Design of Six Pulse Bridge Multiplication Converter Model for Current Harmonic Elimination of Three Phase AC-DC Converter

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ABSTRACT

The recent developments of semiconductor technology and wide spread use of power electronic devices in power system have open the era of the power system harmonics due to increasing penetration of non-linear loads. Harmonics are widely admitted as most important issues of power quality which must be eliminated to maintain power system reliability. The tolerable THD (Total Harmonic Distortion) values must be bounded in well-defined limits recognized by IEEE-519 standard.

In order to eliminate the current harmonics produced by non-linear loads, six pulse multiplication converter technique in conjunction with STSHPF (Single Tuned Shunt Harmonic Passive Filter) is proposed in this work. The proposed model has the capacity of harmonic cancellation of the dominant 3rd order harmonics. Besides that, the 5th and 7th order harmonics are also reduced to a diminishing level. The hardware model has been experimentally tested by PQA (Power Quality Analyzer) and simulation model is designed using MATLAB software. The acquired results have been measured by considering THD values in terms of current and voltage. Furthermore, they have been compared against IEEE-519 performance standards. The prosed model, successfully bounds the total harmonic distortion under defined limits by IEEE-519 standard.

Key Words: **Total Harmonic Distortion, Harmonic Mitigation, Six Pulse Bridge Multiplication Converter, Shunt Harmonic Passive Filter, Power Quality Analyzer.**

1. INTRODUCTION

In current socioeconomic setup, indeed, energy is the prime mover for overall growth which affects economic, social and environmental variables. The depleting world energy reserves and increasing demand has outstretched the problems of energy scarcity resulting in resources diversification and efficient utilization. The efficient utilization of electric energy is critical for energy deficit countries like Pakistan, where supply demand gap is driving system instability and distressing the country's economy [1]. The voltage,

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current, and frequency disturbances in power system are related to power quality issues [2]. Amongst Power quality problems, power system harmonics are the most dominant, always been around in electrical distribution system [3]. But with the widespread use of power electronic devices in general and AC-DC converters in particular by the residential and commercial consumers have result in renaissance of the harmonics [4]. Power system harmonics are the prime concerns for both energy consumers and utility power producers as it directly distress the power system efficiency.

The elimination of power system harmonics is a challenging job especially in case of complex nonlinear loads in conjunction with power electronic converters [5]. AC supply is used for generation, transmission and distribution of electric power but most of the use of DC supplies and electronic converters in numerous applications cannot be ignored. When conversion between AC and DC takes place, pure sinusoidal waveform does not appear which distorts the power supply in terms of current, voltage, frequency and power factor, consequently, harmonics are generated. These harmonics are mathematical representation of distortion in current and voltage waveform [6]. Typically, harmonics have been described as an integral multiple of fundamental frequency (i.e. 50Hz/220V or 60Hz/120V). These harmonics are categorized into voltage and current harmonics. The 3rd order current harmonic is severe and appears with maximum effect thereby disturbing the efficiency and safe performance of power supplies [7]. The harmonic mitigation is admitted as the major concern of both the electric user and service provider. The prime harmonic standard around the world is IEEE-519, envisioned for industrial and commercial power system applications to control the harmonics in defined limits [8].

The current research to improve the power quality is more related with harmonic mitigation techniques [9,10]. Based on this approach, harmonic filters needs to be installed. These filters have been categorized into Active, Passive and Hybrid Filters [11]. Active harmonic filter is very effective to compensate harmonic current and voltages but they are complex and expensive. Therefore, Active filters are only installed for large industrial power plants [12]. A stand alone six-pulse converter harmonic currents approach is proposed in [13], to identify the ripples of the DC current redirected back into the AC line current. On contrary, passive filtering techniques with 12-pulse converter have been used to eliminate the THD_i (Total Current Harmonic Distortion of the AC mains [14], but, this topology is very complex thereby requiring two six pulse converters along with phase shifting mechanism of star delta transformer connection, which results in the increased capital cost. Moreover, THD values of current and voltage are more than 10% at full load whereas THD values increases as load decreases such as 17% at half of the load, which do not fulfill IEEE-519 performance standards [15]. Besides this, 18-pulse converters [16] and 24 pulse converters [17] have been used which however, cancel the harmonic currents but face too much problems of complexity and economy.

In this work, we have proposed the six pulse multiplication converter technique in conjunction with STSHPF. The passive filtering particularly HPF (High Pass Filters) has the capacity of allowing higher order frequencies; consequently, undesirable frequencies can be blocked [18]. The harmonic order is the critical consideration, given in Equation (1).

$$H_p = K_p \pm 1 \quad (1)$$

Where H_p represent harmonic order, p indicates the pulse number and K is any positive integer.

The proposed model has the capacity of harmonic cancellation of the dominant 3rd order harmonics. Besides, the 5th and 7th order harmonics are reduced to a diminishing level. The hardware model has been experimentally tested by PQA and simulation model is also designed using MATLAB software. The acquired results have been measured considering THD values in terms of current and voltage. Furthermore, they are compared against IEEE-519 performance standards. The proposed model is simple, reliable, economical and fault tolerant. Moreover, the energy efficiency is achieved with higher maintainability. It covers wide range of applications comprising of many power electronic loads like ASD (Adjustable Speed Drives), Fluorescent lighting ballasts, SMPS (Switched Mode Power Supplies), UPS (Uninterrupted Power Supply), PC's (Personal Computers), and other electronic equipment etc.

The rest of paper proceeds as follows. In Section 2, the characteristic of passive harmonic filter in terms of six pulse multiplication bridge converter and single tuned harmonic passive filter are discussed, followed by modelling of proposed shunt harmonic passive filter in Section 3. Hardware and Simulation results are discussed in Section 4. Section 5 conclude the the work and point to future work.

2. CHARACTERISTIC ANALYSIS OF PASSIVE HARMONIC FILTER

Passive harmonic filters use passive components as frequency selective circuits. R (Resistance), L (Inductance) and C (Capacitance) are basic components for passive filters. These filters do not need any external source [19] and are cost effective. In this model a six pulse bridge rectifier is used as load.

2.1 Six Pulse Multiplication Bridge Converter

The widespread application of power electronic devices in the power distribution system injects the harmonic currents effects due to their characteristics of nonlinear loads [20]. These devices may cause resonance conditioning, motor overheating and failure problems both at intermittent and steady state levels if generated 5^{th} and 7^{th} harmonic currents are not reduced to a IEEE 519-1992 THD_i standard, that is to reduce below 5% at normal generating loads [21]. Amongst various other harmonic mitigation techniques multiphase and multi pulse techniques brings out most attractive solutions [22]. Six pulse bridge produces harmonics at $6n \pm 1$. Since, the magnitude of every individual harmonic is the reciprocal of the fundamental harmonic number, so 20% of 5^{th} harmonic and 9% of 11^{th} harmonic, will be the consequent result.

Six pulse converters is basically a power electronic circuit, comprises of six thyristors, where each thyristor is connected to one of the three phases, one side and one of the two DC terminals on the other. The switching element is considered as a valve, regardless of its configuration structure. At any moment of operation, two valves in the bridge are usually conducting, as one on the top row and other (from a different phase) on the bottom row. This configuration is shown in Fig. 1. Three phase (3-Ø) AC supply voltage is connected in series with two conducting valves which afterwards is connected to DC terminals. Thus, the series combination of two AC phase voltage are required to give DC output voltage at any given instant. For example, if valves V_1 and V_2 are conducting, the DC output voltage is obtained by subtracting the voltage of Phase-1 from the voltage of phase 2. Use of thyristors allows control of power flow by varying firing angle.

2.2 Harmonic Passive Filters

Passive filtering is one of the most economical, simple and cost effective method of harmonic control. It has been extensively used to overcome the dominant harmonic orders from harmonic generating loads. These filters include RLC elements which are configured and tuned in parallel with AC supply for the control of harmonic currents. A single tuned filter (Fig. 2(a)) comprises of various types of shunt passive filters, is more preferable because of its availability and cheapness and most importantly self-sufficiency for the power system applications. These filters are tuned in series to prevent the undesirable effects of harmonic currents flowing into the power distribution system either by connecting a high series impedance to control their flow or distracting their flow by providing least impedance parallel path. In consequence, the current harmonics are distracted from their well-defined path. A passive filter covers wide range of frequencies using HPF type to cancel out the higher order harmonic frequencies. The three system configuration of high pass filter i.e. 1^{st}, 2^{nd} and 3^{rd} order are shown in Fig. 2 (b-d). 1^{st} order HPF is avoided because it offers the drawback of high power loss at fundamental frequency. Along with the implementation easiness, 2^{nd} order HPF delivers satisfactory filtration characteristics thus dipping harmonic frequency effects. 3^{rd} order HPF offsets the harmonic effects completely, overshadowing fine harmonic filtration achieved by 2^{nd} order HPF.

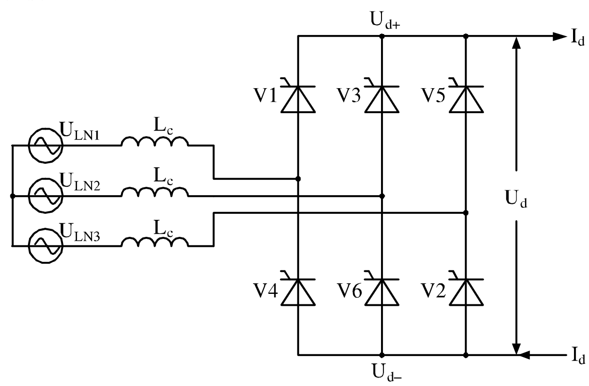

FIG. 1. SIX PULSE BRIDGE CONVERTER CONFIGURATION

2.3 Characteristic Parameters of Single Tuned Harmonic Passive Filter

Single tuned harmonic passive filter is simple and cost-effective in construction to qualify for the performance of power system products. For design purposes, the choice of appropriate capacitor size becomes absolutely necessary thereby providing the advantage of significant power factor at fundamental frequency. Usually an acceptable limit for power factor is set for power system loads (i.e. <0.8 leading and >0.75 lagging) at minimum power. The schematic configuration of single tuned harmonic passive filter is illustrated in Fig. 2(a). The impedance - frequency curve of the single tuned filter is demonstrated in Fig. 3, which establishes that value of impedance is quite high at fundamental frequency which can be eliminated step by step at 250Hz i.e. 5th harmonic frequency.

It means that, the disastrous effects of 3rd and 5th current harmonic levels are either eliminated or reduced in accordance with conformities of IEEE-519 THD*i* specifications. This effort limits the customer current distortion based on relative size of the load. However, the impedance value increases linearly with higher frequency which is beyond the scope of proposed filtering method. The equivalent impedance of the passive filter comprises of passive elements of the harmonic filter like RLC circuit as well as angular frequency of the power system, expressed in Equation (2).

$$Z = R + j\left|\, \omega L - \frac{1}{\omega_C} \right] \quad (2)$$

Since, the passive filter suffers from the zero reactance condition which is the fundamental cause of the resonance in the filter, so the impedance of the filter will then be equal to its resistance only, as given in Equation (3).

$$Z = R \quad (3)$$

The value of ω determines the series resonance frequency which defines the harmonic frequency for which filter is required to be designed, given in Equation (4).

$$f_r = \frac{1}{2\pi\sqrt{LC}} \quad (4)$$

The tuning order is simply the ratio of the harmonic frequency to the fundamental frequency Therefore, the inductive and capacitive reactance at the specified tuning frequency revealed as describe in Equation (5).

$$X_{ch} = h\omega_L \quad (5)$$

Likewise, capacitive reactance can be represented as describe in Equation (6).

$$X_{ch} = \frac{1}{h\omega_C} \quad (6)$$

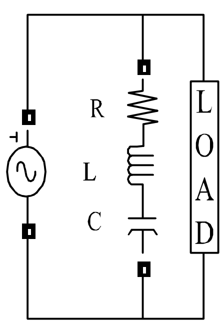

FIG. 2(a). SINGLE TUNED FILTER CONFIGURATION

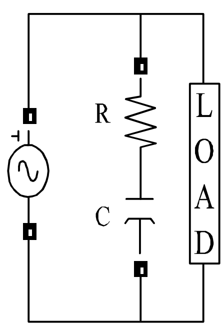

FIG. 2(b). 1ST ORDER HIGH PASS FILTER

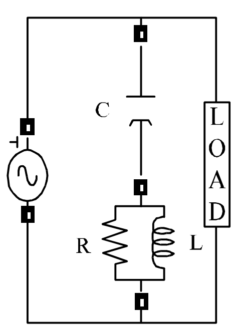

FIG. 2(c). 2ND ORDER HIGH PASS FILTER

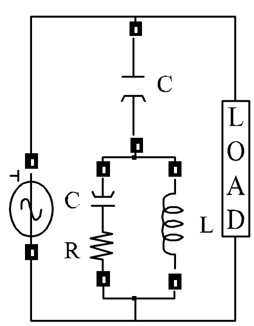

FIG. 2(d). 3RD ORDER HIGH PASS FILTER

FIG. 2. DIVERSIFIED CONFIGURATIONS OF HARMONIC PASSIVE FILTERS

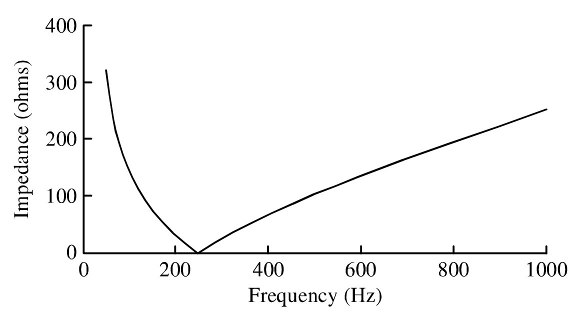

FIG. 3. IMPEDANCE- FREQUENCY RESPONSE CURVE IN PASSIVE HARMONIC FILTER

As actual reactance specifies the zero value at resonance frequency, thus can be illustrated as shown in Equation (7).

$$X_{Lh} = X_{Ch} \tag{7}$$

From above relationship, the harmonic order (h) can be determined as shown in Equation (8).

$$h = \sqrt{\frac{X_C}{X_L}} = \frac{f_h}{f_f} \tag{8}$$

Where, f_h is defined as harmonic frequency and f_f as the fundamental frequency of the power system.

3. MODELLING OF SHUNT HARMONIC PASSIVE FILTER

The shunt type harmonic passive filter model is designed with three phase isolation transformers, six pulse bridge converter circuit, line reactors and capacitor banks. 3-Ø AC supply is given to facilitate the nonlinear loads. In order to evaluate the various parameters of current and voltage harmonics, PQA has been used. The dominant 3rd harmonic currents generated by nonlinear loads can be eliminated by line reactors connected in series with the six pulse bridge converter circuit as proposed in the model. At this point, the power electronic loads are connected to point of common coupling from 3-Ø supply. For this purpose, line reactors are connected between tuned filter terminals and AC line. Fig. 4 shows the designed hardware model to mitigate dominant harmonic order currents. In the first phase, results of the experimental model are taken with six pulse bridge converter. Secondly, the harmonic passive filter has been injected along with six pulse converter circuit. The results of this model are taken separately before and after the injection of harmonic passive filter. The obtained results are analyzed and recorded accordingly using PQA.

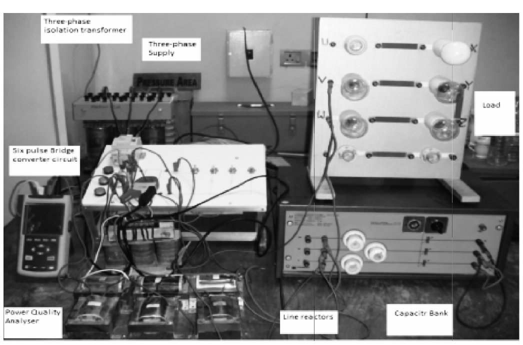

FIG. 4. PROPOSED HARDWARE MODEL FOR THREE PHASE AC TO DC CONVERTERS

4. RESULTS AND DISCUSSION

4.1 Hardware Results

In this section, experimental hardware model is tested and analyzed for two scenarios of six pulse converter before and after harmonic filter injection.

4.1.1 Without Three Phase Harmonic Passive Filter With Six Pulse Converter

As a first scenario, the supply voltage and supply current were observed by using PQA before addition and compensation of 3-Ø harmonic passive filter. The measured supply voltage and current was recorded as 261.5V and 2.95A respectively as shown in Fig. 5(a). The resultant voltage waveform seen on PQA is purely sinusoidal. The sinusoidal voltages and currents have THD of zero value. Therefore, nonlinear characteristics of these devices and equipment make distortion in their current waveform. Then, the six pulse bridge converter circuit is inserted for the same load. Results for THD_i values recorded through spectrograph, are shown in Fig. 5(b). THDi value of 26.9% is observed for 2.94A, which clearly exceeds the allowable limit. These current harmonics injected in supply system will harmonically distort the supply voltage hence affect the performance of system components and other consumer appliances. It is necessary to eliminate their intermittent and steady state effects for the reliability and efficiency of power distribution system.

4.1.2 Addition of Three Phase Harmonic Passive Filter with Six Pulse Converter

To minimize THDi, harmonic passive filter are used with six pulse converter. The resultant AC mains voltage and current waveforms are shown in Fig. 6(a), indicating that two waveforms are in agreement with each other. This investigation indicates that disastrous effects of electronic devices are minimized which ensures the reliability and maintainability of power distribution system. The THDi value as seen from spectrograph is 4.8 % at current rating of 2.46 A as shown in Fig. 6(b). These values are under the IEEE 519-1992 standards boundaries i.e. THD should be at 5% or below with full load and up to 8% when used with variable load [23]. These results confirm the suitability of the proposed model with the applications of 3-Ø AC-DC converters without damaging them.

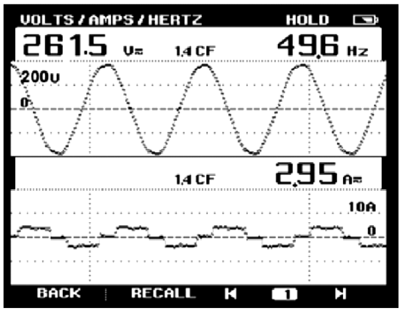

FIG. 5(a). MEASURED AC MAINS VOLTAGE AND CURRENT WAVEFORM

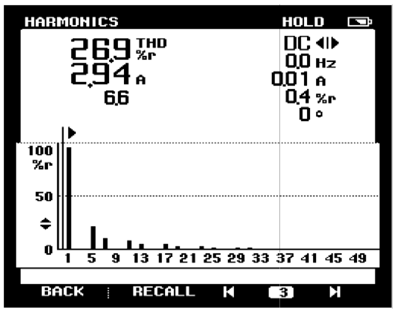

FIG. 5(b). THD_i VALUES MEASURED THROUGH SPECTROGRAPH

FIG. 5. AC MAINS VOLTAGE/CURRENT WAVEFORMS AND SPECTROGRAPH SHOWING THD_i VALUES BEFORE MAKING COMPENSATION OF THREE PHASE HARMONIC PASSIVE FILTER WITH SIX PULSE CONVERTER

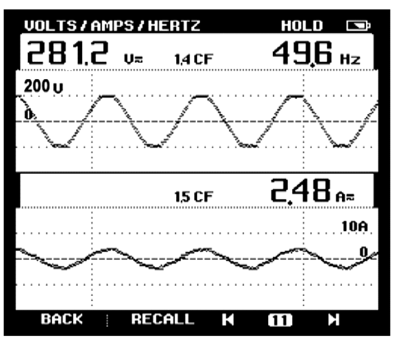

FIG. 6(a). AC MAINS VOLTAGE AND CURRENT WAVEFORMS

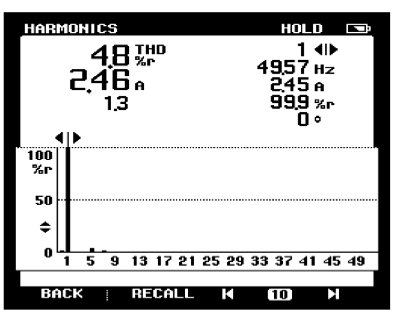

FIG. 6(b). THD_i VALUES RECORDED BY SPECTROGRAPH

FIG. 6. AC MAINS VOLTAGE/CURRENT WAVEFORMS AND SPECTROGRAPH SHOWING THD_i VALUES AFTER ADDITION OF HARMONIC PASSIVE FILTER WITH SIX PULSE CONVERTER

4.2 Simulation Results

The proposed model containing six pulse bridge multiplication converter circuits along with STSHPF has been simulated to demonstrate the performance of three phase converter circuit when operated with nonlinear loads. The Simulink model of 3-Ø AC-DC converter is shown in Fig. 7, which defines the features of supply current and supply voltage waveforms. Table 1 illustrates the selected parameters and their characterized ratings used for simulation in the Simulink model. In this section the simulation results before and after the compensation of proposed STSHPF are analyzed. Fig. 8 determines the response of AC mains supply and voltage and current waveform. These results suggest that supply voltage is sinusoidal but supply current is distorted due to the nonlinear behavior of loads in the power distribution system as shown in Fig. 8(a). Furthermore, simulation results show that six pulse converter however eliminates the 3rd harmonics yet the *THDi* value is 29.22% at current rating of 2.922 A as shown through spectrograph in Fig. 8(b). It means that the selected six pulse converter needs filtering to minimize THD. Therefore, shunt harmonic passive filter are included not only to reduce the *THDi* values below 5% as per defined IEEE standards but also compensates the reactive power to ensure that more active power is available for the service of power distribution loads.

The results shown in Fig. 9 describe that both supply voltage and supply current waveform are sinusoidal which illustrates that proposed system can work effectively for the purpose of 3-Ø power distribution system.

TABLE 1. SIMULATION PARAMETERS WITH RATED VALUES

Simulation Parameter	Rating
Supply Phase Voltage	$220V_{rms}$
Load Resistance	78Ω
Load Capacitance	$50\mu F$
Supply Inductance	1.6 mH
Rectifier Front-End Inductance	$23mH$

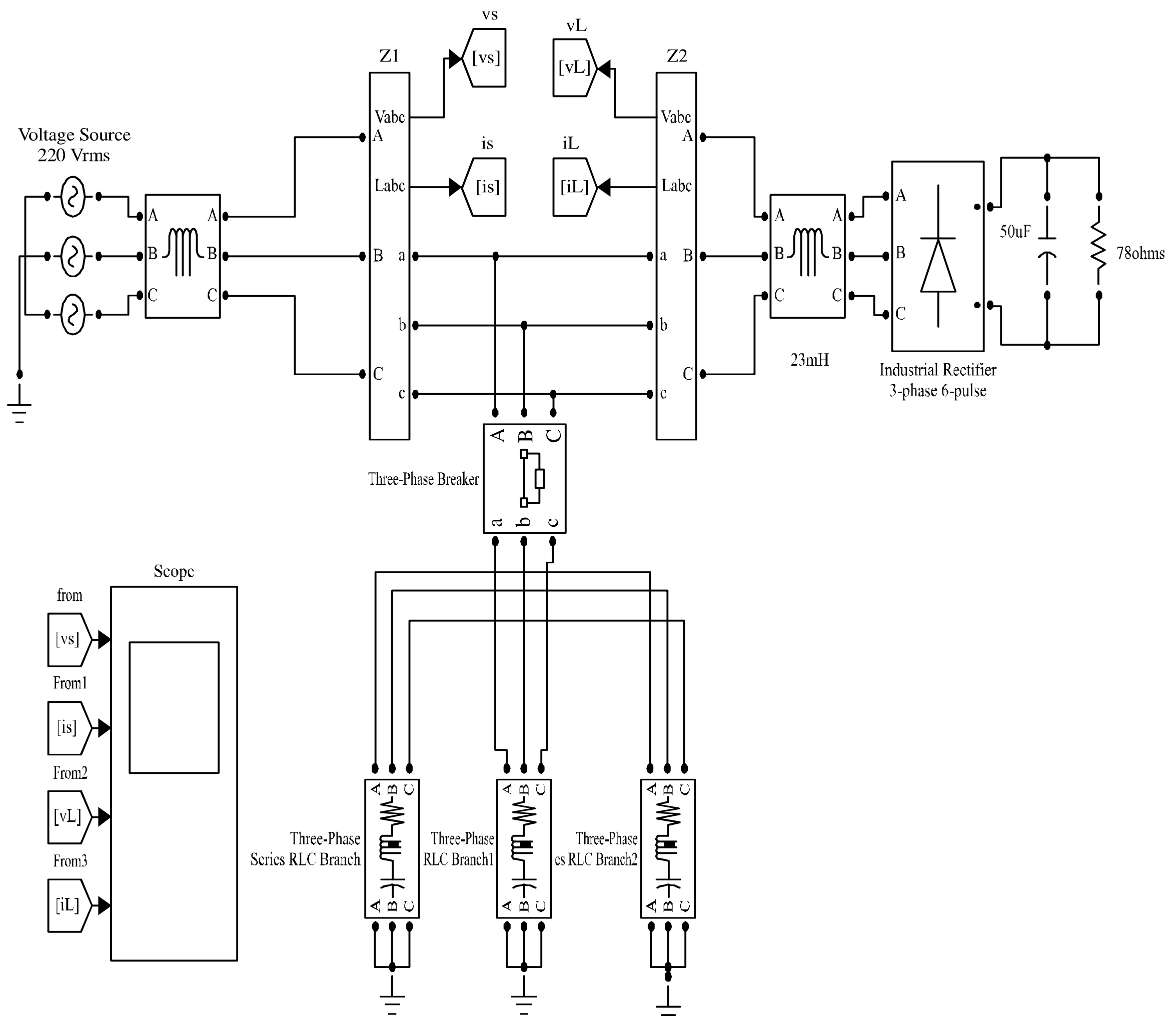

FIG. 7. MATLAB/ SIMULINK BLOCK DIAGRAM OF THREE PHASE AC TO DC CONVERTER

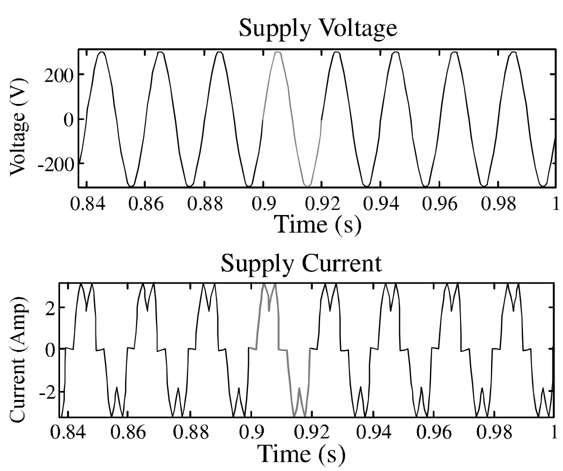

FIG. 8(a). RESPONSE OF AC MAINS SUPPLY AND VOLTAGE AND CURRENT WAVEFORMs

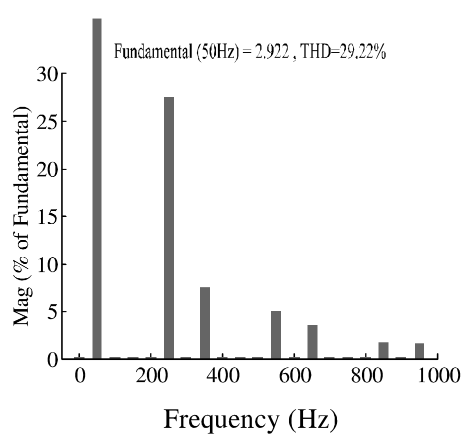

FIG. 8(b). HARMONIC SPECTRUM IN A SIX PULSE BRIDGE CONVERTER

FIG. 8. RESPONSE OF AC MAINS SUPPLY VOLTAGE/CURRENT WAVEFORM ALONG WITH ITS HARMONIC SPECTRUM IN A SIX PULSE BRIDGE CONVERTER

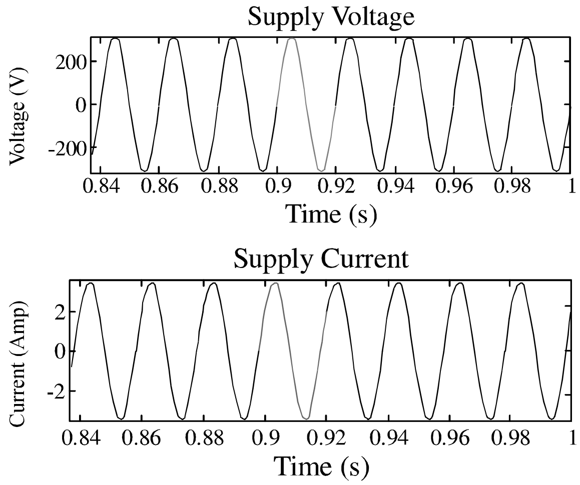

Fig. 9(a) RESPONSE OF AC MAINS SUPPLY VOLTAGE AND CURRENT WAVEFORM

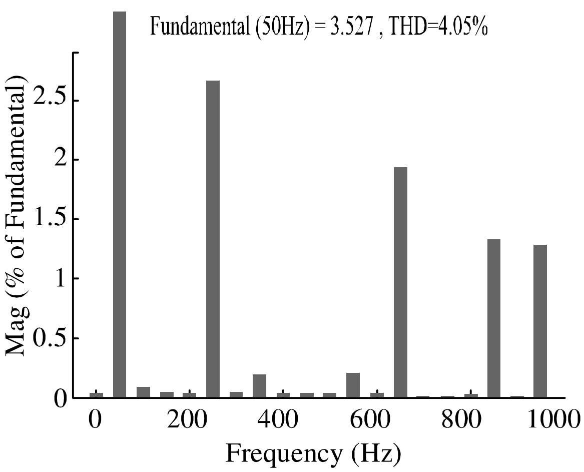

FIG. 9(b) HARMONIC SPECTRUM IN A SIX PULSE BRIDGE CONVERTER WITH SHUNT HARMONIC PASSIVE FILTER

FIG. 9. RESPONSE OF AC MAINS SUPPLY VOLTAGE/ CURRENT WAVEFORM ALONG WITH ITS HARMONIC SPECTRUM IN A SIX PULSE BRIDGE CONVERTER WITH SHUNT HARMONIC PASSIVE FILTER

5. CONCLUSIONS

The widespread application of power electronic devices in the power distribution system undesirably injects the harmonic currents effects due to their characteristics of nonlinear devices. These devices may cause resonance conditioning, motor overheating and failure problems both at intermittent and steady state levels if generated 5th and 7th harmonic currents are not reduced. The power quality problems upraised by different non-linear loads may possibly annoy the tolerable harmonic limits defined by IEEE-519 *THDi* standard, which must be reduce below 5% at normal generating loads.

In this work, in order to eliminate the current harmonics produced by non-linear loads, six pulse multiplication converter technique in conjunction with STSHPF is proposed. The proposed model successfully cancels out the dominant 3rd order harmonics and reduces the 5th and 7th order harmonics at diminishing level. The prosed model also bounds the total harmonic distortion under defined limits by IEEE-519 standard.

We can conclude that proposed STSPHF model is simple, reliable, economical and fault tolerant. Moreover, the energy efficiency can also be achieved with higher maintainability. In future work, to prevent the power system harmonic and quality problems in the distribution network, the more research on distributed harmonic sources and assessment of inter harmonics must be carried out.

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