Design and Modeling of a GaN-Based Nine-Level Flying Capacitor Multilevel Inverter

Mrs.M.Anusuya, Assistant Professor, Dhanalakshmi Srinivasan Institute of Technology, Samayapuram- Trichy
M.Rushwani, R.Subashini, K.Yazhini Student, Dhanalakshmi Srinivasan Institute of Technology, Samayapuram- Trichy

Abstract: GaN-Based Nine-Level Flying Capacitor Multilevel Inverter are plays an important role in industrial power applications. Generally conventional MLIs are categorized into diode clamped, flying capacitor clamped and cascaded H bridge type. They are having a more number of switches with less number of levels or more. Due to this it can provides a more switching losses and less accuracy. And also it can require more drivers for turn ON the switches, also difficulties in pulse width modulation. The proposed MLI is a new configuration in Flying Capacitor Multilevel Inverter (FCMI). The introduced MLI gives that it consists of less number of switches and gate drivers. And also it has features of voltage balancing property, purge the more dc source, double the output voltage levels, get better the output frequency range. The PWM control by using phase shift PWM. The simulations are made with help of PSIM simulation package and captivating all the parameters values.

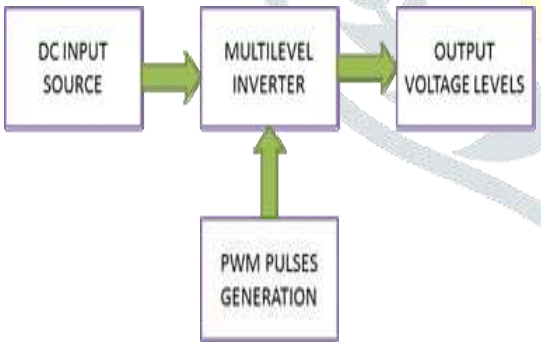
Keywords: Classical Flying capacitor MLI, proposed Flying capacitor multilevel inverter(FCMI), Phase-Shift pulse width modulation(PSPWM)

1. Introduction

The conversions of DC to AC are called Inverters. The reasons in the inverters are to change the dc input to ac output voltage and current of an optimal amplitude and frequency. The output voltage might be variable or fixed. The following kinds of inverters are operated as mentioned. They are,

1. Voltage Source Inverter (VSI)
2. Current Source Inverter (CSI)
3. Resonant pulse Inverter and all other types except multilevel nverters.

Conventional inverters can either produce the output levels as zero or maximum. So it is called a two level inverter. For an high power application, these type of inverters are not used. Because of it consists of losses with ripple content, frequency deviations, switching losses and device ratings.

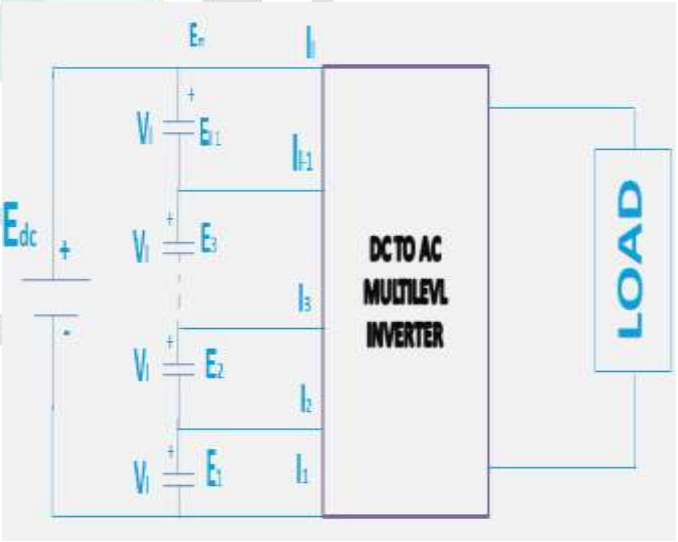


Multilevel Inverters are tremendously interest to use in power inverters. The Fig.1 shows the common blocks in MLI. And it is also suited for compensation of reactive power. MLIs are providing the high power and high voltage inverters with its structure. By increasing the number of output levels it is not requires high power rating devices. With a configuration of MLIs allows the high ratings with minimum losses without use of transformers. The harmonic content in MLI can be significantly reduced by increasing number levels [8], [10]. The dc voltage E_{dc} and the series of capacitor have the stored energy and MLI are connected to each capacitor nodes. All the capacitors has the same voltage drops Fig.2. That is

$$V_t = \frac{Edc}{l-1}$$

Where

l – Number of levels referred as number of nodes for l number of level (l-1) capacitors is required



In general MLIs are producing an approximate sinusoidal voltage from several input dc levels. It provides more steps which produce a staircase stepped output. The different kinds of MLIs are following [4], [7], [10].

1. Diode clamped MLI
2. Flying capacitor MLI
3. Cascaded MLI
4. H-bridge MLI

All the MLIs have a various switching states with several levels. The important features of MLIs are following below.

a) MLIs are Possible to operate at lower frequency.
b) Reducing the stress in switches and motor bearings due to it does generate minimum common mode voltage.
c) The input current can be drawn with low distortion.
d) The most important is to generate a multi output levels with low distortion and less dv/dt.

2. Classical Flying Capacitor MLI

The classical flying capacitor multilevel inverter is shown in Fig.3. The number of switches are $S_1, S_2, S_3, S_4, S_1, S_2, S_3, S_4$

Each leg has identical structure and each series connected capacitors have a same voltage rating. The three inner loop capacitors are C1, C2 and C3. And all the phases shared by equal dc link capacitors are C1, C2, C3 and C4 [1]. The voltage can be divided by Vdc/2, Vdc/4 and -Vdc/2, -Vdc/4 and Van. The switches from S1- S4 are called upper arm main switches and switches from S1 - S4 are called lower arm auxiliary switches. [1] & [2]. The voltages from classical MLI are five level output are based on the switching pattern and PWM signal. The switches are conducts based on five different combinations.

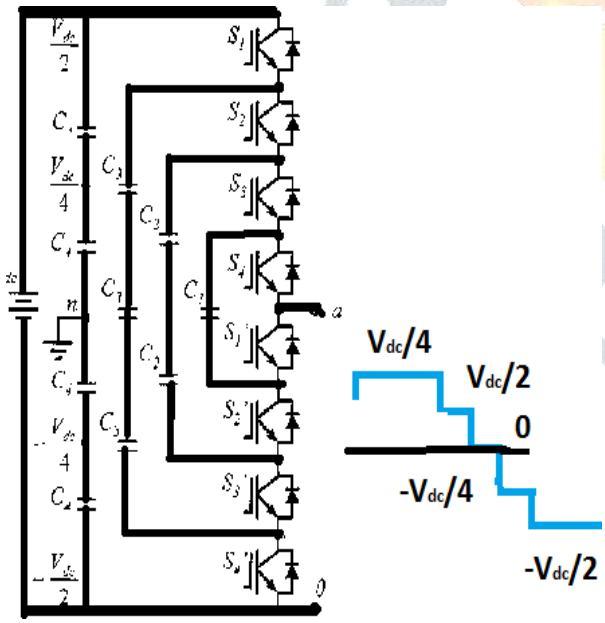


Fig.3 *Classical Five level Flying Capacitor MLI*

The voltage level Van=0, it has six combinations, voltage level Van= Vdc/2, it has one combinations and voltage level Van= -Vdc/2, it has one combinations. Similarly for voltage level Van= Vdc/4, it has three combinations and voltage level Van=- Vdc/4, it has three combinations respectively. Totally it consists of five output voltage levels. In this operation, during the positive and negative sign periods the capacitors can discharge and charge respectively.

A. Capacitor calculation

Let the number of level in l then the following design procedure is to be followed.
That is

DC bus capacitors (DC link Capacitors) = (l-1)
Balancing clamped capacitor
(Flying Capacitors) = (l-1)*(l-2)/2

B. One possibilities of switching combinations

(1=ON 0=OFF)

TABLE I. *SWITCHING PATTERN*

Output V_{dc}	S_1	S_2	S_3	S_4	S_1	S	S	S
$V_{dc}/2$	1	1	1	1	0	0	0	0
$V_{dc}/4$	1	1	1	1	1	0	0	0
$-V_{dc}/2$	0	0	0	0	1	1	1	1
$-V_{dc}/4$	1	0	0	0	1	1	1	0
$V_{an}=0$	1	1	0	0	1	1	0	0

The Table I. shows the switching combination of classical flying capacitor. Each series connected capacitors have a same voltage rating. And the three inner loop capacitors are C1, C2 and C3. And all the phases shared by equal dc link capacitors are C1, C2, C3 and C4. The capacitors voltage drops are Vc1, Vc2, Vc3 and Vc4 respectively as shown in Fig.3 [4], [6].

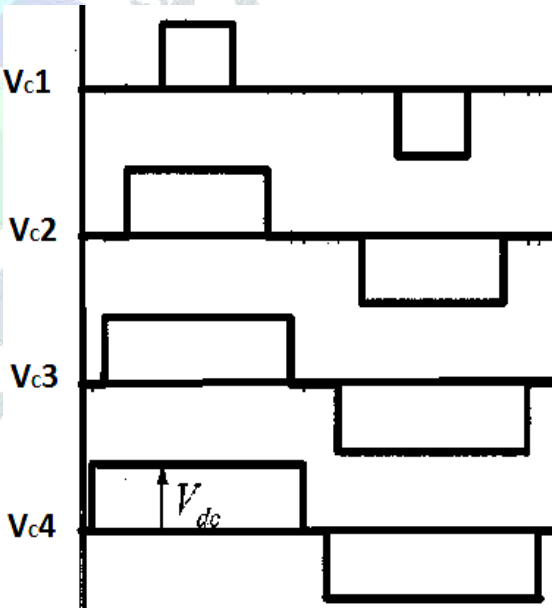


Fig.4 *Flying Capacitor voltage at each level*

C. Output Voltage Level

The output of classical MLI consists of five output voltage levels. In this operation, during the positive and negative sign periods the capacitors can discharge and charge respectively. And the output levels are shown in fig.5

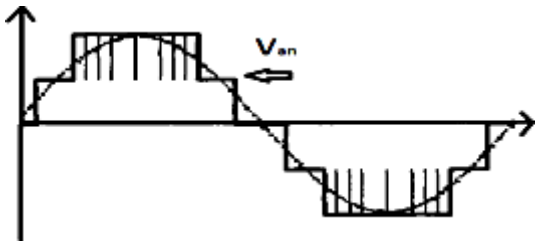


Fig.5 *Classical Flying Capacitor MLI output voltage waveform*

D. Drawbacks in Classical Flying Capacitor MLI

a). Enormous quantity of capacitor storage offer capability during power outages.
b). Harmonic content is more when the switching losses are more.
c). Poor power regulation.
d). The inverter control is more difficult.
e). Number of switches is more compare to others and reduces the number output levels.
f). Not a self balancing of voltages.
g). Requires more driver circuit for this configuration

There are plenty ways of get better the switching of the devices to implement the efficiency of MLIs and diminish the switching losses. The usual switching pattern is different from two level inverter circuits. However the different kinds of MLI, the selection of switching can be in the form of various possible circuit combinations.[7][8]

3. Proposed a New Configuration of Flying Capacitor Multilevel Inverter

Multilevel inverters are used in various industrial applications with a manner of effective efficiency. The reason beyond the all the MLIs are to increase the number of voltage levels. This paper shows a new configuration in Flying capacitor MLI (FCMI). The proposed MLI carries a less number of switches with more output levels. Compared with classical MLI the new configuration provides twice the RMS and the number of output levels. It can improve the frequency spectrum. And also eliminating the more dc sources (cascaded MLI) and flying capacitors.

A. Proposed Structure

The proposed structure of FCMLI is has the four cell with two pair of switches. The switches are might be used MOSFET/IGBT The number of switches are $S_1,S_2,S_3,S_4,S_1,S_2,S_3,S_4$ Each leg has identical structure and each series connected capacitors have same voltage ratings. The three inner loop capacitors are C1, C2 and C3. Each cell includes parallel of capacitor with the dc input source E. The capacitors are acts as a voltage balancing and voltage dividing purpose. It has a initial voltage charge of dc input. That is dividing voltages into E/4, E/2 and 3E/4 respectively.

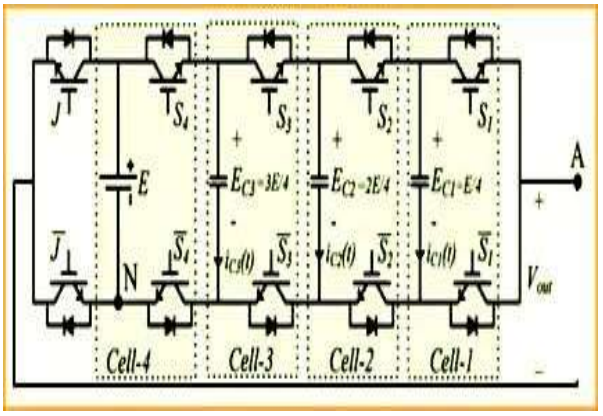


Fig.6 *Proposed Flying Capacitor Multilevel Inverter*

The new configure of FCMLI provides nine level output voltage with minimum switches. The nine levels can be obtained with the help of adding two low frequency switches K and K. And two switches are operates at low frequency. It can triggered at twice when a full cycle of fundamental output. When K is on for negative and K¯is on during positive output voltage respectively

B. Operation at different combinations

It has different switching combinations at different levels. For a one possible combination are shown in following Table.2.

Table II. *One possibilities of switching combinations (1=ON 0=OFF).*

Output Voltage level	S_1	S_2	S_3	S_4	K	K	Combination of states
E	1	1	1	1	0	1	1
3E/4	0	1	1	1	0	1	4
E/2	0	0	1	1	0	1	4
E/4	0	0	0	1	0	1	4
E=0	0	0	0	0	0	1	2

C. The Positive peak operations are as follows

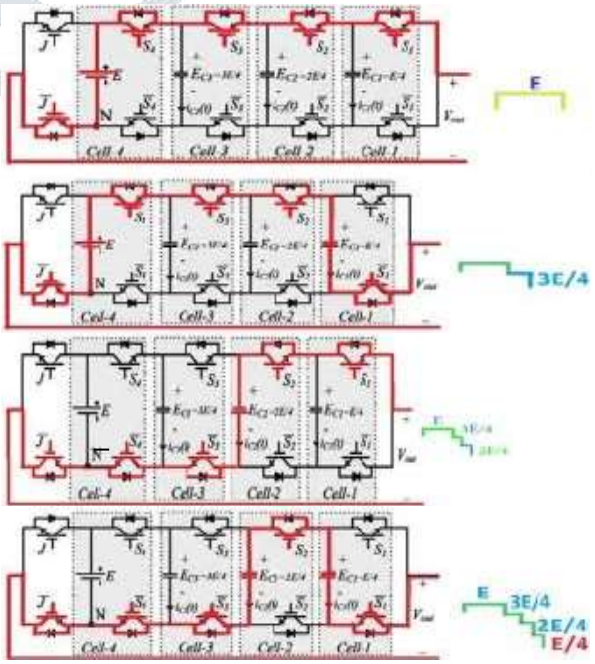


Fig.7 *Positive peak operation for one possible combination.*

Here the 1 and 0 indicates also incoming switches and outgoing switches respectively. The same operation in negative peaks also.

TABLE III. *Switching Combinations for +E (1=ON 0=OFF)*

Output Voltage level	S_1	S_2	S_3	S_4	K	$\bar{K}$	Combination of states
E	1	1	1	1	0	1	1
3E/4	0	1	1	1	0	1	4
E/2	0	0	1	1	0	1	4
E/4	0	0	0	1	0	1	4
E=0	0	0	0	0	0	1	2

D. The Negative peak operations are follows

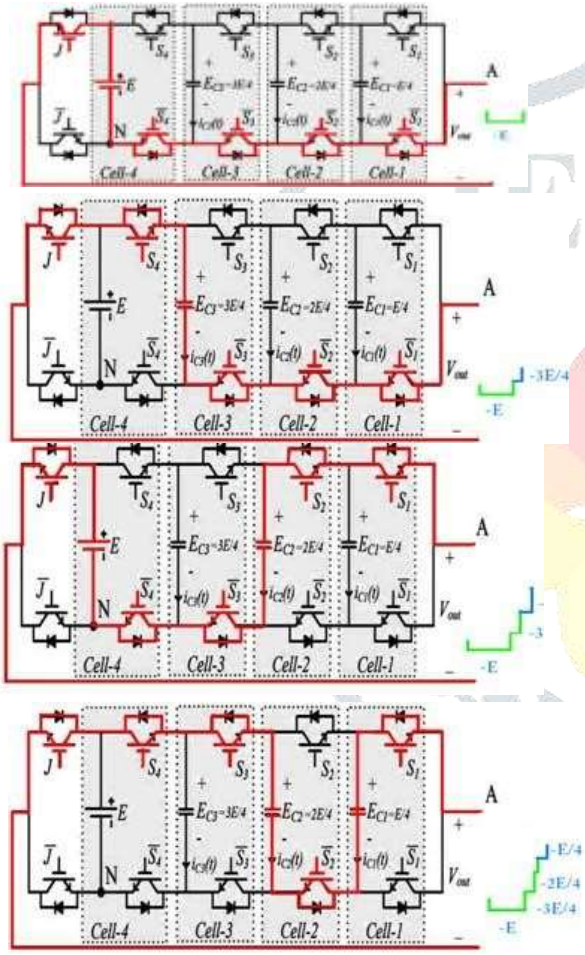


Fig.8 *Negative peak operation for one possible combination.*

The nine levels can be obtained with the help of adding two low frequency switches K and $\bar{K}$

TABLE IV. *Switching Combinations for –E (1=ON 0=OFF).*

Output Voltage level	S_1'	S_2'	S_3'	S_4'	K	$\bar{K}$	Combination of states
-E	1	1	1	1	1	0	1
-3E/4	0	1	1	1	1	0	4
-E/2	0	0	1	1	1	0	4
-E/4	0	0	0	1	1	0	4

Two switches are operates at low frequency. It can triggered at twice when a full cycle of fundamental output. When K is triggered for negative and K is switched during positive output voltage respectively.

E. Switching Combinations

The possible switching combinations are based on voltage divider rule, and the operations are performed based on that only.

The voltage equations are follows below

1) Similarly for Positive peaks are follows

Calculation of switching states for E consists of one state and one combination.

$$E=E$$

Switching states for 3E/4 consists of four states and four combinations

$$E=\frac{3E}{4} \text{ ----------(a)}$$

$$\frac{3E}{4}=E-\frac{E}{4} \text{ ----------(b)}$$

$$\frac{3E}{4}=E-\frac{3E}{4}+\frac{2E}{4} \text{ ----------(c)}$$

$$\frac{3E}{4}=E-\frac{2E}{4}+\frac{E}{4} \text{ ----------(d)}$$

Switching states for 2E/4 consists of four states and four kind"s combination

$$\frac{2E}{4}=\frac{E}{2} \text{ ----------(1)}$$

$$E=\frac{2E}{4}-\frac{E}{4} \text{ ----------(2)}$$

2) Similarly for negative peaks are follows

Switching states for -E consists of one state and one combination.

$$E=-E$$

Switching states for -3E/4 consists of four states and four combinations. For example

$$E=-\frac{3E}{4} \text{ ----------(1)}$$

Switching states for -2E/4 consists of four states and four kind"s combination. For example

$$-\frac{2E}{4}=-\frac{E}{2} \text{ ----------(a)}$$

$$-\frac{2E}{4}=-E+\frac{2E}{4} \text{ ----------(b)}$$

Switching states for -E/4 consists of four states and four type"s combination. For example

$$-E=-\frac{E}{4} \text{ ----------(3)}$$

$$-\frac{E}{4}=\frac{2E}{4}+\frac{E}{4} \text{ ----------(4)}$$

These are the possible combinations of proposed Flying Capacitor Multilevel Inverter

F. Switching pattern & output PSPWM wave form

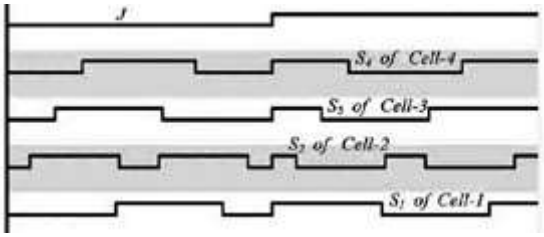


Fig.9 *The switching and output waveform for proposed FCMI*

In this Fig.9 shows that switching of FCMI and the nine level output voltage waveform. The nine levels can be obtained with the help of adding two low frequency switches K and ¯k And two switches are operates at low frequency It can triggered at twice when a full cycle of fundamental output When K is on for negative and K is on during positive output voltage respectively [9], [10].

G. Significance of Proposed FCMI

- The nine level output can be obtained by simply adding two low frequency switches
- Reduce the number of flying capacitors.
- Increases the number of output levels.
- Control the gates by PSPWM technique

Compared to classical flying MLI,

1. It can provide twice the RMS and output voltages.
2. Eliminate the more dc source.
3. Improve the frequency band.
4. The high frequency switches are kept constant during full cycle period

H. Calculation of Flying Capacitor Ratings and Values

Let the output voltage can be defined as,

$$V=\delta*E \quad (1)$$

Where the δ is a value from 0 to 1 and is in switches on time.

Let

$$\text{Duty cycle } \delta=d \quad (2)$$

$$Vo = d * E \quad (3)$$

The current in the inductor L will assimilate up at a rate that is found by the voltage and inductance as

$$V = L * (dI/dt) \quad (4)$$

Rearrange equation (4) yields;

$$dI = V /L * dt \quad (5)$$

$$\int dI = \int V /L * dt \quad (6)$$

$$\Delta I = V /L \int dt \quad (7)$$

$$\Delta I = (V) * (\Delta t) /L \quad (8)$$

Where L is the inductance in Henries and Δt is the switch on time in seconds.

Case (i) when the switch is turned on

$$V_L = E – Vo \quad (9)$$

Sub in equation (9) into (8) yields

$$\Delta I=(E – V_o)* \Delta t/L \quad (10)$$

Sub in equation (3) into (10) yields

$$\Delta I = (E– (d * E)) * (\Delta t) /L \quad (11)$$

The switch on time can be defined as

$$\Delta t = d * \text{PWM period or} \quad (12)$$

$$\Delta t = d * 1/\text{PWM Frequency} \quad (13)$$

Let"s define the PWM frequency as f,

$$\Delta t = d * 1/f \quad (14)$$

Sub in equation (14) into (11) yields;

$$\Delta I = (E– (d * E)) * (d)/(f * L) \quad (15)$$

Simplifying equation (15) yields;

$$\Delta I = d * (1– d) * E/ (f * L) \quad (16)$$

The greatest E/ (f * L) , when d is equal to 0.5 or 50% ð.Therefore, the maximum ΔI is when the ð is 50%. Sub in 0.5 for d in equation (16) yields;

$$\Delta I\ 0.5t = 0.5 * (1– 0.5) * E/ (f * L) \quad (17)$$

$$\Delta I\ 0.5t = 0.25 * E/ (f * L) \quad (18)$$

The Flying capacitance value can be determined by,

$$C = E/ (32 * L * \Delta V0.5t * f 2) \quad (19)$$

Where

E – Input dc source.

L –Inductance in Henries.

ΔV0.5t- the maximum peak to peak ripple voltage across the capacitor.

f - frequency in Hz.

4. Simulation Results

The performance of proposed FCMI can be done with the help of PSIM simulation package software. And the simulation parameters are given by following table. The tools in PSIM software provide to draw a all components in proposed FCMI. Their corresponding output can view by scopes in software. The following TABLE- V provides the detailed parameters used in software

TABLE V. *Simulation Components and their Ratings*

Simulation Components	Ratings
DC input source (E)	200 V
Flying Capacitors (C)	1µF
Switching Frequency	700 Hz
Modulation index (M)	0.8
Resistive Load (RL)	20 Ω
Inductive Load (Ll)	100 mH
Harmonic orders in THD	6.269

A) Simulation of Proposed System Circuit Diagram

The simulation circuit of proposed circuit is shown in theFig.10.

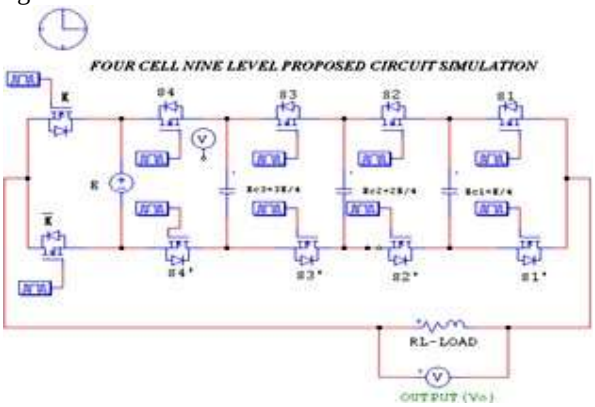


Fig.10 *Simulation Circuit of Proposed FCMI*

A. Nine Level Output voltage

The nine level can be obtained with the help of adding two low frequency switches K and $\bar{k}$

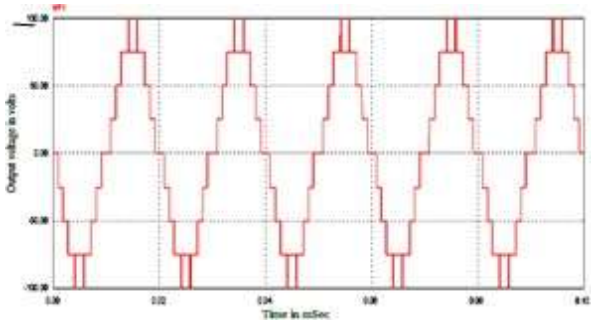


Fig.11 *Nine Level Output Voltage in Flying Capacitor Multilevel Inverter*

B. PSPWM of the Proposed Configuration

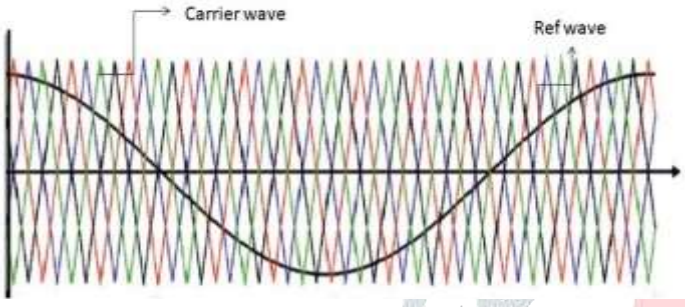


Fig. 12 *Phase Shift PWM waveform*

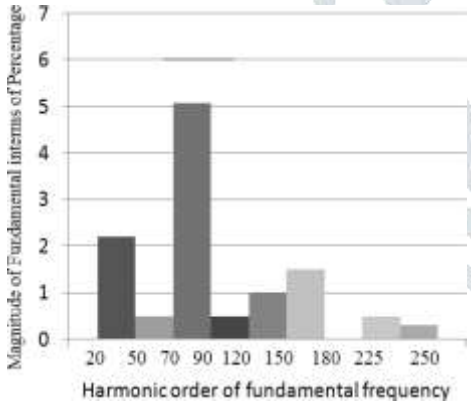


Fig.13 *Frequency band range of Output voltage levels*

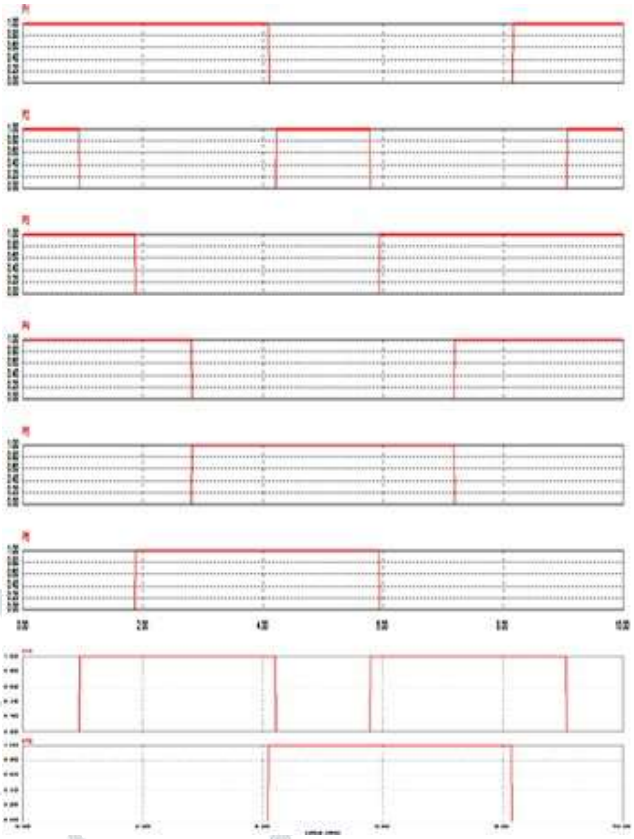


Fig.14 *Pulses for Corresponding switches*

V. CONCLUSION

The introduced FCMLI gives that it consists of less number of switches and gate drivers. And also it has features of voltage balancing property, purge the more dc source, double the output voltage levels, get better the output frequency range. The phase shift PWM technique can be used to achieve nine level output voltage. But in a new structure of FCMI the two low frequency switches makes to provide the full DC input i.e., $\pm E$ for both the peak levels. And also produce a double RMS and increasing the output levels. And it is decreases the count of flying capacitors. The output voltages with nine level FCMI as shown in the figure. The THD and other parameters analysis are taken as from the simulation itself. The simulation output give a efficient, no distortions and without losses in the output levels. The proposed structure has a possibility to withstand in high power rating applications, such as ac drives, filters, FACTS controllers and etc., both the simulation and hardware results provide good performance and feasibility of proposed Flying Capacitor Multilevel Inverter (FCMI).

REFERENCES

[1]. B. P. McGrath and D. G. Holmes, "Analytical modeling of dynamics for a flying capacitor multilevel converter," IEEE Trans. Power Electron., vol. 23, no. 2, pp. 543–550, Mar. 2008.

[2]. S. H. Hosseini, A. K. Sadigh, "Estimation of flying capacitors voltages in multicell converters," in Proc. 6th Int. ECTI Conf., Thailand, May2009.

[3]. T. Meynard, A. M. Lienhardt, "Flying capacitor MultiCell converters with reduced stored energy," in Proc. IEEE Int. Symp. Ind. Electron., Canada, Kul. 2006, pp. 914–918.

[4]. A. Shukla, A. Ghosh, "Improved multilevel hysteresis current regulation and capacitor voltage balancing schemes for flying capacitor multilevel inverter," IEEE Trans. Power Electron., vol. 23, Mar. 2008.

[5]. Z. Du, L. M. Tolbert, B. Ozpineci, and K. N. Chiasson, "Fundamental frequency switching strategies of a seven-level hybrid cascaded H- bridge multilevel inverter," IEEE Trans. Power Electron., vol. 24, Kan.2009.

[6]. B.W Williams „Power Electronics Circuit Devices and Applications".

[7]. Robert W. Erickson &Dragon Maksimovic, " Fundamentals of Power Electronics", Second Edition, 2001 Springer science and Business media.

[8]. Rashid M.H., " Power Electronics Circuits, Devices and Applications ", Prentice Hall India, Third Edition, New Delhi, 2004.

[9]. D.Grahame Holmes and Thomas A.Lipo, "Pulse Width Modulation for Power Converters", IEEE press a Kohn Wiley & Sons, Inc., Publication.

[10]. Mohan, Undcland and Robins, "Power Electronics – Concepts, applications and Design, Kohn Wiley and Sons, Singapore, 2000.