

Investigation of Multilevel Inverter for the Next Distributed Generation Using Low-Cost Microcontroller

Original Scientific Paper

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Abstract – Nowadays, more research projects have described a converter that is widely used at the distributed generation (DG) level in order to increase the amount of electrical power generation. The converter is known as an inverter when only one DG source is used or as a multi-inverter when several DGs are used. Here, the application of a multilevel inverter with a C2000 microcontroller (Texas Instruments (TI) TMS320F28335 microcontroller), which can be implemented with a current feedback loop, is investigated. This microcontroller acts as a communication interface between MATLAB SIMULINK and the multilevel inverter. Meanwhile, the current control model is modeled in MATLAB for designing the control strategy. It is where the multilevel inverter switches are triggered by using pulse-width modulation (PWM) signals generated by the microcontroller output. At the same time, the proportional integral derivative (PID) current control is used in order to allow the load current to follow the reference current. Based on the results, it can be summarized that the multilevel inverter is a very useful device for the next DG sources when it is combined with current control for load current distribution. From this investigation, it can be seen that in the future DGs could be connected to a multilevel inverter structure, where it will reduce the dependency on filter design and have a more sinusoidal output to the load for different DG power ratings.

Keywords – current control loop, distributed generators, multilevel inverter, PID control, microcontroller

1. INTRODUCTION

A multilevel inverter has been used at the distributed generation (DG) level for connecting renewable energy (RE) sources to the existing electrical network. Previously, it was applied at the load which requires high-quality voltage or high-rated voltage from the low or bad input source. However, the fundamentals of the inverter process still remain, where it is used to change DC to AC signals. For DGs, the multilevel inverter is used when there are different rated values from each DG connected to the same bus bar network. Currently, it can be found in the network of renewable energy sources [1, 2].

There are different types of topologies for the multilevel inverter, such as the diode-clamped multilevel

inverter [3], the flying capacitor multilevel inverter [4], the cascaded multilevel inverter [5], and many more. However, it has certain problems that need to be avoided, such as that it could damage other appliances during high power output and that it requires a higher number of components [6].

There are few types of multilevel inverters that exist today based on the $(2n-1)$ formula, where n is the number of inverters used. However, there are only a few of them, which are usually selected upon several important considerations regarding their functionality and ability at the DG. Currently, most of the DGs are connected with an individual inverter. The main functions of the multi-level inverter for the DGs are as fol-

lows: 1) to generate high voltage when DGs are connected to the grid, 2) to stabilize the grid when there is a fault at the electrical network, and 3) to supply excess power to the load when it is required. Table 1 shows a comparison of several multilevel inverters that are currently used.

As compared to the control strategy that has been applied, inverter control can be categorized into two categories, i.e., voltage control and current control. Voltage control is easier to be developed and it has a higher stability margin compared to current control. Moreover, current control requires a specific rated load and a sensitive current sensor or analog-to-digital converter [7].

Due to the importance of a multilevel inverter for DG configuration, this project is conducted in order to investigate a simple current control strategy by using a current feedback loop using a low-cost microcontroller that can be developed for an undergraduate project. The papers [5, 11, 12] used MATLAB SIMULINK as code generation between the controller and the microcontroller. All of those papers used a low-cost microcontroller. A low-cost microcontroller implies here the price of the device that is acceptable to be bought by a student or a beginner.

The Texas Instruments microcontroller is the device that processes control feedback behavior and then generates a suitable pulse-width modulation (PWM) signal to the gate inverter. As given in the datasheet [13], this microcontroller is able to work between low and medium frequency switching. As for the inverter, the best switching operation is between 1 kHz to 5 kHz with a low-voltage load.

Therefore, this project selects a cascaded 7-level multilevel inverter because it can be connected to three input

sources with different voltage rating input sources. This topology is widely used in the industry application. It can also use a simple PWM switching algorithm with a phase opposite disposition (POD) technique. Other reasons are that the topology can be developed easily, it can be combined with a simple current feedback loop for a closed-loop control application and can be constructed quickly.

One of the aims in this paper is that the authors would also like to see the effectiveness of the PID control response in the current control topology. Moreover, this project is divided into two conditions, i.e., it is first conducted in the MATLAB simulation program and then tested in the hardware setup. The MATLAB software is widely used because it has simple instructions [11, 12] compared to other types of software and it has an available support package with the microcontroller. The strength of this dynamic system lies in the source codes of its built-in functions and tools that are open and can be viewed and edited by the users [14].

Figure 1 shows a block diagram of the project either in the simulation or hardware environments. The sources for this project are constant DC sources for the multi-level inverter. An LC filter is used to remove the unwanted frequency component from the inverter output. Then, the current sensor is used to sense the value of the load current and as the input to the current controller to be read in MATLAB SIMULINK at the microcontroller device. A gate driver is used to provide a suitable range of voltage operation for the switches based on the signal generated by the microcontroller output. The output of the current sensor is controlled and this process is kept operating in order to maintain the desired output condition to follow the desired reference current for the current control strategy.

Table 1. Comparison between the existing multilevel inverter topologies

| Types | Advantages | Disadvantages | Efficiency |
|--|---|---|------------|
| Diode-clamped [8] | Reduces voltage strength of the device. | Uneven loss distribution at the device. | Medium |
| | Uses low-frequency switching. | Complicated PWM switching pattern. | |
| Flying capacitor [9] | Number of switching devices is reduced. | Maximum level is limited. | High |
| | Able to balance input voltage. | Needs recharging of the capacitor. | |
| Five switches multilevel inverter [10] | Reduces the number of switches. | Complexity of the PWM algorithm increases | High |
| | Switches are operated unidirectionally. | The balancing on the input cannot be maintained. | |
| | Two switches as polarity changes. | | |
| Cascaded H-bridge inverter | Applied widely in the market. | Separated DC sources with a capacitor are required. | Medium |
| | Does not need a capacitor or a diode for clamping purposes. | More complex controller as the number of output level is increased. | |
| | | Each capacitor should be balanced. | |

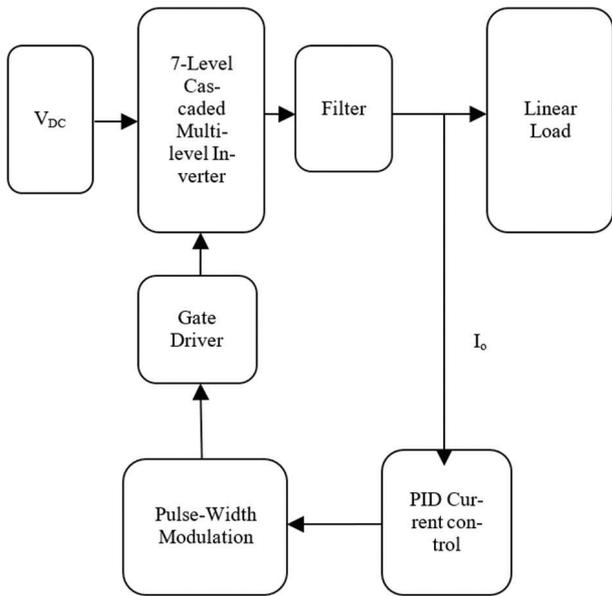


Fig. 1. Project block diagram

2. MODELING OF MULTILEVEL INVERTER

In this section, modeling of the multilevel inverter in simulation and hardware environments will be discussed. Figure 2 shows modeling of the multilevel inverter designed in MATLAB SIMULINK. The configuration of the model is based on the cascaded H-bridge multilevel inverter with several DC input sources that can be represented as DG sources. Three inverters are connected in series to produce a 7-step level output for the voltage.

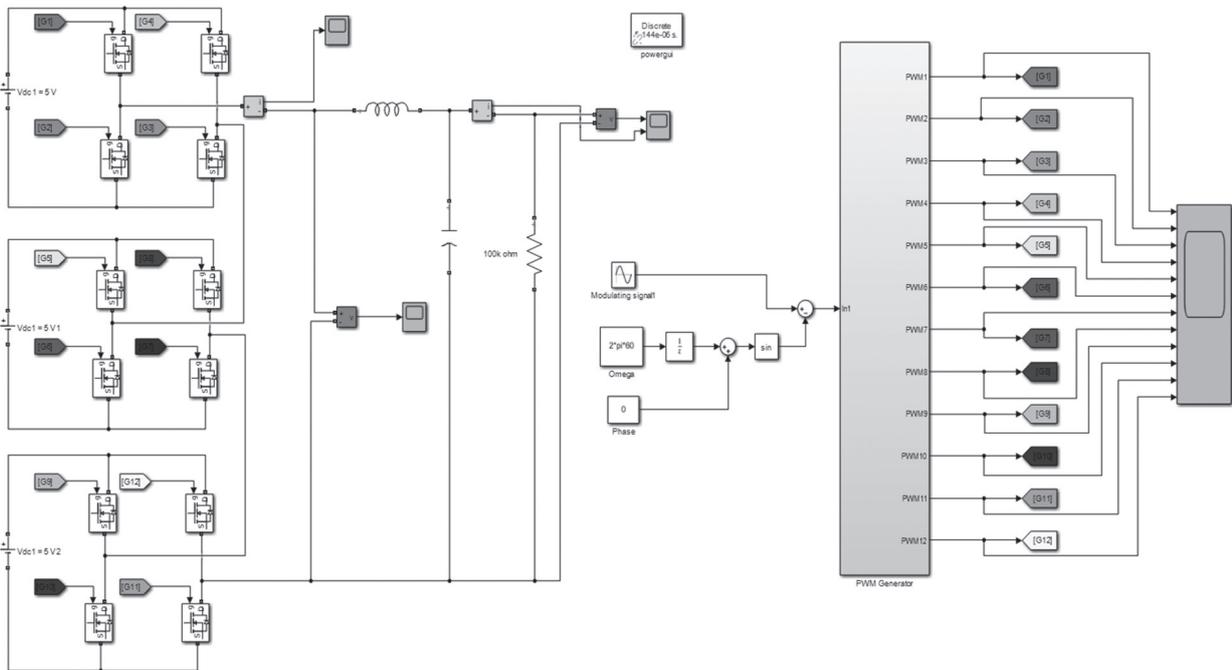


Fig. 2. Multilevel inverter in MATLAB

There is a subsystem inside multilevel inverter PWM control, which is used for PWM system generation. Figure 3 shows PWM block generation in a closed-loop

Due to high voltage and low current characteristics of the device, power electronics switches used are MOS-FETs. In order to have a good sinusoidal signal at the converter output, a low-pass LC filter is placed before the load. The value for the LC filter is based on the value that is available on the market. The whole simulation system is in a closed-loop mode, where the analog-to-digital (ADC) model is applied to the control response for feedback operation. At the same time, the model of the POD strategy is also included in order to make sure that the switching pattern is achievable due to 7-level voltage generation.

Table 2 shows the values of the filters and PID control gains used in this project. The load used is a variable resistive load with a value ranging from 0 Ω to 15 Ω .

Table 2. Parameters used in the multilevel inverter

| Types | Simulation and hardware parameters | |
|-------|------------------------------------|-------------|
| | Item | Value |
| LC | L | 68 mH |
| LC | C | 470 μ F |
| PID | Kp | 10 |
| PID | Ki | 0.9 |
| PID | Kd | 0.01 |
| R | Rload | 15 Ω |

applied or not applied. In the closed-loop mode, internal sinusoidal generation is required to generate a sine wave block in order to create the reference current signal. The reference current is adjusted according to the modulating signal generated from the controller. The gain values of the PID are determined by using a trial-and-error method that is not discussed in this paper. There are 12 GPIO for digital outputs and 1 input signal that are injected/collected between the microcontroller and the hardware. PWM generations are modeled based on the comparison between the reference signal generated by the controller and the switching frequency in the POD mode, as shown in Figure 3.

Meanwhile, Figure 4 shows a block diagram that is constructed in MATLAB SIMULINK for the PID controller to control the load current of the multilevel inverter during the hardware mode. Figure 4 also shows the inverter with PID current feedback that uses the analog signal from the microcontroller as the feedback loop. The development of an analog-to-digital converter (ADC) or vice versa (DAC) is not explained here because the implementation is the same as with other microcontrollers. The only difference is the bits setting on each microcontroller. The ADC and the DAC should include the sensitivity equation of the current sensor. The equation is given based on 8 bits as:

$$I(mA) = \left[\left(\text{Voltage at sensor} \times \frac{5V}{4096\text{bits}} \right) - 2.5 \right] \times \frac{1A}{0.185} \quad (1)$$

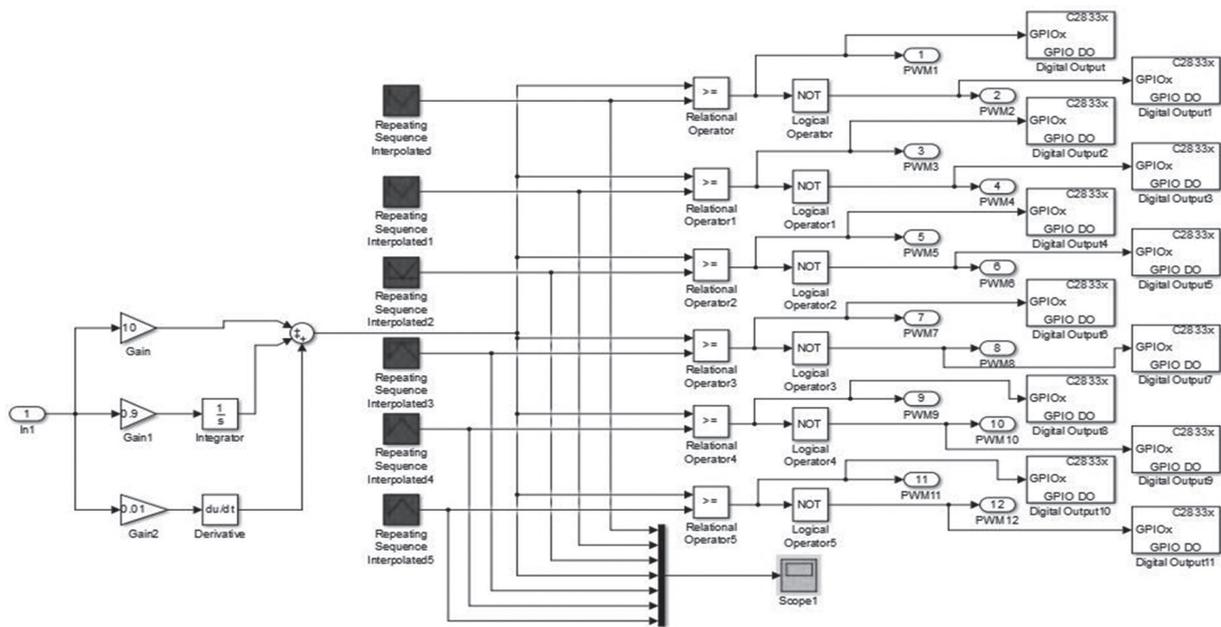


Fig. 3. Simulation of closed-loop PID control

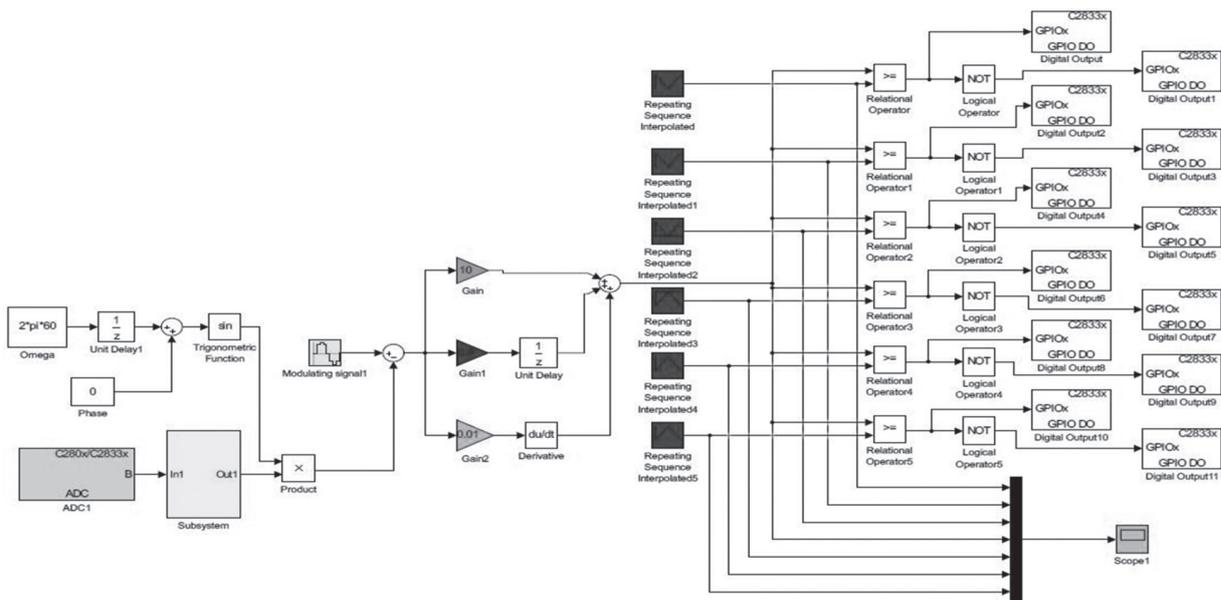


Fig. 4. Hardware of closed-loop PID control with the ADC

The testing of the models is preceded by a flow process of the whole project. Figure 5 shows the overall operation aimed at developing hardware in a closed-loop mode. The hardware consists of six important parts, which are the TI microcontroller, the gate driver circuit, the 3-level multilevel inverter, the LC filter, the Rload and the current sensor. At first, the communication network between MATLAB SIMULINK and the microcontroller needs to be established. This is where all mathematical models can be transferred and deployed to and from the microcontroller. Next, we test the gate driver, which re-quires 3-level gate drivers on each cycle in order to inject the pulses into the multilevel inverter to produce a 7-level inverter output voltage. The gate driver works properly when the voltage at the output gate is about 15 V when the voltage regulator boosts up the value to 15 V based on the PWM signal output.

Finally, a 3-level inverter is used to produce a 7-level square-wave output voltage. Inverter input sources are supplied with a 5 VDC constant voltage on each level. As for the controller, the current input will be measured by checking the output voltage and the current of the closed-loop system using a scope function available in MATLAB.

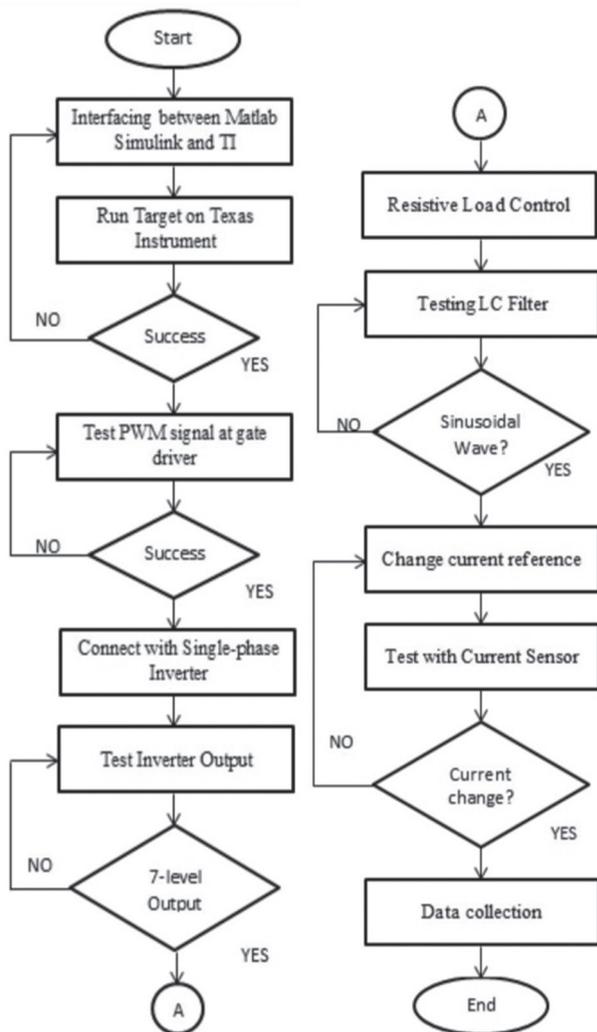


Fig. 5. Flowchart showing system development

Figure 6 shows the complete hardware setup. The hardware parts start with the microcontroller, which is TMS320F28335. The PID current controller is constructed in MATLAB SIMULINK and then downloaded by using Code Composer Studio. The PWM is generated to run the gate driver. The gate driver outputs are operated by operating output 1 and 2 at the same time, while the signals at output 3 and 4 (different leg operation) are off simultaneously within the same level. This produces a 7-level inverter output with a maximum peak of 30 V. Then, a filter connected after the inverter to remove an unwanted signal frequency component from the signal is used to enhance the desired result. The resistive load is a variable type and its value ranges between 0 Ω and 15 Ω in order to get the load current at 1 A maximum.

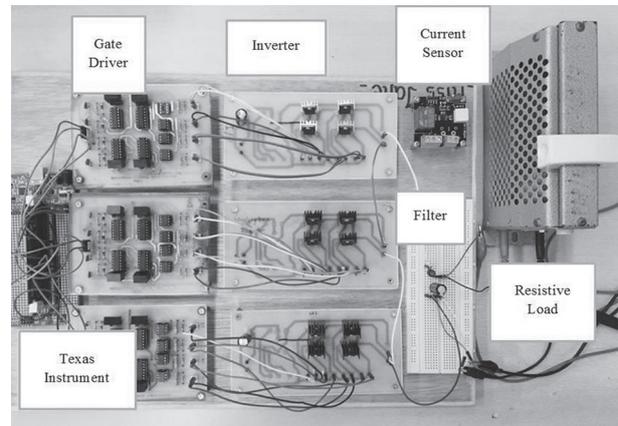


Fig. 6. Hardware setup for the multilevel inverter

3. SIMULATION RESULTS AND DISCUSSION

For closed-loop simulation, the 7-level inverter model is implemented with the PID current controller to reduce the error between the output current and the target reference current. During simulation tests, several changes on the reference current are conducted to determine the effectiveness of the controller response in following the target value for the load current.

Figures 7 and 8 show closed-loop simulation results with a current feedback loop. Both load currents can follow the reference currents given. When reference current changes happen, the load current is changed according to the new reference value.

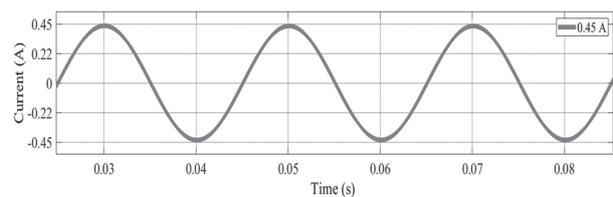


Fig. 7. Load current when reference current is at 0.5 A

Figure 7 shows that when the reference current is set at 0.5 A, the load current is at 0.45 A. Here, the current at the load follows the desired target with a small re-

duction due to non-precise LC filter design. Meanwhile, Figure 8 shows that the measured load current is 0.9 A when the target is set at 1 A. Both figures show that the current feedback can be controlled by using MATLAB SIMULINK whenever the reference current is changed.

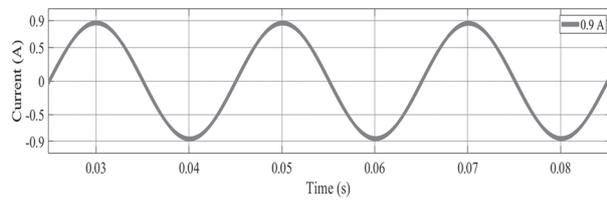


Fig. 8. Load current when reference current is at 1 A

Figure 9 shows the inverter output voltage, which gives the 7-level inverter output. It indicates that the operation of each inverter level is based on the switching pattern from Figure 10. The switching algorithm for Figure 10 is the same as the conventional 7-level multilevel inverter and is not discussed in this paper.

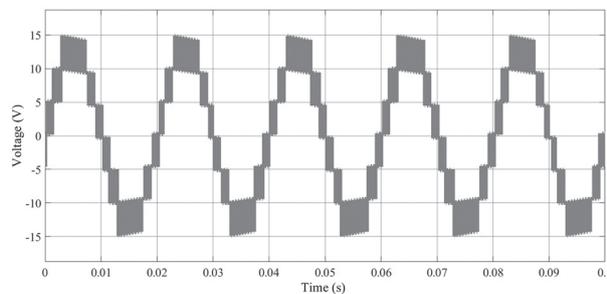


Fig. 9. Inverter output voltage

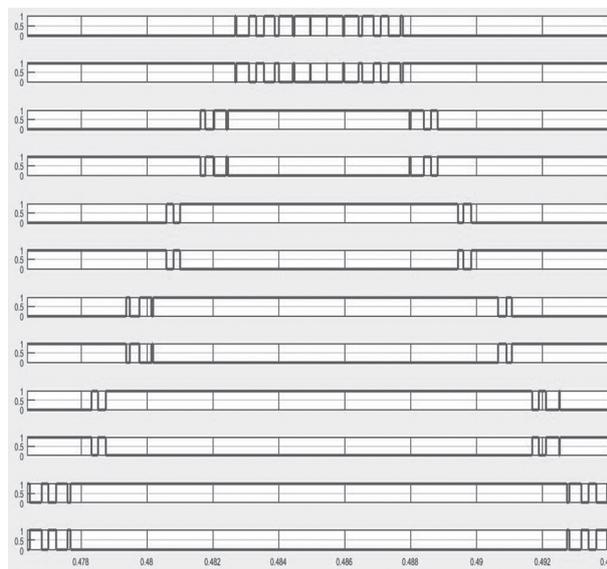


Fig. 10. PWM signal operation of each POD

4. HARDWARE RESULTS AND DISCUSSION

Closed-loop hardware basically involves a feedback system and a current sensor. The ADC for current sensor detection for the load current is needed for the reference current feedback to the PID controller. In order

to observe the closed-loop system, the output current needs to be measured so that the desired value is known. Therefore, the change on the output current at the sensor has confirmed that the PID controller successfully controls the load current.

Figure 11 shows the inverter output voltage before the filter is applied. It can be seen from the result that the pattern of the 7-level step for the multilevel inverter output voltage has been achieved. Figure 12 shows the inverter output voltage after the LC filter is applied. It shows that the low-pass filter can remove the step signal and turn it into a sinusoidal signal.

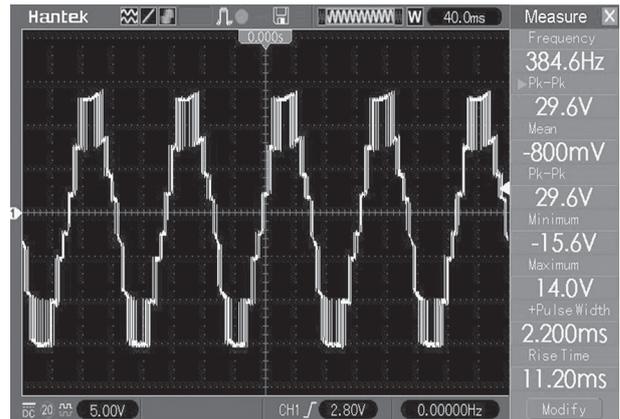


Fig. 11. 7-Step multilevel inverter

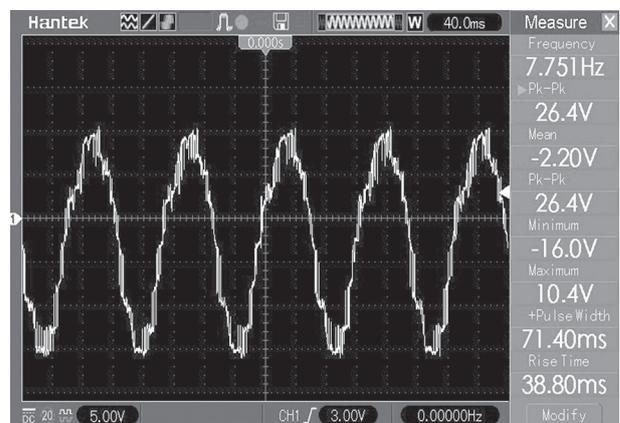


Fig. 12. Multilevel inverter output voltage after the filter is applied

As for the analysis of the PID current controller response, the signal is collected on the basis of the current sensor configuration, which is based on equation 1. The relationship between the sensor current and the voltage generated from the output sensor is based on equation 2:

$$V_{out} = (2.5V + sensitivity\ sensor \times \Delta I), \quad (2)$$

where the sensitivity is based on the types of the current sensor used. For this project, a WSC2702 current sensor is used. Meanwhile, the measured current from the multimeter measured voltage and the sensor sensitivity data is given by:

$$I_{actual} = \frac{2.5V - \text{measured voltage}}{\text{sensor sensitivity}} \quad (3)$$

Figure 13 shows the measured current when the PID reference current is set at 0.5 A by adjusting the reference value from Figure 4. According to equation 2, the value of the load current can be determined by knowing the voltage from the sensor. This technique is used due to the limitation of the current sensor probe.

Moreover, Figure 14 shows the result when the reference current is set to 1 A. It shows that the voltage at the current sensor is changed due to a different current signal from Figure 13. For an easy comparison, Table 3 shows the values of the current at the current sensor. As for the hardware measurement, the output from the sensor is measured in terms of voltage. It needs to be calculated and involves the value of sensitivity.

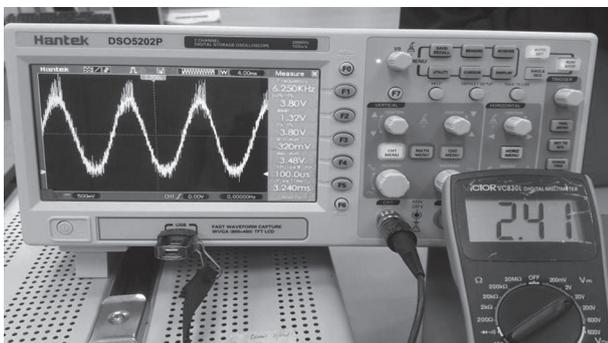


Fig. 13. Voltage measurement at the current sensor for the reference current set to 0.5 A

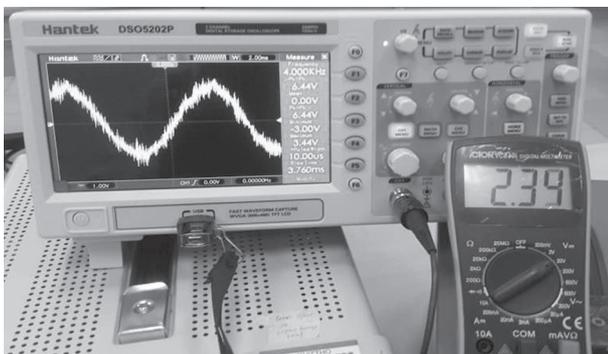


Fig. 14. Voltage measurement at the current sensor for the reference current set to 1 A

Table 3. Comparison of current measurements based on the voltage measured at the current sensor

| Ref. Current | Comparison of the reference current for simulation and hardware measurement | |
|--------------|---|--------------|
| | Simulation (A) | Hardware (A) |
| 0.5 A | 0.45 | 0.48 |
| 1 A | 0.9 | 0.865 |

As evidenced in Table 3, the current can be calculated by using the current sensor sensitivity of 0.185 V, as given in the current sensor datasheet. For the first

measurement, when the control current is set at 0.5 A, the sensor current is calculated to be 0.48 A by using equation 3. As shown in Figure 13, the voltage output (V_{out}) measurement at the multimeter is 2.41 V. Based on equations 2 and 3 and as shown in Figure 14, when the reference current is changed to 1 A, while the voltage measurement is at 2.34 V, the actual current is 0.865 A. Both values indicate that the measured values are close to the simulation values. Hardware results show that the application of PID closed-loop control in the 7-level multilevel inverter allows the load current to follow the suggested reference current due to the specific load application.

5. CONCLUSION

This project investigates a 7-level multilevel single-phase inverter using a low-cost microcontroller that can be conducted by undergraduate students. This has helped the authors to understand advantages and disadvantages of the multilevel inverter for the next DG applications. At the same time, current feedback control by using a PID controller enables control of the load current based on target reference control. The model is designed in a closed-loop system using MATLAB SIMULINK for simulation and the hardware test. The result shows that a single-phase 7-level inverter is able to produce a staircase output waveform compared to a 1-level inverter. Once closed-loop design is implemented, which consists of a PID controller, it is successfully simulated in MATLAB and the PWM of the closed-loop system can be downloaded into the microcontroller. At the same time, the current sensor detects the current signal and converts it into a voltage signal. The signal is changed due to the value of the reference current, and it is shown that the current can be controlled.

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