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# Step Down Resonant Modular Multilevel DC-DC Converter

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ABSTRACT: Modular multilevel converters (MMCs) provide more than two levels which can be adjusted by changing the number of modular cells. Cells with a fault can also be bypassed while keeping the converters operating. High reliability and modularity are the main features of MMC. The modular multilevel converter (MMC) has very high importance in medium and high-voltage applications. Power electronics transformerscan be used for high step-down ratio dc–dc power conversion, with high power rating and efficiency achieved. But this requires a large number of high isolation voltage transformers and a complicated balancing control scheme. The new MMC can achieve high step-down ratio depending on the number of sub modules and voltage balancing is very simple. The converter also exhibits simplicity and scalability with no necessary requirement of high-voltage isolation transformers. Resonant conversion is achieved between the series inductor and sub module capacitors. This new MMC is simulated using MATLAB/2011a Simulink.

**KEYWORDS*:*** Modular multilevel converters(MMCs), ZVS, ZCS, phase-shift control, resonant converter, step-downratio.

## I.INTRODUCTION

A modular multilevel converter (MMC) is one of the next-generation multilevel converters intended for high- or medium-voltage power conversion without transformers. The MMC is based on cascade connection of multiple bidirectional chopper-cells per leg, thus requiring voltage-balancing control of the multiple floating dc capacitors. MMCs [2], [3] require a complicated balancing control to maintain the voltage levels.

Even though a requirement is placed on the tolerance of the cell capacitors, measuring capacitor voltages for balancing control is indispensable. This new converter can achieve voltage-balancing control with simulation verifications. The operating frequency of the conventional control for MMCs is not higher than the switching frequency. Hereoperating frequency is higher than switching frequency. High switching frequencies are used to reduce the sizes of passive components. Tradeoffs between switch ratings and converter size should be made, but it is hard to find a good solution for high-voltage, high-step-down ratio, and low-power applications.

These converters exhibit good efficiency and modularity, but are not suitable for high-voltage applications. For high-voltage applications, conventional diode clamped, flying capacitor [5], or other types of converters are also not suitable as the circuit configuration becomes quite complicated with increased number of levels. These converters have highermodularity and reliability. High step-down voltage conversion ratios can be achieved by using large numbers of sub modules.

## II. SYSTEM CONFIGURATION

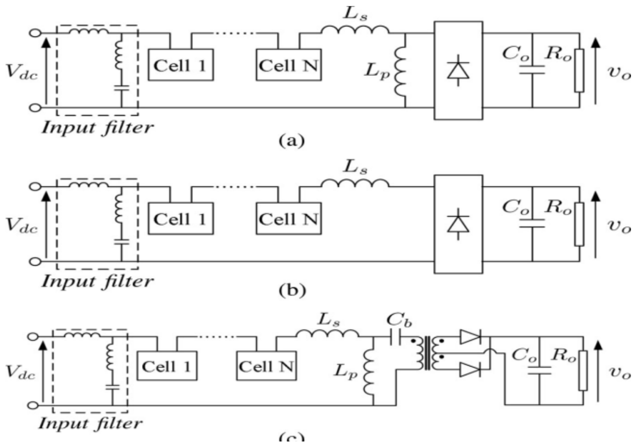


Fig. 1.High step-down ratio unidirectional dc–dc converter topologies.(a) Transformer less converter with series–parallel resonance. (b) Transformer less converterwith series resonance. (c) Transformer isolated converter

There are three system configurations to implement resonant modular multilevel step down dc-dc converter. Fig. 1(a) and (b) shows series–parallel and series, resonant versions in which the resonance is between the series inductors and the sub module capacitors. The sub modules are illustrated in Fig. 2. The output rectifier can be coupled via a transformer but only by adding a capacitor to block the dc current as shown in Fig. 1(c). For the circuits of Fig. 1(a) and (c), the dc current drawn from the input and through the cells returns via the parallel inductor $L_p$. For the circuit of Fig. 1(b), where this path is absent, the return of the dc input current is via the rectifier and load.

Here series parallel configuration is used. To support the input voltage, the sub modules of Fig. 1 are used predominantly in the "one state" in which the upper switch is ON and the module inserts the capacitor voltage into the circuit. Phase-shifted PWM is then applied with a high duty ratio such that an excitation is applied to the resonant components. The effective frequency of this excitation is much higher than the frequency of switching of an individual cell. This is arranged so that only one cell at a time is in "zero state," and thus, the step-down ratio of the circuit becomes dependent on the number of cells $N$.

## III.OPERATION PRINCIPLE

To demonstrate the general operation principle, the converter in Fig. 1(a) with five half-bridge cells is used as an example. Fig. 2 shows the circuit diagram with the input filter removed to simplify the analysis. The dc input voltage is Vdc. The capacitor voltage and output voltage of $j^{th}$ ($j = 1, 2 \ldots 5$) cell are represented by vCjand vj, respectively. The input current is is composed of the dc component and ac component. The dc current component returns to the converter input mainly through the parallel inductor Ls , where an ac current component mainly flows to the rectifier. The sum of the parallel inductor current ipand the rectifier input current it is equal to is. The output current io is rectified from it. The switching frequencies and duty-ratios of cells are equal, but the PWM signals from Cell 1 to Cell 5 are shifted by 0◦, 72◦, 144◦, 216◦, and 288◦, respectively.

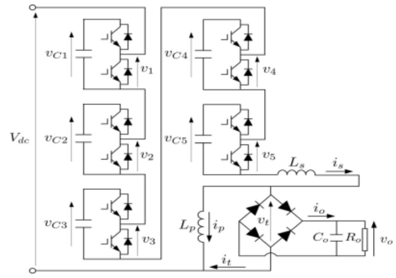


Fig. 2. Five-cell step-down series–parallel resonant converter

To analyse the circuit operation, the following assumptions are made:

1) The switches are lossless and the cells are identical with the same parameters.
2) The cutoff frequency of the input filter is much lower than the series current frequency in the converter. The input ac current and dc current flow through the parallel branch and the series branch of the input filter, respectively.
3) The dc voltages of the cell capacitors are balanced at a steady state.
4) The rectifier diodes are synchronously switched ON with the rectifier input voltage.

When the converter is operating at a steady state, the switching frequency is $f_s$and the duty-ratio of each cell is 90%. Based on the previous assumptions, the key voltage waveforms of the converter are shown in Fig. 4. With the phase-shift control, th output voltage of $j$th cell $v_j$is square wave ranging from 0 to the steady-state cell capacitor voltage $v_{Cj}$.Define output voltage across all the cells as

$$v_s = \sum_{j=1}^{N} v_j \qquad (1)$$

Therefore, $v_s$is ranging from the sum of four cell's capacitor voltages to the sum of five cell's capacitor voltages. As all the cell capacitor voltages are assumed to be equal to $v_C$, the stack voltage *vs* is comprised of a square wave ripple with the amplitude of $0.5v_C$and a dc offset of $4.5v_C$. It can be observed from Fig. 4 that the ripple frequency is five times of the switching frequency.

Assume there is no ac voltage drop across the passive components, the rectifier input voltage *vt* is a square wave with the amplitude of $0.5v_C$ but in an opposite phase compared to the ripple of $v_s$. As the dc offset of *vs* is $4.5v_C$with $N = 5$, the cell capacitor voltage can be derived as

$$v_C= V_{dc}/4.5$$

In a more general case with $N$ cells, the average cell capacitor voltage can be derived as

$$v_c = 2V_{dc}/(2N-1)$$

With the phase-shift angle of $360^\circ/ N$ and the duty-ratio of $2N -1/2N$ .Hence, the peak voltage value of $v_t$is $0.5v_C$ . If the converteroutput voltage $v_o$ is close to the peak input voltage of the rectifier,this converter achieves a step-down ratio of $2N - 1$, which is afunction of the number of half-bridge cells. With more cells inthe converter, higher step down voltage ratio can be achieved. The phase-shift angle is usually a fixed value but the duty-ratio can be flexible. Duty-ratios such as $(2N -k)/2N$ ;($k = 1, 3, 5 . . .$) are also applicable, resulting in lower step-down ratios such as $2N -k$. This arrangement for the converter gives the possibility of reducing the ratio of the series ac current to the dc current.

The equivalent operating frequency $f_e$is expressed by

$$f_e = Nf_s \qquad (2)$$

This is used to choose the passive components for the resonant operation. Assume that the dc component and root mean square (RMS) value of an ac component of the series current are $I_{dc}$ and $I_{ac}$ , respectively. If we neglect the losses of the converter, the input power is almost equal to the output power, which can be written as

$$V_{dc}I_{dc} = v_oI_{ac} \qquad (3)$$

$$\text{As } V_{dc}/v_o= 2N - 1,$$

it can be derived from (3) that

$$I_{ac} = (2N - 1)I_{dc}.$$

With a rated power $P$, the RMS of the ac current can be derived as

$$I_{ac} = (2N - 1)\, P/V_{dc} \qquad (4)$$

This means that when the output power is constant, the current RMS value and switch stress are proportional to the step-down ratio. As the ac current is usually much higher than the dc current, the conduction losses mainly come from the ac current. If we assume that the average voltages across IGBTs and diodes are the same as $V_{\text{semi}}$, the conduction losses caused by the ac current can be written as

$$Pac = I_{ac}V_{\text{semi}}N.(5)$$

Therefore, comparing $P$ac to the input power, it can be derived that the efficiency $\eta$ is limited by the conduction losses as

$$\eta < \frac{1-N(2n-1)V_{semi}}{V_{dc}}(6)$$

In most cases, if the current flowing through semiconductors is increased, the voltage drop on semiconductors increases. This gives a higher $V_{\text{semi}}$ and the efficiency will reduce. As a result, the converter is only suitable for high-voltage and low-power applications. It can be seen from (6) that with a higher step-down ratio, the efficiency reduces significantly. Therefore, the step-down ratio achieved by cells should be limited. In high voltage applications, IGBTs connected in series can also be used to construct a half-bridge. An isolation transformer can be used to further increase the step-down ratio without increasing the series ac current. Under such condition, the topology of Fig. 1(c) involving a step-down transformer becomes a good solution.

## IV. MODES OF OPERATION

To demonstrate the operation principle in a simple way, the starting point is selected at the time when the capacitor of Cell 1 is involved into the resonant operation and the end point is selected at the time when capacitor of Cell 2 is out of the resonance. The relevant time interval can be found in Fig. 3 which is marked by the equivalent operating cycle $T_e$. Note that fixed dead time is used for all switches. Considering operation mode with dead band, there are four operation modes in each operating cycle, which are shown in Fig. 4.

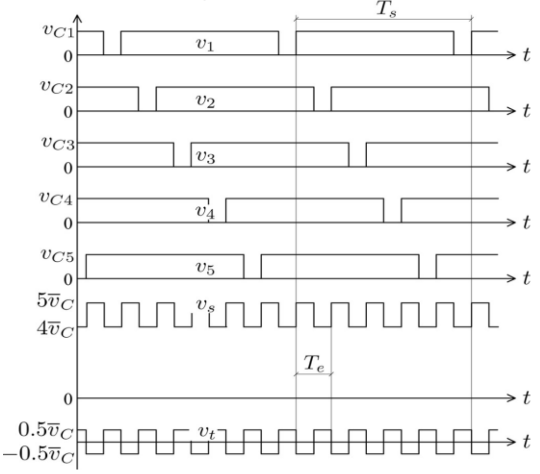


Fig. 3. Time-domain key voltage waveforms of the five-cell converter

### Operation modes in the first equivalent operating cycle

### Mode 1

To analyse the circuit operation, we assume the parallel current $i_p$is above zero. The first mode starts when the lower switch in Cell 1 is turned OFF, and the circuit enters the dead time mode of Cell 1 which is shown in Fig. 4(a). In this mode, no current flows through cells and all the current circulates between the parallel inductor and the rectifier.

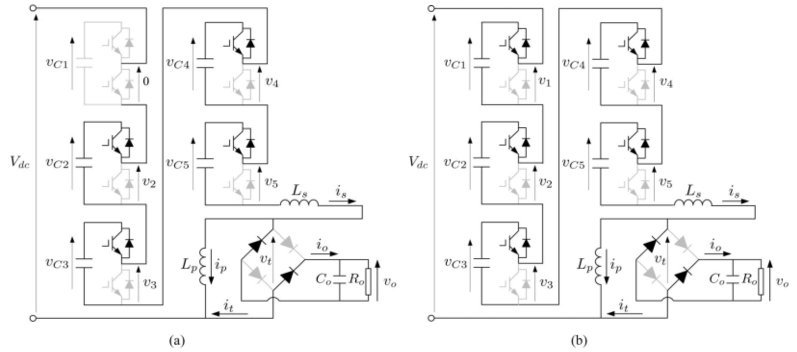


Fig.4 (a) .Mode 1Fig.4 (b) .Mode 2

**Mode 2**

After a short time, the upper switch in Cell 1 is turned ON and the circuit enters mode 2 as shown in Fig. 4(b). All the cell capacitors are in series with the inductor $L_s$. The input voltage of the rectifier is negative. Therefore, the input current$i_t$is negative. This mode lasts until the upper switch of Cell 2 is turned OFF.

**Mode 3**

This mode is the dead time mode of Cell 2. As there is no series current, all the current on the parallel inductor flows to the diode rectifier.

**Mode 4**

Shortly after that, the lower switch of Cell 2 is turned ON and the circuit becomes another resonant circuit only with capacitors of Cells 1, 3, 4, and 5 in series with $L_s$as shown in Fig. 4(d). As *vt* becomes positive in this mode, the series current starts to rise with its resonant waveform.

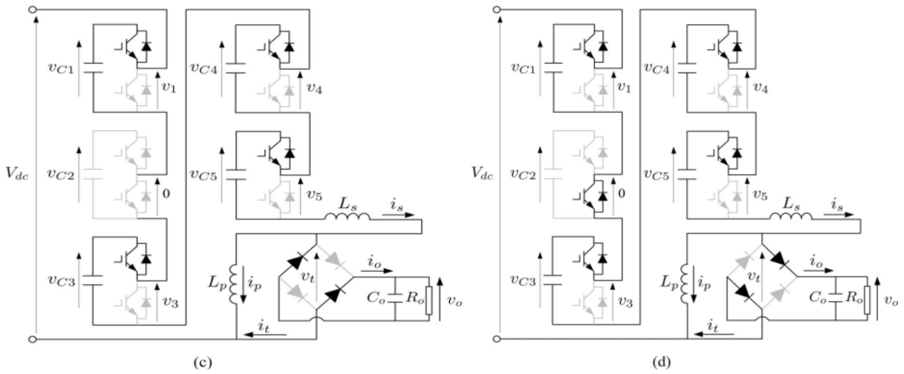


Fig.4 (c).Mode 3Fig.4 (d).Mode

## V.RESONANT OPERATION OF THE CONVERTER

Resonant operation can achieve very low switching loss. The resonant inductor $L_s$and $L_p$ and resonant capacitor $C_s$ are in series. They form a series parallel resonant tank. The resonant tank will then in series with the load. From this configuration, the resonant tank and the load act as a voltage divider. By changing the frequency of input voltage, the impedance of resonant tank will change. This impedance will divide the input voltage with load. Since it is a voltage divider, the DC gain of resonant circuit is always lower than 1. At resonant frequency, the impedance of series resonant tank will be very small; all the input voltage will drop on the load. So for series parallel resonant converter, the maximum gain happens at resonant frequency.

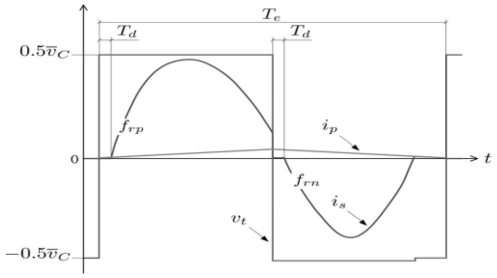


Fig. 5. Time-domain waveforms of the resonant tank.

From the mode of operation it is clear that the total voltage on the series capacitors is always clamped through the diode bridge by the constant output voltage and the input voltage

Therefore, the dc voltages of all the capacitors should be equal in the steady state. This gives the inherent-balancing ability of the cell capacitors during the series operation. When there are five capacitors in, the resonant tank is formed by five capacitors in series with $L_s$.When there are four capacitors in, the resonant tank is formed by four capacitors in series with $L_s$. Therefore, two resonant frequencies exist in the operation. Furthermore, for a general converter, the resonant frequency in the negative half-cycle is written as

$$f_{rn} = \frac{1}{2\pi\sqrt{L_s c / N}}$$

The resonant frequency in the positive half-cycle is

$$f_{rp} = \frac{1}{2\pi\sqrt{L_s \, c / N - 1}}$$

As $f_{rp} < f_{rn}$, $f_{rp}$and $f_{rn}$are defined as the first resonant frequency and the second resonant frequency, respectively. The resonant tank waveforms of the proposed converter when using an operating frequency between $f_{rp}$and $f_{rn}$are shown in Fig. 6. Here, a low dc current plus an ac current on the parallel inductor are assumed. Note that this converter is operating differently to the classic LLC [5] resonantconverters as two resonant frequencies exist during an operation cycle. In the case of Fig. 5, as in the positive half-cycle $f_e > f_{rp}$ , the series current resonates with frequency of $f_{rp}$and the converter operates in the CCM. In the negative half-cycle $f_e > f_{rn}$, the series current resonates with frequency of $f_{rn}$and the converter operates in the DCM. There are five operating cycles in each switching cycle.

## VI.SIMULINK MODEL AND SIMULATION RESULTS

SIMULATION PARAMETERS

| Symbol | Quantity | Value |
|---|---|---|
| $V_{dc}$ | Nominal input dc voltage | 500v |
| $V_o$ | Output voltage | 55 v (54v) |
| $I_{pk}$ | Maximum switch current | 30 a (27 a) |
| $L_s$ | Series inductance | 6.5 uh |
| $L_p$ | Parallel inductance | 3 uh |
| $C_1$ | Cell 1 capacitor | 57.9 uf |
| $C_2$ | Cell 1 capacitor | 69.1 uf |
| $C_3$ | Cell 1 capacitor | 58.2 uf |

| | | |
|---|---|---|
| $C_4$ | Cell 1 capacitor | 57.7 uf |
| $C_5$ | Cell 1 capacitor | 57.8 uf |
| $C_o$ | Output capacitor | 3 mf |

**OPEN LOOP CONDITION**

SIMULINK MODEL

The simulation of the proposed series parallel resonant multilevel dc-dc converter in open loop system done with the help of MATLAB. Simulink model of the resonant step-down modular multilevel dc-dc converter at open loop condition are shown in the Fig.7.

Fig.7.

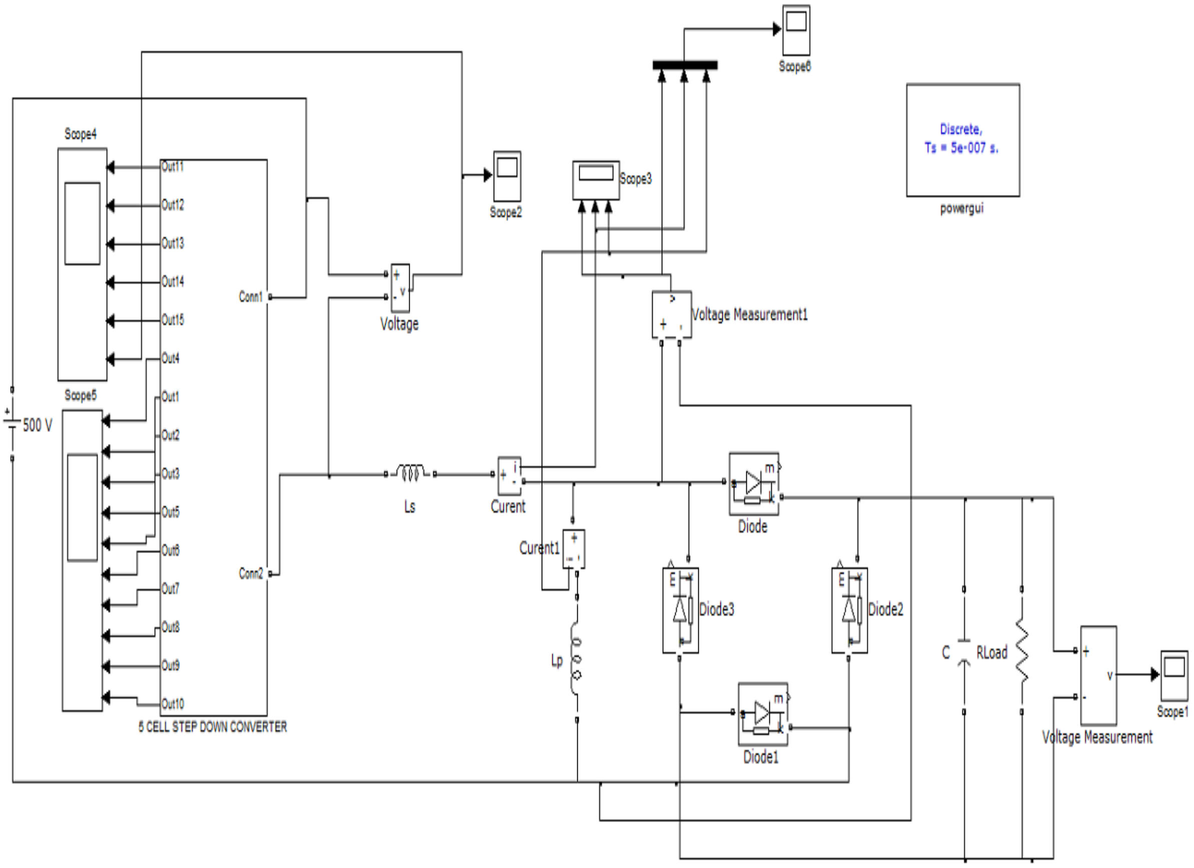
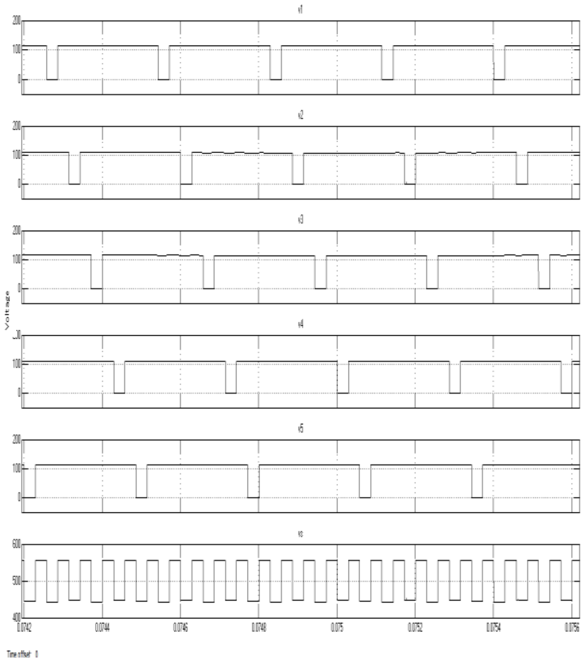


Fig. 7.Simulink model of proposed system under open loop condition

**SIMULATION RESULTS AND ANALYSIS**

Triggering pulses are given by pulse generator blocks with a phase shift of by 0◦, 72◦, 144◦,216◦, and 288◦, respectively.The half bridge cells were implemented using capacitors and IGBTs .Each cell switched at switching frequency 3.5 kHz with a dead band of 5.3 $\mu$s. Triggering pulses to new step-down resonant MMC is shown Fig .8. Voltage waveforms obtained is shown in Fig.9 in which $v_s$, the stack voltage is ranging from the sum of four cells capacitor voltages to the sum of five cells capacitor voltages. Here capacitor voltage in one cell obtained is approx. 111V. Here we take fe > frp , the series currentresonates with frequency of frp and the converter operates in the CCM. In thenegative half-cycle fe > frn , the series currentresonates with frequency of frn and the converter operates in the DCM.



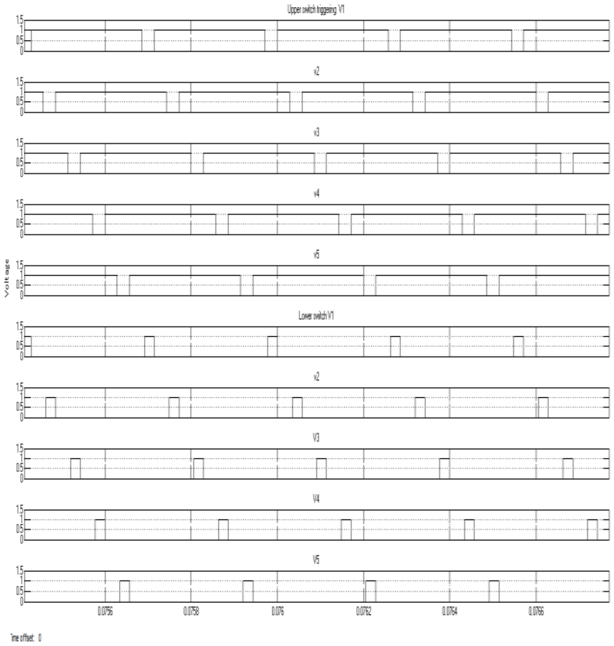


Fig.8.Switching pulses for each switch Fig. 9.Voltage waveforms open loop

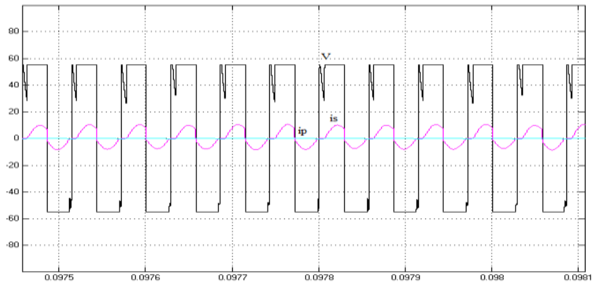
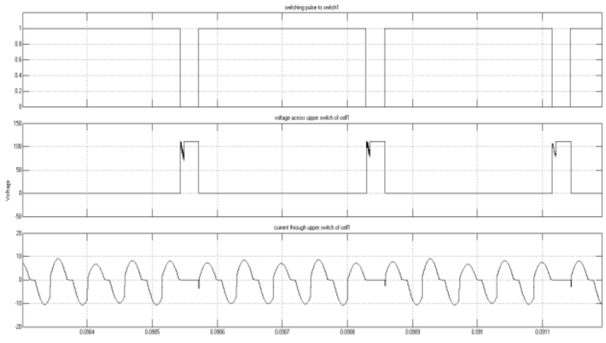


Fig. 10.Waveforms of Resonance Circuit

Note that when a switch is OFF, the current is zero. It can be seen that the converter can achieve ZCS and ZVS for the upper switches.



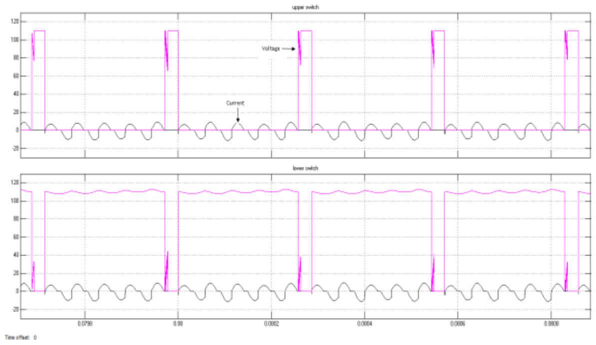


Fig. 11. ZVS and ZCS of upper switch of cell1 Fig. 12.Voltage and current waveforms across upper and lower switch

Output waveform under open loop condition are shown in Fig.16 and output voltage obtained is approx. 53V and it almost constant

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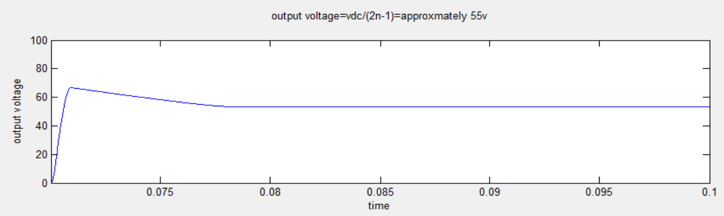

Fig. 13.Output waveform under open loop condition

## VII.CONCLUSION

This new step-down resonant modular multilevel converter can have several advantages like Reliability, scalability, and simplicity & suitable for high-voltage and low-power applications. The step down ratio of this new step-down resonant MMC can increase by increasing the number of cells.This converter has a simple configuration and inherent-balancing capability. Two resonant operating frequencies exist in the converter. The converter can operate under open-loop control as a dc transformer.

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