An Implementation of Switched Capacitor Inverter

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Abstract— A DC-AC inverter containing no inductors or transformers is presented. In the common inverter always contains the magnetic elements and so it results in the electromagnetic interference problem. For avoiding the EMI effect, it is a quite excellent choice to adopt a switched capacitor (SC) circuit scheme, containing only capacitors and switches. There are two methods of voltage conversions are possible. One of conventional method as a two stage inverter, this method has a several disadvantages. The most notable ones are (i) Cost (ii) Component stress. To solve this problem a single stage inverter is used. In this project work the switched capacitor inverter arrangement is fabricated, wired up, interfaced with a dc source and was tested. There are two main components of this arrangement. These components include a switched capacitor inverter and Arduino controller. The switched capacitor inverter is used to boost the input voltage and generates a regulated ac output. The Arduino controller is controlled the switched capacitor block switches and H-bridge inverter switches. It is used to regulate the ac output by varying the duty cycle. The advantages of the SC inverter are: no use of bulky inductors and a cost effective low profile design. A single stage switched capacitor inverter is simulated in PLECS (Piecewise Linear Electrical Circuit Simulation) environment and the practical implementation of this single stage inverter is done to validate the theoretical results. Closed loop control of single stage switched capacitor inverter is tested and the experimental results were observed.
Key words: Inverter, Switched Capacitor, Arduino, Single Stage, PLECS

I. INTRODUCTION

Recent switching power conversion systems are required to be small in size, light in weight, and high in conversion efficiency and reliability. A switched capacitor (SC) power conversion technique, eliminating magnetic elements, is one approach to meet these requirements. In the early 1970‟s SC power conversion circuits didn't yet have high performance. In the 1980‟s, as the power MOSFET switch and the multilayer ceramic capacitor became available, these new circuit devices enable SC power conversion circuits to improve their configuration and performance. Switched capacitor (SC) power conditioners achieve power conversion by electronically switching capacitors between the input power source and the load. SC power conditioners are extensively used for dc-dc conversions. A lot of literature dealing with analysis, control methods, topologies efficiency issues and applications of SC dc-dc converters are available. The most distinguishing feature of SC dc-dc converters is the absence of inductors and transformers for handling power, leading to higher power densities compared to conventional dc-dc converters. The advantages of SC dc-dc converters are efficiency over 95% under certain operating conditions for a wide range of load variation, amenability for mass production and cost effectiveness, ruggedness and compactness due to the absence of magnetic components, easy thermal management by heat steering techniques and a wide spectrum of output power ranging from a few milli-watts for single chip power solutions to over a kilowatt of output power.SC power conditioners are not restricted only to dc-dc applications. SC power conditioners have been used for dc-ac, ac-ac and ac-dc conversions also. However, compared to SC dc-dc converters, the use of SC power conditioners for these applications has been relatively less explored.

A switched capacitor (SC) based inverter that tracks the maximum power point (MPP) of a photovoltaic (PV) source and generates a pure sine output is presented in [1]. A DC-AC inverter containing no inductors or transformers is presented in [2]. The role of the magnetic devices is played by a switched-capacitor (SC) circuit, formed by two sub circuits. In [3], using CMOS-TG as a bidirectional switch, the various topologies can be integrated in the same configuration for achieving two functions: boosting and alternating; boosting for getting a sinusoidal output in which the peak is the result of a many times step-up of the input; alternating to realize the positive/negative half sinusoidal of the output. A closed-loop multistage (n -stage) multiphase (p -phase) switched-capacitor boost dc-ac inverter (MPSCI) is used in [4] by combining a variable-phase control (VPC) and sinusoidal pulse width-modulation (SPWM) technique for low-power step-up inversion/regulation. In [5], several modular converter topologies based on a switched-capacitor-cell concept are introduced for high-power applications. Two types of switched-capacitor cells, including the full cell and the half-cell, are discussed in [5]. A new type DC-AC converter using a voltage equational type switched capacitor transformer is presented in [6]. A test circuit which converts DC voltage (160 V) to an AC voltage (100 V/60 Hz) was built.[7] introduces a new transformer-less multilevel topology for PV arrays systems. The 7-levels structure ensembles the best characteristics of three basic topologies to obtain a step-up DC-AC converter with only a single DC input and nine power switches. [8] Proposes a switched-capacitor approach to generate a high voltage sinusoid at a frequency of few hundred Hertz for driving a highly capacitive load. The need for such a driver stemmed from an ITS (intelligent transportation systems) project that requires efficient inverters for driving electroluminescent (EL) displays. [9] presented to propose a new inverter topology for a multilevel voltage output. This topology is designed based on a switched capacitor (SC) technique, and the number of output levels is determined by the number of SC cells. A novel switched-capacitor-based cascaded multilevel inverter is proposed in [10], which is constructed by a switched-capacitor frontend and H-Bridge backend. Through the conversion of series and parallel connections, the switched-capacitor frontend increases the number of voltage levels. A novel switched-capacitor inverter is used in [11]. The inverter outputs larger voltage than the input voltage by switching the capacitors in series and in parallel. In [12], SunShot aims to make solar energy a low-cost electricity source for all Americans through research and development efforts in collaboration with public and private partners. In [13], Boundary conduction mode (BCM) and discontinuous conduction mode (DCM) control strategies are widely used for the flyback micro inverter. The BCM and DCM control strategies are investigated for the interleaved flyback micro inverter concentrating on the loss analysis under different load conditions. Switched capacitor multilevel output DC-DC converters are evaluated as panel integrated modules in a solar maximum power point tracking system [14]. The recommended system includes a central input current-controlled ripple port inverter. The use of a switched capacitor (SC) dc-dc converter for tracking the maximum power point (MPP) of a photovoltaic (PV) array with the possibility of partial shading is described in [15]. The SC converter topology can be reconfigured to maximize conversion efficiency depending on the solar radiation and load.

A. Two Stage Conversion

It has two converter stages – a DC/DC boost converter that can step up voltages and a single-phase VSI converter that can step-down voltages. If it is desired for this two-stage DC/AC converter to operate with maximum voltage gain (ratio of output to input voltage), all that must be done is to have the front-end boost converter operate with maximum step-up voltage gain and the inverter to operate with its maximum gain and not step down voltage.

B. Disadvantages of Two Stage Conversion

There are several disadvantages with the two-stage approach. The most notable ones are (i) cost, as two separate and independent converters are needed; (ii) component stress, as the front-end boost switch and front-end diode must conduct considerable current. As a result, DC/AC converters that can step up voltage using only a single stage has been proposed.

C. Single Stage Conversion

Single stage Buck/Boost inverter is a converter which performs two actions in a single stage. It boosts the DC voltage and invert to AC in a single stage. This project work uses a new step-up DC-AC converter. It consists of switched capacitor cells and each cell includes four switches, one capacitor, and H-bridge inverter. Since the components are less, it makes the system more compact, reliable, less weight, low cost etc.

II. SYSTEM OVERVIEW

The overall schematic of the Switched Capacitor based single stage boost inverter is given in Fig.1. The Switched Capacitor block that forms the basic building block of the inverter. In this type of switched capacitor topology with the help of capacitors output voltage is greater than input voltage. Whenever the capacitors get connected in parallel, these are charged and when these are connected in series it discharges. This phenomenon is similar to charge pump. By increasing the no of capacitors output voltage magnitude also increases i.e. output voltage magnitude depends on number of capacitors. The Arduino controller generates the switching pulses of the switches and regulates the voltage. It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs and a reset button. In this work 9th and 10th is used to generate the switching pulses. It contains everything needed to support the microcontroller simply connect it to a computer with a USB cable or power it with an AC-to-DC adapter or battery to get started.

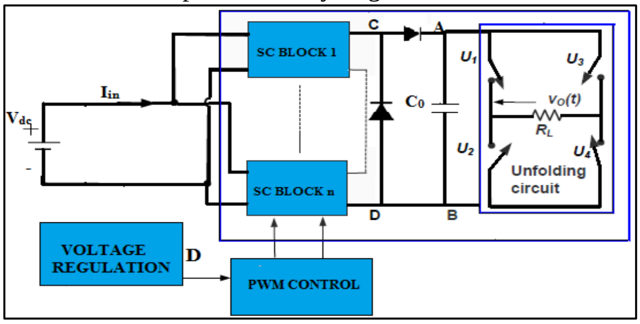


Fig. 1: Overall Configuration Single Stage SC Inverter

Switched Capacitor Block

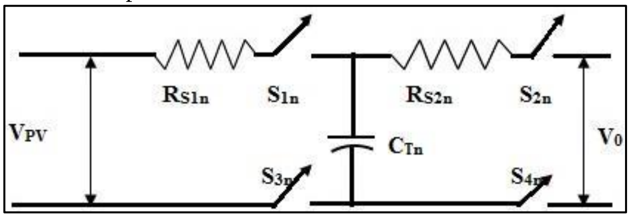


Fig. 2: nth Basic SC Building Block of the Inverter

The SC block consists of capacitor and four MOSFET switches. No of SC block based on the output voltage level. In this work, there are two SC blocks are used. The above figure shows that the circuit configuration of the one SC block. When S_{1n} and S_{2n} are closed, C_{Tn} is getting charged. Then there is a dead when all switches are opened. Next S_{3n} and S_{4n} are closed. Now C_{Tn} is discharged into the load. Thus, this topology generates a floating output voltage with respect to the source V_{DC}. By connecting the inputs of multiple basic SC blocks in parallel across the input source V_{DC} and their floating outputs in series, the topology can be used as a buck or boost depending on the duty ratio (D1 and D2) of the switches.

III. DETAILED OPERATION OF THE SWITCHED CAPACITOR INVERTER TOPOLOGY

Here the detailed circuit operation is examined by sub dividing a complete charge-discharge cycle of time period $2T_S$ into four sub intervals. The expected waveforms are given in Fig. 3.

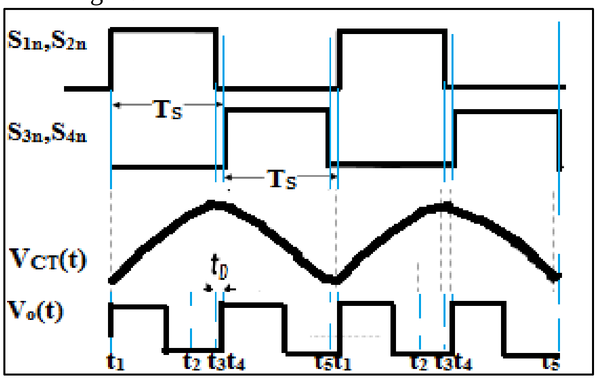


Fig. 3: Theoretical Waveforms

1) t_1 to t_2

This is part of the interval during which the input switches S_{1n} and S_{2n} of all the SC blocks are ON and output switches S_{3n} and S_{4n} are OFF. The charge transfer capacitors C_T of all blocks are connected in parallel across dc source and they are charged in parallel. C_0 is charging upto its maximum value. R_L is supported by C_0.

2) t_2 to t_3

The input switches S_{1n} and S_{2n} continue to be ON, charging C_T. The output switches S_{3n} and S_{4n} continue to be OFF. Now R_L is supported only by Co.

3) t_3 to t_4

This is the dead time when all switches S_{1n} to S_{4n} of all the SC blocks are OFF.R_L continues to be supported only by Co.

4) t_4 to t_5

The input switches S_{1n} and S_{2n} of all the SC blocks are OFF and output switches S_{3n} and S_{4n} are ON. All C_T'S are connected in series and they discharge serially into the circuit comprising Co and R_L in shunt. Co starts charging.

5) t_5 to t_1

This is the dead time. All switches S_{1n} to S_{4n} of all the SC blocks are OFF. At that time, freewheeling diode starts its operation.

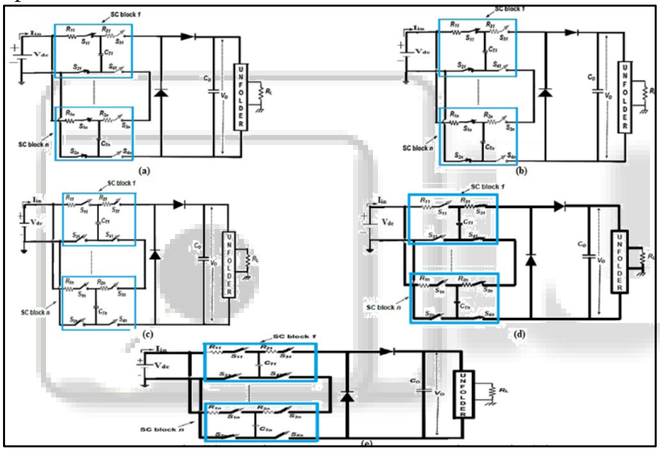


Fig. 4: Circuit configurations of the SC based inverter during different subintervals: (a) t_1 to t_2; (b) t_2 to t_3; (c) t_3 to t_4; (d) t_4 to t_5 (e) t_5 to t_1

IV. DESIGN PROCEDURE FOR THE SC INVERTER

A. Determine n (the Number of SC Blocks)

'N' SC blocks are connected to boost the input voltage. The minimum value of N depends upon the required output voltage. In this project, two SC blocks are used. The SC blocks are parallel connected across the source and serially discharging. The discharging voltages of two SC blocks are 10V.

B. Design of C_T

Value of CT decides the maximum amplitude of ripple in the voltage and f is the frequency of the fundamental cycle of the voltage, then the design value of CT is given by,

$$C_T = \frac{2\times P}{4\times 2\times \Pi\times V\times \Delta V} \quad (1)$$

Where V = Input Voltage

ΔV = Ripple in voltage

C. Design of C_0:

C_0 affects the average output ripple ΔV. Referring to Fig 3.5, R_L is supported C_0 during the time period t_5 to t_4. When V_0 (t) = $V_{0\text{-peak}}$, the duty ratio is maximum and if we neglect the dead time t_D , the time duration between t_5 and t_4 is T_S. Now R_L is supported fully by C_0 for about $0.5T_S$. Thus C_0 is given by,

$$C_0 = \frac{-0.5\ T}{R * \ln \{(Vpeak - \Delta V)/Vpeak\}} \quad (2)$$

Where R = load resistance

V_{peak} = Output Voltage

ΔV = Ripple in voltage

T = Total time period

D. Selecting MOSFET's

MOSFET switches are usually used in SC power conditioners. MOSFET optimization implies choosing MOSFETs with lowest V_{DS} and I_{DS} ratings and highest $R_{DS\text{-}ON}$ rating to meet the required design since MOSFETs with higher V_{DS} and I_{DS} and lower $R_{DS\text{-}ON}$ are more expensive due to larger die size.

MOSFETs with lower $R_{DS\text{-}ON}$ are used in the charging circuit; the efficiency does not improve since charging circuit resistances do not play a part in the capacitor charging efficiency. The MOSFETs are chosen so that $I_{DS} > I_{CT}max$ (t).

$$I_{DS} > I_{CT} \max(t) = \frac{Vin - Vct}{R} \quad (3)$$

Hence MOSFETs with $V_{DS} > 2V_{in}$ are chosen. The input MOSFETs that are selected have a V_{DS} = 100V.

E. Components Specification

Components	Ratings	Quantity
Capacitor C_T	1000µF	2
MOSFET	IRF540N	12
Optocouplers	MCT2E	12
Capacitor C_0	2200µF	1
MOSFET driver	IR2110	2
Diode	IN5408	6
Arduino Controller		1

Table 1: Components Specification

V. OUTPUT VOLTAGE REGULATION

The Output Voltage is controlled through the voltage regulation loop. The difference between the input voltage and output voltage is calculated. If the difference is greater than the 0.5V, then it check the output voltage is less than the set voltage and duty cycle is less than the 100. If it is yes, then the duty cycle will be incremented. Otherwise, the duty cycle will be decremented.

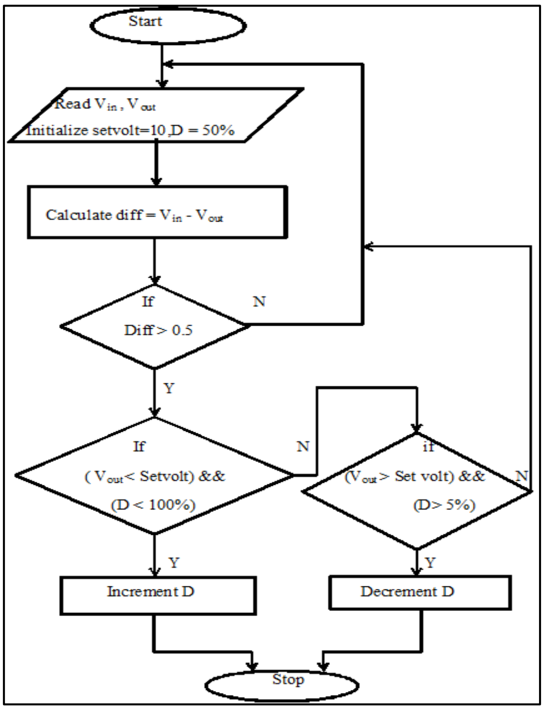


Fig. 5: Flowchart

VI. Overall Experimental Setup

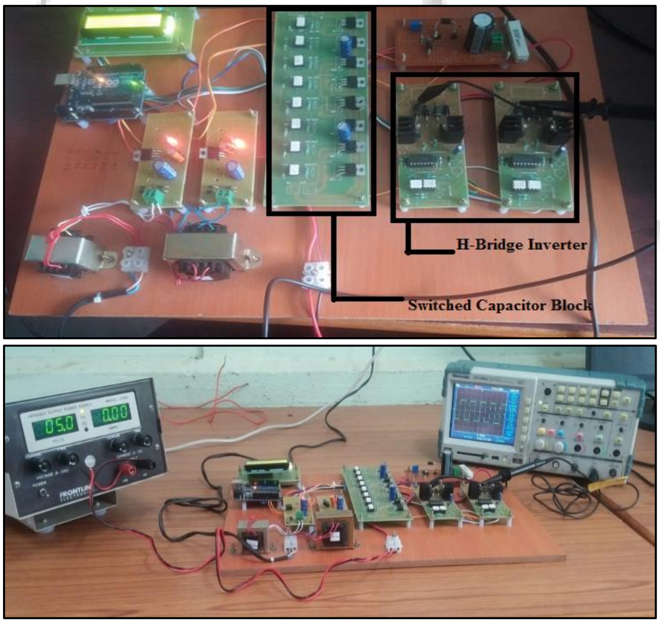


Fig. 6: Overall Experimental Setup

The Input voltage is taken from the regulated power supply. The input voltage is setting to 5v by varying the knob. The Arduino controller takes the supply from the step down transformer 230/12V. The optocoupler takes the supply from the step down transformer 230/12V.

The arduino controller generates the switching pulses. It is given to the MOSFET switches via the optocoupler. The switching frequency of the switches used in the switched capacitor block is 200HZ. The switching frequency of H-bridge inverter is 50HZ.

A. *Switching Pulses*

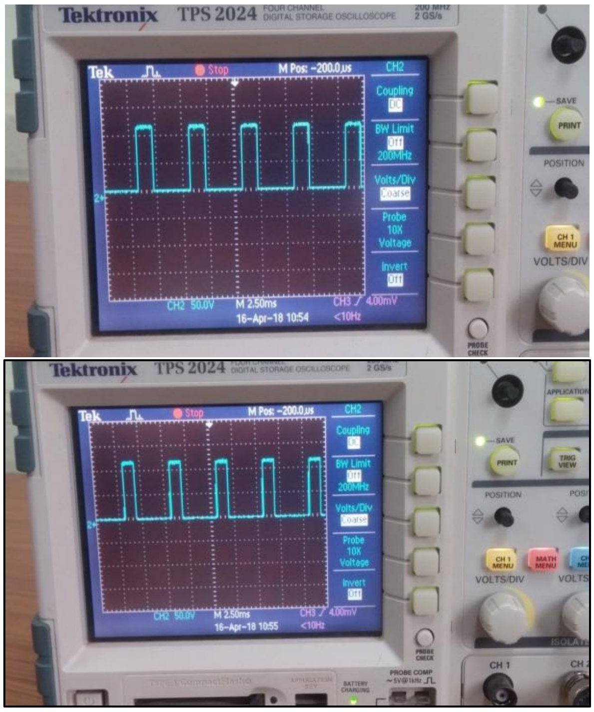


Fig. 7: Switching Pulses for S_1 and S_2 Switches

Fig. 7 shows that the switching pulses of S_1 and S_2. These pulses are taken from the 9th pin of the arduino controller. The switching frequency of S_1 and S_2 switches are 200HZ.

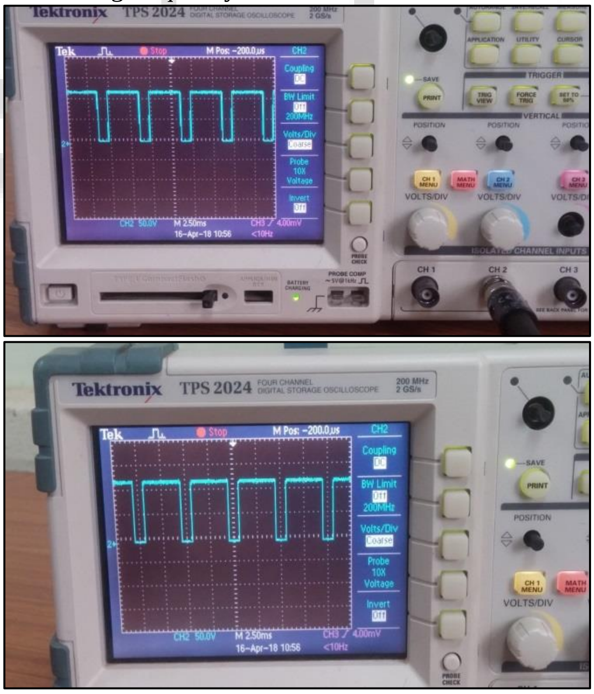


Fig. 8: Switching Pulses for S_3 and S_4

Fig.8 shows that the switching pulses of S_3 and S_4. These pulses are the complementary pulses of the above pulses. It is taken from the 10^{th} pin of the arduino controller. The gate pulses of S_5 and S_6 are similar to the pulses of S_1 and S_2. The gate pulses of S_7 and S_8 are similar to the pulses of S_3 and S_4.

B. H-bridge Inverter Pulses

Fig.9 shows that the gate pulse for H-bridge inverter. In the H-bridge inverter consist of four MOSFET switches. This inverter circuit need a MOSFET driver IR2110. The switching frequency is 50HZ. This frequency is less than the Switched capacitor block switching frequency

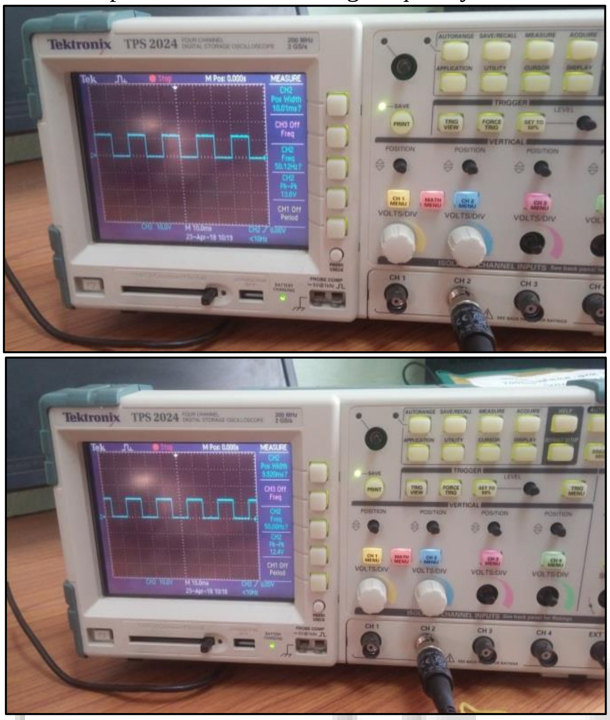


Fig. 9: Gate Pulses for H-bridge Inverter

C. Output Voltage

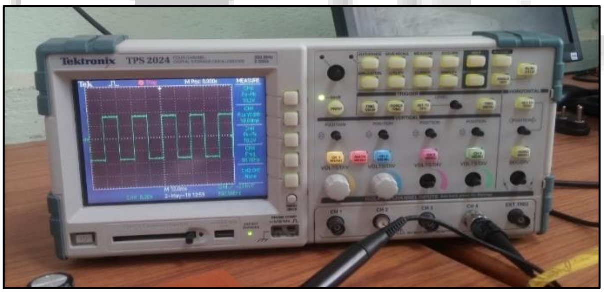
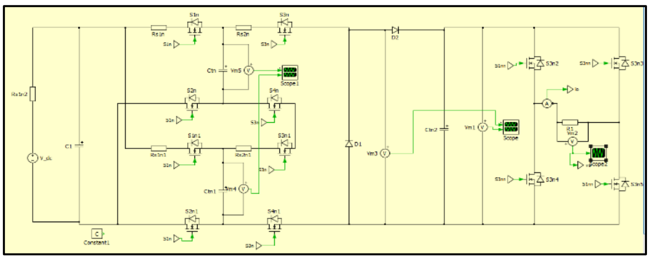


Fig. 10: Output Voltage

Fig.10 shows that the output voltage waveform. When the input voltage is 5V, the output voltage is 18.2V.

D. Comparison between Simulation Results & Experimental Results



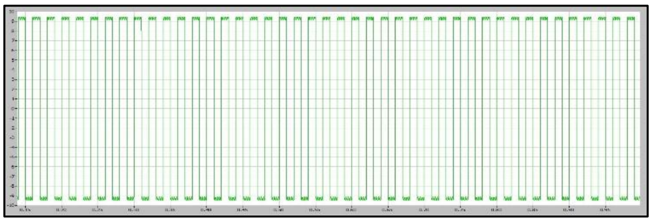


Fig. 11: Simulation Results

The above figure shows that the simulation results .If the input voltage is varied, the output voltage is boosted and inverted. From the simulation, when the input voltage is 5V, the output voltage is 18$V_{pk\text{-}pk}$.

Input voltage	Simulation Results	Hardware results
5V	18$v_{pk\text{-}pk}$	18.2$v_{pk\text{-}pk}$

Table 2: Comparison between Simulation Results & Hardware Results

Table.2 shows that the comparison between simulation results and hardware results. The set voltage value is 10v.If we vary the voltage above or below the set voltage value, the voltage is maintained the constant value by varying the duty cycle.

VII. CONCLUSION

This project has presented a single stage switched capacitor inverter. The circuit topology and operating principle of the switched capacitor inverter have been analysed in detail. The switched capacitor inverter is studied and simulated in PLECS environment. Furthermore, the implementation of single stage switched capacitor inverter has been done successfully. The hardware model of single stage switched capacitor inverter was tested in the laboratory. The Arduino controller generates the switching pulses and regulates the output voltage. The input voltage is inverted through the single stage conversion is achieved. Moreover, the comparison is made between the simulation results and experimental results. As a result, the overall system is highly portable and cost effective. One of the drawbacks of SC power conditioners is the large number of MOSFET switches needed compared to conventional power conditioners.

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