Design and Control of a Diode Clamped Multilevel Wind Energy System Using a Stand-Alone AC-DC-AC Converter

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Abstract-

The major application of the stand-alone power system is in remote areas where utility lines are uneconomical to install due to terrain, the right-of way difficulties or the environmental concerns. Villages that are not yet connected to utility lines are the largest potential market of the hybrid stand-alone systems using diesel generator with wind or PV for meeting their energy needs. The stand-alone hybrid system is technically more challenging and expensive to design than the grid-connected system that simply augments the existing utility system. This paper presents a regulated AC/DC/AC supply to convert wind energy to stand alone system.

Multilevel inverter technology has emerged recently as a very important alternative in the area of high-power medium-voltage energy control. The topology of the diode-clamped inverter is presented with the relevant control and modulation method developed for this converter, which is: multilevel selective harmonic elimination, where additional notches are introduced in the multi-level output voltage. These notches eliminate harmonics at the low order/frequency and hence the filter size is reduced without increasing the switching losses and cost of the system. The proposed modulation method is verified through simulation using a five-level Diode-clamped inverter prototype. The harmonic of the supply generator current affect the electromechanical torque which has an impact on the vibration of the wind turbine. A multiphase transformer is designed to eliminate lower order harmonics of the generator current.

The system consists of a wind-driven permanent magnet synchronous generator whose output is stepped down via a multiphase transformer, whose secondary voltages are rectified through an uncontrolled AC/DC converters to provide different input DC voltage levels to the diode clamp quazi phase multilevel inverter where the pulse widths are adjusted to eliminate low order harmonics of the output voltage whose magnitude is kept constant with different loading condition by controlling the inverter switching and maintaining low total harmonic distortion THD.

Keywords- Selective Harmonic Elimination; stand alone systems; converters; wind energy; renewable energy and Diode clamped Multilevel Inverter.

I. INTRODUCTION

In this paper a regulated AC-DC-AC converter to supply a stand-alone system from a wind power small turbine is studied, where the AC-DC converter has lower THD while the elimination of harmonics using diode-clamped multilevel inverter (DCMLI) has been implemented. The problem of eliminating harmonics in switching inverters has been the focus of research for many years. The current trend of modulation control for multilevel inverters is to output high quality power with high efficiency. For this reason, popular traditional PWM modulation methods are not the best solution for multilevel inverter control due to their high switching frequency. The selective harmonic elimination method has emerged as a promising modulation control method for multilevel inverters. This method is used to eliminate lower order harmonics. The diode clamped inverter has drawn much interest because it needs only one common voltage source. Also, it is efficient, even if it has inherent unbalanced dc-link capacitor voltage problem [1]-[2]. By increasing the number of levels in the inverter, the output voltages have more steps generating a staircase waveform, which has a reduced harmonic distortion [3]-[9].

The system configuration, as shown in Fig.1, is made-up of wind stand-alone system, multi-phase transformer connected to pulse series-type diode rectifier, dc link filters, diode clamped multilevel inverters, trap filters, and the load.

An interior permanent magnet synchronous generator IPMSG is feeding a multi-phase transformer with four secondary windings specially designed to reduce the generator current THD. Consequently, each winding of the transformer is connected to 6-pulse diode rectifier whose DC output is regulated by a DC link LC filter to feed a diode clamped inverters which are controlled independently in order to improve the performance under different load conditions. The output voltage of the inverter is supplying a three-phase 380V, 60kVA load with regulated voltage through a feedback signal from output load voltage to control the pulse width of the DCMLI upper transistor.

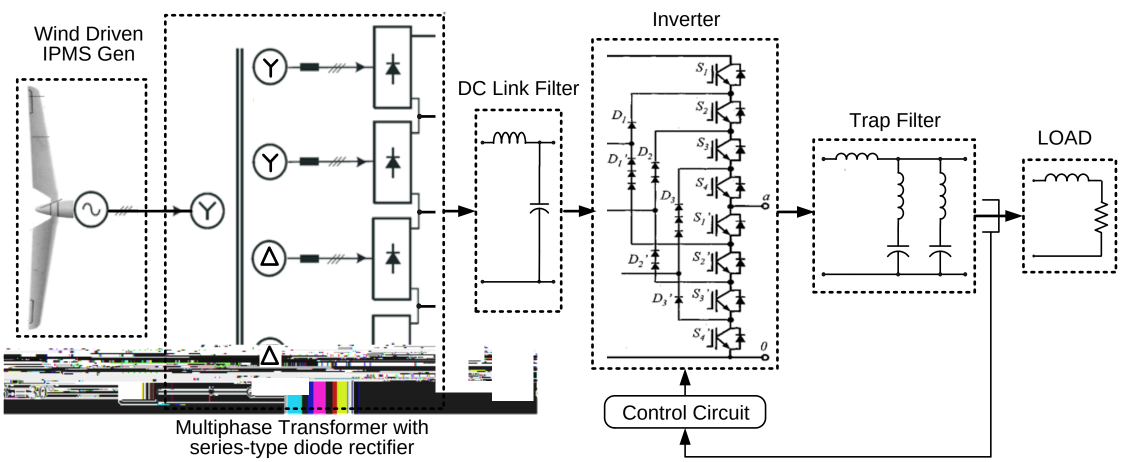


Fig.1. Diode clamped multilevel wind energy system using a stand-alone AC-DC-AC converter system.

II. WIND DRIVEN IPMSG

For a small hybrid system supplying local loads, a permanent magnet IPMSG makes a wind system simple and easier to operate. The battery is charged by an AC to DC rectifier and discharged through a DC to AC inverter.

The wind stand-alone power system is often used for powering farms. The generalized d-q axis model of the generator is used to model the 690V, 120 low speed RPM, 16 poles, 80KVA, 0.85 pf IPMSG [10].

III. MULTI-PHASE TRANSFORMER CONNECTED TO 6-PULSE DIODE RECTIFIER

Fig. 2 shows the typical configuration of the phase-shifting transformers with two secondary windings. To eliminate low-order harmonics in the line current i_A, the line-to-line voltage v_{ab} of the wye-connected secondary winding is in phase with the primary voltage v_{AB} while the delta-connected secondary winding voltage $v_{\tilde{a}\sim b}$ leads v_{AB} by $\delta = 30°$. The rms line-to-line voltage of each secondary winding is $V_{ab} = V_{\tilde{a}\sim b} = H\, V_{AB}/2$. From which the turns ratio of the transformer can be determined by [11]:

$\frac{N_1}{N_2} = 2H$ and $\frac{N_1}{N_3} = \frac{2}{\sqrt{3}}H$, where H is the effective turns ratio to step down the 690 generator voltage to 380 load voltage and to obtain different dc voltage level to feed the DCMLI.

At any time instant, the dc current i_d flows through four diodes simultaneously, two in the top six-pulse rectifier and two in the bottom rectifier. The dc current ripple is relatively low due to the series connection of the two six-pulse rectifiers. The waveform of the line current i_a in the wye-connected secondary winding looks like a trapezoidal wave with four humps on the top. The waveform of $i_{\tilde{a}}$ in the delta-connected winding is identical to i_a except for a 30° phase displacement. The currents i_a and $i_{\tilde{a}}$ in Fig. 2 are the secondary line currents i_a and $i_{\tilde{a}}$ referred to the primary side. Since both primary and top secondary windings are connected in wye, the waveform of the referred current i_a is identical to that of i_a except that its multiplied the turns ratio of the two windings. When $i_{\tilde{a}}$ is referred to the primary side, the referred current $i_{\tilde{a}}$ does not keep the same waveform as $i_{\tilde{a}}$. The changes in waveform are caused by the phase displacement of the harmonic currents when they are referred from the delta-connected secondary winding to the wye-connected primary winding. It is the phase displacement that makes the 5^{th} and 7^{th}, in $i_{\tilde{a}}$ out of phase with those in i_a. As a result, these harmonic currents are canceled in the transformer primary winding and do not appear in the primary line current. The magnitude of the 5^{th} and 7^{th} harmonics is 18.6% and 12.4%, respectively, which are much higher than other harmonics. The THD of the primary line current i_A is only 8.38% in comparison to 24.1% of the secondary line current i_a. The substantial reduction in THD is owing to the elimination of dominant harmonics by the phase-shifting transformer. The input power factor PF is also improved due to the lower line current THD and higher displacement power factor.

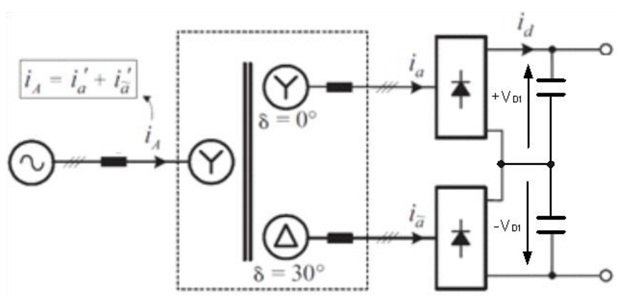


Fig. 2. Phase shifting transformer.

In the five level DCMLI, the dc bus voltage is normally equally distributed across the four capacitors to provide equally stepped $\pm V_{dc}/4$ waveform but, as will be shown, this paper proposes a selective harmonic elimination modulation using non-equal dc voltages. These voltages obtained with the help of the multiphase transformer and the series type diode uncontrolled rectifier as shown in Fig. 3, where the transformer has four secondaries such that the two coils T_1-Y and T_1-Δ has turns ratio of $2H_1$ and $2\frac{H_1}{\sqrt{3}}$ respectively resulting in dc voltage of $\pm V_{d1}$ across the 2nd and 3rd capacitors respectively an in the same time will also ensure to cancel the 5th and 7th current harmonics of the secondaries from the primary generator current, while the other two coils T_2-Y and T_2-Δ has turns ratio of $2H_2$ and $2\frac{H_2}{\sqrt{3}}$ respectively resulting in dc voltage of $\pm V_{d2}$ across the 1th and 4th capacitors respectively and again cancel the 5th and 7th current harmonics from the primary generator current.

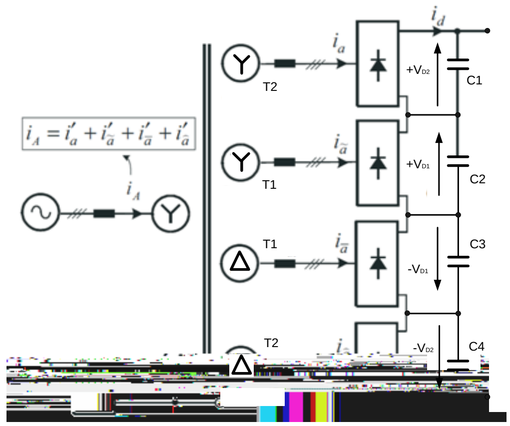


Fig. 3. 12-pulse diode rectifier.

The phase-shifting transformer is an indispensable device in multipulse diode rectifiers. It provides three main functions: (a) a required phase displacement between the primary and secondary line-to-line voltages for harmonic cancellation, (b) a proper secondary voltage, and (c) an electric isolation between the rectifier and the utility supply [11].

IV. DIODE-CLAMPED MULTILEVEL INVERTER

The diode-clamped inverter, or the neutral-point clamped (NPC) inverter, effectively doubles the device voltage level without requiring precise voltage matching [12]. Fig. 4 shows a five-level diode-clamped converter in which the dc bus consists of four capacitors, C_1, C_2, C_2, and C_4. For dc-bus voltage the voltage across each capacitor is $+V_{d2}$, $+V_{d1}$, $-V_{d1}$, and $-V_{d2}$ respectively [13]-[15].

Considering the neutral point *n* as the output phase voltage reference point, there are five switch combinations to synthesize five level voltages across *a* and *n*.

1. For voltage level $V_{an} = V_{d1}+V_{d2}$, turn on all upper switches S_1–S_4.
2. For voltage level $V_{an} = V_{d1}$, turn on three upper switches S_2–S_4 and one lower switch S_1'.
3. For voltage level $V_{an} = 0$, turn on two upper switches S_3 and S_4 and two lower switches S1'and S2'.
4. For voltage level $V_{an} = -V_{d1}$, turn on one upper switch S_4 and three lower switches S_1' – S_3'.
5. For voltage level $V_{an} = -V_{d1}-V_{d2}$, turn on all lower switches S_1' – S_4'.

Therefore, the voltage levels of the staircase are determined by the capacitor voltages while the time periods of the output waveform are determined by the switching sequence of the transistors.

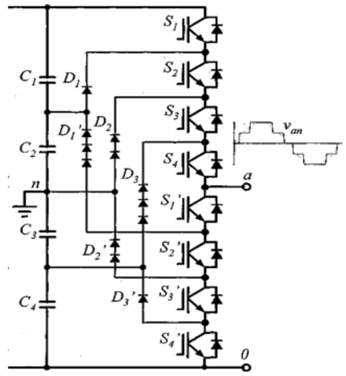


Fig. 4. Diode-clamped five-level multilevel inverter circuit topologies.

V. DETERMINATION OF OUTPUT WAVEFORM SHAPE

The concept of the proposed technique is to apply the Selective Harmonic Elimination (SHE) method which introduces additional notches in the basic voltage waveform of the square wave inverter. The inverter output voltage is “chopped” a number of times at an angle(s) to eliminate the selected harmonic(s) [16]-[19]. These angles are calculated in off-line correlating the selected harmonics to be eliminated in the inverter output voltage [20].

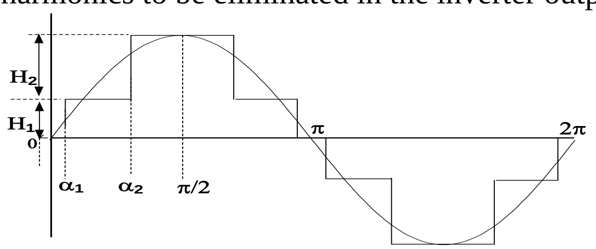


Fig. 5. Output voltage waveform of a diode clamped inverter.

The output voltage waveform V(t) shown in Fig. 5 can be expressed in Fourier series as [21]:

$$V(t) = \sum_{n=1} V_n \ \sin n \ {}_{n} \qquad (1)$$

The amplitude of the n^{th} harmonic is expressed only with the first quadrant switching angles α_1, α_2, as:-

$$V_n = \frac{4V_{dc}}{n}\left[H_1(\cos n\alpha_1) + H_2(\cos n\alpha_2)\right] \qquad (2)$$

Where $0 < \alpha_1 < \alpha_2 < \frac{\pi}{2}$

V_n is equated to zero for the harmonics to be eliminated [21], rather than the tripplen harmonics which are normally zero, as follows:

$$V_5 = 0 = H_1(\cos 5\alpha_1) + H_2(\cos 5\alpha_2) \qquad (3)$$

$$V_7 = 0 = H_1(\cos 7\alpha_1) + H_2(\cos 7\alpha_2) \qquad (4)$$

$$V_{11} = 0 = H_1(\cos 11\alpha_1) + H_2(\cos 11\alpha_2) \qquad (5)$$

Also, $H_1 + H_2 = 1$ (6)

Solving these four equations together using MATHCAD software, the value of H_1, H_2, α_1, and α_2 can be obtained as shown in table 1. Having got the values of the angles α and DC voltage heights H, the spectrum analysis using Fourier Transformation for the output voltage can be obtained. This voltage waveform of Fig. 5 is determined by four parameters; 1) the two heights H_1 and H_2 which are determined by a proper design to the turns ratio of multiphase transformer, as shown in section (III), (2) the two switching angles α_1 and α_2 which are determined by a proper design to the switching sequence of the inverter transistors.

TABLE I

$_1$ = 11°;	$_2$ = 35°;
H_1 = 0.63;	H_2= 0.37;

VI. VOLTAGE CONTROL OF THE OUTPUT WAVE

The voltage waveform, shown in Fig. 5, is a fixed operating point designed specifically for the full load condition. For other practical loads, this specific voltage waveform will result in effective higher voltage rating across the load because the voltage drop across the system wiring cables will decrease. Therefore, the effective RMS value of the voltage wave of Fig. 5 should decrease. A simple method for implementation is proposed, where the two heights H_1 and H_2 are constants because simple uncontrolled rectifiers in the AC/DC converter are used. Also, the angle $_1$ will be kept constant while the angle $_2$ is only increased between 35° and 90° to effectively decrease the no load voltage across the inverter resulting in almost constant voltage across the load. Therefore, an error signal between the command reference voltage and the feedback signal from the output voltage is used to regulate the voltage across the load.

VII. TRAP FILTERS

To attenuate the penetration of harmonics into the a.c system, harmonic filters can be connected to the neutral from each line as shown in Fig. 6. For the proposed SHE modulation technique tuned harmonic filters are designed for the 13th and 17th harmonic components.

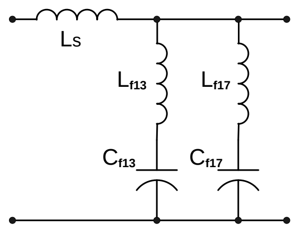


Fig. 6. Harmonic trap filter.

When, trap filters are designed to eliminate the 13th harmonic, they provide a low impedance path for that harmonic [22] such that $13\omega L_f = \frac{1}{13\omega C_f}$

VIII. SIMULATION

The 60 KW, 380V, stabilized AC-DC-AC power supply used is shown in Fig. 7 which consists of a step down transformer with one primary and four secondary coils, followed by an uncontrolled rectifier and then a dc link low pass filter, therefore, two different DC voltages are obtained V_{d1} and V_{d2}. Each DC voltage is feeding a quazi-single inverter whose angles are $_1$, and $_2$ which are clamped to get the required wave form. A load voltage feedback control signal in order to maintain the voltage of the load constant irrespective of the loads variations by the system has been tested from 10% to 20% of full load at time t = 0.9s, from 80% to 100% of full load at time t = 1.9s, and from 100% to 110% of full load at time t = 2.9s. The transient response results are shown in Fig. 8.

The value of the series inductance of the trap filter is 2mH, while that of the parallel inductance of the 13th harmonic is 0.002H, and it has a capacitance of 19.2μF. While the inductance and capacitance of the 17th harmonic is 0.0013H and 19.2μF respectively. The value of the inductances of the four DC link filters is the same 5mH, while their capacitances are 8800 μF.

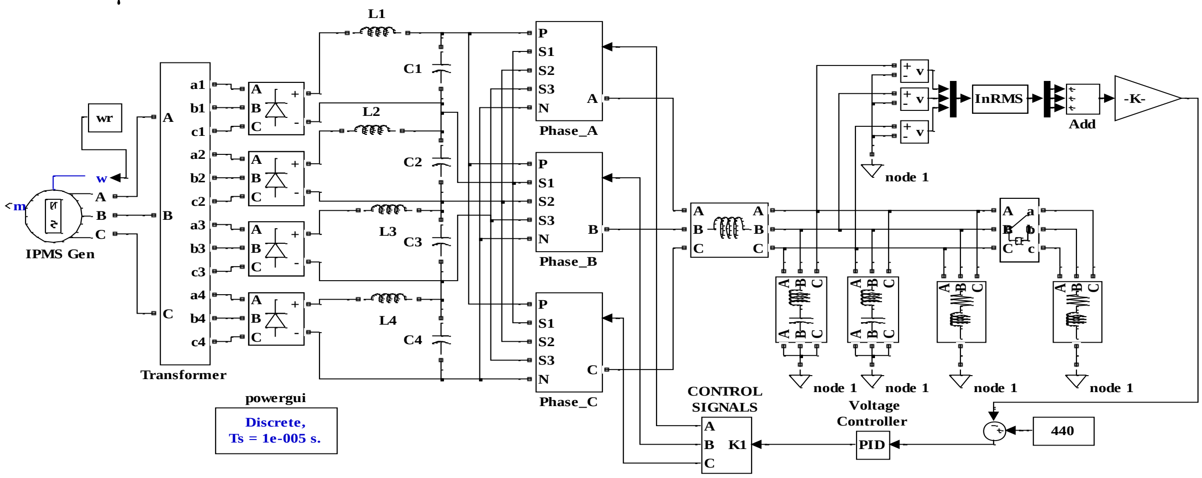
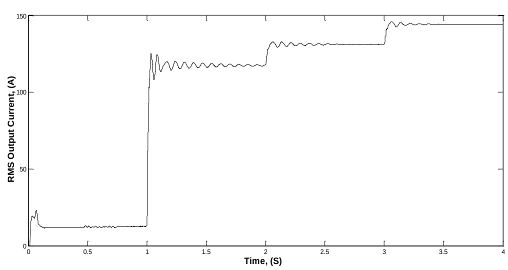
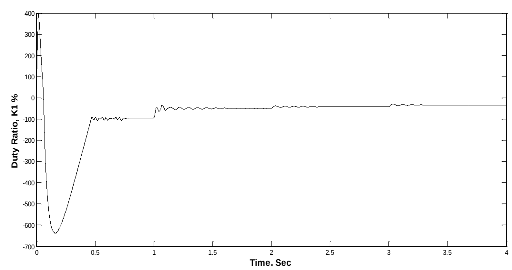


Fig. 7. Simulink block diagram.

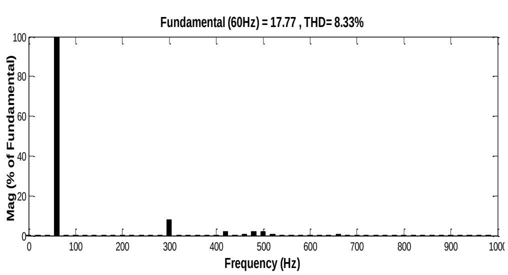


(a)

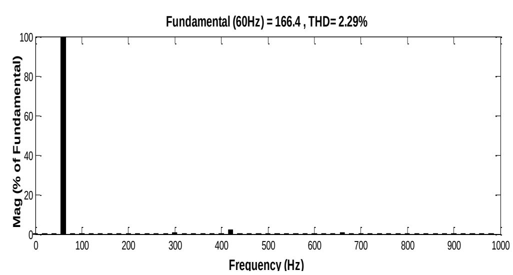


(b)

Fig. 8. (a) RMS output current, (b) Duty ratio H_1.



(a)



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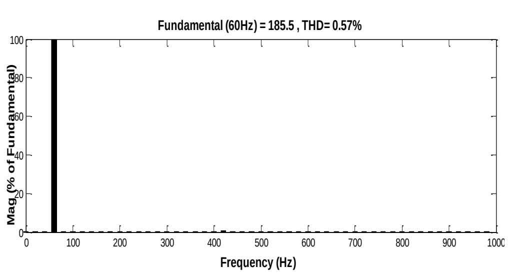
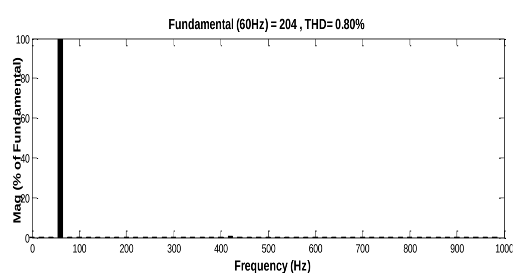


(c)



(d)

Fig. 9. Spectrum analysis of O/P current at: (a) 10%, (b) 80%, (c) 100%, (d) 110% of the load.

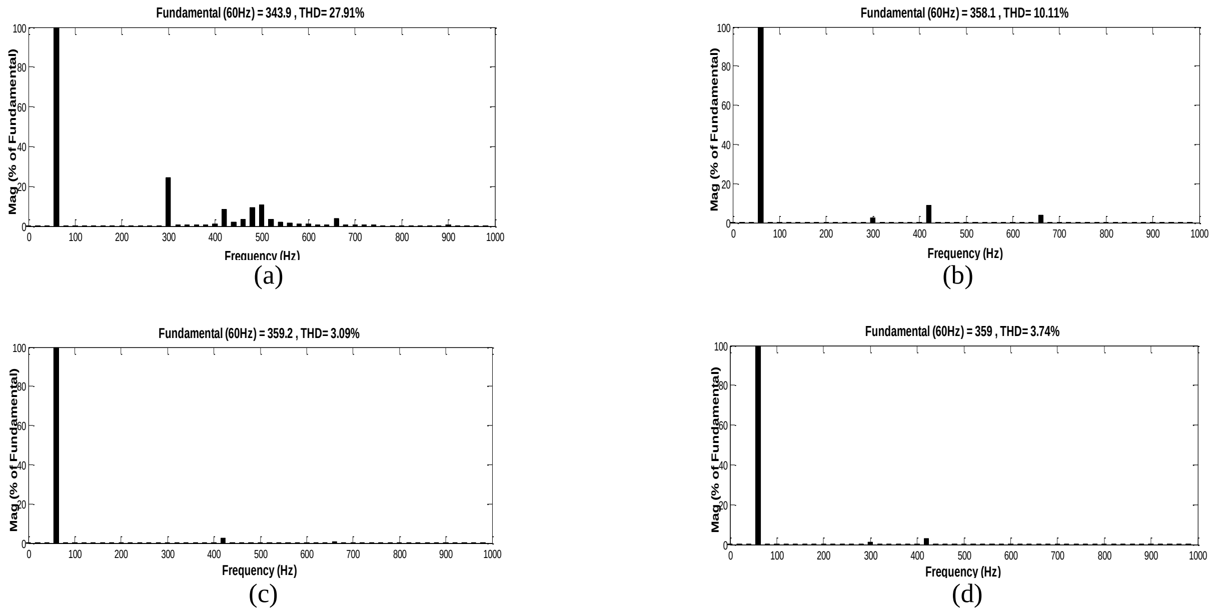


Fig. 10. Spectrum analysis of O/P voltage at: (a) 10%, (b) 80%, (c) 100%, (d) 110% of load.

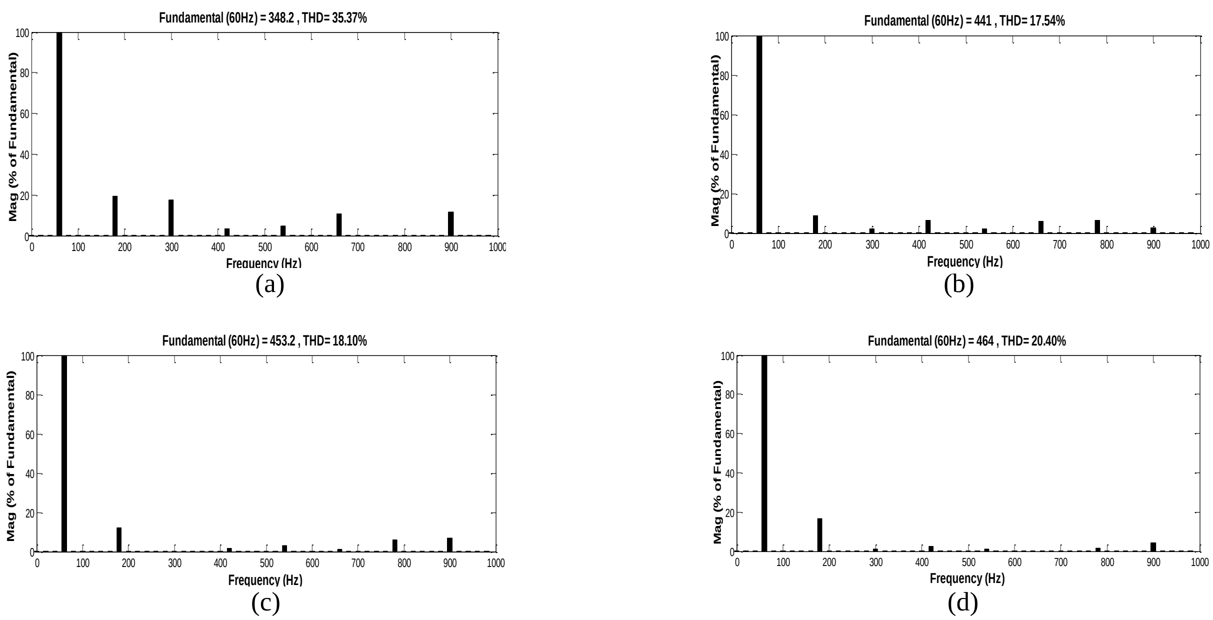


Fig. 11. Spectrum analysis of Strain voltage at: (a) 10%, (b) 80%, (c) 100%, (d) 110% of the load.

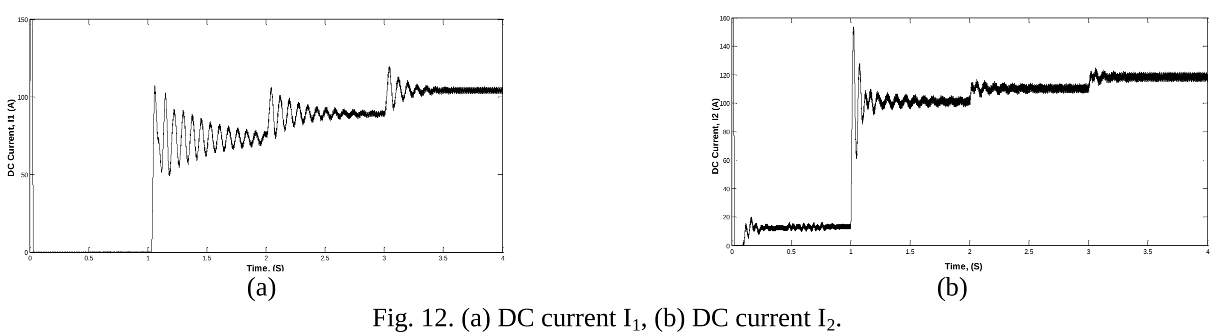


Fig. 12. (a) DC current I_1, (b) DC current I_2.

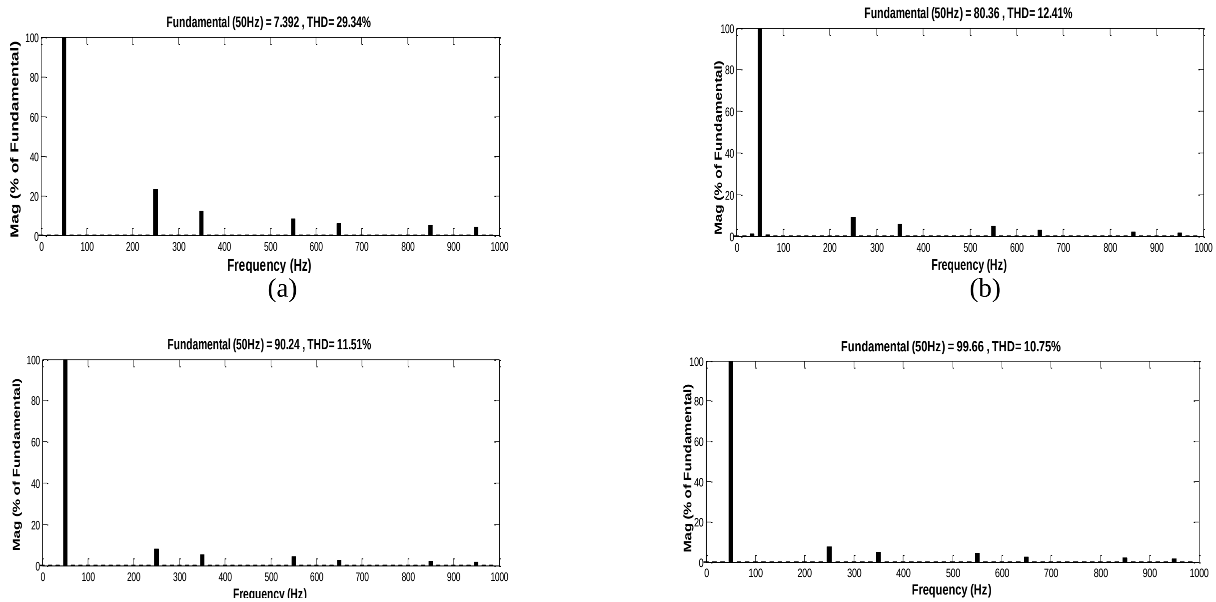


Fig. 13 Spectrum analysis of input current at: (a) 10%, (b) 80%, (c) 100%, (d) 110% of the load.

The results of Fig. 8 to Fig. 13 show that the effectiveness of this AC/DC/AC converter to supply a regulated AC voltage regardless of the load changes with low THD.

IX. CONCLUSION

The proposed selective harmonic elimination method for DCMLI has been validated in simulation. The simulation results show that the proposed algorithm can be used to eliminate number of specific lower order harmonics effectively and results in a dramatic decrease in the output voltage THD.

A high performance static AC-DC-AC converter is designed. The controller has a good control property. The system topology adopts two single-phase diode clamped inverters such that they are controlled independently in order to improve the performance under different load conditions. With the help of the developed algorithm, the switching angles are computed from the non-linear equation characterizing the Selective Harmonic Elimination problem to contribute minimum THD in the output voltage waveform. Therefore, the lower order harmonics like 5th, 7th, 9th, 11th, while two trap filters are used to eliminate the 13th , and 17th and higher-order harmonics are optimized.

From the simulation results, it can be noted that the phase-shifting transformer is an indispensable device in multipulse diode rectifiers. Also, it is clear that the trap filters are provided to eliminate the 13^{th} and 17^{th} harmonic components.
The inverters are diode clamped together to result in an output voltage free of 5^{th}, 7^{th}, 9^{th}, and 11^{th} harmonics. The result showed that the output voltage resulted in an almost sinusoidal current.

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