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Three Phase Space Vector PWM Based Multilevel Inverter for Pumping Applications

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Abstract:
This paper presents a three phase modular multilevel inverter (MMLI) topology with reduced number of sources, switches and eliminates the need of flying capacitors and its associated problems like capacitor unbalancing, capacitor overcharging bulky size, cost etc. The switching pulses for the MMLI are generated through space vector modulation (SVM) algorithm for reduced harmonic distortion (HD) in output voltage and current. The MMLI consists of basic three phase two level inverter with additional bidirectional modules in each phase. The bidirectional module consists of four diodes and a switch that can conduct in both directions. This topology can be easily extended for higher output levels with appropriate number of modules in each phase. Theoretical description is given for five level MMLI and results are presented for 11- level MMLI feeding an induction motor suitable for pumping applications. Also, the reliability of the inverter is tested for two conditions open circuit and short circuit of a phase in a module.

Keywords: *MMLI; Space vector PWM; Pumping applications.*

I. INTRODUCTION

Utilizing renewable energy resources for various applications like drives, electric vehicles, standalone applications etc., has been an interesting area for researchers. With the advancement in power semiconductor technology and caution towards global warming various photovoltaic (PV) based systems has been proposed in the literature [1-4]. Some researchersconcentrated on DC-AC conversion topologies for PV based applications [5,6,7,8].Numerous MLI topologies are proposed in the literature with reduced switch count, voltage stress, total harmonic distortion (THD) [9,10,11]. Among them the traditional topologies are neutral point clamped (NPC)[12], flying capacitor(FC)[13] and cascade H bridge inverter(CHB)[14] topologies with each having their own merits and limitations. These three basic topologies has one common drawback that these requires more number of switches, *2(n-1)* switches per phase, where *n* is the output level of the pole voltage. For the proposed MMLI the number of switches required per phase is *n*. In [15] a MLI with single dc source is proposed which requires capacitors whose number increases with output level. In [16,17]aMMLI converter is proposed, but failure of one module can't provide reliable operation and number of increases with increase in the number of levels.In [18] a multilevel medium frequency link inverter for utility scale applications is proposed withmore components.In [19] a hybrid multilevel converter with cascaded H-bridge cells is proposed with series connected cells with each cell containing one capacitor and four switching devices and generates 12 level output voltage with 144 switches and 35 electrolytic capacitors which increases the sizeand cost. In [20,21,22] SVPWM algorithms for MLI are proposed. The algorithms are complex and are not feasible to extend for higher output levels.

The main objective of this paper is to implement a PV system feeding Space vector PWM based MMLI for induction motor drive used for pumping applications. The present topology mitigates the problems foreseen by the conventional topologies by offering a reliable performance during normal and faulty conditions. Also the switch count, capacitor balancing problems are not present with the proposed scheme. The performance of the proposed SVPWM based MMLI is tested for 11- level output pole voltage. The phase voltages generated are fed to a three phase induction motor to validate the suitability of the inverter for pumping applications. The details of the proposed work is organized in sections as follows: First section describes the basic equations for the design of a PV system, second section deals with working of the proposed MMLI, third section deals with Space vector PWM algorithm for the proposed MMLI, fourth section presents simulation results to validate the performance of the drive with the proposed scheme under normal and fault conditions. The validation of the results is done by comparing the THD in voltage and current waveforms with the conventional NPC MLI.

II. Design of PV System

The PV system is designed with number of cells connected in series to form PV module. Individual PV modules are connected in series and parallel to obtain the necessary current and voltages of the load. The PV cell can be developed as in[23] with the current and voltage equations as in Eq.(1) and Eq.(2) respectively.

$$\mathrm{I} = I_{ph} - I_o * \exp\left[\left(\frac{\mathrm{q}(\mathrm{V}+\mathrm{I}R_s)}{\mathrm{AK}T_c}\right) - 1\right] - \left[\frac{\mathrm{V}+\mathrm{I}R_s}{R_{sh}}\right] \quad (1)$$

$$\mathrm{V} = \frac{\mathrm{AK}T_c}{\mathrm{q}} \ln\left[\frac{I_{ph}+I_o-\mathrm{I}}{I_o}\right] - \mathrm{I}R_s \quad (2)$$

Here, I is the cell output current in amps, $I_{ph}$is photo current in ampere, q is the electron charge which is equivalent to 1.602e-19 C, k is the Boltzmann constant(1.38e-23 J/^{0}K, V is the output cell voltage in volts, T_c is the cell operating temperature in o_K and A is the diode idealistic factor.

III. Proposed Modular Multilevel Inverter Topology

Fig. 1 shows the proposed MMLI topology for *n*-level inverter. To synthesize n-level output MMLI needs *(n–1)* dc sources, *(n–2)* modules per phase, in addition to six main switches that are there in conventional two-level inverter.

The advantage of having *'n–1'* dc sources in place of a single voltage source of higher rating*(n–1) E*is that, it can be easily generated through four PV modules in series each consisting of 36 series connected cells. A single module which performs the operation of a bidirectional switch consists of a single switching device with four diodes connected as shown in Fig.1(b).The diodes D_1 and D_2 allow forward conduction of current from source to load and diodes D_3 and D_4 aids current path from load to source. Table 1gives the generalized expressions for pole voltage levels and their corresponding switching states of switches in each module of a phase.

The operation of the proposed MMLI is explained with reference to a five level MMLI shown in Fig.2.

It consists of four equal dc sources, three modules and two main switches per phase. The position of the switch is indicated as 1 which ⇒ switch ON and as 0 which ⇒ switch OFF states.

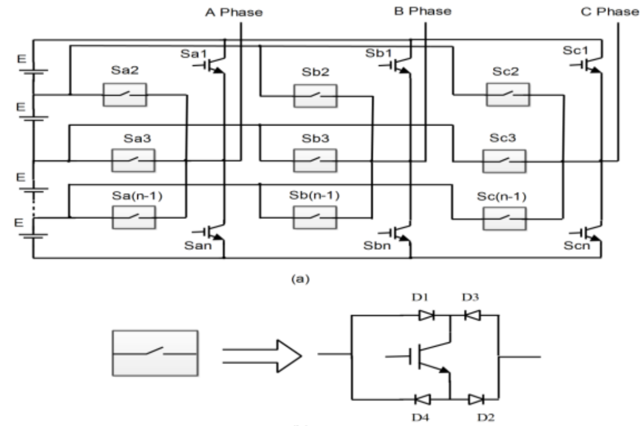

Fig.1. (a) *n*- level inverter (b) Modular switch

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TABLE I
Switching States, Switch position and the Corresponding Output Pole Voltages

Switching States	Switches						Pole voltage	
	Sa1	Sa2	Sa3	…	Sa(n-1)	San	n is ODD	n is EVEN
n–1	1	0	0	….	0	0	$\left(n-\frac{n+1}{2}\right)E$	$\left(n-\frac{n}{2}\right)E$
n–2	0	1	0	….	0	0	$\left(n-\frac{n+1}{2}-1\right)E$	$\left(n-\frac{n}{2}-1\right)E$
n–3	0	0	1	….	0	0	$\left(n-\frac{n+1}{2}-2\right)E$	$\left(n-\frac{n}{2}-2\right)E$
…..	…..	….	….	….	….	….	…..	…..
0	0	0	0	….	0	1	$\left(n-\frac{n+1}{2}-(n-1)\right)E$	$\left(n-\frac{n}{2}-(n-1)\right)E$

In the proposed five level MMLI generation of different levels of pole voltage of a phase is explained through Table 2.Fig.3(a) shows five level pole voltage and the modes of operation for synthesizing the pole voltages are shown in Fig.3(b), Fig.3(f). In Fig. 3(b) to Fig. 3(f) the conduction path of different switches for the required pole voltage generation is shown. It can be observed that in each phase no two switches in the same leg will conduct at any instant.

TABLE II
Switching states, switch position and the corresponding pole voltages

Switching states	**Switch**					**Pole voltage (V_{a0})**
	Sa1	**Sa2**	**Sa3**	**Sa4**	**Sa5**	
4	1	0	0	0	0	2E
3	0	1	0	0	0	E
2	0	0	1	0	0	0
1	0	0	0	1	0	–E
0	0	0	0	0	1	–2E

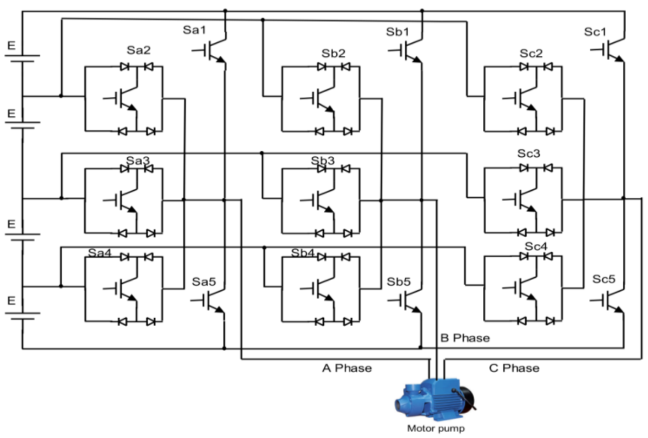

Fig.2. Five level MMLI feeding motor pump

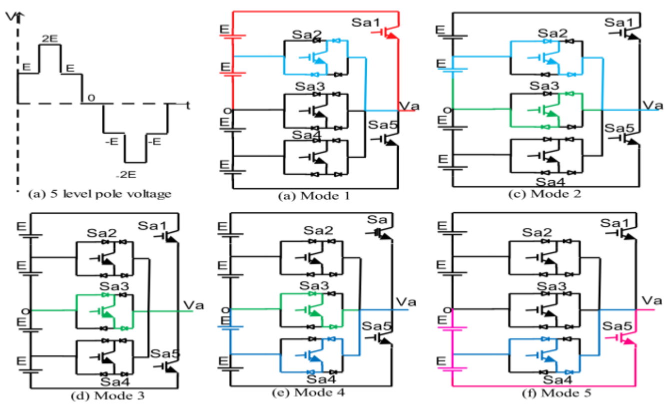

Fig.3.(a) 5 level pole voltage.Device conduction during (b) Mode 1 (c) Mode 2 (d) Mode 3(e) Mode 4 and (f) Mode 5

TABLE III
Line voltages and their corresponding switch states

Line Voltages			**Switching States**														
V_{ab}	V_{bc}	V_{ca}	**Sa 1**	**Sa 2**	**Sa 3**	**Sa 4**	**Sa 5**	**Sb 1**	**Sb 2**	**Sb 3**	**Sb 4**	**Sb 5**	**Sc 1**	**Sc 2**	**Sc 3**	**Sc 4**	**Sc 5**

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4E	–2E	–2E	1	0	0	0	0	0	0	0	0	1	0	0	1	0	0
4E	0	–4E	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1
4E	–4E	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0
3E	–4E	E	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0
3E	E	–4E	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1
2E	–4E	2E	0	0	1	0	0	0	0	0	0	1	1	0	0	0	0
2E	2E	–4E	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1
E	3E	–4E	1	0	0	0	0	0	1	0	0	0	0	0	0	0	1
E	–4E	3E	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0
0	–4E	4E	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0
0	4E	–4E	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1
–E	–3E	4E	0	0	0	0	1	0	0	0	1	0	1	0	0	0	0
–E	4E	–3E	0	0	0	1	0	1	0	0	0	0	0	0	0	0	1
–2E	–2E	4E	0	0	0	0	1	0	0	1	0	0	1	0	0	0	0
–2E	4E	–2E	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1
–3E	–E	4E	0	0	0	0	1	0	1	0	0	0	1	0	0	0	0
–3E	4E	–E	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1
–4E	0	4E	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0
–4E	4E	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1
–4E	2E	2E	0	0	0	0	1	1	0	0	0	0	0	0	1	0	0

With V_{a0}, V_{b0}, V_{c0} as pole voltages the corresponding line voltages and phase voltages with respect to the neutral of the load can be synthesized using Eq. 3 and Eq. 4respectively. The line voltages and their corresponding switch states of a five level inverter are tabulated in Table 3. It can be seen that at any instant the line voltages are balanced $(V_{ab} + V_{bc} + V_{ca} = 0)$.

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} V_{a0} \\ V_{b0} \\ V_{c0} \end{bmatrix} \qquad (3)$$

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & -1 & 0 \\ -1 & 2 & 1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} V_{a0} \\ V_{b0} \\ V_{c0} \end{bmatrix} \qquad (4)$$

IV. Space Vector Modulation Technique

SVM algorithm is used to generate the appropriate switching sequence for the proposed MMLI topology. SVM provides better fundamental voltage and efficient use of supply voltage compared to other PWM techniques and improved spectral performance. The SVM algorithm is explained considering a five level space plane as shown in Fig.4. The unused redundant states are not shown in Fig.4.A five level space vector plane consists of layers L1, L2, L3 and L4 that are concentric about zero states 000 and 111. The inner most layer is similar to the traditional two level hexagon. The triangles of inner hexagon are called base triangles, designated asT1,T2, T3, T4, T5, T6 as shown in Fig. 4.The space plane is divided into six 60^0 regions called sectors. Each sector is further divided into sub triangles. The execution of SVM algorithm is explained in the following steps.

- The reference voltage vector needs to be synthesized from the instantaneous phase voltagesV_a, V_b, $V_c$through three phase to two phase transformation as written in Eq. 5. $V_d$andV_q are direct and quadrature axis components. These

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are further transformed into polar coordinates using Eq. 6

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = 2/3 \begin{bmatrix} 1 & \cos\frac{2\pi}{3} & \cos 2\pi/3 \\ 0 & \sin\frac{2\pi}{3} & -\sin\frac{2\pi}{3} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (5)$$

$$V_{ref} \llcorner \alpha = V_d + jV_q \qquad (6)$$

- The layer in which the reference vector lies is evaluated as in Eq. 7

$$\mathrm{L} = 1 + int(\frac{V_{ref}}{0.866}) \qquad (7)$$

Here L is the layer number and *'int'* is a mathematical function that rounds to near zero.

- The sector in which the reference vector lies is identified from θ and the corresponding input states are used to synthesize all apposite states. For instance, if sector is identified as '1' then corresponding two level states 100 and 110 are used to find the remaining states. Using input states andΔ $(110 - 100 = 010)$ the remaining states 300, 310, 320, 330 can be synthesized by generating a loop for (n–1) times.

- The nearest state corresponding to the reference vector is identified by measuring distances from all states to the reference vector as written in Eq. 8.The hexagon corresponding to the nearest switching state as centre is identified.

$$\,^{(n-1)}_{i=1}D_i = |v_d - d_{di}| + |v_q - d_{qi}| \;(8)$$

whereD_i is the distance from i^{th} state to the reference vector, d_{di} and d_{qi} are the direct and quadrature axis components of the i^{th} state.

- To find the switching times of the corresponding switching states of the reference vector it is mapped into the new hexagon by subtracting the nearest switching vector from the given reference vector using Eq. 9 where i^{th} state is the nearest switching state .$\bar{D}_i$lies in a sub hexagon with the nearest switching state as centre.

$$\bar{D}_i = (V_d - d_{di}) + j(V_q - d_{qi}) \qquad (9)$$

$$V_{nref} \llcorner \theta = (V_d - d_{di}) + j(V_q - d_{qi}) \qquad (10)$$

- The switching states and their corresponding timesT_a, T_b, T_z are synthesized similar to the conventional two level approach using Eq. 11,Eq. 12and Eq. 13. For instance if nearest switching state NAS is identified as 320 and triangle is T2 then the nearest switching states are 000+320, 010+320, 110+320, 111+320.

$$T_a = T_s * V_{nref} * \sin\left(\sin\left(\frac{\pi}{3} - \alpha\right)\right) \qquad (11)$$

$$T_b = T_s * V_{nref} * \sin(\alpha) \;(12)$$

$$T_z = T_s - T_a - T_b \;(13)$$

Where T_s is the switching frequency and α is angle of rotation of new reference vector

The switching states and their corresponding switching times are dwelled to synthesize optimum switching pulses to generate the required reference voltage vector in an average sense.

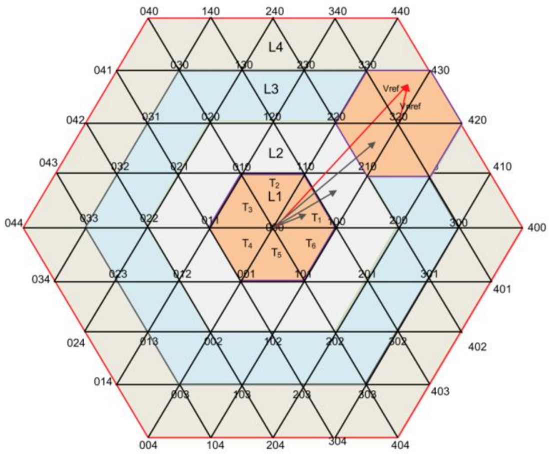

Fig. 4.Five level Space vector diagram

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V. SIMULATION RESULTS

To validate the working of three phase space vector PWM based MMLI and its suitability for pumping applications, simulationin MATLAB/Simulink environment is performed. The advantage with the modular nature is that the same switch can provide path in both directions thereby reducing the switch count. Also instead of a single bulky dc source (n-1) dc sources each of rating ‘E’are used to synthesize a balanced three phase output voltages, hence making it suitable for photovoltaic applications. The specifications of the PV module that can synthesize the required dc voltage level are given in Appendix. The proposed MMLI is tested for 11 level MMLI, for three cases that perk up the reliability of the system. The three cases are normal motoring, motoring with one open circuited module in a phase and motoring with one short circuited module in a phase. For each case the phase voltages synthesized are fed to the induction motor and motor currents, speed and torque waveforms are observed during steady state as shown in Fig. 5 to Fig. 10.

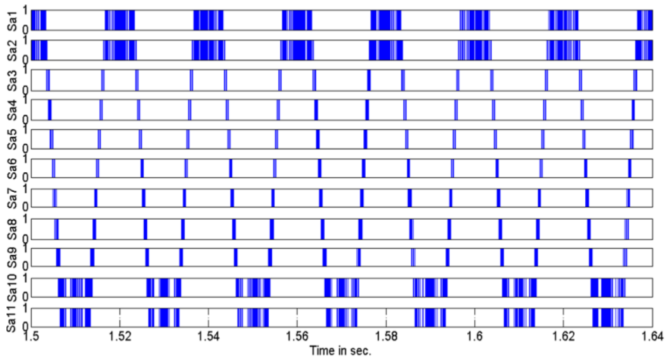

Fig. 5 Switching pulses for 11 level MMLI in normal working conditions

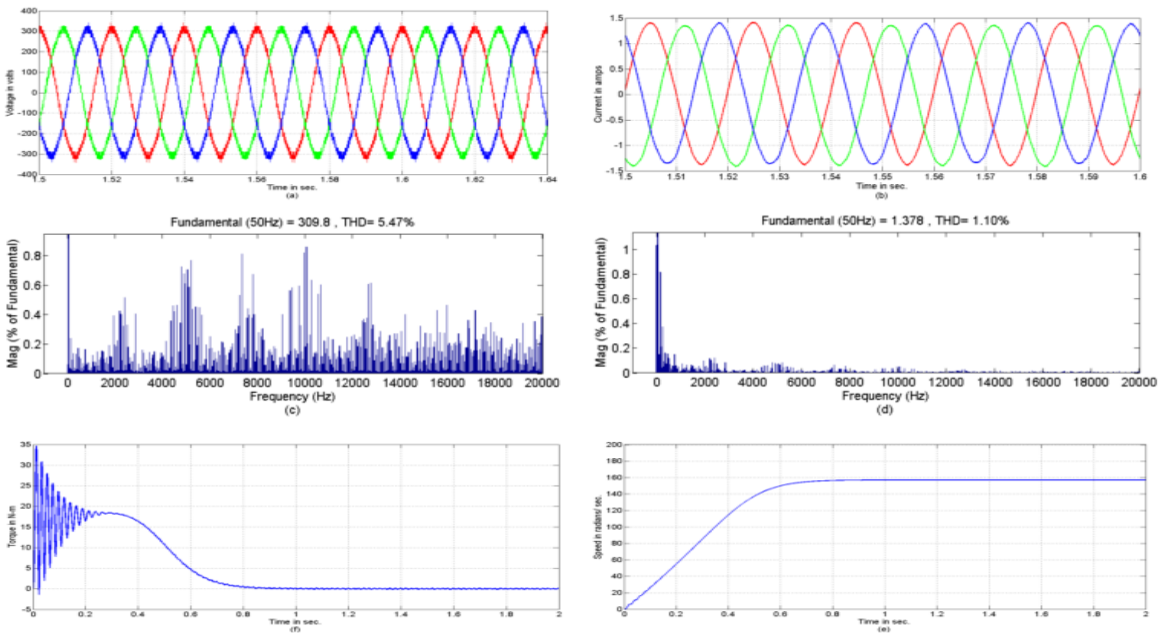

Fig.6 11 level MMLI in normal working condition (a)Motor phase voltage (b) Motor currents (c) Harmonic spectra of phase voltage(d) Harmonic spectra of a phase current (e) Motor torque(f) Motor speed

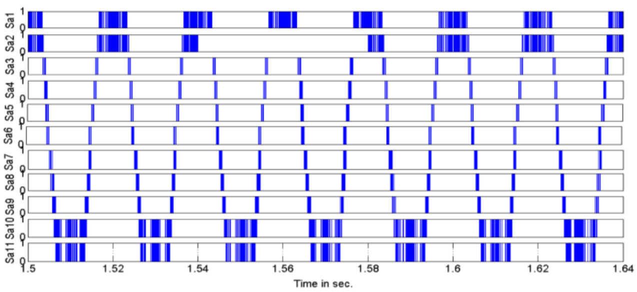

Fig. 7 Switching pulses for 11 level MMLI with open circuit of switch Sa2 from 1.54 sec to 1.58 sec.

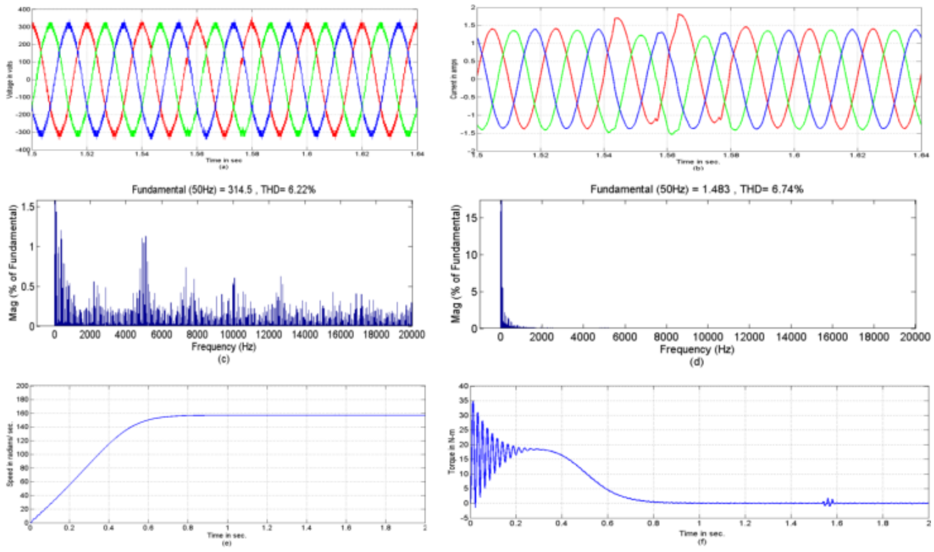

Fig.8 11 level MMLI with Open circuit of switch Sa2 from 1.54 sec to 1.58 sec (a) Motor phase voltage (b) Motor currents (c)Harmonic spectra of phase voltage(d)Harmonic spectra of phase current (e) Motor speed (f) Motor torque

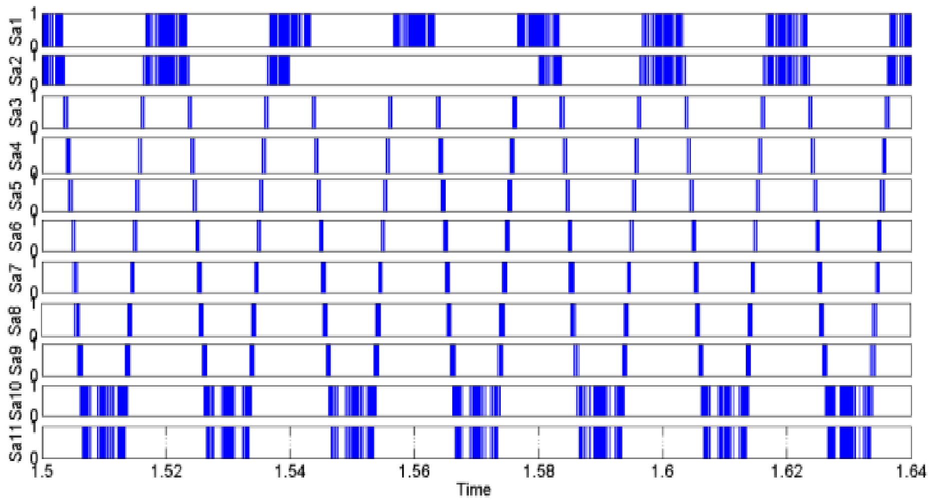

Fig. 9Switching Pulses for 11 level MMLI with short circuit of switch Sa2 from 1.54 sec to 1.58 sec.

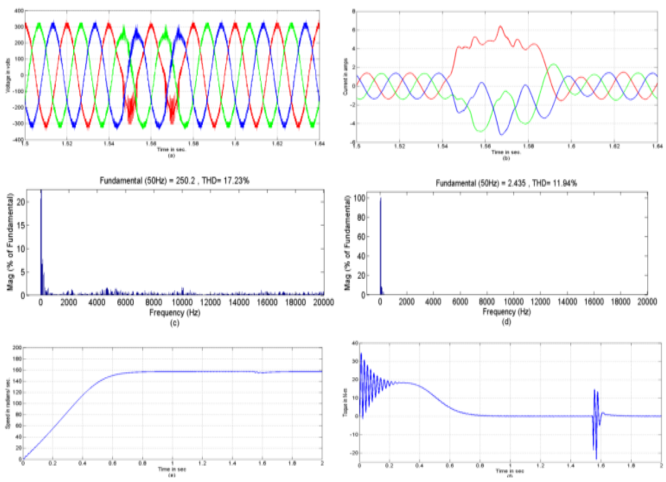

Fig.10. 11 level MMLI with Short circuit of switch Sa2 from 1.54 sec to 1.58 sec (a) Motor phase voltage (b) motor currents (c) harmonic spectra of phase voltage (d) Harmonic spectra of phase current (e) Motor speed (f) Motor torque

A comparison of proposed MMLI topology with the NPC MLI for 11 levels is given in Table 4.With the proposed MMLI topology the harmonic distortion in voltage and current is found to be less and better fundamental voltage and current are synthesized compared to the NPC MLI topology for the three cases mentioned.

TABLE IV
Comparison of Proposed MMLI topology and NPC topology for 11 level

Topology	Motor voltage		Motor current	
	Fundamental voltage in volts	**% THD**	**Fundamental current in Amps**	**% THD**
Proposed MMLI	309.8	5.47	1.378	1.10
NPC MLI	310.1	5.66	1.382	1.15
Proposed MMLI with open circuited switch	316.5	6.22	1.483	6.74
NPCMLI with short circuited switch	276	9.94	0.8364	43.01
Proposed MMLI with short circuited switch	250.1	17.23	2.435	11.94
NPC MLIwith short circuited switch	250	17.15	4.178	16.71

VI. Conclusion

In this paper a new MMLI topology for standalone PV system with induction motor as load is developed. The switching algorithm to the MMLI is obtained from the space vector PWM algorithm which provides efficient modulation strategy. The reliability of MMLI is tested under fault conditions like short circuit and open circuit of a switch in a phase that may occur due to switch failure. The MMLI requires less number of switching devices and only one switch in a phase will be ON to synthesize a level and so switching losses are comparatively less than with the conventional topologies. Also the driver circuit design is simple as it requires minimum number of switches. The %THD of the output voltage and current is compared with the conventional NPC MLI for normal and faulty switch operating conditions. The results prove that the proposed MMLI topology with space vector PWM algorithm can be efficiently utilised for renewable energy resources and also for grid and HVDC applications.

VII. Appendix

PV Panel specifications

Parameter	Rating
Short circuit current(Isc)	5 A
Open circuit voltage (Voc)	13.5 V
Series resistance(Rs)	0.23 OHM
Parallel resistance(Rp)	415.405
Number of series connected cells	36
Number of modules in series	4
Number of modules in parallel	1
Irradiance at standard test conditions	1000 W/m^2
Temperature at standard test conditions	25^o C
Total number of PV panels	10

Motor specifications of three phase induction motor

Parameter	Rating
Power	1.5 H. P
Motor voltage(V_{rems})	400 V
Speed	1440 rpm
Frequency	50 Hz
Number of poles	4
Stator resistance	7.83 OHM
Rotor resistance	7.55 OHM
Stator inductance	0.4751 H
Rotor inductance	0.4751 H
Magnetizing inductance	0.4535 H
Moment of inertia	0.06 kg-m^2

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