

# A Simple Technique Adoption of Hardware-in-The-Loop Process for Multilevel Inverter Teaching at the Undergraduate Level

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## ARTICLE HISTORY

## ABSTRACT

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*This project describes a single phase multilevel inverter simulation by using a Hardware-in-the-loop (HIL) technique with a low cost microcontroller. The interconnection between PC host (computer), Arduino (PWM and PI control) and Raspberry Pi (HIL interface) are the main parts in this project that creates the complete HIL process. Those microcontrollers are able to communicate with MATLAB SIMULINK in order to execute the functionality of the real time process in a closed loop control manner for the multilevel single phase inverter with voltage control technique. Real time simulations are executed for 7-levels inverter output by adjusting the reference signal of the voltage controller.*

**Keywords:** hardware in the loop; multilevel inverter; Raspberry Pi; Arduino; Matlab

## 1. INTRODUCTION

A multilevel inverter is a power electronic device which is capable of providing desired AC level at the output using multiple DC voltage as inputs. A multilevel inverter is mostly applied in renewable energy (RE) sources system as to generate high power ratings [1-2] whenever several RE sources are being connected to the inverter input. The most considerable multilevel inverters are diode-clamped multilevel inverter, flying capacitor (capacitor clamped) multilevel inverter and cascaded H-bridge multilevel inverter [3-4]. Conventionally, the H-bridge is the mostly used inverter because it gives minimum total harmonics distortion (THD) and it requires less number of components [5] while simultaneously generating more quality power to the load.

Currently, before the hardware system can be developed and tested, a mimic hardware operation needs to be conducted but in simulation real time environment which can act as real hardware configuration and results. Due to this, Hardware-in-the-Loop (HIL) is a suitable process that can be applied without any circuitry but can give the exact outputs as in hardware results. For example, it has been widely used in many sectors such as medical devices, industrial machines, power generation systems, aerospace, automotive, process control and white goods [6]. As for aerospace application, the simulation is applied in the embedded system of HIL as for the real air flight experience [6]. It allows pilots to test and train in real

situation without any physical hardware but in safe, secure and control environment. However, the cost for HIL is still expensive due to high sampling rate where it requires a high frequency rate that is not available for the undergraduate usage.

As an initiative, this paper has taken a step to use a low-cost HIL simulation based on low cost microcontroller that is suggested by the authors in [7] by applying to a simple multi-level inverter with 7-level output voltage using a voltage control strategy. Therefore, this project consists of Raspberry Pi (RPi) and Arduino, which are known as a low cost microcontroller that had been integrated to run in HIL mode. It is where, the HIL simulation will be modelled in MATLAB-SIMULINK and then communicate with the microcontrollers [8,11]. It has been proven by [8], where the Raspberry Pi is able to execute in the Linux Operating System software. Those microcontrollers have also been selected because they are able to be applied as a comprehensive controller that have been used in several applications [9-11]. This control strategy is a simple control format by only using the mathematical blocks function available in the Simulink to be designed within a short period of time.

Figure 1 shows the block diagrams of HIL process blocks diagram for this project. The embedded voltage control will be downloaded to the Arduino where it consists of Analog to Digital (ADC) and Proportional-Integral (PI) control strategy which generate bits signal to correspond to the voltage control. Hence, those signals are then fed into RPi where it acts as the interface to the PC for real time simulator. The multilevel inverter is operated by injecting the suitable pulse width modulation (PWM) signal to run continuously in PC host within real time mode in order for real time results observation.

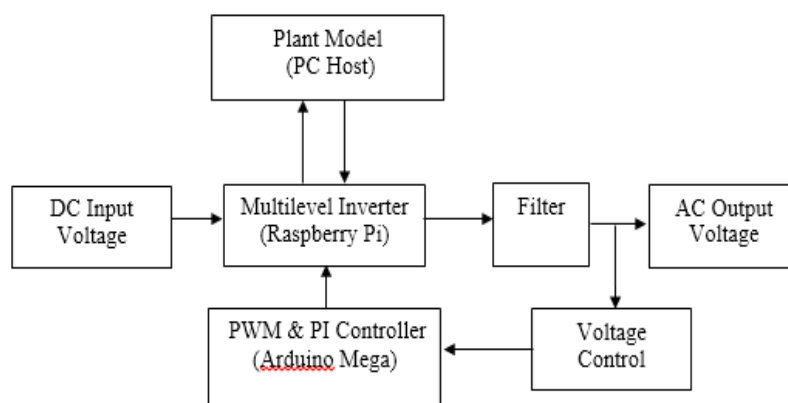


Figure 1: Block Diagram of Project

## 2. CONCEPTS OF HARDWARE-IN-THE-LOOP (HIL)

The HIL simulation is a technique which acts as a testing platform for development of a complex system under a real-time condition in the form of software environment. With the existence of HIL simulation, the physical hardware of the system will be replaced with blocks diagram or Simulink models. However, if site testing needs to be conducted, it may consume a large amount of money and also raises the issue of working hazards. The HIL simulation is

now getting widespread attention as the ability in reducing those disadvantages. Testing with a real simulated plant also could damage and even destroy the entire real plant but HIL simulation could enhance the safety and the safe operation of machines.

In a HIL virtual simulation, the system is always in ideal/actual value, safe and secure but able to operate in actual condition which is no different from the real-world hardware condition. It allows the system to run efficiently in real-time situation without errors or failure when physical plant has been constructed in Simulink model. Therefore, any breakdowns or malfunctions of equipment in the embedded system during the numerous times of testing executed can be implemented in a safe condition.

The HIL simulator has grown with the design of the real plant and can be used by control engineers to continuously test the control systems. This test will reveal the problems and errors that would have been detected at the final stages of design process with the control system before the plant can be implemented [12]. With HIL simulation, any error can be detected earlier and solved prior to the physical setup of the system. HIL simulation is an effective technique to reduce the commissioning time and the overall cost [12].

Some examples of HIL in power system education is when Hardware-in-the-loop Simulation, Modelling and Close-Loop Testing for Three-level Photovoltaic Grid-connected Inverter Based on RT-LAB [13] where HIL simulation by implementing DSP chip. Authors in [13] adopted HIL simulation in the field of grid-connected photovoltaic (PV) inverter performance test.

### 3. PROJECT OPERATING SYSTEM

For this project, a single phase H-Bridge inverter has been used as a power converter study. This inverter will be arranged in 3 levels which can give 7-steps inverter output voltage as shown in Figure 2. In order to control the inverter output, the PI controller gains have been selected with selected  $K_p$  and  $K_i$  values which are not discussed in this paper. This controller is used to maintain the control error between the reference voltage with the output voltage at the multi-level inverter. As for the load, a resistive load has been applied with the low pass filter in order to change the step signal to sinusoidal signal. The inverter gates are used to receive the signal from the PWM output.

Figure 3 and Figure 4 show the Simulink blocks diagram that have been developed using RPi and Arduino libraries which are available in the MATLAB. In Figure 3, the PI control block has been integrated with the ADC block for digital output/input to the RPi. It is where the output from the inverter voltage is used as the feedback input to the PI control before it can generate 3 bits signal that are suitable to be used in RPi. As stated in [9-11] the RPi does not contain the analog input capability, so it needs a signal from Arduino which has been modeled with an analog to digital converter as shown in Figure 4. Meanwhile, Figure 5

shows the complete setup for the HIL process. The total cost of those micro-controllers were about RM 500.00 categorizing them as low cost microcontrollers.

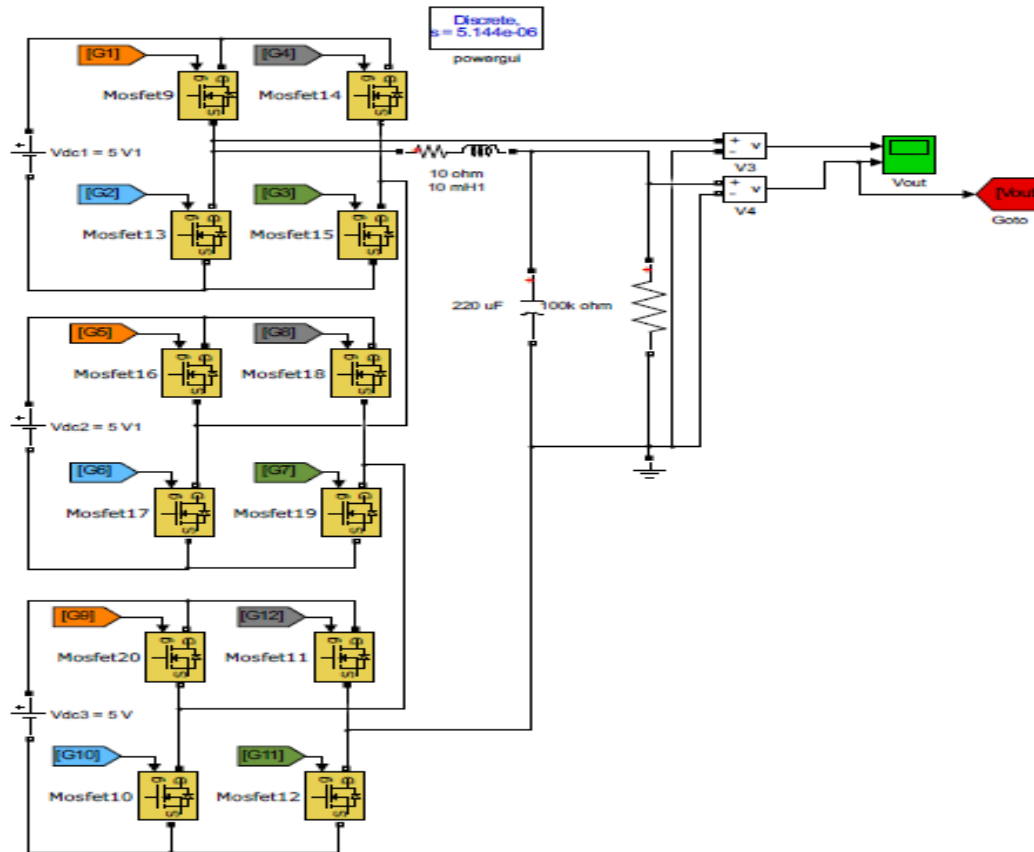


Figure 2: Single Phase 7-Level Inverter Embedded in Raspberry Pi

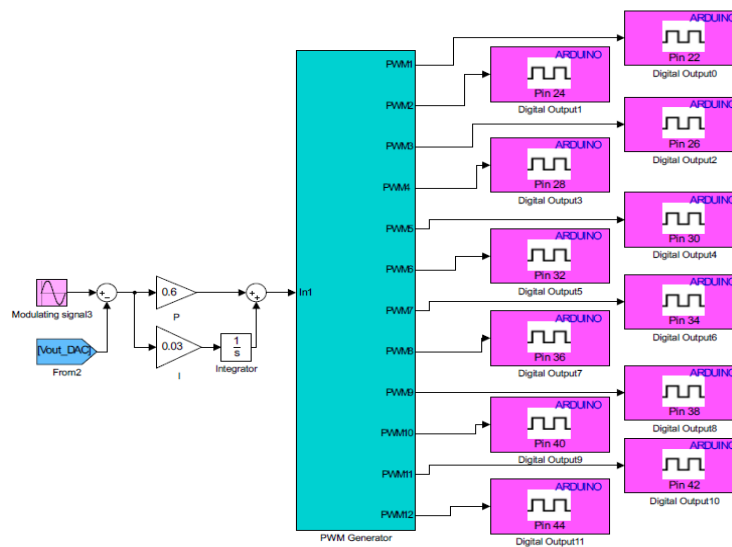


Figure 3: PI Control and PWM Generator in Arduino

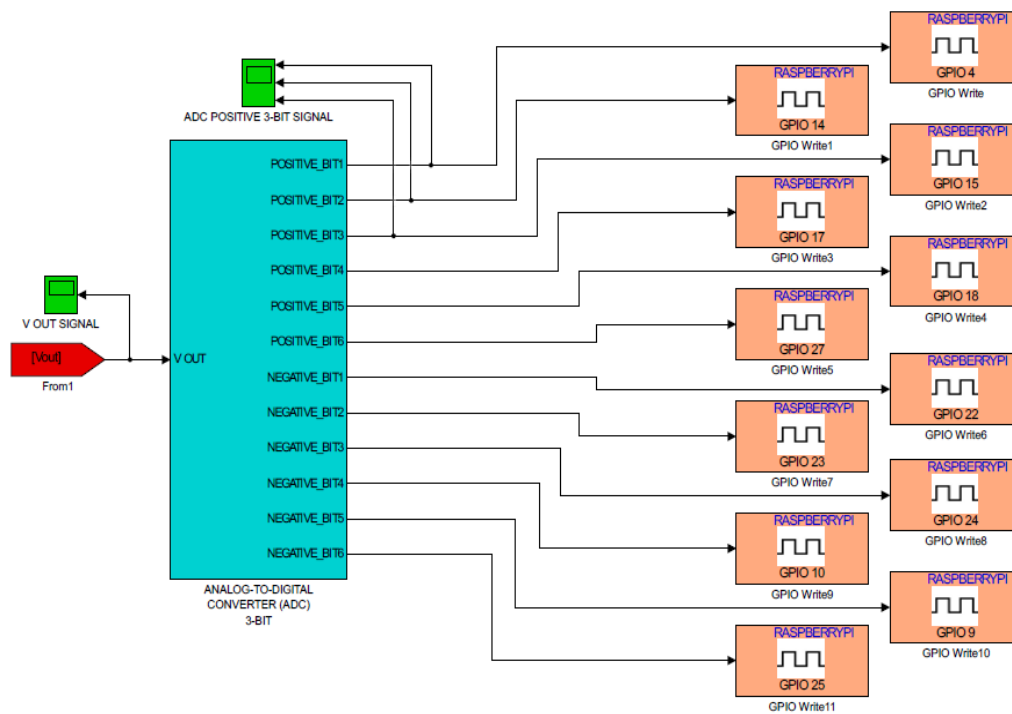


Figure 4: PWM Generator of 7-Level Inverter in Raspberry Pi

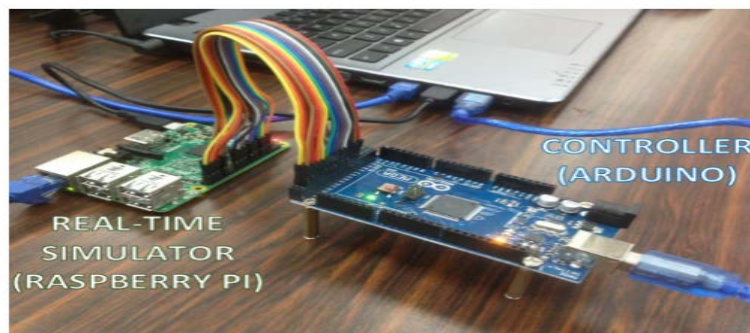


Figure 5: Complete Hardware Setup for HIL Process

#### 4. RESULT AND DISCUSSION

A closed loop HIL simulation tests have been conducted using a 7-levels inverter using RPi and Arduino Mega 2560 as microcontrollers for real time process. Here, the Arduino is was downloaded with the PI control strategy with voltage control feedback and the ADC function block while the RPi is was used to run the 7-steps level inverter in real time mode.

The first test on closed loop result of the HIL simulation is shown in Figure 6. This configuration was run with different time on both microcontrollers in order to see the effectiveness of the HIL. Therefore the output signal was distorted. Figure 6 (a) shows, the 7

levels output voltage before filter circuit been was applied and Figure 6 (b) shows the voltage output result after the filter has been was applied. As for the PI voltage control operation, it (it-ambiguous term- refers to filter? Voltage?) has been used when the reference voltage was set for 15V and it (ambiguous) showed that the inverter output gave 14.2V which was close to 15V and it(ambiguous) was captured on real time mode. (please rephrase and clarify the different terms of IT)

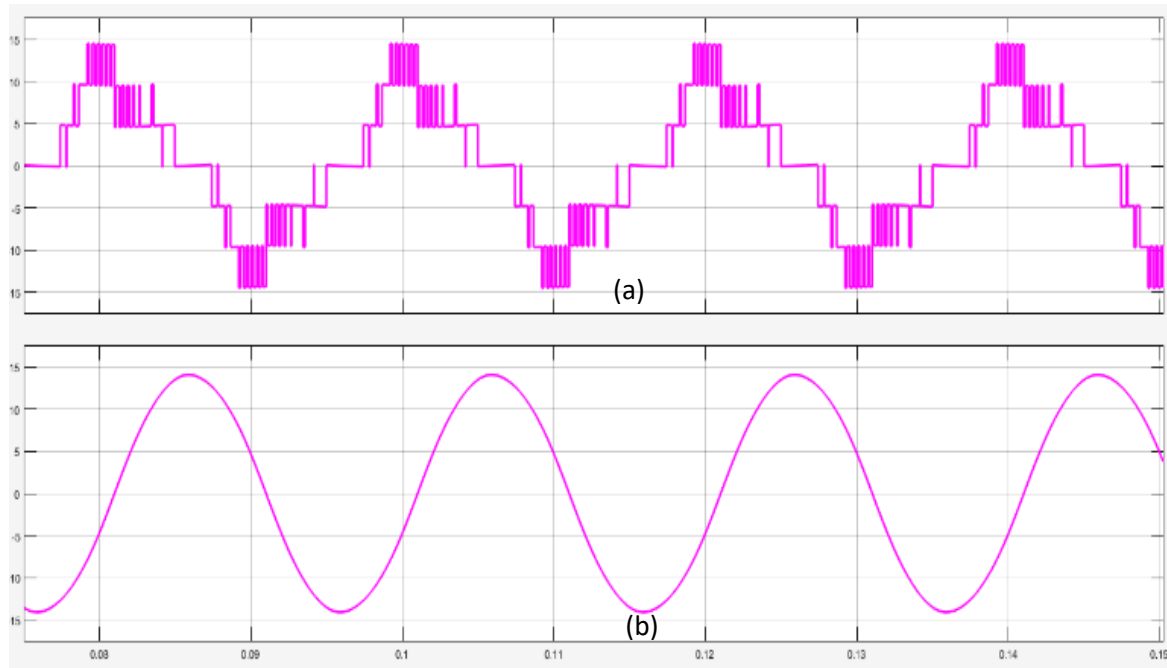


Figure 6: Closed Loop Hardware Simulation for 15V: (a) Multilevel Voltage, (b) Filter Voltage

At the meantime, Figure 7 shows the second test when the  $V_{ref}$  is changed to 10V and the inverter was running in 5-level steps. This level can be seen from Figure 7(a) while Figure 7(b) is the output voltage before and after using the filter. In the meantime, the reference voltage was set to 10V while the output voltage was shown at 8.4V. This simulation showed that, the multilevel inverter was also working even after the step level was changed by changing the PWM switching? (the changes taking place in the PWM switching).

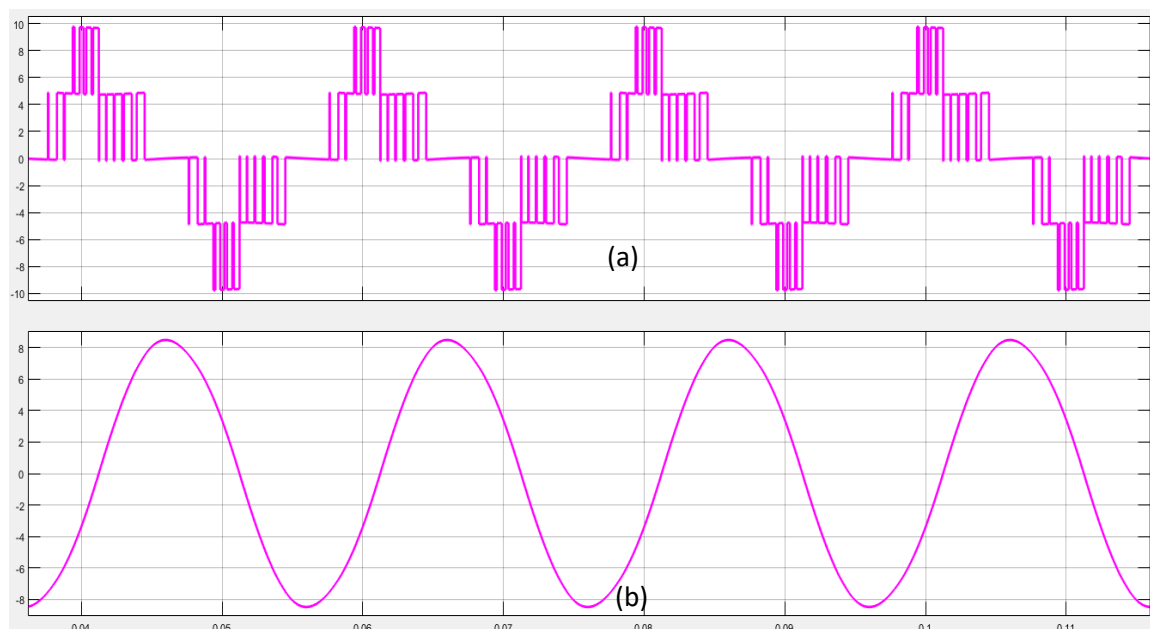


Figure 7: Closed Loop Hardware Simulation for 10V: (a) Multilevel Voltage, (b) Filter Voltage

Meanwhile, Figure 8 (a and?) shows the 7-level inverter output after the PI gains were changed several times and the sampling time of the RPi and Arduino was changed [13] for synchronization based on the setting on the PC sampling time. It shows that, the step signal is more accurate as compared to Figure 7. Both figures were measured in real time processing mode.

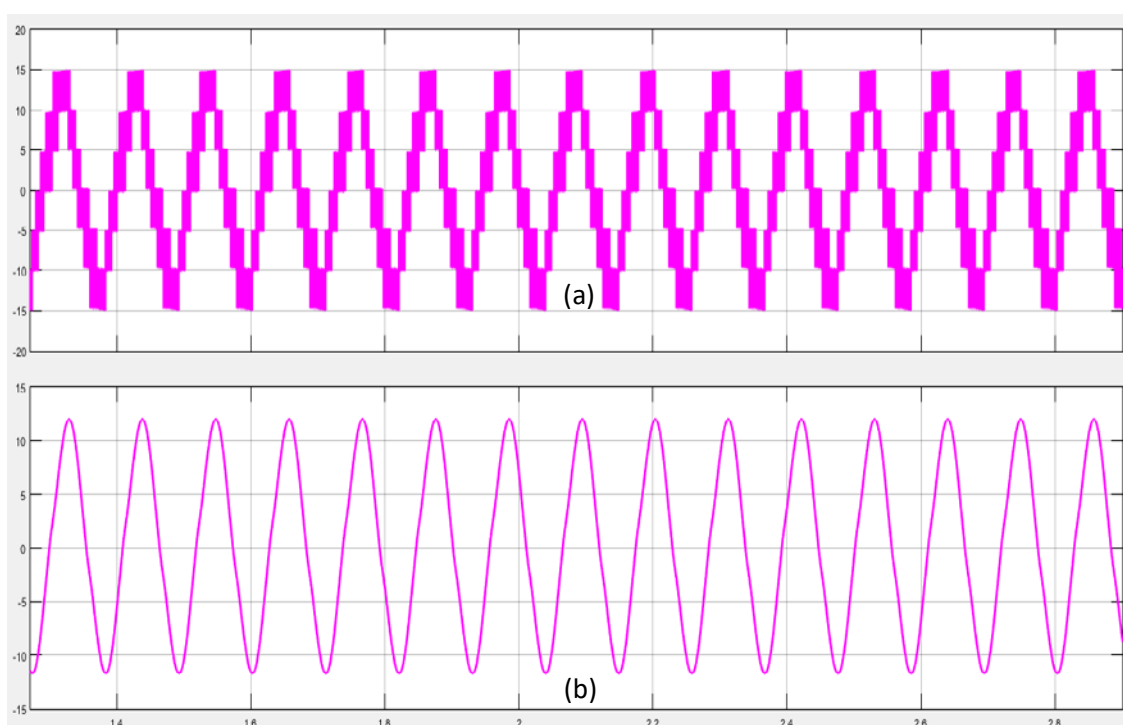




Figure 8: Output Voltage for HIL Simulation 15V: (a) Multilevel Voltage, (b) Filter Voltage

Meanwhile, Figures 9 and 10 show the inverter output voltage signal for 15V reference voltage and 10V reference voltage. Both figures show that, the inverter outputs were managed to follow the reference voltage (a) more accurately after the modification was made with inverter voltage (b).

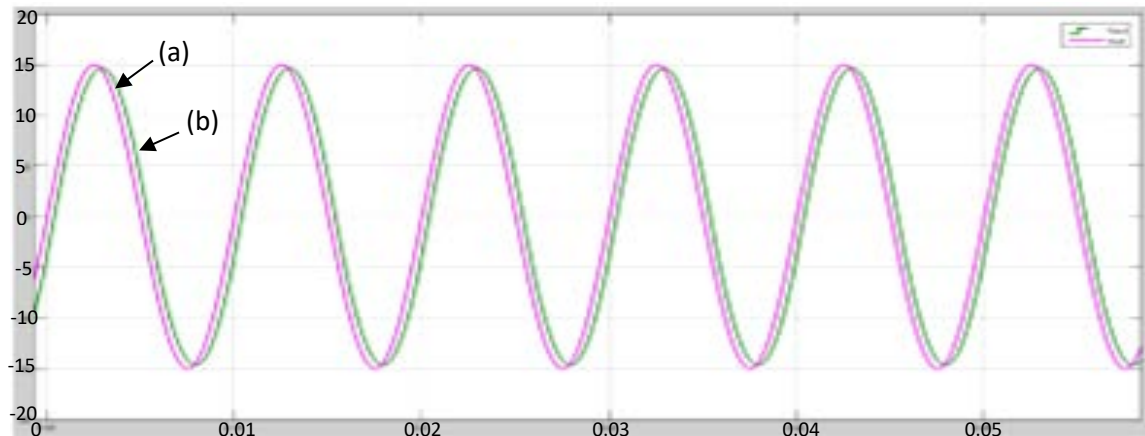


Figure 9: Inverter Output (a) and Voltage Reference (b) Signals when  $V_{ref} = 15V$

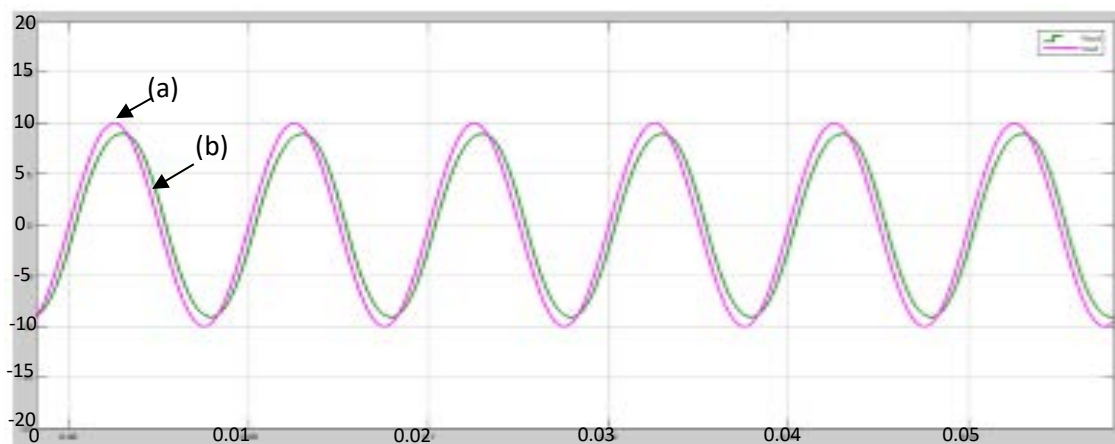


Figure 10: Inverter Output (a) and Voltage Reference (b) Signals when  $V_{ref} = 10V$

## 5. CONCLUSION

This project is successfully conducted by developing the multilevel inverter which was able to control the inverter output voltage by using PI control strategy in real time mode. The results show that, the single phase 7-levels inverter is able to produce a staircase output waveform compared to a normal 1-level inverter. As the number of levels increased, more accurate waveform to sin wave output can be achieved. The interconnection between these microcontrollers is achieved through ADC and DAC for data-transferring purpose. Therefore, by applying the HIL strategy in the multilevel inverter, the inverter was able to be tested and



developed under a real-time condition without developing the hardware circuits. In addition to that, the MATLAB SIMULINK allows authors to execute real-time simulation by selecting the external mode with the connection between PC host, RPi and Arduino Mega. In short, the HIL simulation with its low cost microcontrollers is advantageous and it can be extended to more complicated electrical system suitably used for teaching power converters process at the undergraduate level.

## REFERENCES

- [1] K. Roopa. and S. T. M.Murugesan, "A Hybrid Multilevel Inverter with Reduced Number of Switches for Induction Motor Drive," *African J. Sci. Res.*, vol. 4, no. 1, pp. 220–234, 2011.
- [2] A. Maheswari and I. Gnanambal, "A Novel Cascaded H- Bridge Multilevel Inverter Based On Optimal PWM Technique," *IU-JEEE*, vol. 13, no. 1, pp. 1613–1621, 2013.
- [3] E. Beser, B. Arifoglu, S. Camur, and E. K. Beser, "Design and application of a single phase multilevel inverter suitable for using as a voltage harmonic source," *Journal of Power Electronics.*, vol. 10, no. 2, pp. 138–145, 2010.
- [4] S. Umashankar, T. S. Sreedevi, V. G. Nithya, and D. Vijayakumar, "A New 7-Level Symmetric Multilevel Inverter with Minimum Number of Switches," *Hindawi Publ. Corp.*, vol. 2, pp. 1–9, 2013.
- [5] C. O. A. Statcom, "Simulation of Cascaded H-Bridge Multilevel Inverter using PD,POD,APOD techniques," *Electr. Comput. Eng. An Int. J.*, vol. 4, no. 3, pp. 27–41, 2015.
- [6] D. Bullock, B. Johnson, R. B. Wells, M. Kyte, and Z. Li, "Hardware-in-the-loop Simulation," *Transp. Res. Part C Emerg. Technol.*, vol. 12, no. 1, 2004.
- [7] B. Lu, X. Wu, H. Figueroa, and A. Monti, "A low-cost real-time hardware-in-the-loop testing approach of power electronics controls," *IEEE Trans. Ind. Electron.*, vol. 54, no. 2, pp. 919–931, 2007.
- [8] F. P. Tso, D. R. White, S. Jouet, J. Singer, and D. P. Pezaros, "The Glasgow Raspberry Pi Cloud: A Scale Model for Cloud Computing Infrastructures," *First International Workshop on Resource Management of Cloud Computing (CCRM)*, pp. 108-112, 2014.
- [9] S.A.Zulkifli and M.Z. Zakaria, "Development of Single Phase Back to Back Converter with Closed Loop Voltage Feedback Controlled by Arduino Microcontroller", *International Journal of Integrated Engineering*, Vol 8, No 1, 2016:.
- [10] S. A. Zulkifli , I. Mamat, M.N.H. Mokhtarudin and S. A. Shah, "Investigation on Raspberry Pi Microcontroller as Digital Processing Controller in Back to Back Converter", *Lect. Notes Electrical Eng*, Vol. 398, Chap. 86, 2017