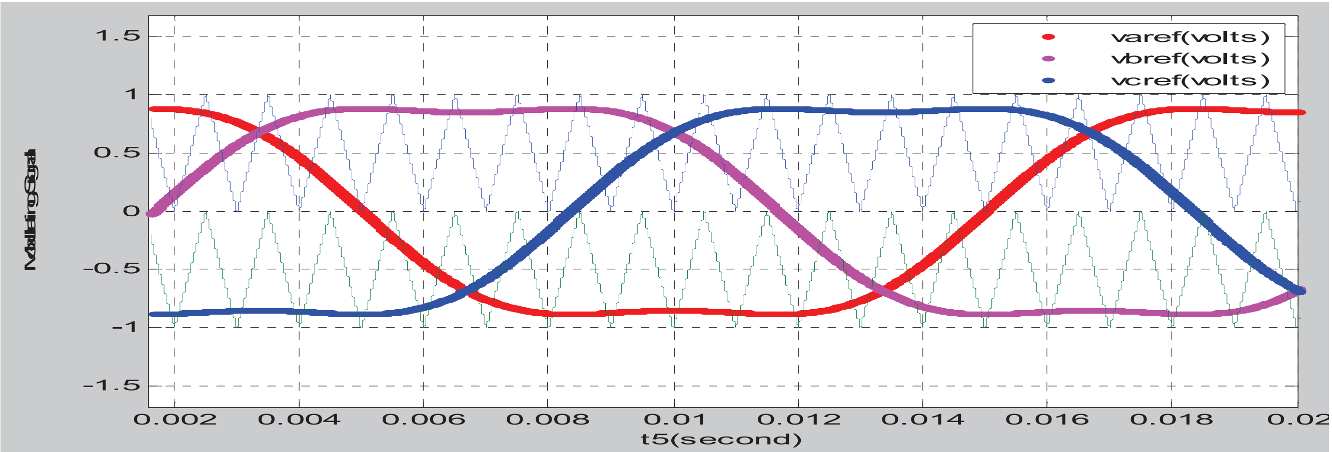

Figure 9: 3-level DCC multi-carrier with modulating signal wave-forms.

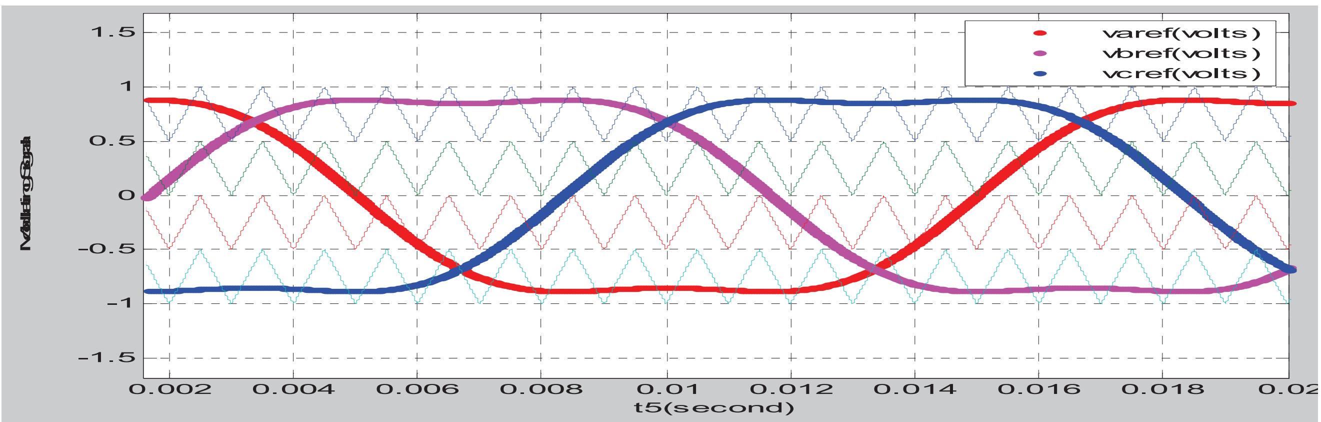

Figure 10: 5-level DCC Multi-carrier with modulating signal wave-forms.

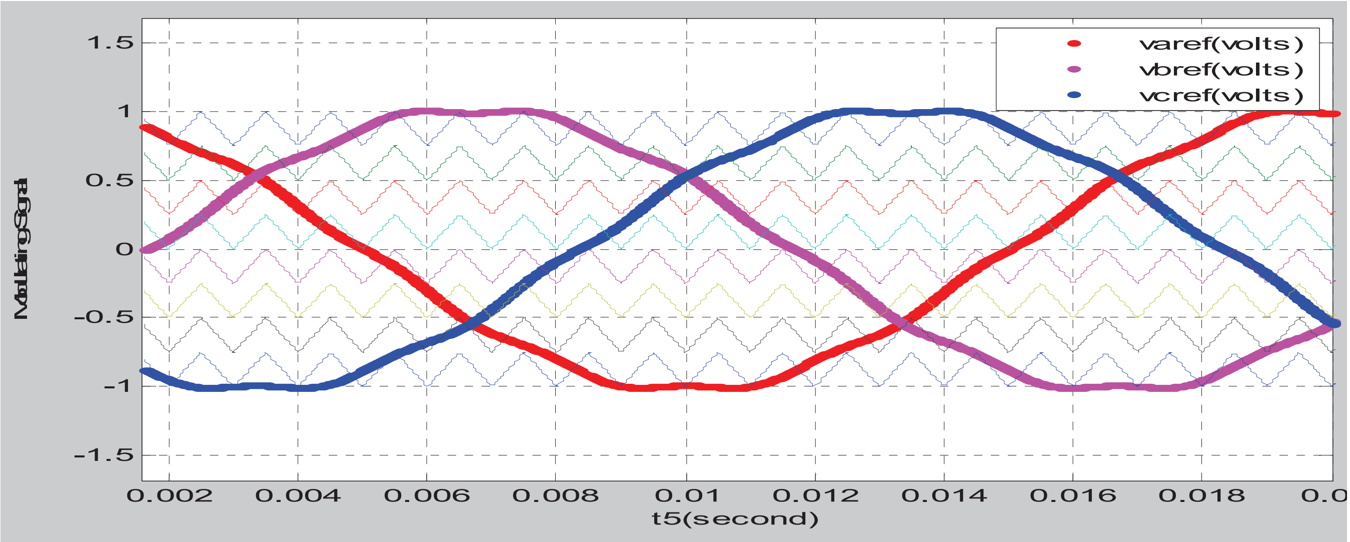

Figure 11: 9-level DCC Multi-carrier with modulating signal waveforms.

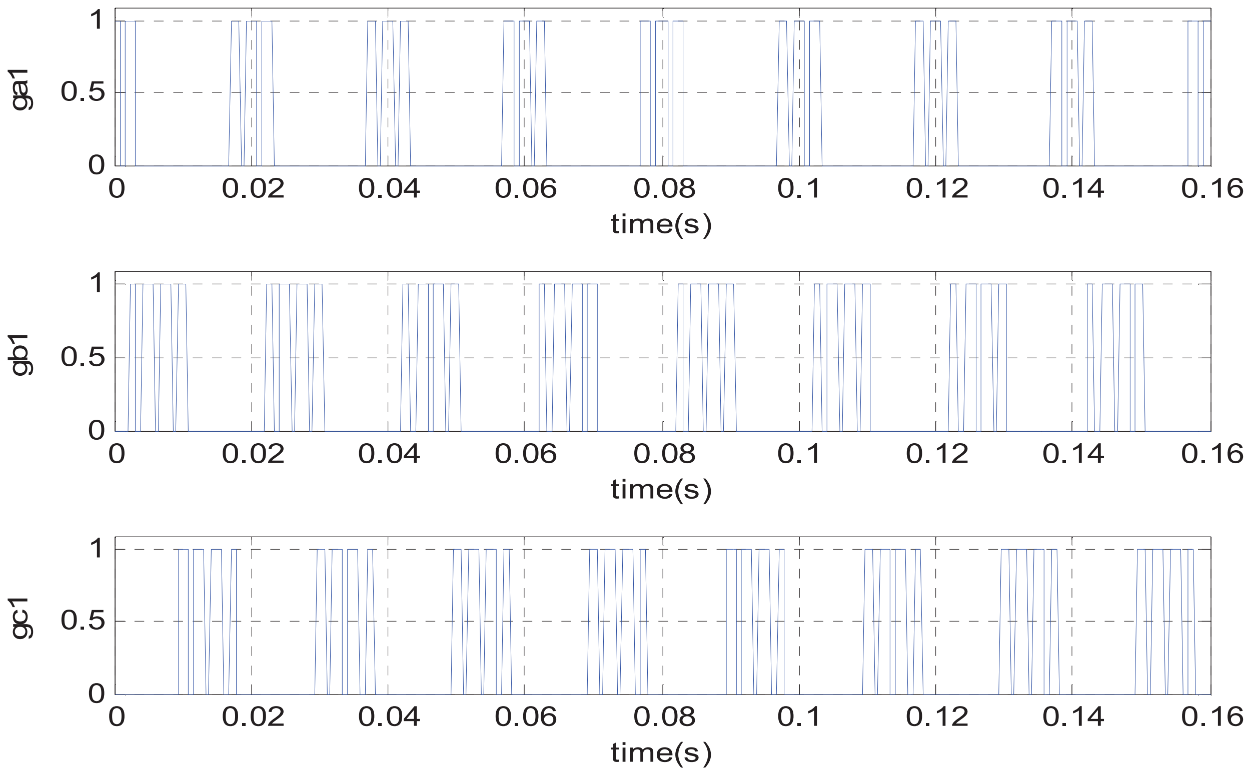

Figure 12: DCC three phase gating signals.

6. Conclusion

Over modulation of a multi-level DCC causes a reduction in the number of pulses produced in the line-line output voltage waveform, leading to the emergence of low order harmonics such as the 5th and 11th harmonic which sometimes are difficult to filter out. It is observed from the simulation result that when a multi-level DCC is operated at a modulation index $mi \geq 1.0$, it loses its multi-level characteristics as manifested in figures 14, 16, 18, 20, 24 and 26 where the peak and frequency of the generated inverter output voltages decrease as opposed to the normal modulation shown in figures 13, 15, 17, 19, 21 and 23. From the foregoing analysis it is obvious that by adding offsets (3rd and 9th harmonics) to the modulating signal, the amplitude of the common mode voltage does not change. The only difference is that the inverter common mode voltage V_{zo} (resultant reference voltage) is less sharp at the peak thus forming a flattened top. This may be advantageous in the area of common mode voltage stress on induction motor winding insulation since a less partial discharge is experienced when supplied by this method.

Table 1 shows that as the inverter level increases the values of THD decreases. It is also shown from the same table that the values of THD decreases comparatively with the 9^{th} harmonic injected modulation than with the 3^{rd} harmonic injection and this formed the basis of this paper. Hence, it is recommended that 9^{th} harmonic injected modulation be used in the designs rather than popular 3^{rd} harmonic injected modulation.

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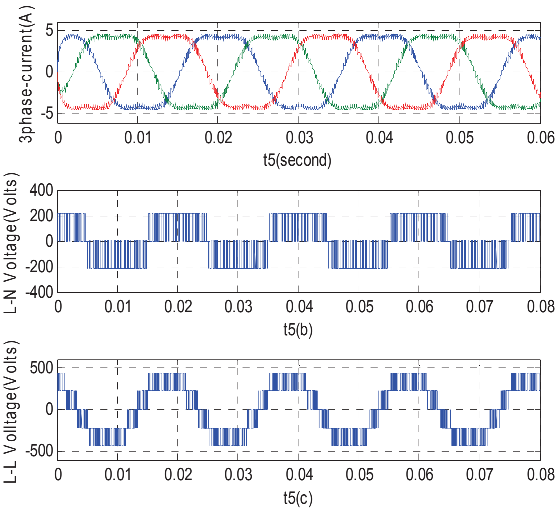

Figure 13: 3 level DCC waveform with 3rd harmonic injection at 0.8 modulation index.

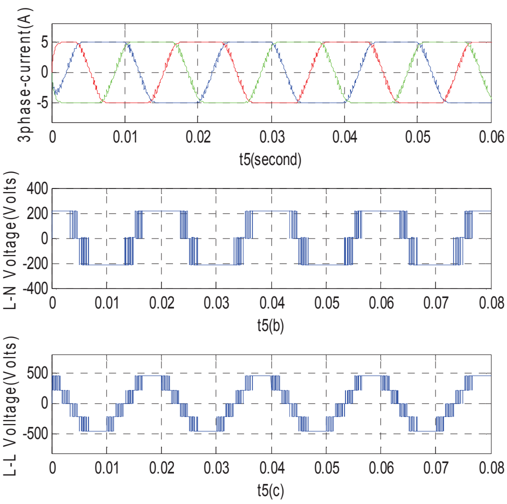

Figure 14: 3 level DCC waveform with 3rd harmonic injection at 1.15 modulation index.

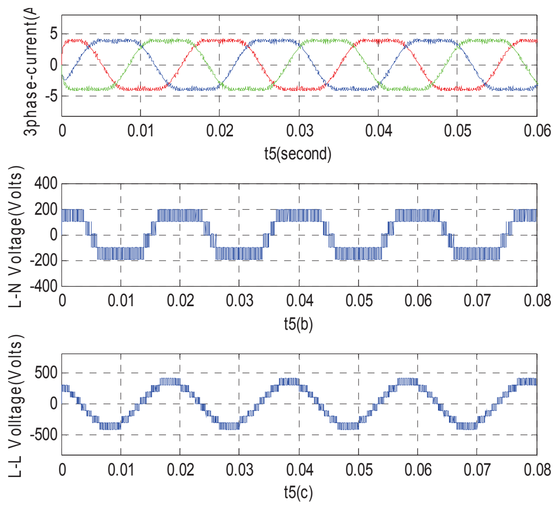

Figure 15: 5 level DCC waveform with 3rd harmonic injection at 0.8 modulation index.

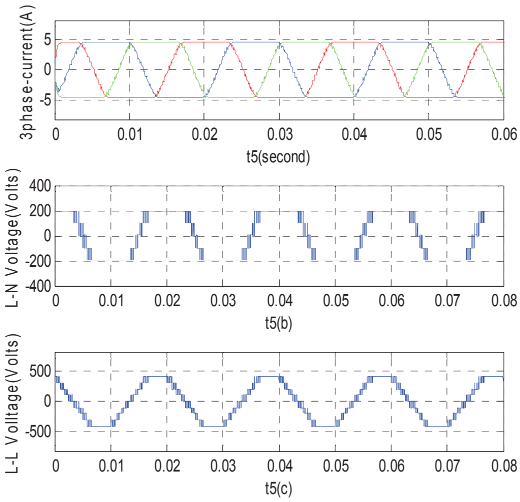

Figure 16: 5 level DCC waveform with 3rd harmonic injection at 1.15 modulation index.

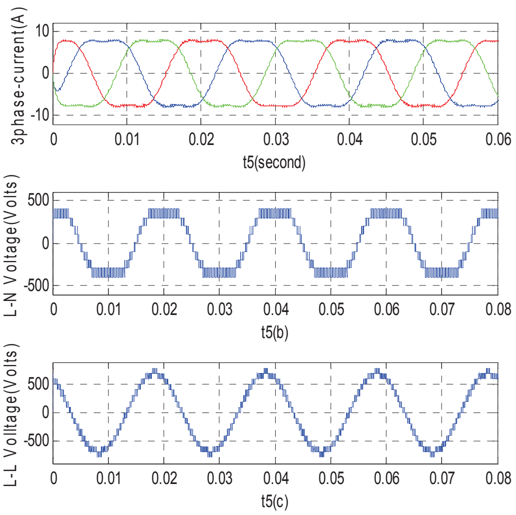

Figure 17: 9-level DCC waveform with 3rd Harmonic injection at 0.8 mod. index.

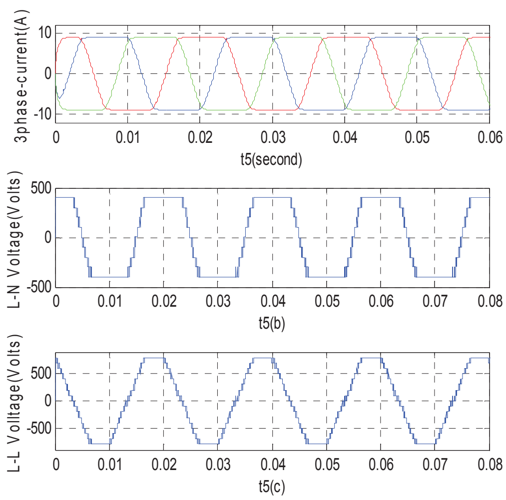

Figure 18: 9-Level DCC waveform with 3rd harmonic injection at 1.15 mod. index.

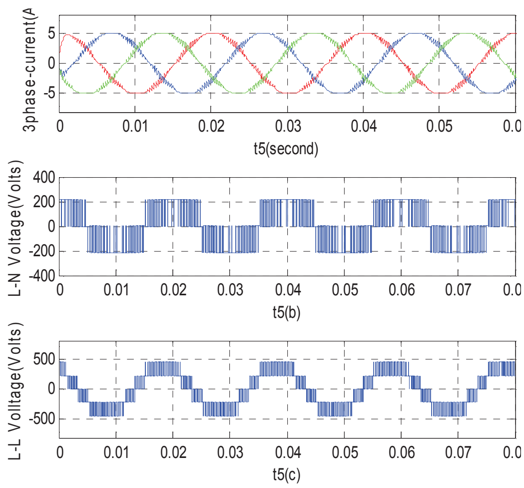

Figure 19: 3-level DCC wave-form with 9th harmonic injection at 0.8 modulation index.

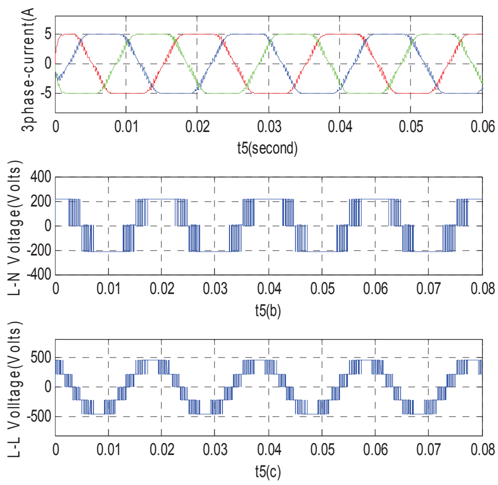

Figure 20: 3-Level DCC waveform with 9th harmonic injection at 1.15 modulation index.

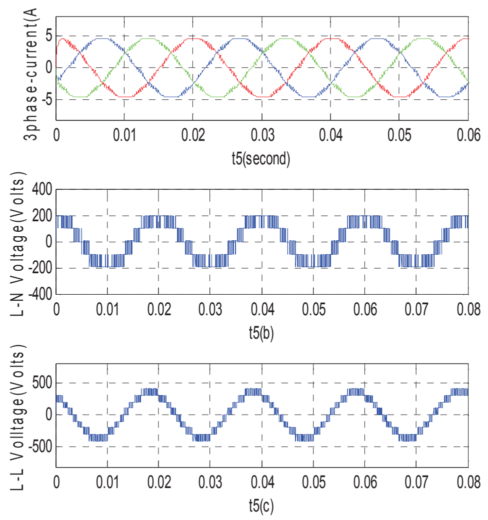

Figure 21: 5-Level DCC waveform with 9th injection at 0.8 modulation index.

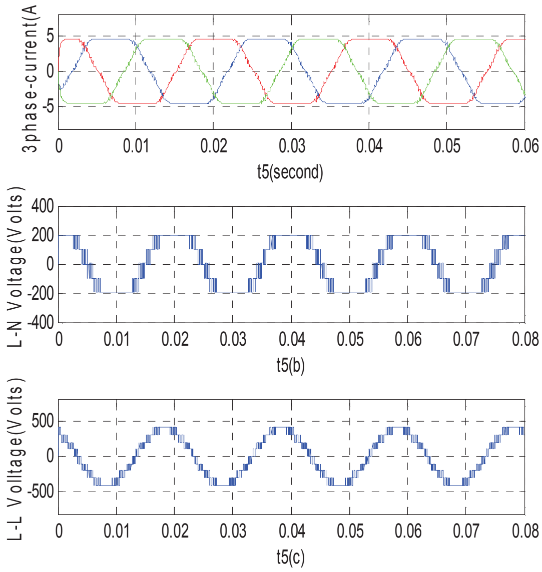

Figure 22: 5-Level DCC waveform with 9th harmonic injection at 1.15 modulation index.

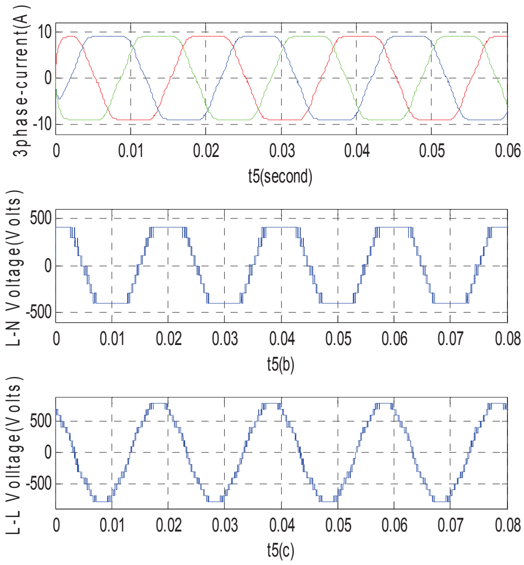

Figure 24: 9-Level DCC waveform with 9th harmonic injection at 1.15 modulation index.

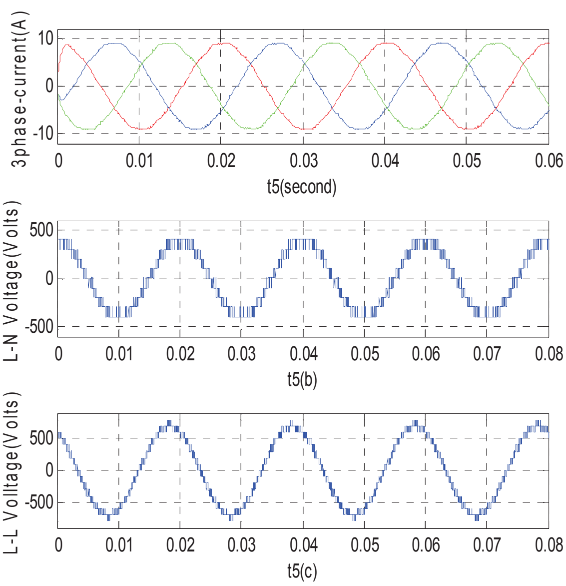

Figure 23: 9-Level DCC waveform with 9th harmonic injection at 0.8 modulation index.

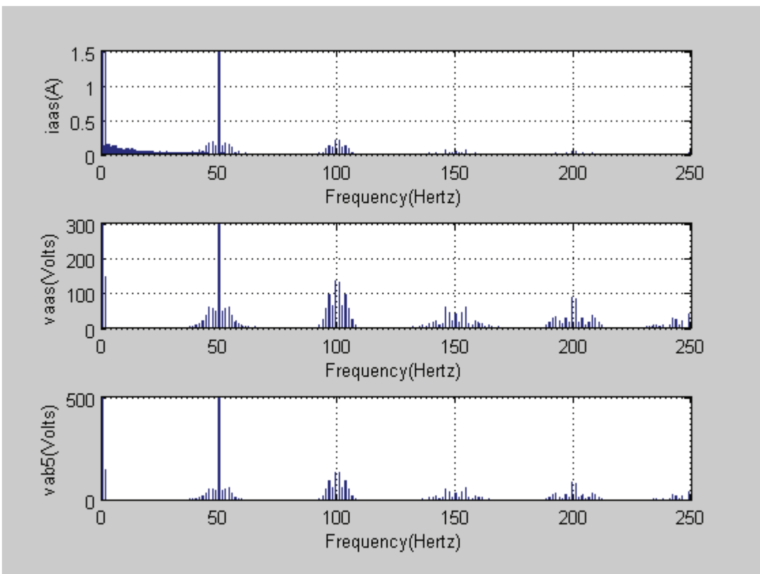

Figure 25: Spectral plot of 3level DCC with 3rd harmonic injected modulation.

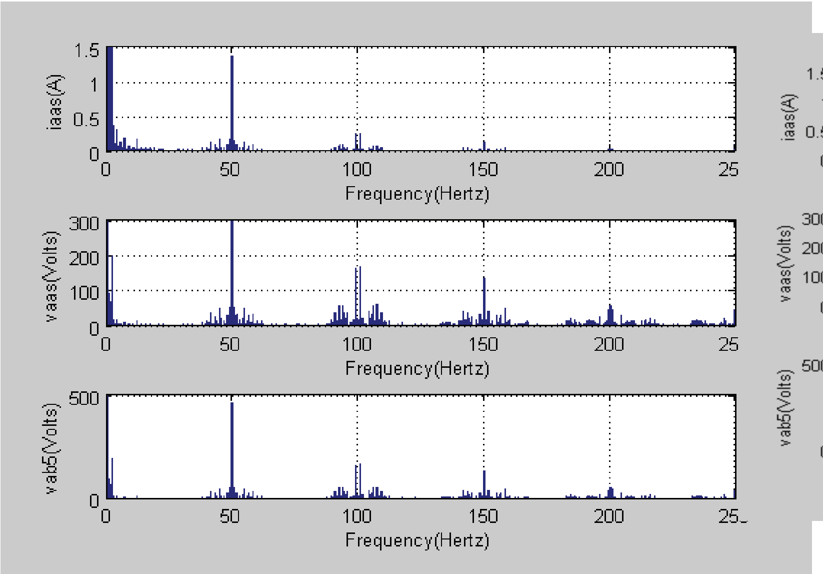

Figure 26: Spectral plot of 3level DCC with 9th harmonic injected modulation.

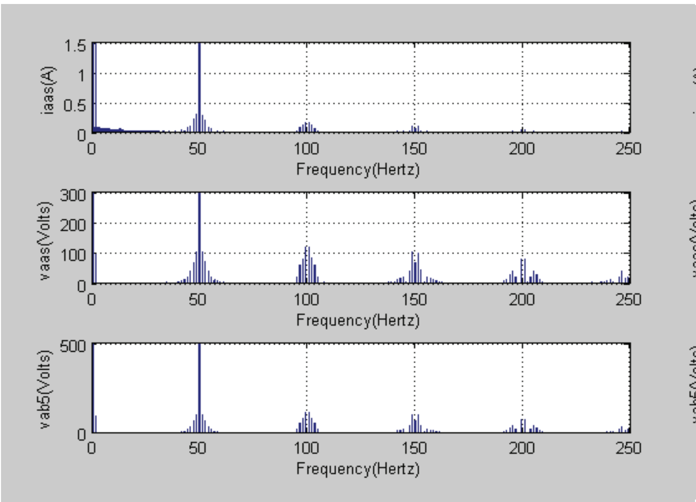

Figure 27: Spectral plot of 5level DCC with 3rd harmonic injected modulation.

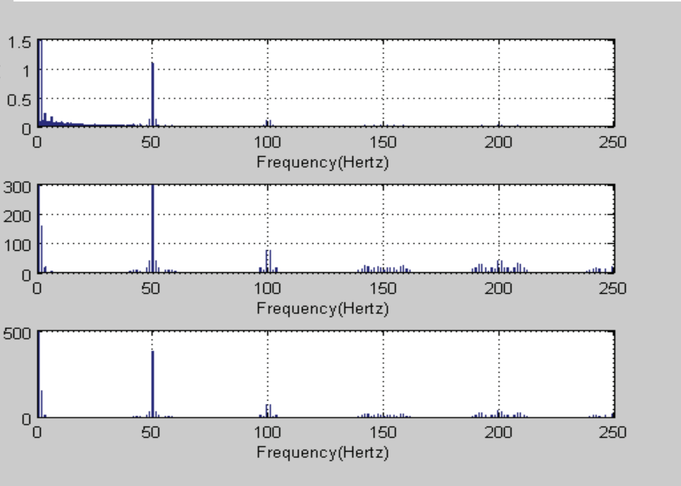

Figure 28: Spectral plot of 5level DCC with 9th harmonic injected modulation.

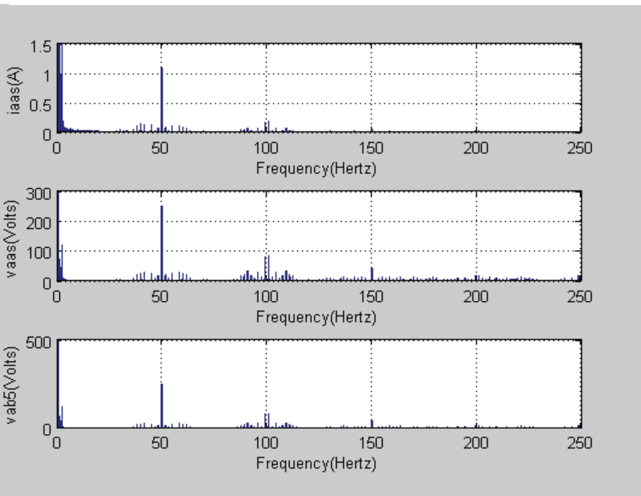

Figure 29: Spectral plot of 9level DCC with 3rd harmonic injected modulation.

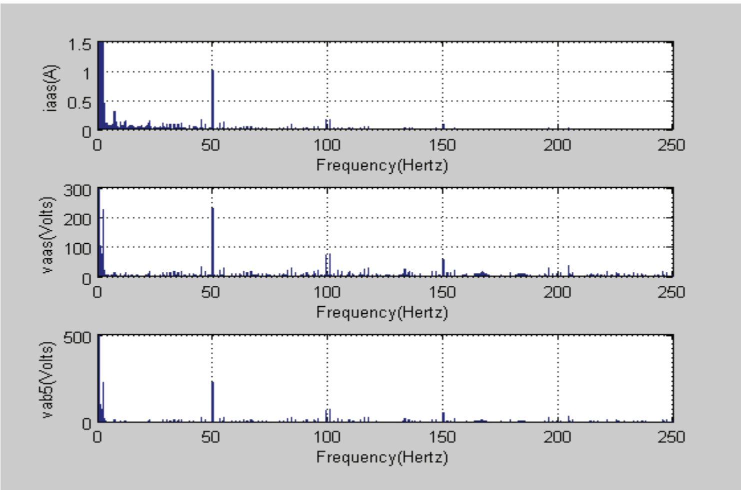

Figure 30: Spectral plot of 9level DCC with 9th harmonic injected modulation.