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RAPID CONTROL PROTOTYPING OF VOLTAGE CONTROLLER FOR THREE PHASE VOLTAGE SOURCE INVERTER

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ABSTRACT

This paper presents rapid control prototyping of voltage source inverter (VSI). Control techniques for power converters are developing day by day. However, it is not practical to implement a controller in hardware to test its performance in real time. It is possible to implement the designed controller with real time simulator and then test it with the actual power converter circuit. Such a simulation is known as rapid control prototyping (RCP). In this paper, a three phase voltage source inverter (VSI) is designed and implemented in hardware and the control technique for the VSI is implemented using a real time simulator and then interfaced with the hardware model of the VSI. The main aim of this paper is to implement rapid control prototyping for verifying the performance of the controller designed for the specific power electronic circuit

Keywords: real time simulator (RTS), rapid controls prototyping (RCP), voltage source inverter (VSI), pulse width modulation, proportional integral (PI) controller.

1. INTRODUCTION

Simulation is the representation of the operation of a real-world process or system over time through the use of other systems [1], [2]. Simulators are widely used for design and verification of electrical circuits. Simulators are categorized into offline simulators or software simulators and real time simulators. During offline simulation, the computational time of the equations and functions representing a system in a given step time maybe less or more than the step time of the simulation [3]. The main objective of offline simulation is to obtain result of the system and not the time at which it becomes available. However, real time simulation should produce the required results and the time at which the results are made available and it must be same as that of its physical counterpart [4]. Real time simulation is categorized into rapid control prototyping (RCP), hardware in loop (HIL), software in loop (SIL). In rapid control prototyping, the controller is implemented using RTS and then connected to the physical plant. Whereas in case of hardware-in-loop, the plant is implemented in RTS and then connected to the physical controller. In software-in-loop, both the plant and the controller are implemented using RTS [5].Rapid control prototyping allows prototyping of new and complex control system and also develop and improve existing control system used in various industrial processes. The main idea of this approach is to design and verify a control algorithm for a system in offline simulation and then implement it using RTS to verify its performance in real working conditions. Thus a real time controller is implemented. The real time implementation of the controller designed in offline simulators is done automatically by the RTS without any handwritten code. However, the offline simulator must be compatible with the RTS [6]. The application of RCP in various fields is highlighted in literature [7]-[10].

Voltage source inverter (VSI) is a power electronic circuit that converts fixed DC power to variable frequency AC power [11]. Three phase VSI is mainly used in AC motor drive, uninterrupted power supply and in grid connected PV system [12]. Fig.1 shows the block diagram of a grid connected PV system [13]. For a grid connected PV system the DC power generated by the PV system is converted into AC before connecting it to the grid. The output of the inverter is synchronized with the grid. The output voltage profile of the inverter must be the same as that of the grid. However fluctuations in the PV side (due to peak/non-peak hours) will result in change in output voltage profile of the inverter [15]. There are various control techniques for grid connected inverter. Any control technique is first verified using simulators and then implemented in hardware. Using RCP simulation, it is possible to verify any control technique with the actual system. This approach provides a better picture about the performance and reliability of the designed controller.

In this paper, a three phase VSI is designed, simulated using MATLAB-Simulink and implemented in hardware. A controller is also designed and implemented for the VSI. The controller basically maintains the output voltage of the VSI constant for any fluctuations in output voltage of the PV array (input). The controller is implemented in RTS and then interfaced with the hardware model of the VSI which is the physical plant. Thus rapid control prototyping of the voltage controller is realized. Opal RT is one of the leading companies of real time simulators and OP-4500 is a product of Opal RT which is used to implement the controller. RT-Lab is used to interface the MATLAB-Simulink model with OP-4500.
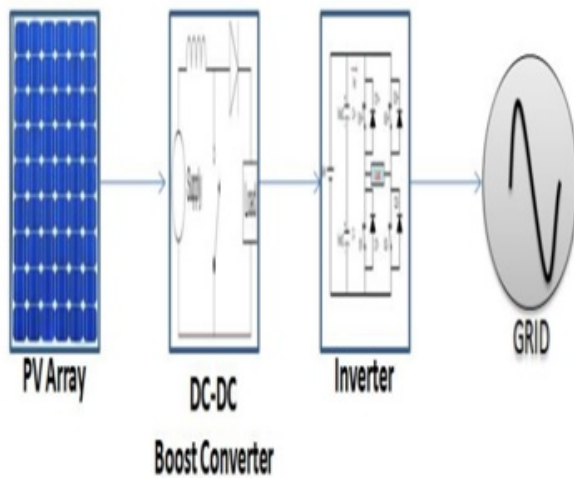
Figure-1. Grid connected PV system.
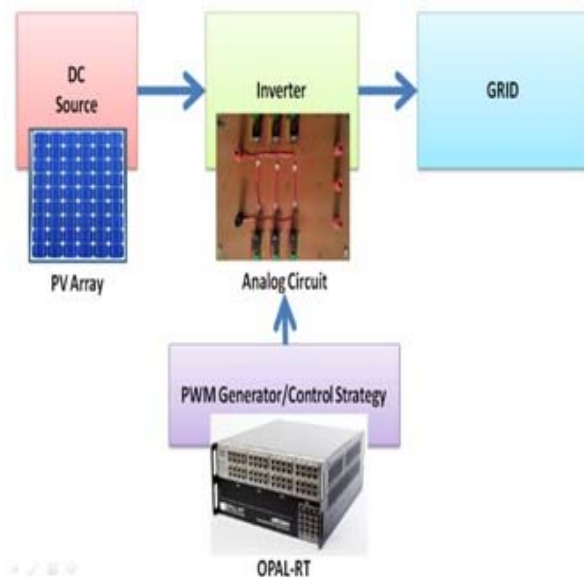
2. METHODOLOGY

Figure-2. Block diagram.

The block diagram of the VSI with real time simulator is shown in Figure-2. The methodology is elaborated as:

1) Design the power converter and verify using offline simulators.

2) Implement the designed power converter in hardware.

3) Test the hardware setup in open loop.

4) Design the controller and verify its operation using offline simulators.

5) Implement the designed controller using RTS.

6) Interface the RTS with the hardware setup and verify its performance.
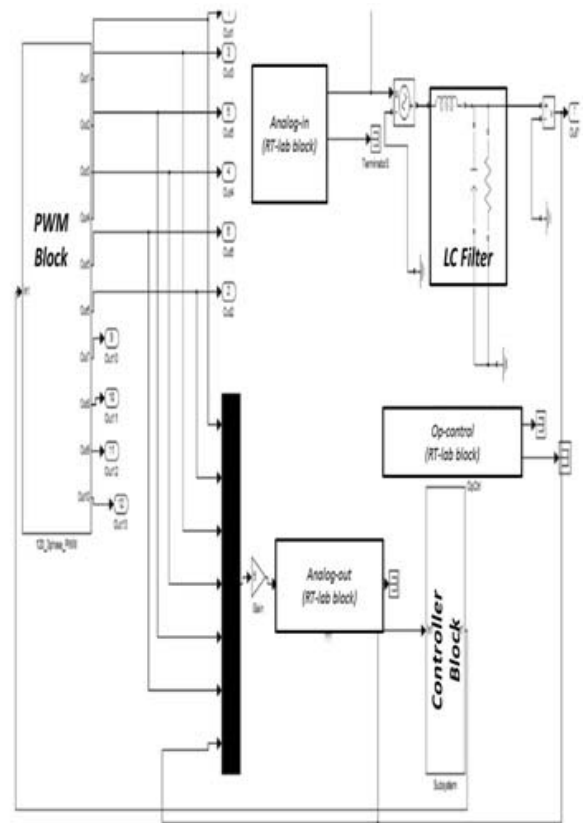

Figure-3. RT-Lab compatible simulink model of the system.

The hardware model of the VSI is the physical plant. The three phase VSI topology used in this paper is the conventional VSI with 120 degrees conduction mode. This topology has six switches and each switch conducts for 120 degrees. Output filter is required to remove high frequency ripple component from the VSI output [17]. The inductor and the capacitor values are calculated using [18]. To reduce complexity, the output filter is implemented in RTS as shown in Figure-3. The output of the VSI is fed to the RTS using the analog input port where it is first filtered and then given to the controller block. OP 4500 has an operating range of 32 volts. Therefore the VSI is operated at 32 volts peak to peak. Internal gain is included to meet the necessary operating conditions.

The control prototype for the plant is implemented in RTS and the performance of the controller is tested in actual condition. The controller is designed in MATLAB-Simulink and interfaced with the RTS using RT-Lab. A set of guidelines are to be followed to make the Simulink model compatible with RT-Lab. Figure-3 shows the RT-Lab compatible MATLAB-Simulink model of the entire system that is implemented in RTS.

3. CONTROLLER DESIGN

The output voltage of the VSI is controlled by using pulse width modulation technique. In this method, the output voltage is controlled by adjusting the ON and

OFF period of the power switches used in the VSI [19]. Multiple pulse width modulation (MPWM) with uniform pulse is used for the VSI. In MPWM the switching pulses are generated by comparing a carrier wave with a reference wave where the reference wave is a square wave and the carrier wave is a triangular wave. The number of pulses, N [20] per half cycle is (1).

$$N = \frac{f_c}{2f_r} \qquad (1)$$

Where f_c is the carrier wave frequency and f_r is the reference wave frequency.

The output rms voltage is calculated using (8).

$$V_o(rms) = [\frac{2N}{2\pi} \int_{(\frac{\pi}{N}-d)/2}^{(\frac{\pi}{N}+d)/2} Vs^2 d\omega t]^{1/2} = Vs\sqrt{\frac{Nd}{\pi}} \qquad (2)$$

Where d is the width of each pulse and V_s is the dc input voltage.

As the switches conduct for 120 degrees, the length of the reference wave is 120 degrees as shown in Figure-4. Let Vr be the amplitude of the reference wave and Vc be the amplitude of the carrier wave. Whenever Vr>Vc the switch is turned ON and whenever Vr<Vc the switch is turned. Modulation index (Ma) is calculated using (3). The variation of pulse width with modulation index is shown in Figure-5 and Figure-6.
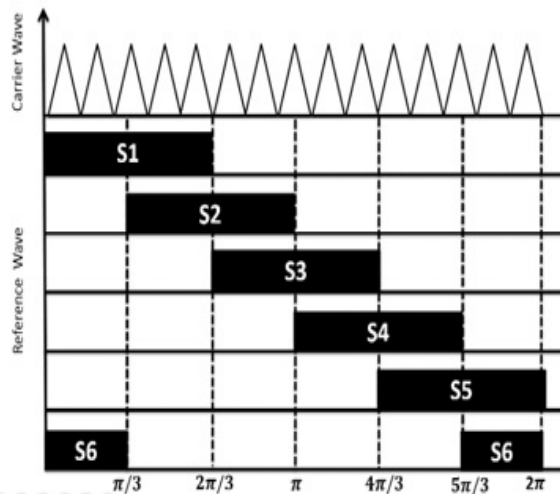
$$Ma = \frac{Vr}{Vc} \qquad (3)$$

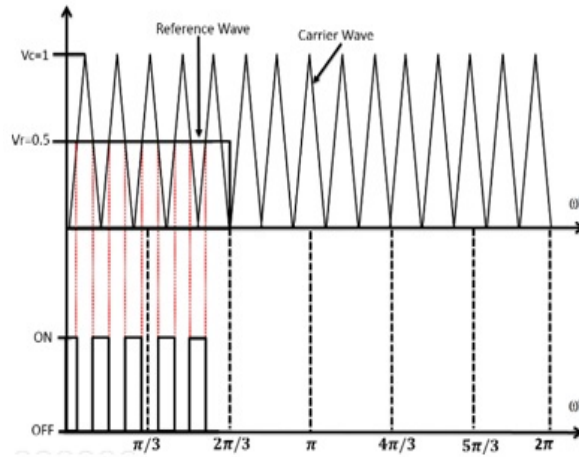**Figure-4.** Carrier wave and reference waves for the six switches.
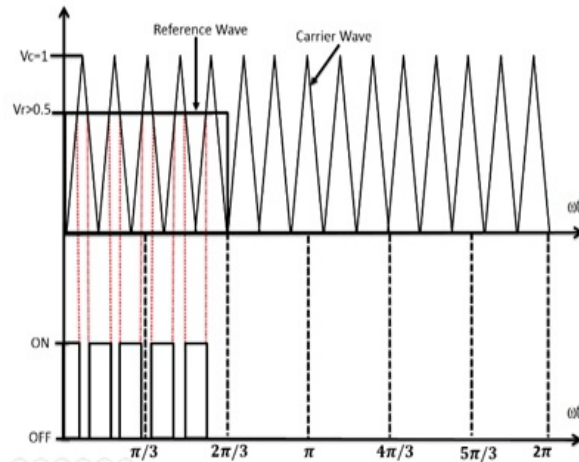

Figure-5. PWM for Ma=0.5.

Figure-6. PWM for Ma>0.5.

To realize the control technique for the VSI a PI controller is used. Figure-7 shows the block diagram of the VSI controller implemented in RTS. The first block is the abc to dq0 frame transformation block, which transforms the three phase VSI output to Vd and Vq. The second block compares the measured Vd and Vq (transformed) with the reference Vd and Vq to calculate the error. The reference value is set depending upon the desired output voltage. The third block is the PI controller which generates the reference wave for the PWM. Depending upon the error the amplitude of the reference wave generated by the PI controller is set, thus controlling the modulation index. The PI controller is tuned using Ziegler–Nichols method. The fourth block transforms reference wave in dq0 frame generated by the PI controller to abc frame. Thus there are three reference waves, one for each phase. Matlab-Simulink model of these four blocks are shown in Figure-8.
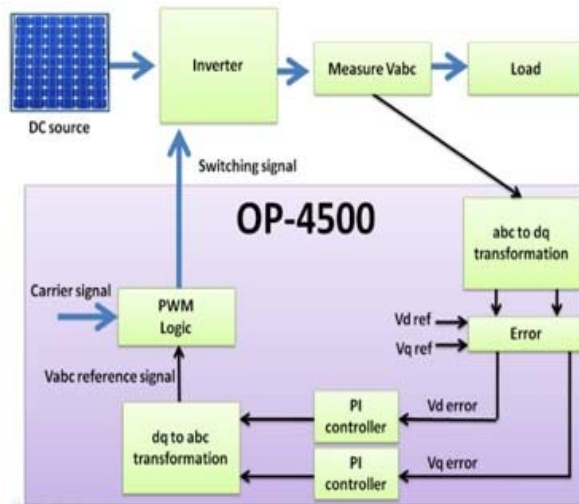
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Figure.7 Block diagram of the voltage controller.

The fifth block is the PWM logic block. This block generates the switching pulse for the VSI. The PI controller output is multiplied with a reference wave of unit amplitude and compared with the carrier wave of unit amplitude as a result the PI controller directly controls the amplitude of the reference wave, ultimately controlling the modulation index. Figure-9 shows the PWM signal for all the six switches (S1 to S6). The closed loop PWM block is shown in Figure-10. The entire controller is designed and implemented in MATLAB-Simulink and then realized using OP 4500.
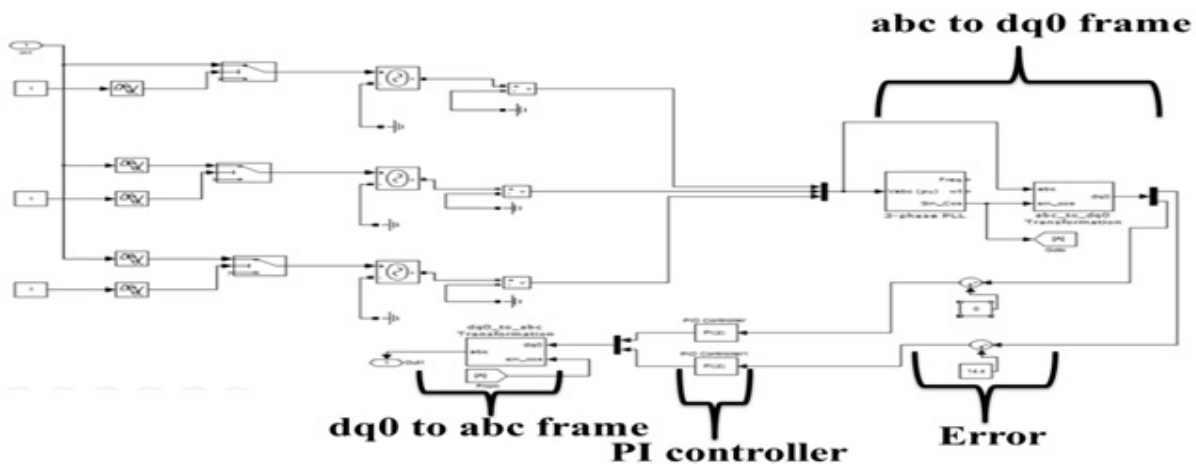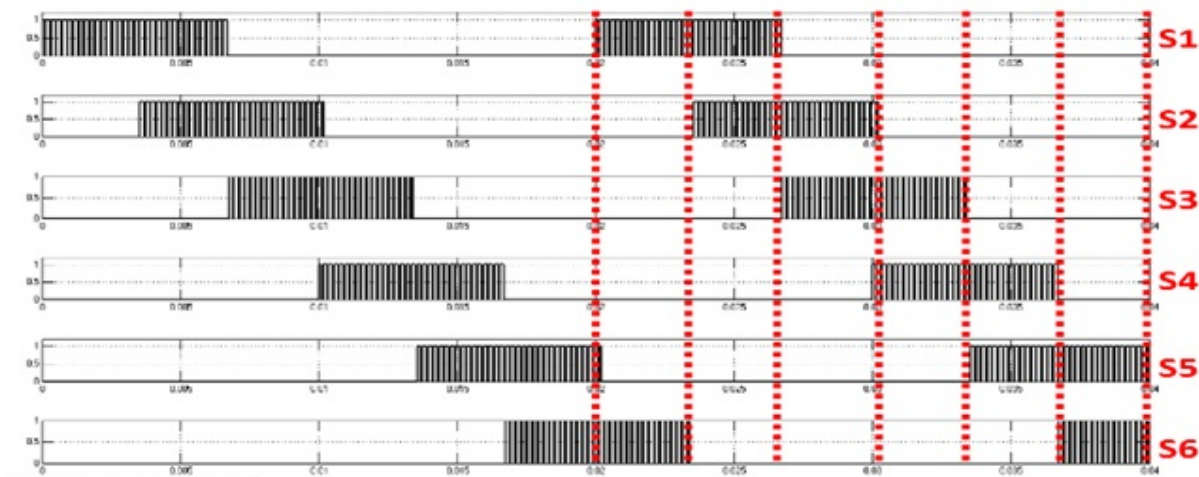

Figure-8. MATLAB-Simulink model of the controller.

Figure-9. PWM pulses for the six switches (S1 to S6).
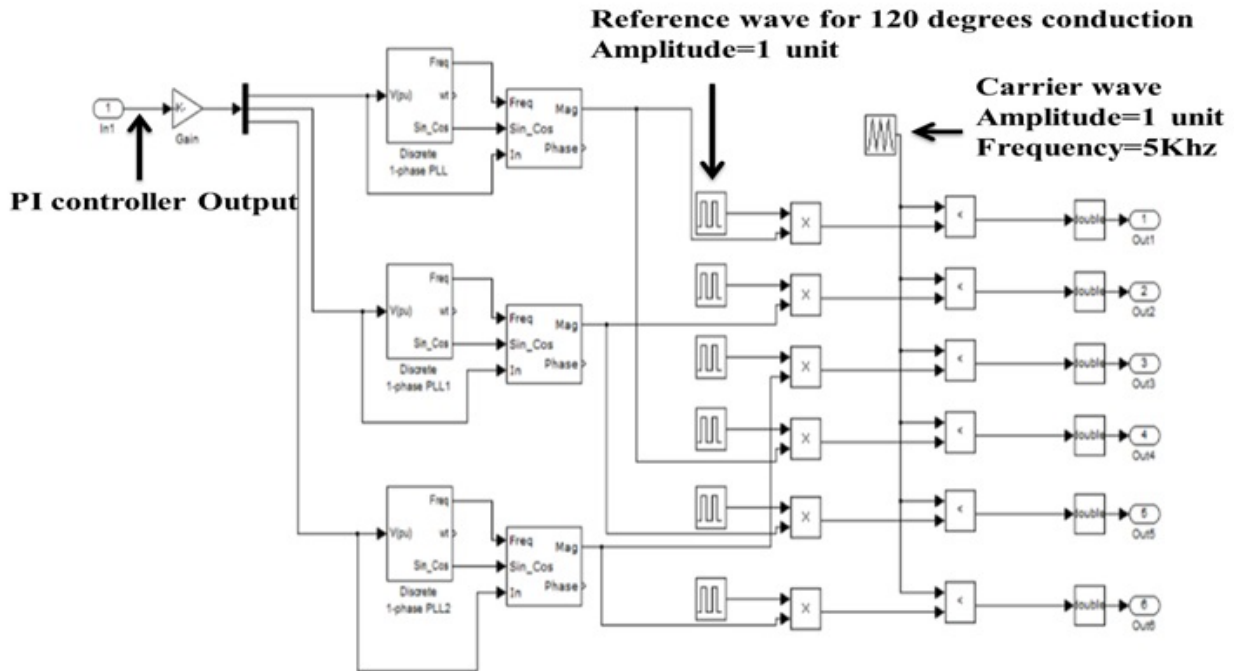
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Figure-10. MATLAB-Simulink model of the closed loop PWM block.

4. RESULTS

OP-4500 has one analog input and one analog output port. Each port has 19 pins i.e. 19 input pins and 19 output pins. OP-4500 has a limit of 32V.The PWM pulses for the six switches are taken from the analog output port of the RTS and the three phase VSI output voltage is fed to the RTS using the analog input port as feedback signal. Since the VSI is operating at 32V the output is directly fed to the RTS. However if the VSI is operating at higher voltage then the voltage has to be scaled down to a limit permissible by the RTS.

The design parameters are tabulated in Table-1.

Table-1. Design parameters.

Parameter	Operating value/device name
Input voltage (Vdc)	16 volts
Conduction mode	120 degrees
Switching frequency	5 khz
Filter inductance	3mH
Filter capacitance	47uF
Switch	Mosfet (IRF640)
PWM technique	Multiple pulse width modulation
Control technique	Voltage controller
Controller	PI controller

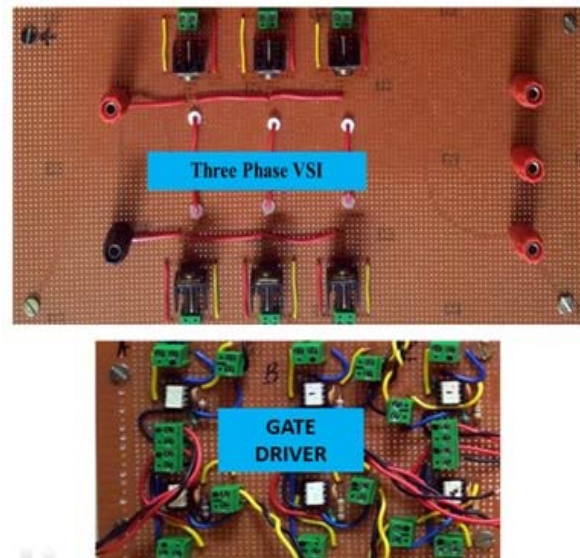The hard ware setup is shown in Figure-11 and the test bench is shown in Figure-12.
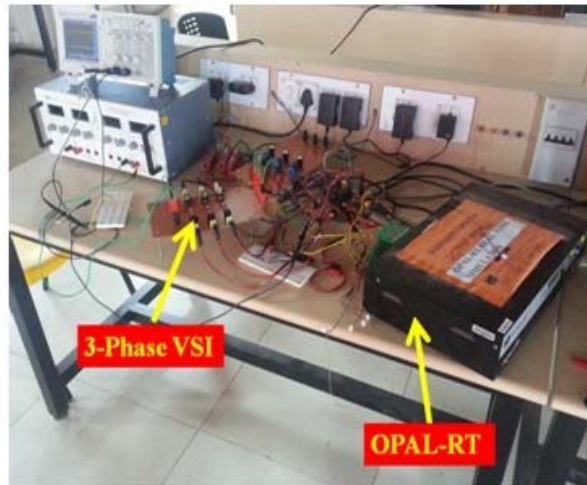

Figure-11. Hardware setup.

Figure-12. Test bench.

Figure-13. Phase to phase voltage of the VSI in simulation.

The simulation result of the VSI is shown in Figure-13. The output of the analog circuit of the VSI in open loop is shown in Figure-14. The output of the VSI is fed to the RTS using analog input port. This voltage is then passed through a LC filter implemented in the RTS before it is sent to the controller block. Internal gains are included to meet the operating conditions. The filtered output from the RTS when viewed from analog output port of the RTS is shown in Figure-15 (channel 2). Figure-16shows four cases, in each case the input voltage and the output voltage (phase voltage) of the VSI when it is controlled by the voltage controller is shown. Channel 1 is the input voltage and Channel 2 is the filtered output voltage (Vab) from the RTS. In all the four cases the input voltage is varied and the corresponding output voltage is observed. Reference voltage is set as 16V (rms). It is seen that with the variation in the input voltage, the output voltage of the VSI is more or less maintained constant.
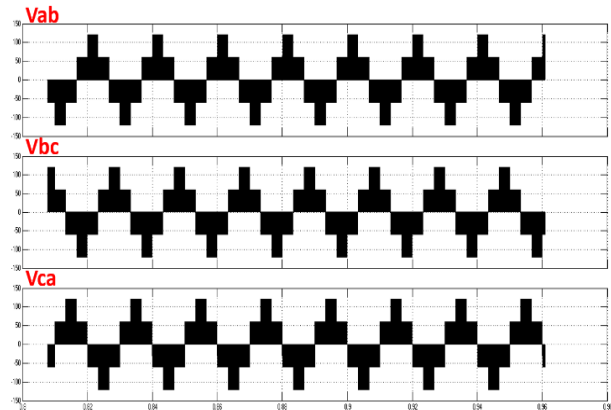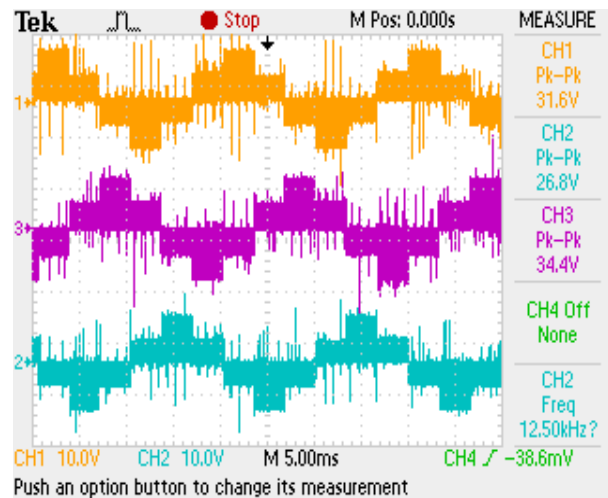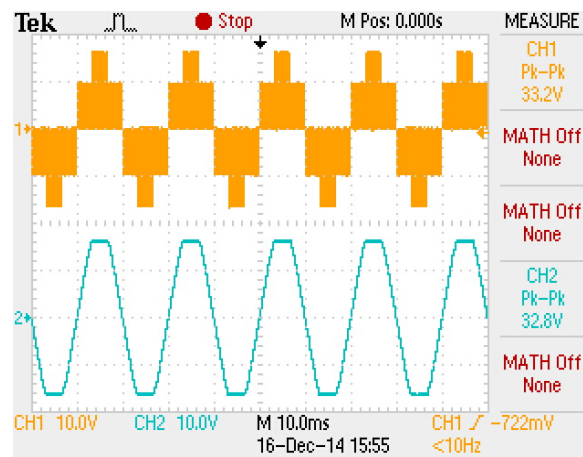

Figure-14. Phase to phase voltage of the hardware implemented VSI.

Figure-15. Output phase voltage (Vab).
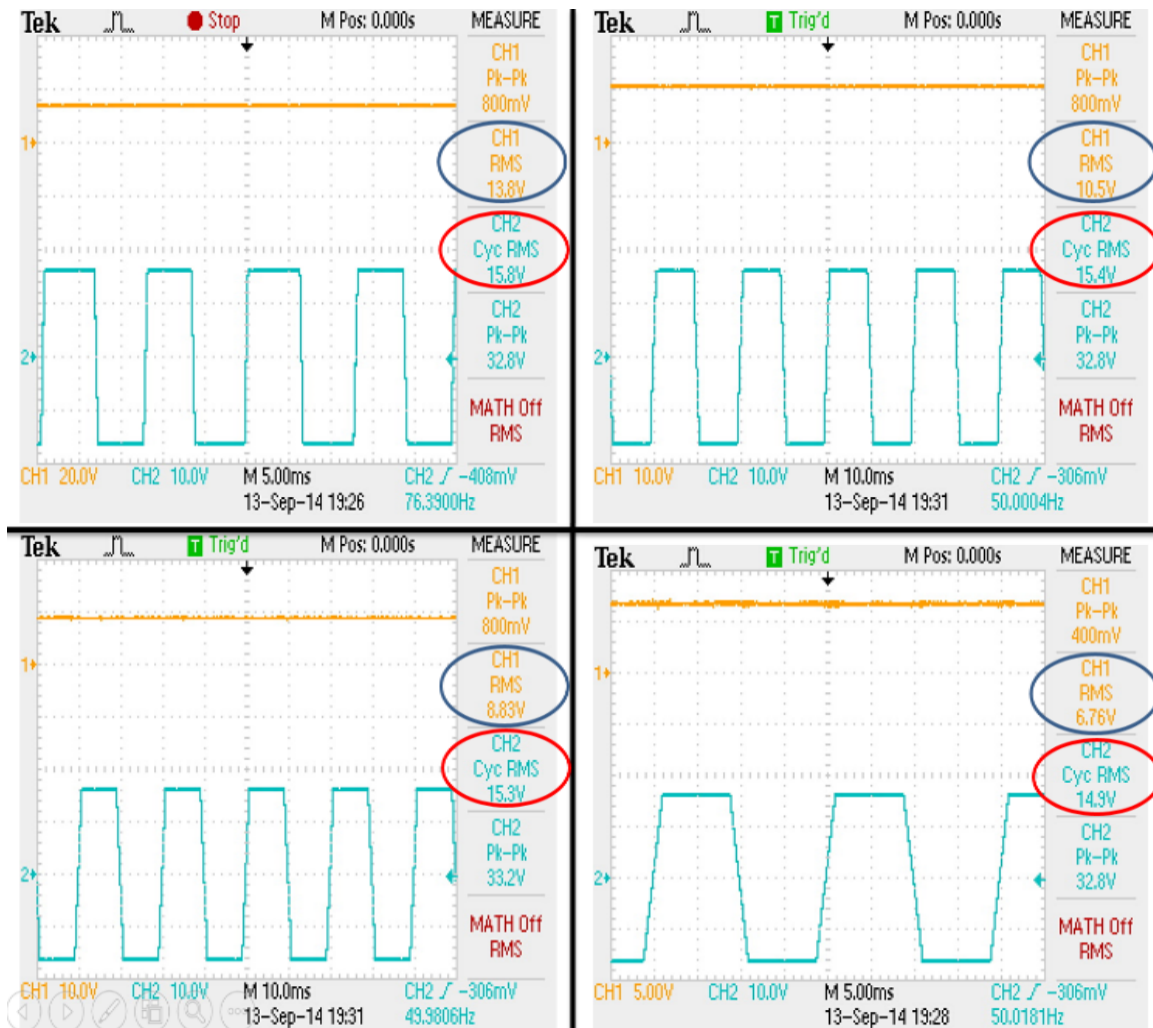
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Figure-16. Input Voltage VS output phase voltage (Vab).

5. CONCULSION AND FUTURE WORK

Rapid control prototyping approach for testing a voltage controller, designed for a VSI is presented in this paper. The VSI is designed and implemented in hardware and then interfaced with the controller which is implemented using real time simulator, OP-4500. OP-4500 is a flexible tool which makes it possible to realize complex circuitry in real time environment and allows the user to test their design and verify its performance before implementing it in hardware. From the results, the performance of the controller when operating in real working conditions is observed and any necessary changes in the controller can be done and then implemented it in hardware to test its operation.

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