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Development of a Novel Three Phase Grid-Tied Multilevel Inverter Topology

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ABSTRACT

The conventional line-commutated ac-to-dc converters/ inverters have square-shaped line current. It contains higher-order harmonics which generates EMI and it causes more heating of the core of distribution or power transformers. PWM based inverters using MOSFET/IGBT have higher switching losses, and the power handling capability and reliability are quite low in comparison to thyristors/ SCR. A thyristor based forced commutated inverters are not suitable for PWM applications due to the problems of commutation circuits. A pure sinusoidal voltage output or waveform with low harmonic contents is most desirable for ac load using dc to ac conversion. This paper presents a new multilevel inverter topology in which three phase ac- to-dc converter circuits are used in inversion mode by controlling the switching angle. Due to natural commutation, no separate circuit is required for synchronization. In this paper simulation and analysis are done for grid-tied three-phase 6-pulse, Two three-phase, 3-pulse and 12-pulse converter. These converters are analysed for different battery voltage and different switching angle combinations in order to reduce the total harmonic distortion (THD). Three-phase harmonic filters are further added to the grid side to reduce the harmonic content in the line current. A comparative study of these converters is also presented in this paper.

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1. INTRODUCTION

At a higher power level, above one kW, normally a three phase system is employed. It reduces the unbalancing of the line current and load voltage. Three phase converters provide higher output voltage, and in addition the frequency of the ripples on the output voltage is higher compared with that of single phase converters. As a result, the filtering requirements for smoothing out the load current and load voltage are simpler. For these reasons, three phase converters are extensively used in high-power variable speed drives [1]. Multilevel topologies generate better output quality by reducing harmonics contents [2]. Multilevel inverters are used in high power applications such as Flexible AC transmission systems [3]. The need of filters is reduced by increasing the voltage level and the efficiency is high because of lesser harmonic [4]. Three-phase, 12-pulse converters are extensively used in HVDC systems for conversion of ac power into dc which is fed in dc transmission line [5]. Earlier, single-phase ac to dc converters were used as an inverter for harnessing solar energy and feeding it to grid using grid-tie inverter [6, 7]. However in these cases, THD was substantially high.

In this paper, three-phase 6-pulse, Two three-phase, 3-pulse and 12-pulse converter circuits are used which work as an inverter by connecting a dc voltage source at the load end and controlling the switching angle α. In this paper, MATLAB/Simulink model is analysed for three-phase 6-pulse, Two three-phase, 3-pulse and 12-pulse converter circuit and THD is found at different conditions of converter circuits.

Circuit diagram of three phase 6-pulse converter is shown in Figure 1. Each phase conducts and line current for 120°. When switching angle becomes higher than 90°, the converter works in inverter operation. Circuit diagram of two Three-Phase, half-wave, 3-Pulse ac-to-dc converter is shown in Figure 2. Here two half-wave converters are connected in anti parallel mode through a same source with independent load. Both group of thyristers are triggered at more than 90° for inversion operation.

Figure 3 shows the circuit diagram of three-phase 12-pulse converter, where converter 1 and converter 2 are basically 6-pulse converter connected with delta and star secondary windings, respectively. The conduction period of the line current for each converter is 120°. The number of turns in each phase winding of delta connection is $\sqrt{3}$ times of star connection as the line voltage of both secondaries are same. Therefore, the reflected current in the primary winding due to delta connected winding is $\sqrt{3}I_0$. The resultant current in the primary winding is sum of I_0 due to converter 2 and $\sqrt{3}I_0$ due to converter1 [8]. Therefore, the reflected current in the primary side is in stepped form [8].

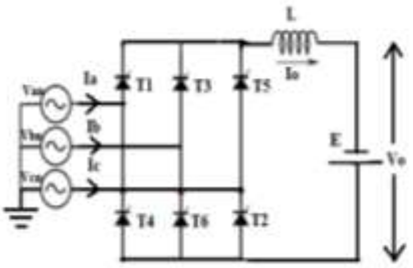

Figure 1. Circuit diagram of three phase 6-pulse converter

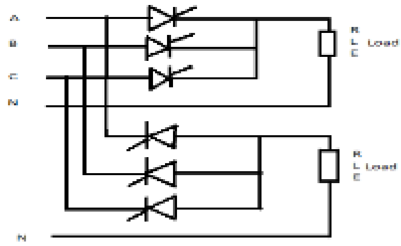

Figure 2. Circuit diagram of two three-phase half-wave 3-pulse ac-to-dc converter

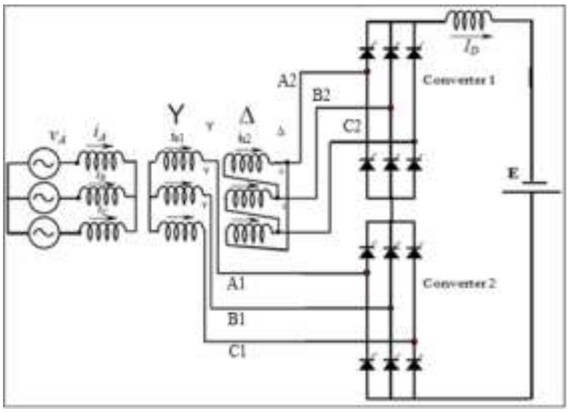

Figure 3. Circuit Diagram of Three-Phase 12-Pulse Converter

2. PROPOSED SCHEME

A multilevel converter circuit with RLE load works in two modes of operation i.e. rectification mode and inverter mode. It works in inversion mode when the switching angle of each of the converter is greater than 90º [8]. Here, a multilevel circuit topology has been proposed for dc-to-ac conversion where batteries are charged from solar PV cells. The circuit has been analyzed for three level as well as six level of line current. It can be extended to higher levels for better performance [9]. However, the increase of level adds to the cost of converter. So, a suitable compromise has to be made between the THD of the line current and cost of additional hardware. For three level, two three-phase half-wave 3-pulse ac-to-dc converter and three-phase 6-pulse converter topologies are used and for six level, 12-pulse converter topology is used. The major advantage of the proposed configuration is that in continuous current mode of operation of each converter, the waveform of line current resembles a stepped sinusoidal wave and with suitable selection of switching angles the harmonic contents can be reduced drastically.

3. CONTROL STRATEGY

In general, the load current can be either continuous or discontinuous. In case of continuous current operation, the current of conducting thyristors does not reduce to zero level. The condition depends upon dc source voltage, phase angle of load or inductor and the switching angle.

a. Three level control strategy: For three level line current, three-phase 6-pulse converter and two three- phase, half-wave, 3-Pulse ac-to-dc converter are used. Two three-phase, half-wave, 3-pulse ac-to-dc converter is shown in Figure 2 in which two 3-pulse half-wave converter are connected in anti parallel through a same source with independent load. Both group of thyristors are triggered at more than 90° for inversion operation.

b. Six level control strategy: For this strategy three-phase 12-pulse converter is used, where converter 1 and converter 2 are connected with delta-star connected secondary windings, respectively. The conduction period of the line current for each converter is 120°. Conduction period of each converter is 30° phase shifted. The number of turns in each phase winding of delta connection is √3 times of star connection [8].

The line current for each converter is approximately square wave of (I_{dc}) with 120° conduction period. The line current for the star connected secondary winding (i_1) is the same as its phase current (i_{s1}). The phase current of delta connected secondary winding (i_{s2}) is obtained by considering the transformer secondary as a current divider rule [10].

Thus, $i_{s2} = 2/3\ I_{dc}$ lines A2 & B2 are both conducting

$= 1/3\ I_{dc}$ only one of lines A2 or B2 conducting

The primary current as the primary is connected in star will be the sum of the secondary winding currents multiplied by the proper turns ratio and is obtained as,

$$i_A = (i_{s1}+\sqrt{3}i_{s2}).\ n \tag{1}$$

where n is the turns ratio

The winding current (i_{s1}) of star connected secondary can be expressed Fourier series as

$I_{s1}(wt) = \sum_{n=1,3,5}^{\infty}[4\ \mathrm{Idc}\ /n\pi \sin\left(\frac{2n\pi}{3}\right) \sin n(wt-\alpha)]$, (n is odd)

Similarly, delta connected secondary winding current is2 can be expressed in Fourier series as,

$I_{s2}(wt) = \sum_{n=1,3,5}^{\infty}[8\ \mathrm{Idc}/3n\pi \sin\left(\frac{n\pi}{6}\right).(1+\cos\frac{n\pi}{3}). \sin n(wt-\alpha)]$,

Hence the combined current drawn by the primary winding (using 1) is obtained as,

$iA = \frac{4\sqrt{3}}{\pi}\ \mathrm{Idc}\ [\sin\theta - \frac{\sin 11\theta}{11} + \frac{\sin 13\theta}{13}$

where $\theta = wt - \alpha$

4. ANALYSIS AND SIMULATION RESULTS

Simulation of the models is done using MATLAB/ Simulink. The triggering pulses are given from the pulse generator block of the simulink blockset. Figure 4 shows the simulink model of three-phase, 6-pulse converter. The value of inductor is 100 mH, resistance is 5 Ω, dc voltage is 24V. In this paper, THD and power transfer analysis is done for various combinations of switching angles (α) [11, 12]. Figure 4(a) shows the line current with THD and harmonics for three-phase 6-pulse inverter for switching angle (α) = 115°. Figure 4(b) and 4(c) shows the variation of power and THD with different switching angles for three-phase, 6-pulse inverter respectively. It is evident from Figure 4(b) and 4(c) that for increasing switching angle the power transfer to grid initially increases thereafter its decreases and the THD is almost constant upto 120° then its increases rapidly. Therefore a suitable compromise is made for selecting switching angle. Figure 4(d) and 4(e) shows the variation of power and THD with battery voltage at different switching angles for three-phase 6-pulse inverter. As the battery voltage increases power transfer to grid increases and the THD decreases. However, at α=105° results are satisfactory.

Figure 5 shows the simulink model of Two three-phase, half-wave, 3-pulse Converter. The value of inductor is 100 mH, resistance is 250Ω and battery voltage is 12V. Figure 5(a) shows the line current with THD and harmonics at switching angle α=95°. Figure 5(b) shows the variation of power with switching angle combinations (α=95°, α=105° and α=115°) with battery voltage of 12V and 24V. Figure 5(c) shows the variation of THD with switching angle combinations (α=95°, α=105° and α=115°). It is evident from figure 5(b) and 5(c) that for increasing switching angle the power transfer to grid decreases and the THD increases rapidly and, so a suitable compromise is made for selecting switching angle.

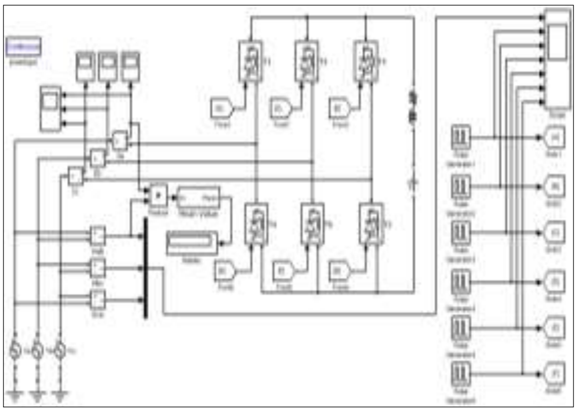

Figure 4. Simulink model three-phase, 6-pulse converter

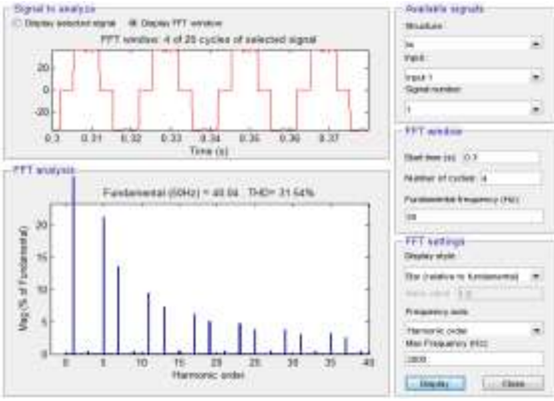

Figure 4(a). Line current with THD and harmonics at switching angle α=95° for three phase 6-pulse inverter

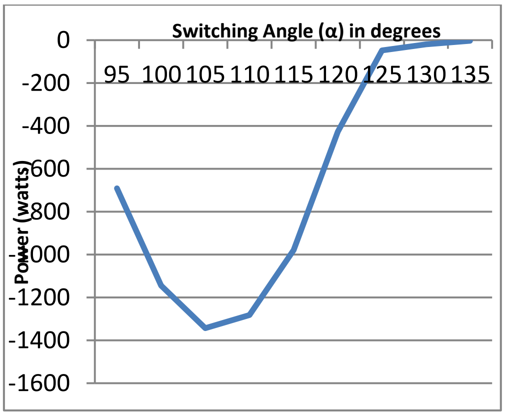

Figure 4(b). Variation of power with switching angle for three phase 6-pulse converter

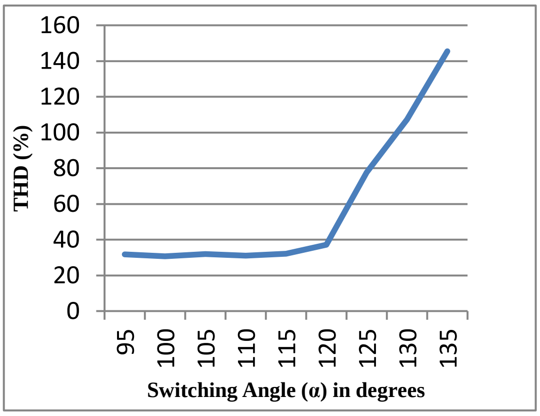

Figure 4(c). Variation of THD with switching angle for three phase 6-pulse converter

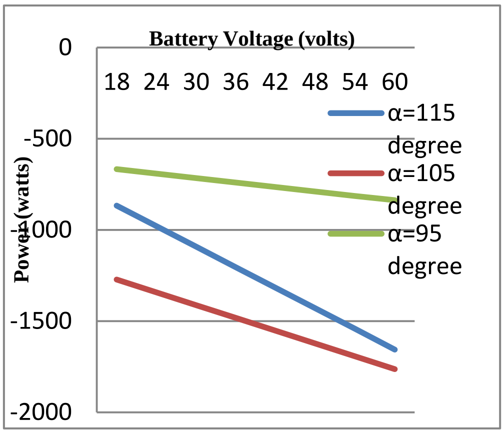

Figure 4(d). Variation of power with battery voltage at different switching angles for three phase 6- pulse converter

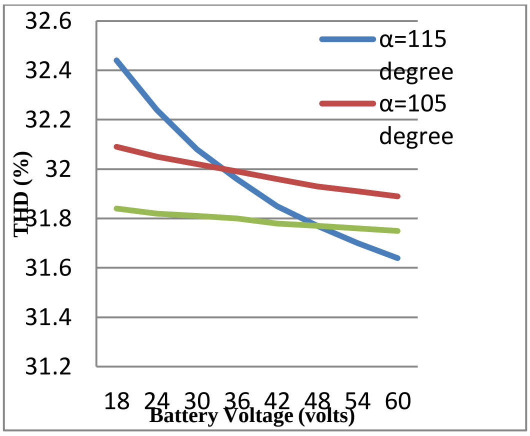

Figure 4(e). Variation of THD with battery voltage at different switching angles for three phase 6-pulse converter

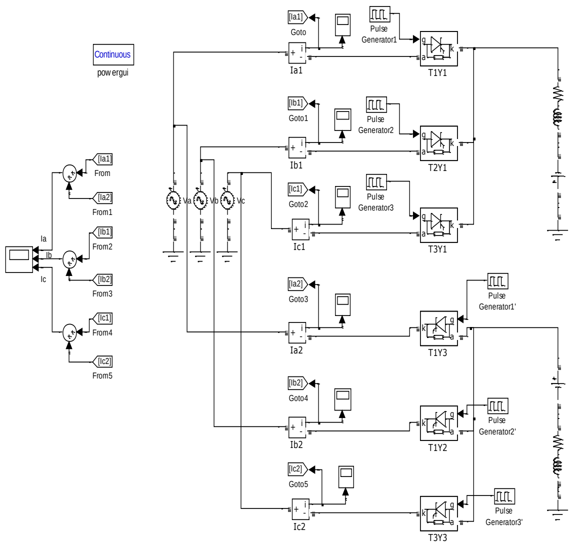

Figure 5. Simulink model of Two three-phase, half-wave, 3-pulse Converter

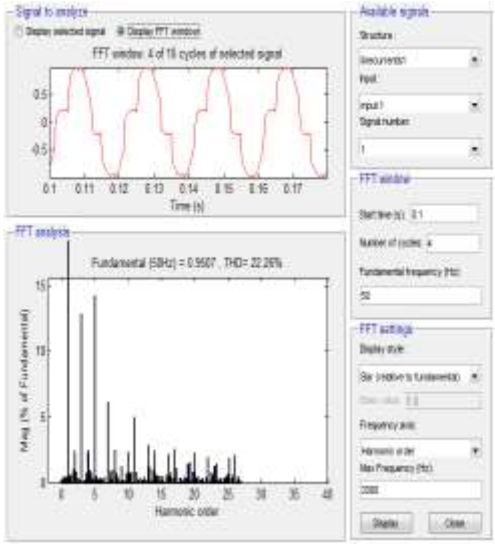

Figure 5(a). Line current with THD and harmonics at switching angle α=95° for two, three-phase, half-wave 3-pulse converter

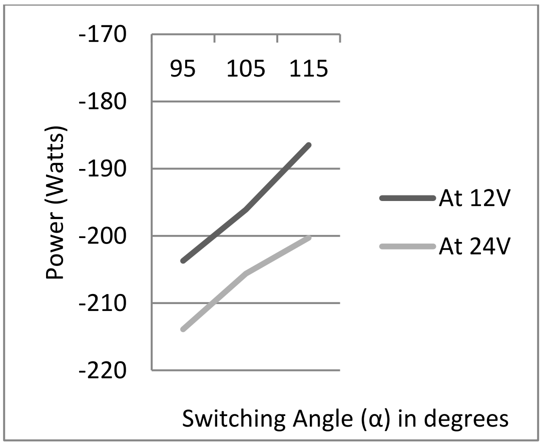

Figure 5(b). Variation of power with switching angle for two three phase half wave 3-pulse ac to dc converter

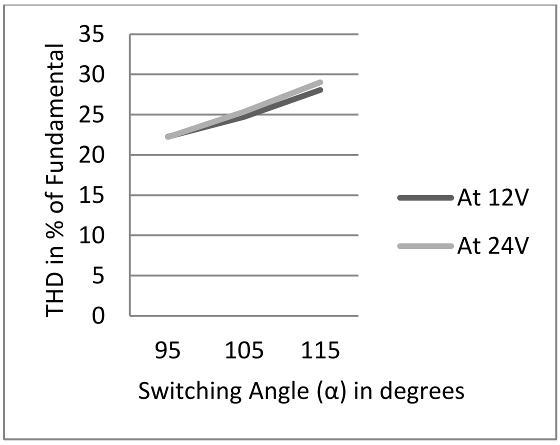

Figure 5(c). Variation of THD with switching angle for two three phase half wave 3-pulse ac to dc converter

THD and power transfer analysis is also done for 12-pulse converter for various configuration of switching angles. Figure 6 shows the simulink model of three phase, 12-pulse converter. The value of inductor is 100 mH, resistance is 10Ω and battery voltage is 24V. Figure 6(a) shows the line current with THD and harmonics for three phase 12-pulse converter for switching angle, α = 95°. Figures 6(b) and 6(c) show the variation of power and THD with various switching angles for three-phase, 12-pulse converter, respectively. It is evident from Figures 6(b) and 6(c) that for increasing switching angle the power transfer to grid initially increases then its decreases and THD remains almost constant upto 115°. Thereafter it increases rapidly and therefore a suitable compromise is made for selecting switching angle. Figures 6(d) and 6(e) show the variation of power and THD with battery voltage at different switching angles for three-phase, 12-pulse converter. As the battery voltage increases power transfer to grid increases and the THD decreases. However at α=115° results are satisfactory as the power transferred to grid increases rapidly.

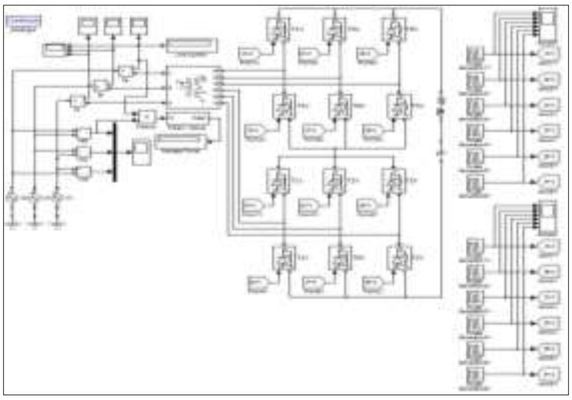

Figure 6. Simulink model of three phase, 12-pulse converter

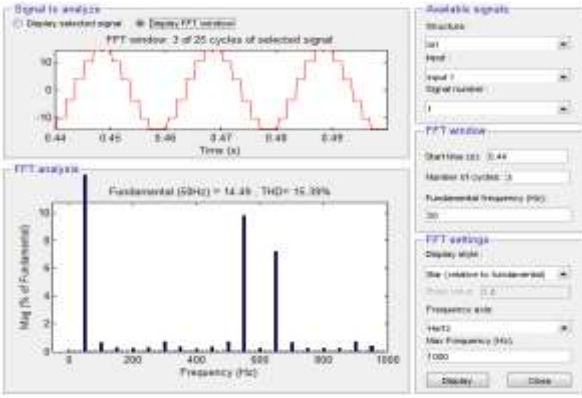

Figure 6(a). Line current with THD and harmonics for three phase 12-pulse converter

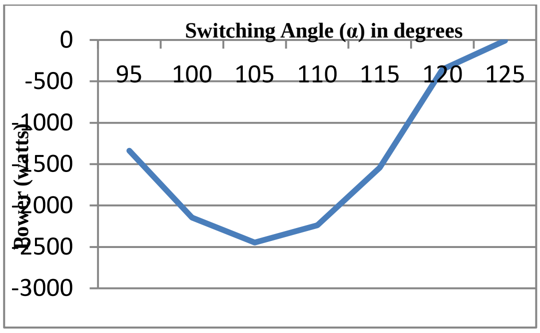

Figure 6(b). Variation of Power with switching angle for three-phase, 12-pulse converter

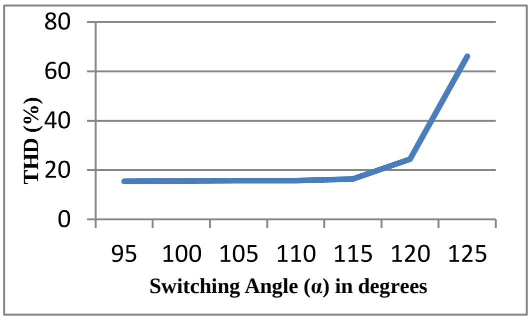

Figure 6(c). Variation of THD with switching angle for three-phase 12-pulse converter

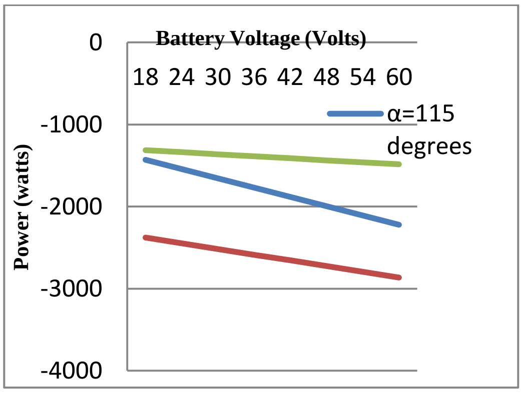

Figure 6(d). Variation of power with battery voltage at different switching angles for three-phase, 12-pulse converter

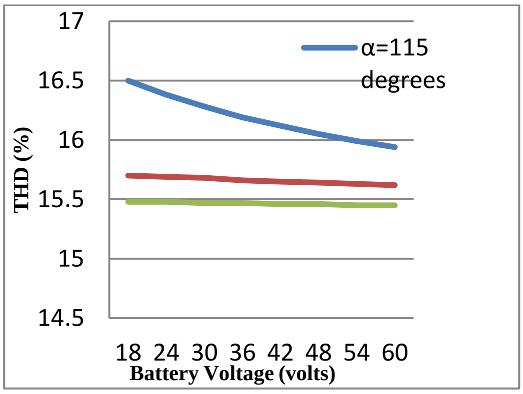

Figure 6(e). Variation of THD with battery voltage at different switching angles for three-phase, 12-pulse converter

To reduce the harmonics of the line current, passive filters can be used. When a three phase filter is added on the grid side, THD reduces drastically. These filters are shunt elements that are used in power systems for decreasing voltage and current distortion and for power factor correction. Harmonic filters reduce distortion by diverting harmonic currents in low impedance paths. The filters are built up from passive RLC components. Their values can be computed using nominal reactive power, tuning frequencies and quality factor. Here a combination of four types of filters are used in parallel, The filter set is made of the following four components providing a total of 4 Kvar, 1 Kvar C-type high-pass filter tuned to the 3rd harmonic (F1), 1

Kvar double-tuned filter tuned to the 11/13th (F2), 1 Kvar high-pass filter tuned to the 24th (F3) and 1Kvar capacitor bank. For C-type high pass filter, nominal reactive power, tuning frequency and quality factor are 1 kvar, 150Hz and 2 respectively. These values for doubled tuned filter are 1kVar, (550Hz and 650 Hz) and 20 respectively whereas for high pass filter are 1kVar, 1200 Hz and 7 respectively. Figure 7 shows the simulink model of the filter whereas figure 7(a) shows the line current with THD and harmonics for three-phase 12-pulse inverter with three phase harmonic filters. It is evident that THD reduces drastically. Figure 7(b) and 7(c) show the three-phase line current on the grid side without filters and with filters respectively.

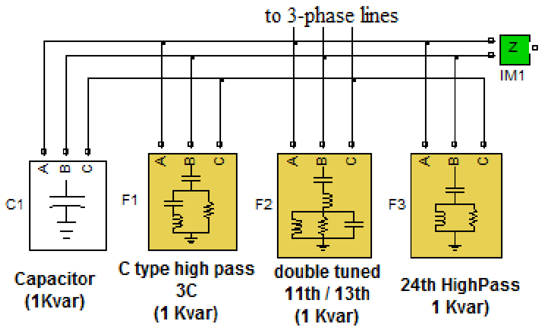

Figure 7. Simulink model of filters

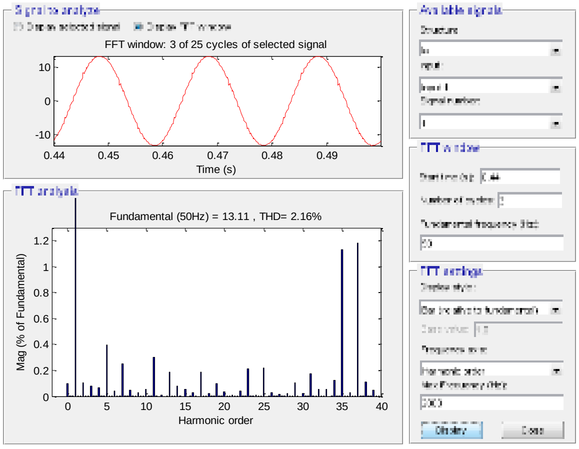

Figure 7(a). Line current with THD and harmonics for three- phase12-pulse converter with three-phase harmonic filters

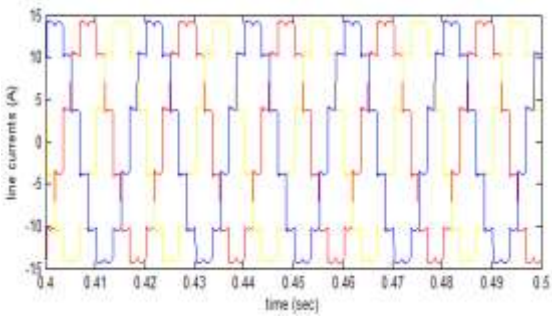

Figure 7(b). Line current for three phase 12- pulse converter

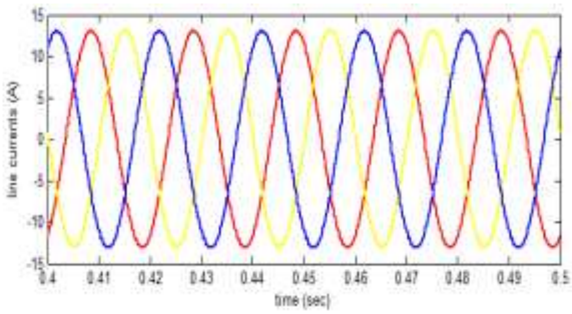

Figure 7(c). line currents for three-phase 12-pulse converter with three-phase harmonic filters

Table-5 shows the comparison of THD and power delivered to grid at different load conditions for 6-pulse, two 3-pulse and 12-pulse converters. On decreasing the load, THD gradually increases and power delivered decreases too for 6-pulse and 12-pulse converters whereas for two 3-pulse converter both THD and power delivered decreases. For the same load resistance, a 12-pulse converter shows better result than two 3-pulse converter and 6-pulse converter. However Two 3-pulse converter shows better performance than a 6-pulse converter. For $\alpha=95^{\circ}$, battery voltage=24V, R=50Ω, THD is 36.04%, 26.65%, 16.75% for 6-pulse converter, two 3-pulse converter and for 12-pulse converter, respectively. On increasing the switching angle, THD increases for 6-pulse and 12-pulse converters whereas for two 3-pulse converter THD decreases.

Table 5. Comparison of 6-pulse, two half-wave, 3-pulse and 12-pulse converter for variation of power transferred to grid and THD of line current for different battery voltage, load resistance and switching angles

Switching angle	Battery voltage	Load resistance	6-pulse Converter (3 level)		Two 3-pulse converter (3 level)		12-pulse converter (6 level)	
			THD in %	Power (watt)	THD	Power	THD	Power
95	12	5	31.35	-595.1	29.96	-8549	15.32	-2639
		10	31.45	-269.5	31.14	-4277	15.29	-1288
		20	32.40	-104.8	29.36	-2142	15.76	-608.6
		30	33.68	-49.17	28.90	-1433	16.09	-381.1
		40	34.99	-20.72	28.25	-1080	16.30	-266.9
		50	36.49	-3.263	27.59	-869.1	16.81	-198.2
	24	5	31.20	-640.3	28.88	-9057	15.12	-2738
		10	31.53	-292	29.08	-4531	15.37	-1337
		20	32.82	-116.1	28.66	-2269	15.51	-633.3
		30	33.94	-56.76	28.16	-1517	16.06	-397.6
		40	34.36	-26.35	27.62	-1143	16.15	-279.3
		50	36.04	-7.782	26.65	-919.9	16.75	-208.1
105	12	5	31.23	-1199	33.27	-7856	15.21	-4651
		10	32.31	-571.4	31.97	-3932	15.50	-2295
		20	33.93	-256.6	32.99	-1973	16.09	-1111
		30	36.43	-149.3	30.65	-1322	16.75	-715.9
		40	39.27	-95.53	29.70	-999	17.80	-517.9
		50	42.59	-62.81	29.22	-806.2	18.26	-399
	24	5	31.17	-1334	32.28	-8329	15.15	-4921
		10	31.79	-639.5	31.28	-4169	15.46	-2430
		20	33.72	-289.6	31.32	-2091	15.96	-1179
		30	35.65	-172	31.32	-1401	16.83	-761.2
		40	38.06	-112.6	29.41	-1058	17.22	-551.9
		50	40.95	-76.42	29.12	-853.6	17.94	-426.2
115	12	5	32.97	-794.7	37.90	-7008	15.93	-2875
		10	35.55	-367.9	37.72	-3511	16.61	-1403
		20	42.90	-153.1	36.13	-1765	18.69	-664.4
		30	52.13	-80.9	35.51	-1187	21.18	-418.3
		40	62.42	-45.54	34.58	-899.8	23.65	-295.3
		50	69.86	-28.27	33.83	-729	26.41	-221.6
	24	5	32.43	-1014	36.82	-7439	15.82	-3314
		10	34.36	-477.6	37.16	-3726	16.45	-1623
		20	39.56	-207.9	38.88	-1873	18.33	-774.7
		30	46.35	-117.5	35.23	-1259	20.08	-491.8
		40	53.90	-71.84	34.24	-953.7	22.22	-350.5
		50	62.80	-44.78	33.52	-772.1	24.50	-265.8

5. CONCLUSION

In this paper, simulation analysis of three-phase 6-pulse, Two three-phase, half-wave, 3-pulse and 12-pulse converter is successfully done. THD and power transfer analysis is done for various combinations of switching angles α, battery voltage and load resistance. It is evident from the results that on increasing the switching angle THD gradually increases for 6-pulse and 12-pulse converter whereas for two 3-pulse converter THD decreases. However, on increasing the battery voltage, power transfer to grid increases and the THD decreases. From the results shown in this paper, it is concluded that for three phase 6-pulse converter, THD of line current comes out to be 31.54 % in comparison with 15.39 % for three-phase, 12-pulse converter at switching angle $\alpha=95^{\circ}$ whereas THD of line current for two three-phase, half-wave, 3-pulse is 22.21 %. Therefore, two 3-pulse converter have good result than 6-pulse converter. THD of line current decreases drastically for twelve pulse converter in comparison with 6-pulse and two 3- pulse converter. On adding harmonic filters on the grid side, THD of 12-pulse converters reduces drastically to 2.16 %. Thus this circuit topology can be used for solar PV based grid-tie inverters.

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