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Analysis of Harmonics and Ripple Current in Multi-module Converters with Increasing Number of Modules for High Power Applications

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ABSTRACT

Controlled rectifiers are considered as the most important hardware part in the field of HVDC systems in transmission lines and can be used for a number of power electronics based system operation, control and utility applications. In this paper, a brief design of a 12-pulse, 24-pulse, 36-pulse and a 48-pulse converter connected to the grid is presented along with the harmonic and ripple current analysis with its comparison statistics and thus providing a justification for the suitable ones. The performance of the 12, 24, 36 and 48-pulse converters are compared for their effectiveness in both quantitatively as well as qualitatively. Further, comparison of the 48-pulse converter on its THD and current ripple which is connected towards the grid with simple pulse width modulation technique is also proposed. It combines all features of the low switching concepts and DC current re-injection techniques. Some basic topological explanation of the controlled rectifiers and simulation results using MATLAB are also presented in this paper in order to justify the harmonic analysis. The simulation results along with the quantitative results shows the effectiveness of the proposed scheme for the cancelation or the elimination of the harmonics result in maximum harmonic mitigation, for high power utility applications, the 48-pulse converter is most fitting to improve the conversion efficiency, low di/dt and dv/dt and active and reactive power controllability.

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1. INTRODUCTION

Multipulse converters are suitable for high-power applications with the advantages of ideal harmonic performance and low switching frequency, but it also has an drawbacks of poor regulation and less controllability. With very low switching frequency a bidirectional pulse width modulation (PWM) converter based on multipulse structure has got the same harmonic performance [1]. The harmonic performance and linear regulation capability of such converters can also be analyzed theoretically. The general structure of the multilevel converter is to synthesize a sinusoidal voltage from several levels of voltages, typically obtained from capacitor voltage sources. The so-called '*multilevel*' generally starts from three levels. A three-level converter, also known as a '*neutral-clamped*' converter, consists of two capacitor voltages in series and uses the center tap as the neutral [13]. To get high dynamic performance the controller parameters are optimized with adequate gain phase margin. A 3-kVA prototype can be built so that the simulation and experiment results could be validated and the proposed converter could be used for high-power conversions [3]. The performance analysis of a 2-level, 24-pulse voltage source converters (VSCs) for high voltage DC (HVDC) system can be used for power quality improvement [4]. High Voltage Direct Current (HVDC) transmission is widely recognized as being advantageous for long-distance, bulk - power delivery, asynchronous interconnections and long submarine cable crossings. HVDC lines and cables are less expensive and have lower losses than those for three-phase AC transmission [11]. For high power application bidirectional PWM converter based multipulse-structure was proposed by Aiguo Xu & Shaojun in [1]. A brief overview of HVDC transmission was presented by Michael Bahrman in [11]. Fujii, *et.al.* presented a STATCOM applying flat-packaged IGBT concept connected in series in [12]. Here, a STATCOM, which compensates a 60 MVA of a negative-phase-sequence power of a high speed train, was used to achieve lower cost, smaller size, and higher efficiency. In order to enlarge the capacity, the authors developed techniques of connecting IGBTs in series which yielded excellent results [12]. One main advantage of the multilevel voltage source converters is that it typically synthesizes the staircase voltage wave from several levels of DC capacitor voltages, which could be seen as more effective in [13]. A brief review of multilevel the converters. A new breed of power level converters was presented in [13] by Jih-Sheng Lai & Fang Zheng Peng. Further, in [14], Peng *et.al.* did extensive work on cascaded multilevel inverters for utility applications. In [15], Sreenivasappa, *et.al.* worked extensively on the performance analysis of PWM strategies for cascaded H-bridge three-level problems. In their work, they presented the performance analysis and comparison of different PWM strategies for cascaded H-bridge three-level inverter in terms of line voltage and motor current THD with their fundamental components. They showed that the harmonic loss minimized optimal-SHEPWM strategy gave better results in terms of voltage THD compared to SPWM, SVPWM and SHEPWM strategies [15]. Saeedifard *et.al.* presented in their work a space vector modulated multi-module converter for back-to-back HVDC system in [17]. The converter in their case [17] operated with a fairly low switching frequency and, thus, it could be used for a high-power application. A mathematical model was also developed for the overall multi-model converter based HVDC system & a controller was designed to evaluate the performance of the system. Research on harmonic characteristic of sample time staggered space vector modulation for multi-modular or multilevel converters was carried out by Wang *et.al.* in [18]. They introduced the concept of sample time staggered SVM, which was a modulation strategy for high power equipments and was successfully applied to multi-modular converters and cascade multilevel converters. In their paper, its modulation model was derived by dual Fourier transforms. The modulation model in frequency domain of STS-SVM was then deduced and the harmonic characteristic of that was analyzed quantitatively. Conclusions were drawn that this technique could be used largely to improve the equivalent switching frequency with no fundamental component loss. Experimental results also verified the theoretical analysis [18].

Modified low switching frequency space vector modulators for high power multi-module converters was developed by Saeedifard *et.al.* in [19]. In their work, they concentrated on force-commutated PWM controlled multi-converter systems and they proposed for high power applications, particularly for reactive power compensation and FACTS devices [19]. A multi-modular multilevel converter with input / output linearity concept was worked out by Bakari *et.al.* in. The technique sinusoidal pulse width modulation (SPWM) inherently need high switching rate, as applied to multilevel [20]. Ghaisari & Bakhshai worked on exact harmonics elimination in PWM multi-module converters and showed that they can combine higher power applications multi-module PWM and multi-pulse converter structures with switching techniques and produced good results in [21]. McGrath and Holmes [22] developed an analytical model of a voltage balance dynamics for a flying capacitor multilevel converter & performed a number of simulations presenting a strategy for the analytic determination of the natural voltage balancing dynamics of flying capacitor converters. Diego Soto and Tim Green developed a strategy for the comparison of high-power converter topologies for the implementation of FACTS controllers in [24]. The authors compared 4 converter topologies for the implementation of flexible AC transmission system controllers. Back-to-back HVDC power transmission systems have increased greatly in a number of industrial power electronic applications. They have got the advantage of interconnecting large power systems [5]. A 36-pulse filter-less configuration for back-to-back HVDC systems [2] has got the possibility of advantages in aspects of design, reliability and capital savings, whereby harmonics could be eliminated within the designed converter. Combining a number of conventional 2 or 3-level converters connected in series and/or in parallel to provide voltage and current sharing among the semiconductor devices is another approach [1]. The combined converter was called a multi-module converter. The outputs of each module are commonly connected with transformers. This approach can give a high-quality output voltage at a much lower switching frequency [6]-[10]. A number of researchers have worked on the multipulse converters, majority of them had one or the other drawbacks, for example with respect to the harmonic contents. Some of the drawbacks (disadvantages/key issues) of the work done by various authors / researchers were observed cautiously and a most effective model was proposed in this paper, thus overcoming some of the key issues like switching losses. The proposed model in this research work has a 48-pulse converter without harmonics filter. A multipulse converter for high power and voltage applications can be used in HVDC conversion along with the proposed work. In [3], the technique proposed were based on re-injection of DC current, further to achieve the same pulse number, the number of components in the auxiliary circuit is decreased, which is one of the main thing discussed in this paper. With the pulse multiplication strategy, the schemes thus demonstrate a 12-pulse, 24-pulse, 36-pulse and 48-pulse characteristics. A two level VSC is used to realize a 24-pulse converter with minimum switching loss by operating it at fundamental frequency switching (FFS). Simulink models are developed, simulation is run for a particular amount of time (0.3 ms) & the results are presented for a 12*n (n=1 to 4) series converters, thus demonstrating its capability of using in high power applications along with the harmonic analysis [5]. The inductance L_{grid} is assumed to be zero and the q-axis of the dq-frame is synchronized to the vector set up by the voltages u_{2a}, u_{2b} and u_{2c}. If a significant inductance is present, then the angle of the dq-frame changes rapidly at steps in the line currents and the inductance L_{grid} should be included in the analytical models because of the rapidly changing angles of the dq-frame models [1]-[5]. The machine parameters are given in the appendix at the end of the paper [1]. The mathematical model is shown here only for theoretical analysis for the purpose of understanding purposes & using this mathematical model, we are developing our proposed Simulink model. Since parks transformation is considered, it only concentrates on fundamental frequencies. The AC side of the converter system is modeled by differential equations for each phase a, b & c. Assuming that the inductors are not saturated and that iron losses and copper losses due to the skin effect can be neglected, the equations for the L-filter can be obtained as shown for a particular operating point in the Equations (1) to (3) as [1]-[5].

$$L_1 \frac{di_a}{dt} + R_1 i_a = u_{1a} - u_{2a} \tag{1}$$

$$L_1 \frac{di_b}{dt} + R_1 i_b = u_{1b} - u_{2b} \tag{2}$$

$$L_1 \frac{di_c}{dt} + R_1 i_c = u_{1c} - u_{2c} \tag{3}$$

By using vector notation, these equations (1) to (3) can be written in the $\alpha\beta$ – frame as

$$L_1 \frac{d\underline{i}^{\alpha\beta}}{dt} + R_1 \underline{i}^{\alpha\beta} = \underline{u}_1^{\alpha\beta} - \underline{u}_2^{\alpha\beta} \tag{4}$$

and in the d-q frame as $$L_1 \frac{d\underline{i}^{dq}}{dt} + \left(R_1 + j\,\omega_g L_1\right)\underline{i}^{dq} = \underline{u}_1^{dq} - \underline{u}_2^{dq} \tag{5}$$

These equations are finally decoupled & using certain transformations, the decoupled equation can be written in the state space form as a generalized model given by

$$\frac{d\mathbf{x}_L}{dt} = \mathbf{A}_L \mathbf{x}_L + \mathbf{B}_L \mathbf{u}_L \tag{6}$$

where A is the system matrix, B is the input matrix, x is the state vector and u is the input vector given by State vector,

$$\mathbf{x}_L = \begin{bmatrix} i_d & i_q \end{bmatrix}^T = \begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{7}$$

Input vector, $$\mathbf{u}_L = \begin{bmatrix} u_{1d} & u_{1q} & u_{2d} & u_{2q} \end{bmatrix}^T = \begin{bmatrix} u_{1d} \\ u_{1q} \\ u_{2d} \\ u_{2q} \end{bmatrix} \tag{8}$$

respectively. The system matrix A and the input matrix B are given by

$$\mathbf{A}_L = \begin{bmatrix} -\frac{R_1}{L_1} & \omega_g \\ -\omega_g & -\frac{R_1}{L_1} \end{bmatrix} \tag{9}$$

And $$\mathbf{B}_L = \begin{bmatrix} \frac{1}{L_1} & 0 & -\frac{1}{L_1} & 0 \\ 0 & \frac{1}{L_1} & 0 & -\frac{1}{L_1} \end{bmatrix} \tag{10}$$

respectively. The state space equation for the AC side of the system linearized about the operating point & a linear state space equation for the *L*-filter & is finally given in short notation form in Eq. (11) as

$$\begin{aligned} \dot{\mathbf{x}}_L &= \mathbf{A}_L \mathbf{x}_L + \mathbf{B}_L \mathbf{u}_L \\ y_L &= \mathbf{C}_L \mathbf{x}_L + \mathbf{D}_L \mathbf{u}_L \end{aligned} \tag{11}$$

The DC side (load) of the system is modeled by the equation (12) as

$$\mathbf{C}_{dc} \frac{du_{dc}}{dt} = i_{load} - i_{dc} \tag{12}$$

For the proposed VSC, the current waveform of the components depends on the phase displacement between the output current and voltage (i.e.) power factor of the converter system. For the system at high power factor operating condition, fundamental components tend to very low power and current at the switching instant is approximately zero. Hence switching losses are reduced, when system operates at high power factor. Better current control. The short-term over current protection is inherent by the presence of the DC side inductor, while the long-term protection is achieved by the current control loop. In order to achieve high quality performance and output voltage regulation, instantaneous feedback control technique is considered for the multipulse-structure based converters. First, the converter model in abc-frame is introduced; including the filter system both AC and DC side of the system. Second, the model is converted to *dq*-frame for the convenience of the design of the controller. Then, the control model is obtained. After adopting the phase delay compensation and decoupling control, the control model (state space model) is simplified and the controller parameters can be optimized for dynamic performance and system stabilization.

2. MULTI-PULSE CONVERTER TOPOLOGIES

In the proposed algorithm, a new global search pattern and a novel Cross-Diagonal-Hexagon local search pattern is introduced. The main advantage of proposed algorithm is that finding the best motion vector in less number of search-points which in turn reduces the complexity of RD cost calculation. Due to this advantages, the proposed algorithm is more suitable for real time applications. In the global search, a large cross search followed by a Multi-Half-Hexagon-Grid search is used. Since the minimum SAD position obtained from large cross search gives the search direction of final motion vector, adopting a Multi-Half-Hexagon-Grid search will search the motion vector in that direction. This avoids the unwanted searches in all direction. In this section, a brief review of the multi-pulse converter technologies is presented for 12n series, where *n* ranges from 1 to 4.

2.1. 12-Pulse Converter

Basically, pulse converters are used to convert the AC voltage present in the power system to DC voltage and it might act reverse also, which is used for HVDC transmission system. The primary side of the transformer is connected in delta form and the secondary side in zigzag form. In a three phase rectifier, the numbers of switches are 6 and each switch will be turned on at each 60° phase delay in order to avoid the short circuit between the switches in the rectifier circuit. Alpha degree (α°) is given to the converter to increase or decrease the output voltage. The equivalent transfer ratio of the phase-shift transformer is assumed to be 1. Coming to 12-pulse converter, two 6-pulse converters could be added in series connection to form the same. Once the series connection is made, a phase delay is required between the two 6-pulse converters connected in series. The delay for two six-pulse converter is 30°.

2.2. 24-Pulse Converter

This type of converter requires the connection of four 6-pulse converter in series. Phase angle between each switch has got a 15° delay (i.e., 60°/*n*). Also, each zigzag transformer has got a 15° delay each.

2.3. 36-Pulse Converter

A 36-pulse converter has three got 12-pulse converter connected in series, each switch has 10° phase shift each. So, the circuit has four zig-zag transformers which has the delay in phase angle of 10° each.

2.4. 48-Pulse Converter

The schematic diagram (block-diagram) for a 48-pulse converter with transformer rectifier connection has got eight 6-pulse converters connected in series as shown in the Figure 5, each switch having a 7.5° phase shift. So, the circuit has four zigzag transformers which have the delay in phase angle of 7.5° across each switch. The Simulink's simulation diagram of the 48-pulse converter is shown in Figure 5

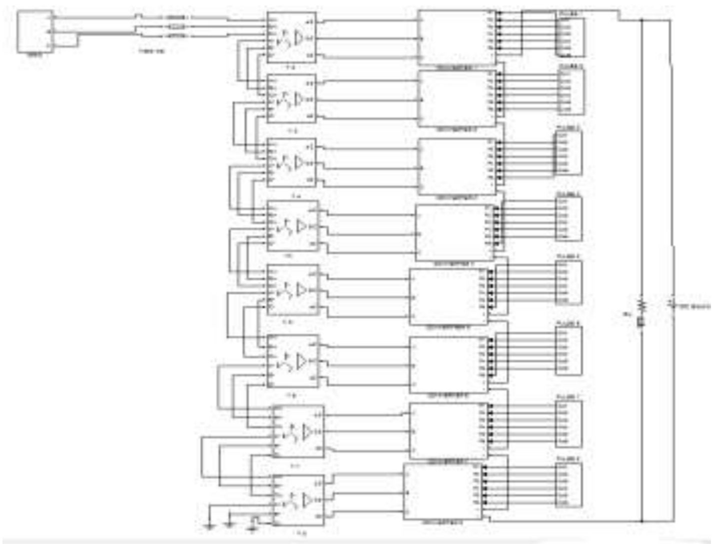

Figure 1. A 48-pulse converter Simulink diagram used for simulation

2.5. Results and Comparison

Four Simulink models were developed for 12*n* series converters. The simulations were run for a particular amount of time period with a 3 KW inductive load. The voltage and current waveforms for the 12n series converters were observed. The results and comparison of the 12-pulse, 24-pulse, 36-pulse and 48-pulse converters results are given in the graphs in Figures 6 – 9 respectively. Each graph has time (in seconds) along the *x*-axis and *y*-axis carries the amplitude of the converter source side voltage or current. The quantitative results of the 4 type of converters for THD & the current ripple are shown in the Table 1 for a 3 KW load.

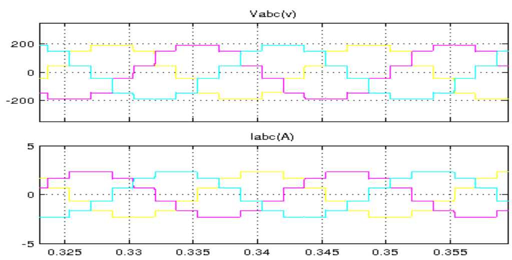

Figure 2. 12-pulse converter Source Side voltage & current with 3KW load

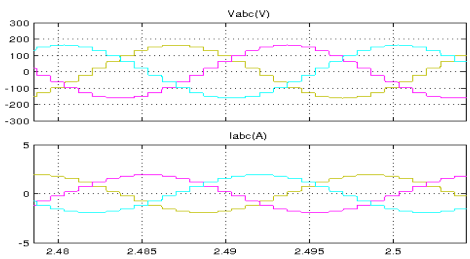

Figure 3. 24-pulse converter Source Side voltage & current with 3KW load

From this table, it can be observed that the THD & the current ripple is the lowest for a 48-pulse converter very near to the converter, which justifies its use for high power applications.

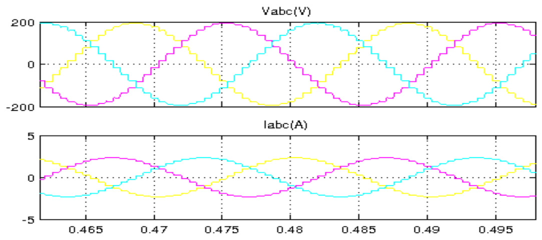

Figure 4. 36-pulse converter Source Side voltage & current with 3KW load

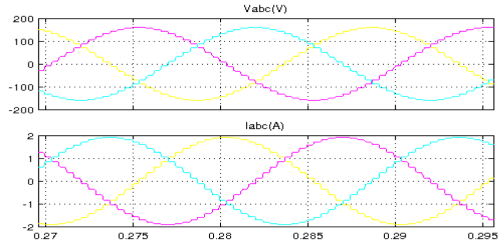

Figure 5. 48-pulse converter Source Side voltage & current with 3KW load

Table 1. Current harmonics with 3KW load

converters	THD in %	Current ripple (%)
12- pulse	15.32	29.7
24-pulse	7.27	7.69
36-pulse	4.70	3.22
48-pulse	3.13	1.81

Table 2. Current harmonics with 3KW load connected after 100 k transmission line

converters	THD in %	Current ripple (%)
12- pulse	2.48	5.0
24-pulse	1.37	3.65
36-pulse	1.0	1.5
48-pulse	0.82	1.2

Further, when a 100 Km long transmission line is considered, then the THD & the current ripple is the still lowest for a 48-pulse converter with a percentage of 0.82 & 1.2 respectively. It has its advantages to moderate the EMI without harmonic traps and filters. It can be further observed that more the number of bridge circuits/switches, the percentage error comes down, but the complexity in the circuit increases with a question on its reliability.

3. FFT ANALYSIS OF MULTI-MODULE CONVERTERS CONNECTED TO GRID

In this section, the harmonic spectrum of the converter & grid side voltage and current is presented in Figures. 10 – 25 along with the discussion on the simulated results for our proposed scheme or model of the work. The simulations were run for a particular amount of time period for the 4 Simulink 12n models. The FFT analysis was also carried out for the converter & grid side. The fundamental frequencies were also observed. The FFT spectrum analysis results are shown in the Table 3. It can be observed from this table that the converter side & the grid side voltage remain constant and perfect sinusoidal grid side current and also with ac line current is perfect, whereas there is a decrease in the THD % value.

Table 3. FFT spectrum analysis w.r.t. the converter & grid sides

converters	Converter side voltage		Converter side current		Grid side voltage		Grid side current	
	FF	THD %	FF	THD %	FF	THD %	FF	THD %
12-pulse	297.7	2.18	3.683	2.96	297.7	2.18	6.731	1.10
24-pulse	277.9	0.76	2.117	2.55	277.9	0.76	7.545	0.19
36-pulse	261.4	0.39	2.321	1.25	261.4	0.39	8.243	0.13
48-pulse	253.1	0.27	2.620	0.80	253.1	0.27	8.833	0.10

3.1. Harmonic Spectrum of Grid Connected 48-Pulse Converter Results

The simulation results for the harmonic analysis for the grid connected 48-pulse converter are shown in the Figures 22 to 25 respectively w.r.t. the converter and grid side voltages & currents. The figures shown in the simulation results section are the harmonic spectrum present in the converters. From the Tables 3, 4 & from the Figures 10 – 25, it can be observed that the harmonics of 12th, 24th, 36th & 48th are high in the 12th, 24th, 36th converters and it is highly reduced in the 48-pulse converter as shown in the spectrum and the notable point is that the grid is not connected with the harmonic traps because of the reduction in the harmonic contents, which finds it more suitable for any control application problem. For the proposed technique and model, since high current density with ripple free for 48-pulse, it can be connected to strong-grid transmission & can be able to produce more active power.

Fundamental (50Hz) = 253.1, THO = 0.28%

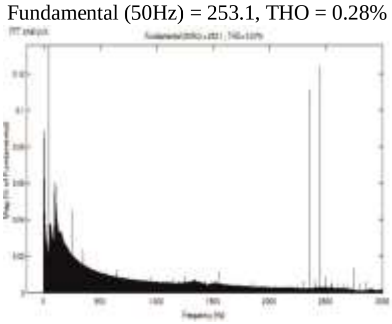

Figure 6. Harmonic spectrum of converter side voltage (48-pulse)

Fundamental (50Hz) = 2.62, THO = 0.00%

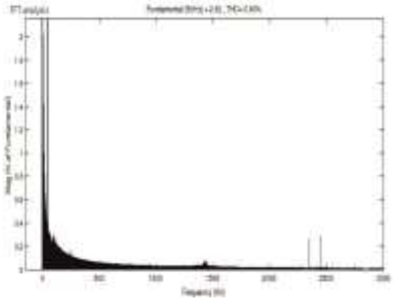

Figure 7. Harmonic spectrum of converter side current (48-pulse)

3.2. Harmonic spectrum of Multi-module converters (VSC) in controlled mode of operation

This paper discusses about the controlled rectifiers. The control elements for these controlled rectifiers are alpha angle (α). If the α angle is zero, the converter is uncontrolled. If the alpha angle is less than or equal to 90 degrees (α<= 90^0) converter will give higher voltage (peak voltage is at 90 degree for sin wave). Table.4 gives the response of the converters presented. For the proposed VSC, the current ripple was obtained 1.1, 0.8 & 0.6 for α = 0°, 30°, 60° cases.

Fundamental (50Hz) = 253.1, THO = 0.27%

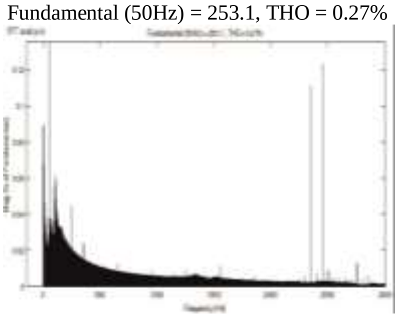

Figure 8. Harmonic spectrum of grid side voltage (48-pulse)

Fundamental (50Hz) = 6.033, THO = 0.10%

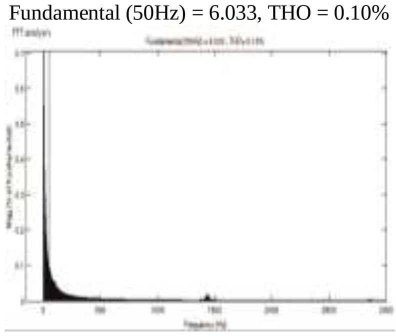

Figure 9. Harmonic spectrum of grid side current (48-pulse)

Table 4. The THD and current ripple of 3 KW load for different α's

Pulse converters	THD in %			Current ripple in %		
	α = 0°	α = 30°	α = 60°	α = 0°	α = 30°	α = 60°
12	1.10	0.62	0.69	7.20	6.5	6.00
24	0.38	0.34	0.28	5.02	4.2	1.07
36	0.29	0.28	0.37	3.10	2.2	3.03
48	0.28	0.28	0.32	1.10	0.8	0.60

4. CONCLUSION

Simulink models of voltage source converters for a 12n series were developed. Simulations were run for a specific amount of time period. The proposed 48-pulse converter was found to be better than the 12-pulse, 24-pulse, 36-pulse converters and the comparison on total harmonic distortion and current ripples are shown in the quantitative results, which further proves that the 48-pulse converter connected towards the grid gives better response towards the load-side and grid-side as the harmonics are highly reduced compared to other converters without any harmonic traps. It is clear that for increasing number of modules with proposed techniques provides excellent performance in terms of power quality and decreases the number of additional circuit for implementation. For high-power application multipulse converters are suitable with the qualities of perfect harmonic performance and low switching frequency using simulation & quantitative results. In this paper, the performance of various multipulse converter strategies in terms of converter & grid voltage and current THD along with their fundamental components are studied and compared for their best performance. The simulation results for different strategies with their harmonic spectrums are also presented. In all these cases, symmetry and synchronization is maintained.

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