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Harmonic Injection Technique to Reduce Harmonic

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Abstract*— A harmonic injection technique, which reduces theline frequency harmonics of the single switch three-phase boost rectifier, has been implemented. In this method, a periodic voltage is injected in the control circuit to vary the duty cycle of the rectifier switch within a line cycle so that the fifth-order harmonic of the input current is reduced to meet the total harmonic distortion (THD) requirement. Since the injected voltage signal, which is proportional to the inverted ac component of the rectified three-phase line-to-line input voltages is employed; the injected duty cycle variations are naturally synchronized with the three-phase line-to- neutral input voltages.

***Index Terms*—Power Factor, Low %THD, Displacement Factor,sensor, Pulse Width Modulation, Active Front End Converter, Unity Modulus Method.**

I. INTRODUCTION

Most of the power electronics applications, diode rectifiers are commonly used in the front end of a power converter as an interface with the electric utility. The rectifiers are nonlinear in nature and, consequently, generate harmonic currents into the ac power source. The nonlinear operation of the diode rectifiers causes highly distorted input current. The non-sinusoidal shape of the input current drawn by the rectifiers causes a number of problems in the sensitive electronic equipment and in the power distribution network. The distorted input current flowing through the system produces distorted voltages at the input of the common coupling. Thus, the increased harmonic currents result in increasing volt-ampere ratings of the utility equipment, such as generators, transmission lines and transformers. In addition to the inefficient use of electric energy, the discontinuous conduction of the bridge rectifier results in a high total harmonic distortion (THD) in the input lines and can lead to malfunctioning of the sensitive electronic equipment. The recommended practice, IEEE-519 and IEC 1000-3 have evolved to maintain utility power quality at acceptable levels.

The power factor correction in a single-switch rectifier is performed by shaping input phase currents into discontinuous waveforms. The average values of these waveforms in one switching cycle are proportional to the instantaneous values of their corresponding phase voltages. As a result, theinputphase currents are forced to track the input voltages, and an almost unity power factor is obtained. One approach is to use three single-phase power factor corrected rectifiers in cascade. The main advantage of this configuration is that a well-known single-phase power factor correction (PFC) technique can be used in three-phase applications. However, this approach suffers from several disadvantages, which include cascading three single-phase PFC circuits requires the use of additional diodes, increased component count and complicated input synchronization logic. Therefore it is clear that lower cost three-phase PFC circuits are required for high power processing.

II. BASIC OPERATION

Amongst the three-phase ac-to-dc rectifiers, boost type topologies are frequently used because of continuous input currents and high output voltages. Basically, two topologies are most popular:

A. A Six-Switch Full-Bridge Boost Rectifier And

B. A Single Switch Boost Rectifier.

The first one uses six switches to achieve sinusoidal input current control and to share the output power, resulting in features, which include continuous input current, excellent power factor and low switch the current rating. However, this circuit is very complicated

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in power stage and control, making it too expensive for medium power level (5-10 kw) applications. The second one uses six diodes and one switch to control input currents and output power as depicted in

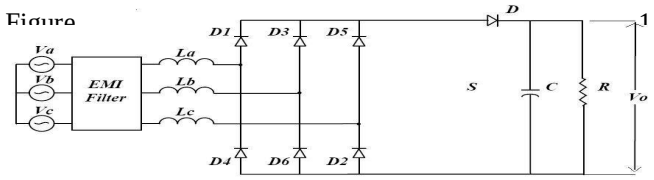

Figure:01 Six diode and one switch circuit

Since these rectifiers have a single switch and perform input current wave-shaping naturally, without a need for a complex control circuitry, they are very suitable for the low cost power three-phase ac-dc applications. In addition, they can achieve extremely high efficiencies because the reverse-recoveryrelated losses of the boost diode are eliminated. As previous studies have shown, the distortion level depends on the ratio of the output voltage to the input line voltage. For example, the output voltage is 720 V and the input phase voltage 230 V, the maximum power of the converter must be limited to about 4.5 kW in order to keep input current harmonics under the limits set by IEC 1000-3. Although increasing the output voltage would permit higher maximal power, it is not practical considering the voltage handling capability of commercially available high frequency power semiconductor devices (MOSFET's and IGBT's). However, the singleswitch three-phase boost rectifier cannot be pushed to high power levels because its input current harmonics cannot meet the IEC 1000-3-2 (A) standard. Based on harmonic analysis, it is found that the current distortions are related to the rectifier voltage gain M, which is defined as:

$$M = \frac{V_o}{V_{lp}} \quad \text{.....(01)}$$

Where, V_o is rectifier output voltage andV_{lp} is input line-line peak voltage. The higher the M is, the lower the harmonics become. A larger M means a high output voltage, yielding a high voltage stress on the devices. To qualify the performance of a switching mode rectifier with power factor correction, the quantity of input current harmonics is an important parameter. Clearly understanding the distorted mechanism will help us to find a proper way to suppress the harmonics. The harmonics in a single-switch three-phase boost rectifier with both constant and variable switching frequency PWMs are analyzed. It is found that the harmonics are greatly dependent on the rectifier voltage gain M. The higher value of M, the lower the distortions. Among all orders of low-frequency harmonics, the fifth order is a dominant order for the rectifier with a constant switching frequency PWM. Therefore, in order to meet the IEC 1000-32 (A) standard, the power levels cannot be pushed above 5 kW (for 3X220 -Vrms input) because the fifth-order harmonic exceeds the limit. A simple way to reduce the fifthorder harmonic and to improve the total harmonic distortions is with a variable switching frequency PWM. However, in a PWM, the switching frequency is relative to the load: the lighter the load, the higher the switching frequency. At light load, a significant increase of switching frequency will complicate the power stage design, resulting in a high cost. Inthis paper, a low cost harmonic injection method for single switch three-phase DCM boost rectifier and its implementation are presented. To reduce the fifth-order harmonic and improve THD's of the rectifier input currents, a periodic voltage signal, which utilizes the voltage ripple of the rectifier output voltage, is injected to modify the duty cycle of the rectifier within line cycle. The injected voltage signal is proportional to the ac component of the rectified three-phase line-to-line input voltages. As a result, the injected signal is naturally synchronized with the three-phase line-to-neutral input voltages. Moreover, the closed loop feedback control of the DCM boost rectifier is not affected by the proposed open loop harmonic injection method. To alleviate this problem to some extent, different modulation techniques have been proposed to reduce the harmonic distortion of the input currents without increasing the output voltage beyond practical levels.

III. CIRCUIT EXPLANATION

The converter circuit is modified in Figure. 2.

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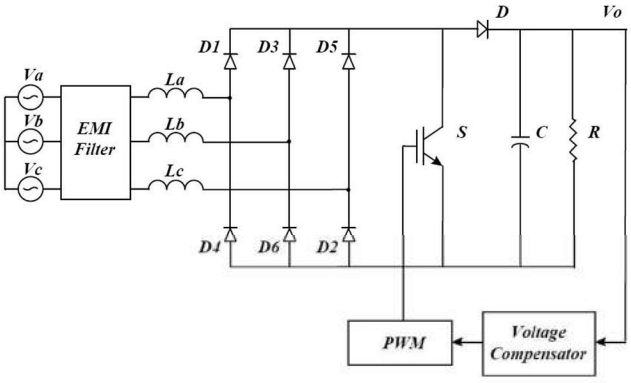

Figure: 02 A single-switch three-phase boost rectifier

The principle can be easily understood by assuming first that the rectifier operates in DCM and the switch S is operated at constant switching frequency (f), s with a fixed duty ratio. Since the boost rectifier is operated in DCM with constant frequency and constant duty cycle, all three-phase currents i,i,i are zero at the end of a a,b,c switching period immediately before boost switch S is turned on. Four operating stages can be identified in a switching period as shown in Figure 3.2

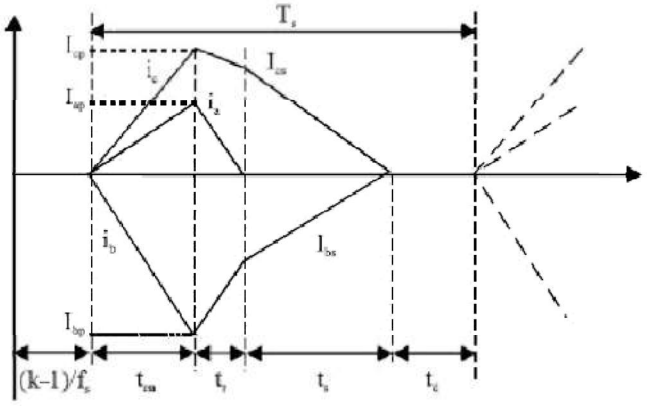

Figure 3.1 Input Inductor Current for a switching period

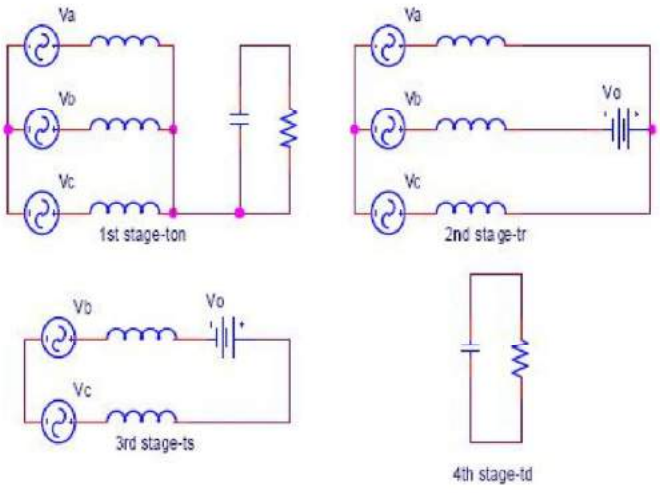

Figure:-3.2 Operating stages of converter

In the first operating stage, the power switch is turned on to linearly charge the input inductors according to the phase voltage that is

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applied across each one. In the second operating stage, the power switch is turned off to reset the inductors, the inductor with the lowest peak current reset first. In the third operating stage, the two remaining inductor currents are reset to zero at the same rate. Once the reset interval has finished, the output load is supplied by the energy stored in the output capacitor until the next switching period restart as shown in the figure 3.2.

IV. CALCULATION

Under balanced and undistorted three-phase input voltages:

$V_a = V_m \sin(wt)$

$V_b = V_m \sin(wt-2\pi/3)$

$V_c = V_m \sin(wt-4\pi/3)$ ……(02)

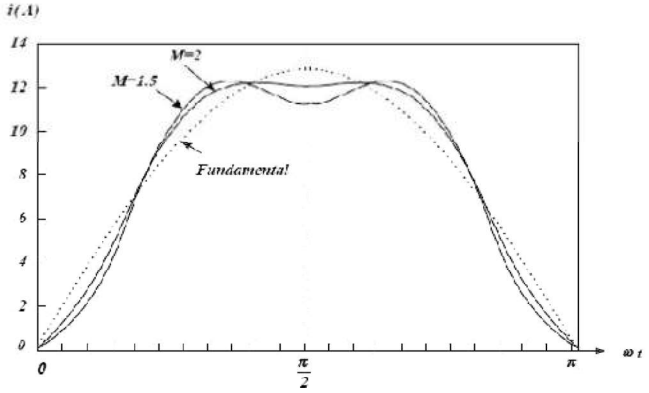
A simple way to improve the input current distortions in a single-switch three-phase boost rectifier is with a variable switching frequency PWM scheme [4]. The power stage and control block with this scheme are shown in Figure. 2. In the power stage, a current sensor is added on the rectifier dc-side to sense the output current of the diode rectifier. When the sensed current falls to zero, the switch is controlled to turn on again immediately. With this control scheme, the switching frequency is variable over one line cycle. On the other hand, the switch turn-off is controlled by the output or the duty cycle is regulated by load, which is similar to the rectifier with a constant switching frequency PWM.

$$0 \le \omega t \le \frac{\pi}{6} \qquad i_a = \frac{V_o T_{on}^2}{2LT_{sw}} \frac{\sin(\omega t)}{\sqrt{3}M - 3\sin(\omega t)},$$

$$\frac{\pi}{6} \le \omega t \le \frac{\pi}{3} \qquad i_a = \frac{V_o T_{on}^2}{2LT_{sw}} \frac{M\sin(\omega t) + \frac{1}{2}\sin(2\omega t - \frac{2\pi}{3})}{[\sqrt{3}M - 3\sin(\omega t + \frac{2\pi}{3})][M - \sin(\omega t + \frac{\pi}{6})]},$$

$$\frac{\pi}{3} \le \omega t \le \frac{\pi}{2} \qquad i_a = \frac{V_o T_{on}^2}{2LT_{sw}} \frac{M\sin(\omega t) + \sin(2\omega t + \frac{\pi}{3})}{[\sqrt{3}M + 3\sin(\omega t + \frac{2\pi}{3})][M - \sin(\omega t + \frac{\pi}{6})]},$$

Where, Vo is the output voltage, Ton= d.Tsw, d is the duty cycle, Tsw is the switching period (Tsw =1/f , f is the switching frequency), L is the input inductor, and M is the rectifier voltage gain. The phase A current ia over (/2, 2), and phase B and C currents ib and ic over (0, 2) can be obtained according to symmetrical properties of the waveforms. In graph 01, the phase A current with M =1.5 and 2 is plotted for a 6 kW rectifier with 3X 220 -Vrms input (L=43uH, fs kHz =45). From both current equations and plot, it can be observed that the current shape is completely determined by the rectifier voltage gain M: the higher the, the lower the distortions. On the other hand, the current shape is load-independent, because at a fixed load, the duty cycle D is constant over line cycles.



Graph:01 Average input current at M=1.5 and M=2

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A. Implementation Of Injection

In this section, a technique used to implement the harmonic injection will be developed. Based on the control loop designed for a constant switching frequency PWM, a synchronized harmonic generator is used to provide a sixthorder sinusoidal signal with unity amplitude. A multiplier is used to modify the amplitude of the sixth-order harmonic by the modulation index. An adder is used to combine the injected signal with the feedback. Therefore, the equivalent duty cycle is going to be

$$d(t)=D[1+ m\sin(6wt+3\prod/2) \quad \ldots\ldots\ldots\ldots(03)$$

B. Harmonic Generator

The harmonic generator is used to sense the three-phase voltages and to generate a synchronized sixth-order harmonic with unity amplitude when the input voltages are nominal: $V_{hg_out}\sin(6wt+270_O)$ ……(04)

From the input to output of the harmonic generator, the phase shift for the sixth order harmonic should be +270

-

0

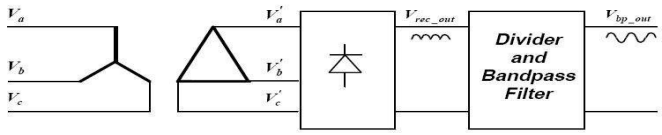

Figure :-04

As shown in Figure.04, the three transformers connected in Y - D style are used to produce a synchronized signal with – 30o phase shift for the fundamental. This phase shift becomes - 180o for the sixth-order harmonic. A full bridge diode rectifier is used to generate high-order harmonics whose fundamental is a sixth-order harmonic with + 90o phase shift. A band pass filter with 0o phase shift is used to get a pure sixth-order harmonic. Then the total phase shift from the input to output of the harmonic generator is

Φ = -180o + 90o + 0o = -90o ……(04)

or + 270o , which meets the required phase shift in equation

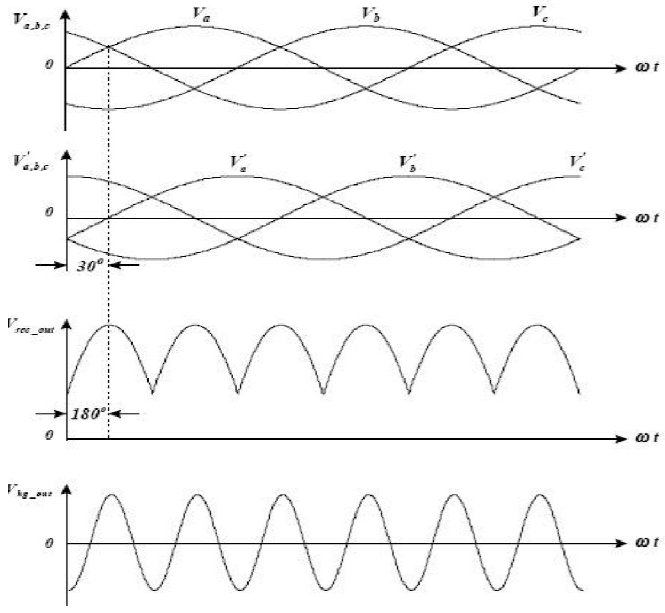

Figure :-05 Waveform of harmonic generator

To get the sixth-order harmonic, the responses of the low pass filter and high pass filter are selected as:

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Low pass filter:3dB at 600 Hz,60 dB at 6 kHz,($f_{c1}=600$ Hz) High pass filter:3dB at 100Hz,60 dB at 10 Hz,($f_{c2}=100$ Hz)

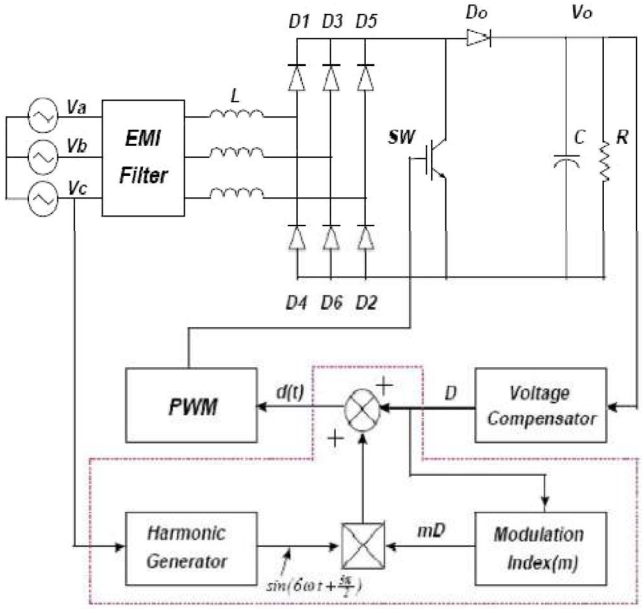

Figure :-06 Block diagram of converter circuit

C. *Modulation Index, Multiplier& Adder*

The multiplier is implemented by an AD 633 chip, whose output-input relation is given by:

$$W = \frac{X_1 Y_1}{10} \quad \ldots\ldots\ldots(05)$$

The modulation index is simply implemented by a resistor divider, R8 and W4 .

$$d(t) = D[1 + \frac{W_4}{10(R_8 + W_4)} V_{hg_out}] . \quad \ldots\ldots\ldots(05)$$

The circuit implementation of the multiplier and modulation index blocks are given in Figure 06.

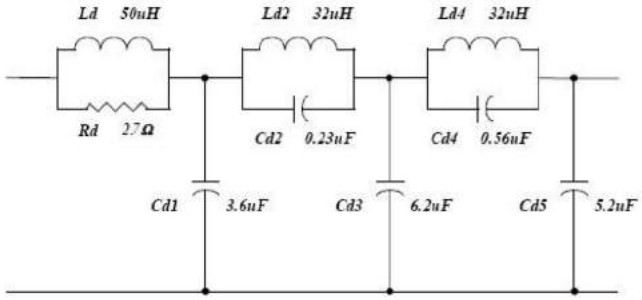

Figure :-09 The differential-mode EMI filter for the designed rectifier

V. RESULT& WAVEFORMS

The single-switch three-phase boost rectifier with harmonicinjected PWM has been studied on both a simulation model and an experimental prototype to demonstrate the validity of the harmonic-injected approach and the system performance. The prototype is designed with the following parameters:

Input : 3×110V/50Hz

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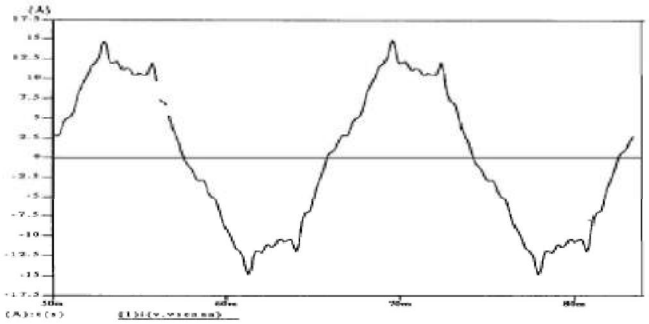
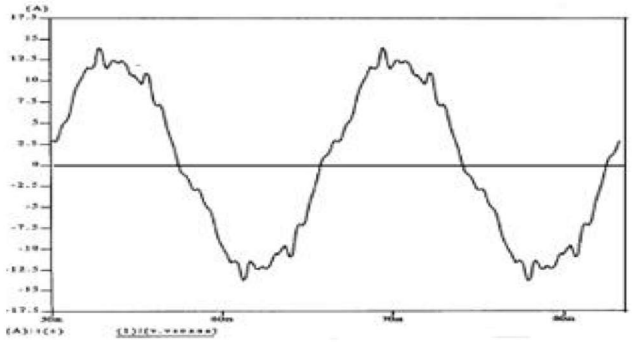
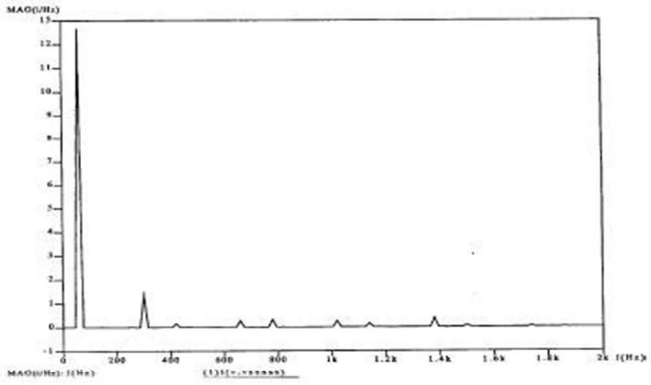
Output : 250V/ 1.1 Kw
Switching frequency : 45kHz
Modulation index m : 4.6
Control band width : 200Hz
Input inductor : 50μH
Output capacitor : 220 μF
In the experimental prototype, an IGBT (IRG4PC50KD) is used as the main switch, the input bridge is constructed with MUR1560 ultra fast recovery diodes and DSEI60-10A is the output diode.



(a) Without harmonic injection (m=0)



(b) With harmonic injection (m=4.6%)



(a) Without harmonic injection (m=0)

Unlike in a single phase rectifier, in which the current harmonics can be dramatically suppressed or even eliminated by using the duty cycle modulation, the harmonic reduction in the three-phase rectifier is restrictive. Because of only one switch connected on the rectifier dc-side, it is impossible to balance three phase currents whose distortions are in different directions. As shown in Figure. 3.2, at almost all time intervals, any attempt to improve the distortions in two phases entails the penalty of increasing distortion in the third

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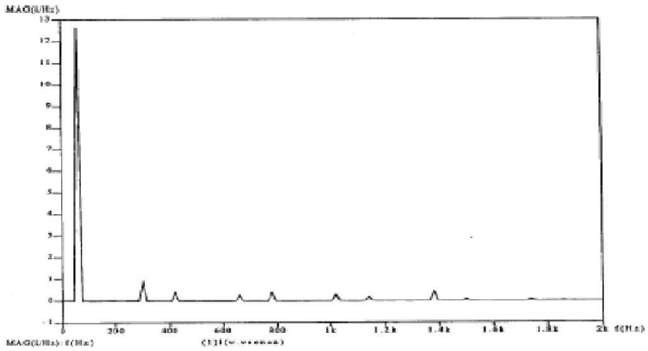

(b) With harmonic injection (m=4.6%)

Frequency spectrum of current waveform

VI. CONCLUSION

The harmonic injection concept was proposed [9] to reducethe line-current harmonics by modulating the converter dc-side currents at a harmonic frequency and then injecting themodulated currents back into the ac-side. So several magneticcomponents operating at low frequency and highvoltage/current stress were required. The proposed approach,sixth-order harmonic injected PWM, simply realizes theinjection concept at the control circuit so that the cost of thepower stage is reduced. By using harmonic injected PWM,the THD in a single-switch rectifier is improved, especiallyfor lower M values. From the results of analysis, simulation,and experiment, it can be concluded that: Simulation of current waveform

1) To meet the THD<10% requirement, the rectifier voltage gain can be designed down to 1.45. So, an application with a 3x220-Vrms-input/800-V output becomes practical.

2) To meet the IEC 1000-3-2 (class A) standard, the outputpower can be pushed up to around 10-kW level for therectifier with a 3x220-Vrms-input/800-V output.3) Owing to constant switching frequency and load-independent harmonic injection, it is easy to design thepower stage, the control circuit, and the EMI filter.So the THD improvement is an optimization problem. The proposed sixth order harmonic injected PWM is a reasonable attempt at a search for this optimum PWM scheme.

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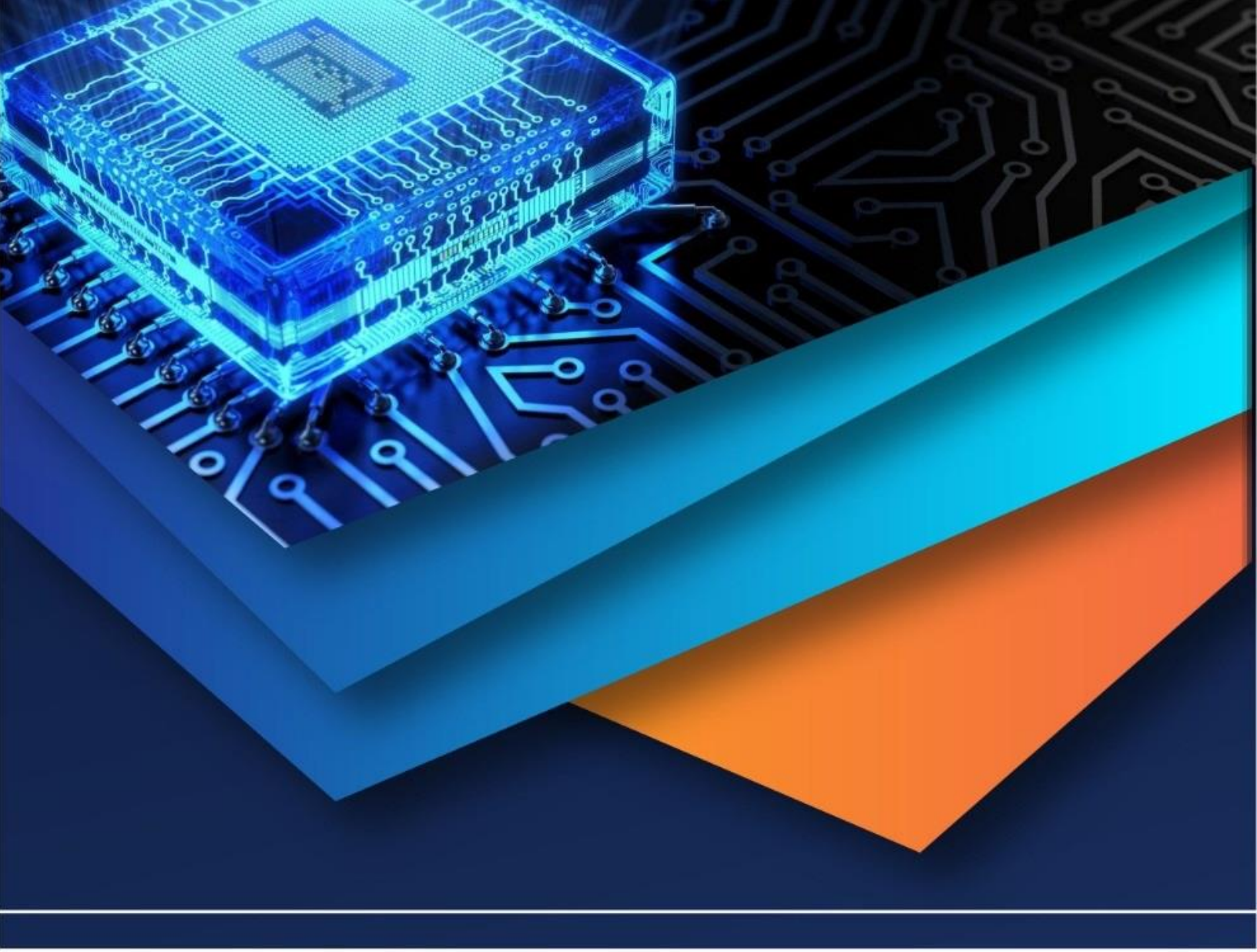

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