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# Integration of Reversing Voltage Multilevel Inverter Topology with High Voltage Gain Boost Converter for Distributed Generation

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**ABSTRACT**

The conventional energy sources available to us are on the verge of depletion. This depletion of conventional energy source leads to concentrate more on alternative energy sources. In this research, the focus is on the role of renewable energy sources (RES) in electrical power generation. Even though, the RES based plants produce power, we cannot directly connect it to the grid or loads. Because, the voltage ratings and nature supply of RES plants would not match with the load. Hence, this is a major issue for connecting RES plants to load or other utility. The power electronic converters are extensively being used as a link between load and supply. As most of the renewable energy power generation is DC in nature, the DC-DC converter is used to increase the voltage level and this DC must be converted to AC for grid connection. Therefore, inverters are used for DC to AC conversion. In this paper, the DC supply of renewable energy is connected to load by using cascade DC-DC converters along with a proposed reversing voltage (RV) multilevel inverter (MLI). The first DC-DC converter is used to enhance the voltage level with high gain and second converter is used to split the DC supply for inverter convenience. In this paper, proposed RV symmetrical and asymmetrical MLI generates 7, 9, 11, 13 and 15 levels with only ten power switches. In-phase level-shifted triangular carrier type sine pulse width modulation (PWM) technique is employed to trigger the commutating switches of proposed RV MLI. Switches of H-Bridge for reverse voltage appearance across the load are triggered by simple pulse generator. The circuits are modeled and simulated in MATLAB/SIMULINK software. Results are presented and discussed.



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## 1. INTRODUCTION

Electrical energy is the highly consumed energy in the global energy system. And, the generation of electrical energy by conventional energy sources is not able to meet the growing load demand. Therefore, the interest on alternative energy sources is being increased. The available renewable energy sources (RES) [1-3] are solar, wind and fuel cell. The power generation using these sources is called as distributed generation (DG) [4-5]. We can install these power plants at distributed level at load centers. Despite, advantages of DG, there is a major drawback that the DG units generate power at very low voltage levels in both AC and DC supply in nature. Hence, it is a major challenge faced by the utilities and loads to convert it to high voltage and required nature of supply. These conversions are possible only by using power electronic converters. Thus, power electronic converters have become key factor for DG systems.

However, while using power electronic converters, the power loss must be low and efficiency must be high. Most of the renewable energy source generation would be DC in nature with low voltage and to convert this low voltage DC to high voltage, DC-DC boost converters are used. There are many boost converter topologies proposed [6-9] earlier. The basic boost converter operation is performed by inductors and capacitors. The way in which we connect or utilize those components decides the gain, complexity and losses of the converter. This high voltage DC can be directly used by the DC loads and if we need to connect it to AC loads then, we prefer inverters. Conventional two-level inverter gives square wave output, which has more harmonics in the output voltage waveform. This distorted wave form causes heat losses, parasitic torques in case of induction motors, and draws ripple current from source.

Multilevel inverters (MLI) are the best solution for this conversion from DC to AC. It is also an inverter which converts DC to AC, but each half cycle has number of levels to get nearly sinusoidal wave form. There are different types of multilevel inverter topologies [10-13] like diode clamped, flying capacitor and cascaded H-Bridge type. The diode clamped and flying capacitor can give more number of levels but, it requires more diodes and capacitors respectively. The cascaded H-Bridge type gives us more levels by having number of H-Bridges. Each H-Bridge consists of four switches. Therefore, as the number of H-Bridges increase, switch count will be increased. Hence, in this paper, a new multilevel inverter topology with less number of switch-count to generate 7, 9, 11, 13 and 15 levels by operating in symmetrical and asymmetrical modes has been proposed. In-phase level-shifted carrier type sine PWM technique is employed to trigger the commutating switches of multi-level inverter. Switches of H-Bridge for reverse voltage appearance across the load are triggered by simple pulse generator. The High voltage gain DC-DC converter is used at first stage of conversion and a single input multi output (SIMO) DC-DC converter is proposed and placed after first converter for voltage balancing.

Figure 1 shows the block diagram of proposed topology. The high voltage gain DC-DC converter and SIMO converter are cascaded to get better performance and the proposed symmetrical or asymmetrical RV MLI is connected between SIMO converter and load. This circuit is modeled and simulated in MATLAB/Simulink software and results are discussed.

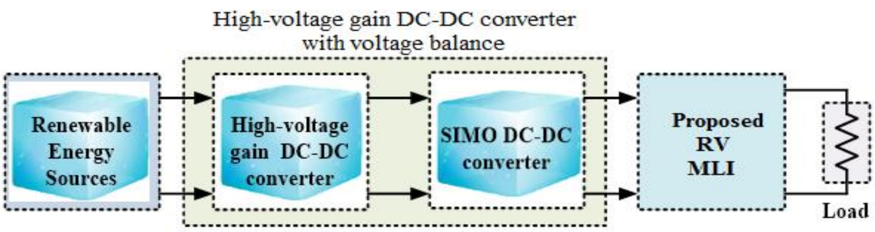



Figure 1. Block diagram of proposed system

## 2. RENEWABLE ENERGY SOURCE FED DC-DC CONVERTERS FOR HIGH VOLTAGE-GAIN BOOSTING AND SINGLE-INPUT MULTI-OUTPUT VOLTAGE BALANCING

Renewable energy sources (RES) are known as renowned source of energy because of many environmental issues these days. Also, the potential of renewable energy sources is enormous as they can in principle meet many times the world's energy demand. The main disadvantage of considering RES for electricity generation is that RES produces low-voltage output which insists for boost operation of voltage using DC-DC converter. This section presents the high voltage-gain DC-DC converter for boosting the low voltage output from RES to required level of output voltage and single-input multi-output converter with voltage balancing. Also, the proposed RV MLI needs three separate DC sources and those three DC sources are replaced with capacitors by cascading DC-DC converter. To avoid the issue of voltage balancing across three capacitors, a voltage balancing converter is placed alongside of high gain DC-DC converter.

### 2.1 Multilevel DC-DC Boost Converter

The configuration of three level DC-DC boost converter is depicted in Figure 2. It consists of conventional boost converter, (2N-1) diodes and (2N-1) capacitors. The main advantages of using the proposed topology are it can be extended to N-number of levels by adding only diodes and capacitors without modifying the main circuit, and also high voltage gain can be obtained without use of transformer and high duty cycle. The proposed converter consists of 3 stages which is operated at duty cycle of 0.5. The operation of the three level boost converter is explained in [6].

*Analysis of DC-DC Multilevel Boost Converter:*

In this section the boost ratio will be analyzed. This is very important because the inductor losses limit the theoretically maximum boost ratio, and the analysis gives important information to designers [11]. From basic principles, the voltage gain of the conventional boost converter is given by

$$\text{Voltage gain, } \frac{V_o}{V_{dc}} = \frac{1}{1-D} \quad (1)$$

For MBC, the voltage gain is expressed as

$$\frac{V_o}{V_{dc}} = \frac{N}{1-D} \quad (2)$$

The input DC current can be expressed in terms of the output current and input-output voltage as,

$$V_{dc}I_L = V_O I_O = V_O \frac{V_O}{R_O} = N\,V_C \frac{NV_C}{R_O} = \frac{N^2V_C^2}{R_O} \quad (3)$$

$$\text{Therefore, } I_L = \frac{V_C}{V_{dc}} \cdot \frac{N^2V_C}{R_O} = \frac{N^2V_C}{(1-D)R_O} \quad (4)$$

From (4), it can be seen that the input current can be controlled with duty cycle ‘D’ in the PWM.

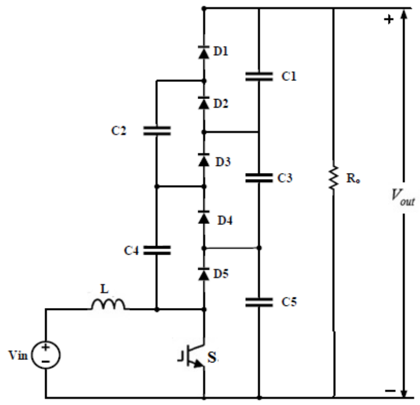



Figure 2. High-Voltage Three level DC-DC Boost Converter

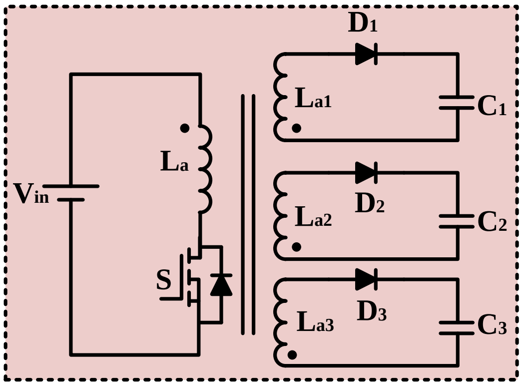



Figure 3. Single-Input Multi-Output (SIMO) Converter with Voltage Balancing

**2.2 Single-Input Multi-Output (SIMO) Converter with Voltage Balancing**

The SIMO isolated DC-DC converter achieves or performs two major tasks - one is to boost the input DC voltage from high gain DC-DC converter to higher value of voltage as boost converter and the other to balance the voltage across capacitors in proposed MLI topology. The circuit representation of single-input multi-output (SIMO) isolated DC-DC converter is shown in Figure 3.

As the name suggests of isolated DC-DC converter, DC-DC converter consists of transformer for isolation of input side to the output. The transformer is a multi winding transformer and gives three output ports and at the input, the transformer is supplied from a DC source. In this paper, the output of high voltage gain DC-DC converter is supplied as input to the transformer primary. A switch MOSFET is connected to the transformer primary and the switching operation of switch decides the charging time of input primary coil of transformer. The secondary of the transformer consists of three output ports with single input port and hence the circuit is termed as single-input multi-output isolated DC-DC converter. Each output port of the DC-DC converter has a diode connected along with the capacitor at the output terminal of the port. The diode is placed to prevent reverse current flow from capacitor to windings of transformer.The operation of switch (MOSFET) connected at primary side of transformer yields mutual flux that links with the three secondary windings of the isolated DC-DC converter. Mutual flux that links to the secondary windings induces self induced EMF in three secondary windings of SIMO isolated DC-DC converter. As the secondary terminals are closed, the self induced EMF forces current to pass through each of the three secondary windings. This phenomenon charges the capacitor connected at the output terminals of each of the input multi-output isolated DC-DC converter.

During the operation of multi-level inverter, the capacitors placed as input DC sources tends to discharge and with multiple DC sources in MLI raises an issue of voltage balance across capacitors of MLI.

As the SIMO converter produces three output ports, the three capacitors of RV MLI will not raise the issue of voltage balance across capacitors and hence reducing the risk of malfunctioning of MLI.

### 2.3 Closed-Loop Operation of SIMO Converter

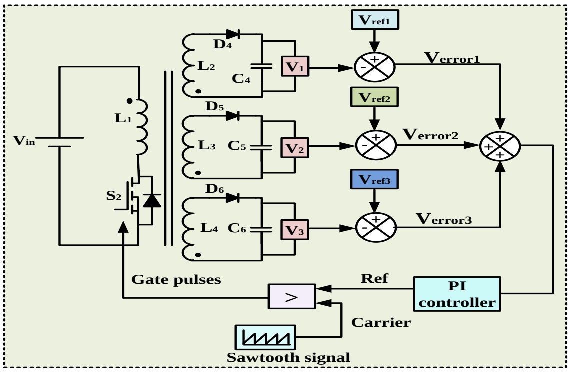



Figure 4. Closed-Loop Operation of Single-Input Multi-Output (SIMO) Converter

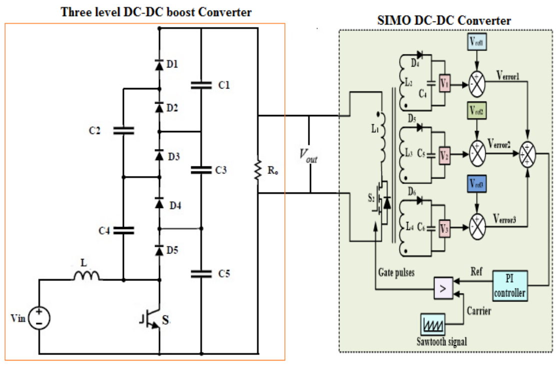



Figure 5. Complete Phenomenon of Renewable Energy Source Fed DC-DC Converters for High-Voltage Gain Boosting and Single-Input Multi-Output Voltage Balancing

The closed-loop control SIMO isolated DC-DC converter is shown in Figure 4. Conventional multi-output converters when operated in closed-loop mode of operation involves multiple PI controllers to reduce the error but this paper presents the use of only single PI controller to reduce the error in all three output ports of DC-DC converter.

The voltage across each of the three output ports of SIMO isolated DC-DC converter are measured across respective individual capacitors connected at the respective output port terminals of DC-DC converter. The actual measured output voltage across capacitor is measured and is compared with reference voltage yielding the error in each of the individual secondary sides. The process error in all the three voltages across capacitors is added and sent to a PI controller block. PI controller reduces the error and yields the reference signal. The reference signal is compared logically with carrier (saw-tooth) signal (when reference greater than carrier signal) which generates switching pulses to MOSFET. ON/OFF times of MOSFET reflects the charging time of primary coil of transformer and hence each of the output capacitors are charged to correct value of voltage. This phenomenon balances the voltage across capacitors. Also, during the ON time of MOSFET, the primary coil of transformer is charged and boosts the input voltage and transfers the input voltage to the secondary side. This SIMO isolated DC-DC converter achieves or performs two major tasks - one is to boost the input DC voltage from high gain DC-DC converter to higher value of voltage as boost converter and the other to balance the voltage across capacitors in MLI topology.

Complete phenomenon of renewable energy source fed DC-DC converters for high voltage-gain boosting and single-input multi-output voltage balancing with their respective closed-loop operations are depicted in Figure 5.

## 3. PROPOSED RV MLI TOPOLOGY

Recently, MLI topology is of paramount importance for high voltage and high power applications. Several topologies of MLI's have been reported in the literature. This paper presents symmetrical and asymmetric cascade based RV MLI employing three equal or unequal DC sources to generate seven, nine, eleven, thirteen and fifteen levels output and its total harmonic distortion (THD) is observed by integrating high voltage-gain boost converter with SIMO voltage balancing control. The block diagram and equivalent structure of proposed RV MLI is shown in Figure 6 and Figure 7 respectively.

Figure 7 shows the proposed topology of single-phase cascade based RV MLI. The proposed type of RV MLI can be operated in symmetrical and asymmetrical modes to produce stepped output to form 7, 9, 11, 13 and 15 level output based on the ratio of DC voltages. The proposed RV MLI topology consists of ten power switches in which six are used for switching operation to generate the required number of levels using level generator unit and four are used for polarity generation in full-bridge topology. The switches Sa1 to Sa6 are used in cascaded structure and switches Sa7 to Sa10 are placed in full-bridge structure in one phase of proposed topology.

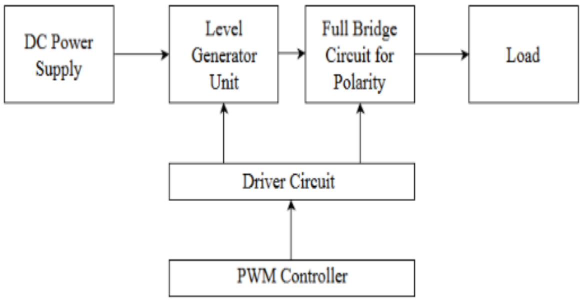



Figure 6. Block Diagram of Proposed Inverters using Reversing Voltage Topology

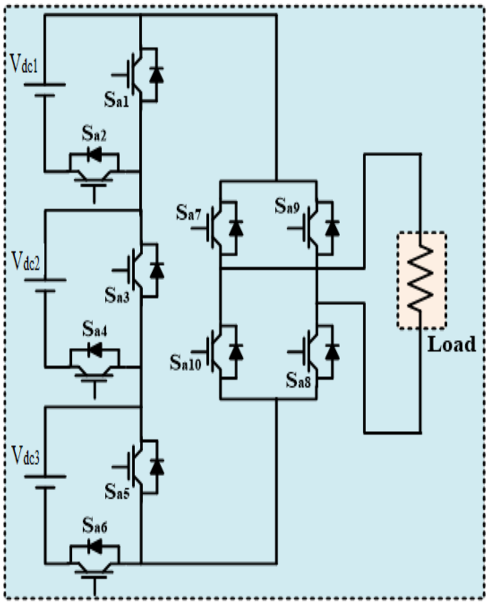



Figure 7. Proposed Single Phase Symmetrical/Asymmetrical RV MLI

The maximum output voltage is the sum of all the dc source voltages, and is given (5) and (6).

$$V_0, \max = V_{dc1} + V_{dc2} + \dots\dots..V_{dcn} \quad (5)$$

$$V_0, \max = \sum_{i=1}^{n} V_{dci} \quad (6)$$

Equations (5) and (6) illustrate the output level of the adder/subtraction circuit. Both the positive and negative levels are synthesized by the polarity generation unit.
At load ($V_o$), the synthesized stepped output voltage level will be obtained as mentioned below:

$$V_0, \max = \sum_{i=1}^{n} + V_{dci}\,, \ \text{If}\ S_{a7}, S_{a8} = 1 \quad (7)$$

$$V_0, \max = \sum_{i=1}^{n} - V_{dci}\,, \ \text{If}\ S_{a9}, S_{a10} = 1 \quad (8)$$

In symmetrical configuration the ratio of DC voltages are same i.e., 1:1:1 and it generates only 7-level output by cascading three equal dc voltages. But, in order to generate high number of output levels, a large number of switching devices and DC sources are required [7–10]. To overcome this problem, asymmetrical arrangements came into survival. In Asymmetrical arrangement the ratio of DC voltages can be reformed. For suppose, if input voltages are reformed in the ratio of 1:1:2, 1:2:2, 1:2:3 and 1:2:4 then proposed RV MLI will produce 9, 11, 13 and 15 level output respectively. Thus, a large number of switching devices are reduced in order to generate high number of output levels.

For a single phase 15-level cascade based RV inverter, the switching sequence to generate the required levels are given in Table 1. The operation of the CBRV MLI is explained in [4].

Table 1: Switching Sequence to Generate 15-Level Output for Proposed RV Inverter Topology

| S.No | Conducting Switches for Level Generator Unit | | | | | | Conducting Switches for Polarity Generation | | | | Voltage Levels | Voltage Rating (Volts) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $S_{a1}$ | $S_{a3}$ | $S_{a5}$ | $S_{a2}$ | $S_{a4}$ | $S_{a6}$ | $S_{a7}$ | $S_{a8}$ | $S_{a9}$ | $S_{a10}$ | | |
| 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 62.85 |
| 3 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 2 | 125.71 |
| 4 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 3 | 188.56 |
| 5 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 4 | 251.42 |
| 6 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 5 | 314.27 |
| 7 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 6 | 377.13 |
| 8 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 7 | 440 |
| 9 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 8 | -62.85 |
| 10 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 9 | -125.71 |
| 11 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 10 | -188.56 |
| 12 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 11 | -251.42 |
| 13 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 12 | -314.27 |
| 14 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 13 | -377.13 |
| 15 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 14 | -440 |

### 3.1. Pulses generation for commutating switches of proposed RV MLI topology

In-phase level-shifted carrier type sine PWM technique is employed to trigger the commutating switches of proposed RV MLI. The pattern of in-phase triangular carrier based level shifted PWM technique inorder to produce firing pulses to the power switches of 15-level proposed topology is shown in Figure 8. In this pattern of producing firing pulses, all the carrier signals will have same amplitude and frequency but the carrier signals are shifted in levels and all the carrier signals will be in-phase. For an n-level of cascaded H-bridge MLI the level shifted modulation requires (n-1)/2 carriers, all this carriers have the same amplitude and frequency.

For the proposed RV inverter 3, 4, 5, 6 and 7 carrier signals are considered along with reference signal for the production of pulses to generate 7, 9, 11, 13 and 15 level output voltage. Pulses for respective switches are produced only at the instant of interaction between reference and carrier signals and when the reference signal is greater than the carrier signal; the pulse will be high and otherwise low for respective switches. When switch Sa2 is ON, the switch Sa1 remains OFF and thus when Sa1 needs to be turned ON, Sa2 switches OFF. The similar procedure is adopted for switch pairs Sa3, Sa4 and Sa5, Sa6. For triggering six commutating signals, three drive pulses are sufficient while the other three switches can be operated using NOT signal of the existing drive pulses. The pulses generated to trigger Sa2 are used to trigger switch Sa1 by complimenting pulses of switch Sa2 using a NOT gate. Similarly pulses for Sa4 are used to trigger switch Sa3 by complimenting pulses of switch Sa4 using a NOT gate and Sa6 are used to trigger switch Sa5 by complimenting pulses of switch Sa6 using a NOT gate and thus using only three driving pulses six switches are triggered in proposed RV inverter topology. The Switches of H-Bridge Sa7 and Sa8 when turned ON, the switches Sa9 and Sa10 are turned OFF and vice-versa.

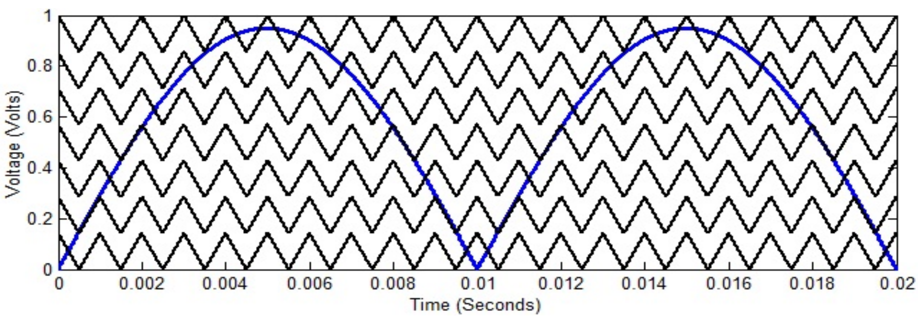



Figure 8. In-Phase Disposition Sine PWM to Generate 15-Levels

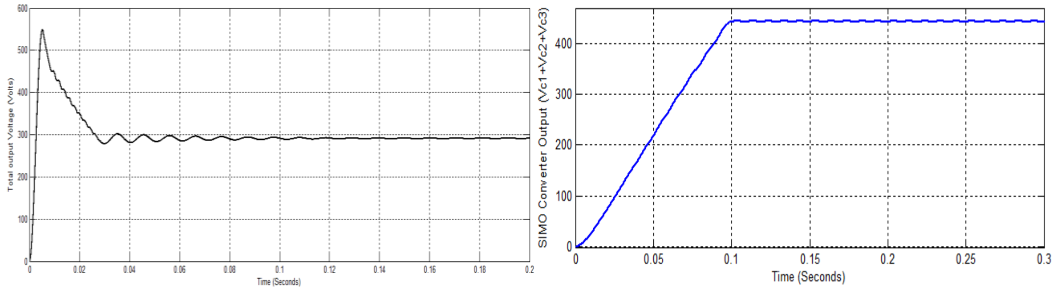
## 4. RESULTS AND DISCUSSIONS

The simulation of the proposed DC-DC converter for high voltage-gain boosting and SIMO voltage balancing with proposed symmetrical and asymmetrical RV MLI fed R-load is carried out and analyzed using MATLAB. The system parameters used to simulate and design the models are depicted in Table 2.

Table 2: System Parameters

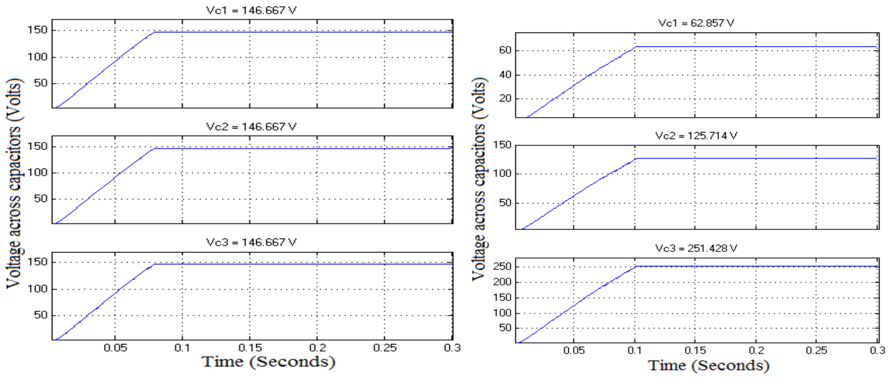
| Parameter | Value |
|---|---|
| Resistance Load | 10 Ohms |
| Duty Cycle | 0.5 |
| RES Output | 50 V |
| Inductance | 1.33 mH |
| Capacitance values in high gain converter | 100 µF |
| Output capacitance of high gain converter | 100 µF |
| Capacitors in SIMO converter (3 Nos) | 9000µF |
| DC-Link voltage to MLI | 440V |
| Switching frequency | 5 kHz |
| Modulation index | 0.866 |

Renewable energy source delivers 50 V output and feeds DC-DC converter. The output of high gain DC-DC converter and SIMO converter output is shown in Figure 9 (a) and (b) respectively. The 50 V output from RES is boosted to 300 V by using three level DC-DC boost converter. The output of boost converter is integrated with SIMO converter to boost the input voltage and also to provide capacitor voltage balance in symmetrical and asymmetrical modes to generate required number of voltage levels. SIMO converter boosts voltage of 300 V from high gain converter to 440V as shown in Figure 9.




(a) (b)

Figure 9 (a) High Gain DC-DC Converter Output and (b) SIMO Converter Output




(a) (b)

Figure 10 (a) SIMO Converter Output of Symmetrical Mode to Generate 7-Level and (b) SIMO Converter Output of Asymmetrical Mode to Generate 15-Level

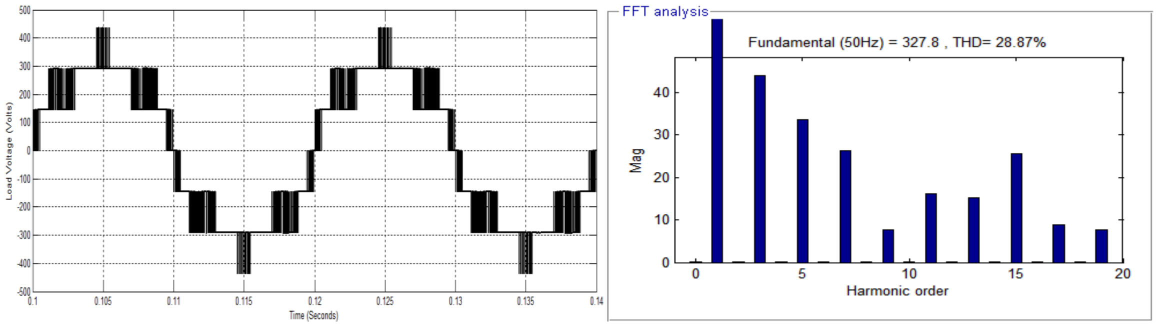
Figures 10 (a )and (b) shows the voltage across each capacitor of SIMO converter in symmetrical and asymmetrical modes for 7-level and 15-level respectively. In symmetrical arrangement each capacitor maintains the output voltage of 146.667 V and voltage balance is achieved across all three capacitors of SIMO converter. The three capacitor output voltages are fed to proposed RV MLI. In asymmetrical arrangement the value of voltage across the individual capacitor s are listed in table 3.

Table 3. Value of Voltage Across the Individual capacItors in Asymmetrical Mode

| S.No | Voltage ratio | Voltage across individual capacitors | | | Voltage levels |
|---|---|---|---|---|---|
| | | $V_{c1}$ | $V_{c2}$ | $V_{c3}$ | |
| 1 | 1:1:2 | 110 | 110 | 220 | 9 |
| 2 | 1:2:2 | 88 | 176 | 176 | 11 |
| 3 | 1:2:3 | 73.33 | 146.66 | 220 | 13 |
| 4 | 1:2:4 | 62.85 | 125.71 | 251.42 | 15 |

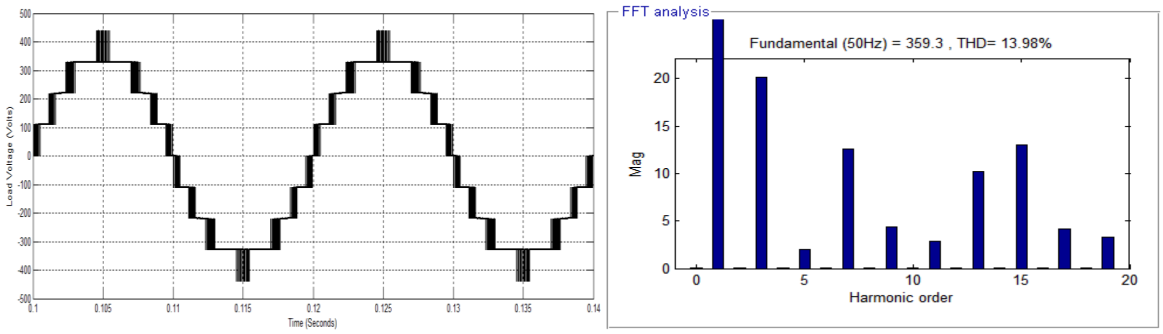
Figures 11 to 15 depicts the proposed RV MLI load voltage and corresponding harmonic spectrum using In-phase level-shifted triangular carrier type sine PWM technique for symmetrical and asymmetrical mode arrangements with a voltage ratios of 1:1:1, 1:1:2, 1:2:2, 1:2:3 and 1:2:4 to generate 7, 9, 11, 13 and 15 level output respectively with a modulation index of 0.866. The values of the output voltages are 327.8V, 359.3V, 362.8V, 366.7V and 379.3V for 7, 9, 11, 13 and 15 levels respectively and corresponding THD values are 28.87 %, 13.98 %, 12.37%, 11.84% and 9.08% respectively.

From the analysis, it is observed that the proposed 15-level asymmetrical RV MLI with a voltage ratio of 1:2:4 can be clearly appreciated to get nearly sinusoidal voltage waveform than 7, 9, 11 and 13 level inverters. From the figures 11 and 15 it was observed that 28.87% of THD for symmetrical RV 7-level inverter and 9.08% of THD for asymmetrical RV 15-level inverter. Also it is noted that the fundamental output voltage of symmetrical RV 7-level inverter attains only 327.8V, but the output voltage of asymmetrical RV 15-level inverter attains about 379.3V which increases the power output. Thus the asymmetrical RV multilevel inverter is used to obtain a high resolution, and to get better the efficiency and reduced harmonics with less number of switching devices.



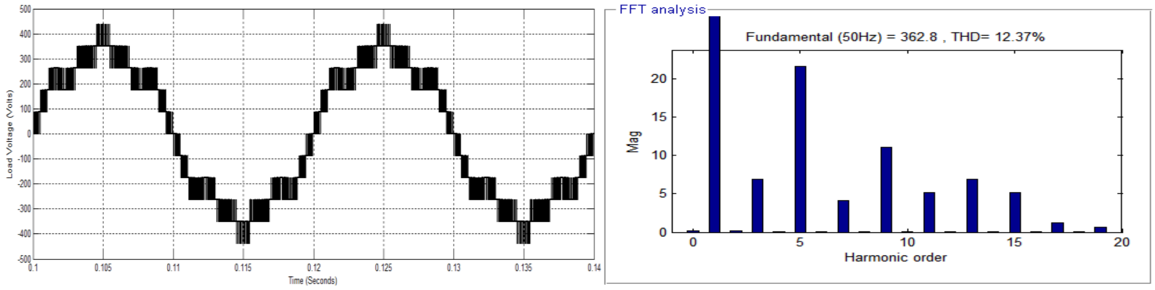

(a) (b)

Figure 11 (a) Single Phase 7-Level RV Inverter Output Voltage and (b) Corresponding THD Spectrum



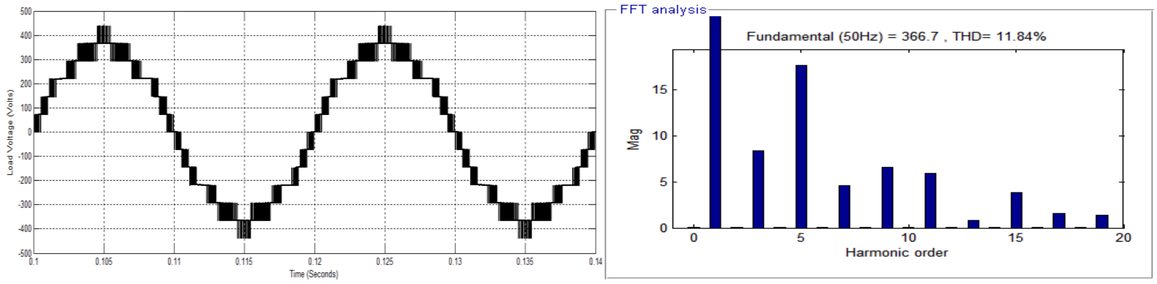

(a) (b)

Figure 12 (a) Single Phase 9-level RV Inverter Output Voltage and (b) Corresponding THD Spectrum



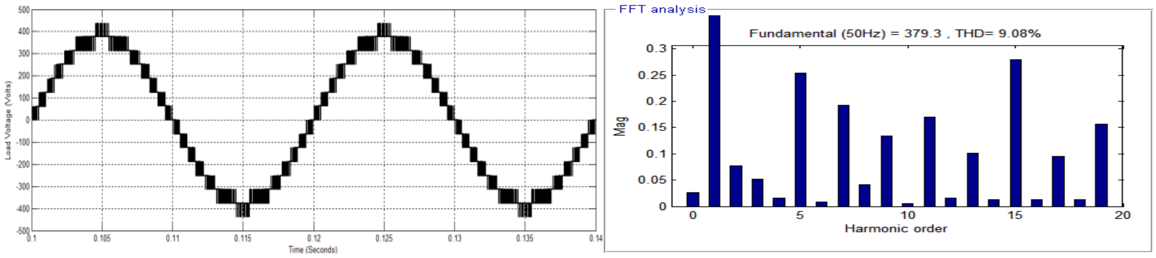

(a) (b)

Figure 13 (a) Single phase 11-level RV inverter output voltage and (b) Corresponding THD spectrum




(a) (b)

Figure 14 (a) Single phase 13-level RV inverter output voltage and (b) Corresponding THD spectrum




(a) (b)

Figure 15 (a) Single phase 15-level RV inverter output voltage and (b) Corresponding THD spectrum

Load voltage and corresponding THD comparison of RES output fed DC-DC converters for high voltage-gain boosting and SIMO for voltage balancing with proposed RV inverter fed R-load are depicted in figures 11 to 15 with different voltage ratios to generate 7, 9, 11, 13 and 15 levels. In this comparison it is concluded that with a different voltage ratios THD can be reduced by increasing number of voltage levels with the same number of components and dc sources.

## 5. CONCLUSION

This paper presents a symmetrical and asymmetrical RV MLI topology with a different voltage ratios for inverting the supply from renewable energy source. The voltage from RES is boosted using a high gain DC-DC converter and the output of high gain converter is split into three port output using a SIMO converter achieving voltage balance across three capacitors of proposed RV MLI. The proposed RV MLI topology is explained and the complete description was depicted to generate 7, 9, 11, 13 and 15 levels with different voltage ratios. RES gives out 50 V and this is boosted to 300V using high gain converter. SIMO converter primarily boosts the 300 V output of high gin converter to 440V and splits into three parts with equal or unequal voltages across three capacitors. Simulation analysis was carried out for the proposed system fed R-load. Load voltage and corresponding THD were shown for 7, 9, 11, 13 and 15 levels and it is clear that by increasing number of voltage levels, the proposed asymmetrical RV MLI reduces number of dc voltage sources and power switches to attain the maximum number of output voltage levels.

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