A Single-Stage Differential Boost Inverter with Modified SPWM Control for BESS Applications

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***Abstract*—The research proposes the single stage differential boost (SSDB) inverter for the single stage battery energy storage system (BESS) in which the topology can transfer AC source supply AC load. This study the single stage circuit architecture let reduce the cell number and enhances the system performance. This work proposed modified sinusoidal pulse width modulation (PWM) to control the SSDB inverter and the proposed control method significantly improved the total harmonic distortion (THD) of the SSDB inverter output voltage. Finally, compare of the PWM and proposed control method that the proposed control method THD is better than the PWM and improves the SSDB inverter output voltage quality.**

***Index Terms*--battery energy storage system, single stage differential boost inverter, total harmonic distortion, sinusoidal pulse-width modulation**

I. Introduction

The inverter technique develops widely due to the inverter's wide range of applications, for example, solar photovoltaic systems, AC microgrids, wind power, battery system, and so on. Among battery systems, inverters use DC to AC and power transfer to AC load. Fig. 1 displays the battery energy storage system with the battery charger block diagram, among AC source, AC-DC converter, battery module array, inverter, LC filter, and AC load [1]-[3]. First, the AC source provides energy to the AC-DC converter. Second, the battery module array's energy from the AC-DC converter. Third, the inverter output AC power from the battery module array and the AC-DC converter. Lastly, when the AC source is damaged, only the battery module array provides energy to the inverter. But the system architecture cost is high, and the battery module array's cell voltage is very low, the range of 1.2 V to 3.7 V. The conventional battery energy storage system needs a high DC voltage level of 380V to 400V; the high DC voltage provides the inverter and the inverter output AC power to the AC load. Because the battery module array's cell voltage is very low, so needs many cells in series, which causes the cell state of charge (SOC) to unbalance. If the cell SOC is unbalanced, the cell will generate a charging issue, furthering the cell will damage and the cell state of health (SOH) is reduced [4]-[6]. Another issue of the battery module array's output voltage is high, causing the high cost, complex control, and so on.

Figure 2 displays the conventional circuit architecture of the battery energy storage system, among battery module, converter, DC capacitor, inverter, LC filter, and AC load. This circuit architecture with converter, a converter let can enhance the voltage level from the battery module. But the converter and inverter are in series, so they need a big DC capacitor. This circuit architecture is better than the other (as shown in Fig. 1). This circuit architecture component number is few, its life is long, implement is easy.

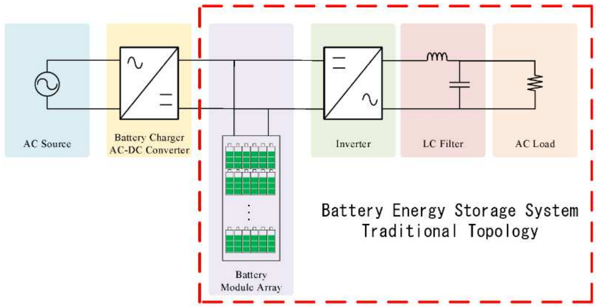


Fig. 1. The battery energy storage system with the battery charger block diagram.

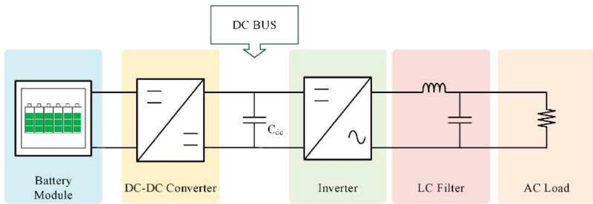


Fig. 2. The conventional circuit architecture of the battery energy storage system.

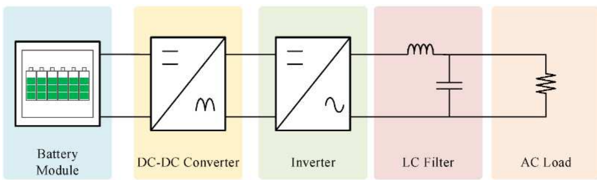


Fig. 3. The battery energy storage system pseudo-DC-link circuit architecture.

The battery energy storage system pseudo-DC-link circuit architecture (as shown in Fig. 3), among battery module, converter, inverter, LC filter, and AC load. This circuit architecture's converter switch control method is different the conventional circuit architecture (as Fig. 2). This circuit architecture's converter switch control method is from sinusoidal pulse width modulation (PWM). Thereby, this converter output voltage is rectified sinusoidal waveform. This circuit architecture lets the battery module output low voltage change to rectified sinusoidal waveform by the converter. This circuit architecture does not need the DC capacitor, the inverter switching frequency is low, and its enhances inverter performance.

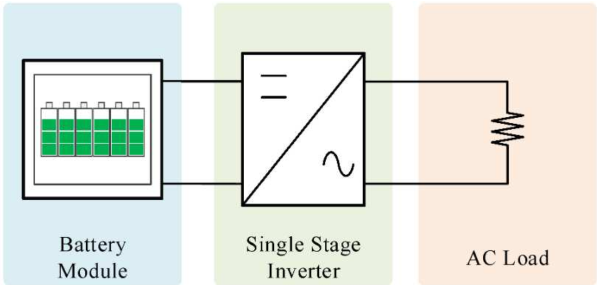


Fig. 4. The battery energy storage system pseudo-DC-link circuit architecture.

The battery energy storage system pseudo-DC-link circuit architecture as shown in Fig. 4, among battery module, single stage inverter (SSI), and AC load. This circuit architecture component is few, high performance, and input DC voltage and output AC voltage with good adjustable. But this circuit architecture still needs more tested and a long time used, further verifying its reliability.

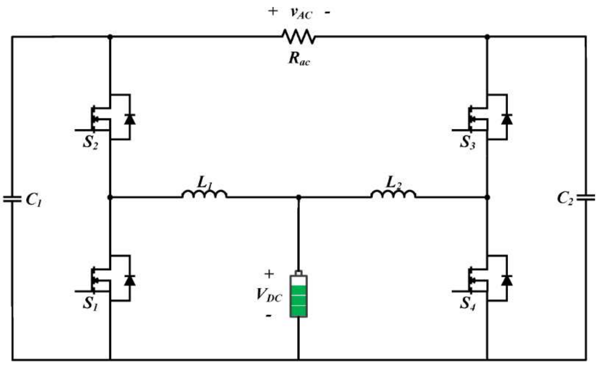


Fig. 5. The SSDB inverter schematic.

The single stage differential boost (SSDB) inverter schematic is shown in Fig. 5. This study proposes an SSDB inverter that lets the input low DC voltage level step up, then its output AC 110 V. This SSDB inverter also can connect to the grid. The SSDB inverter with 2 inductors, 4 switches, and 2 capacitors. The inductor function removes the ripple and storage, and the capacitor function removes the ripple. So the inductor and capacitor size is small and low cost.

In this study, the proposed SSDB inverter with modified sinusoidal pulse width modulation (PWM). From the simulation and experimental verification, the SSDB inverter is reliable, and the output voltage is low THD.

II. SSDB Inverter's System Explain

The SSDB inverter model is shown in Fig. 6. This inverter model with 2 parts because this circuit architecture is single stage differential (SSD). 1st part is converter 1 and 2nd part is converter 2. Among V_{DC} and i_{DC} represents the battery voltage and battery output current, i_{AC} and v_{AC} represents the R_{ac} current and voltage, v_{L1} and v_{L2} represents L_1 and L_2 voltage, i_{L1} and i_{L2} represents L_1 and L_2 current, v_{C1} and v_{C2} represents C_1 and C_2 voltage, i_{C1} and i_{C2} represents C_1 and C_2 current. The $i_{DC} = i_{L1} + i_{L2}$, $v_{AC} = v_{C1} - v_{C2}$.

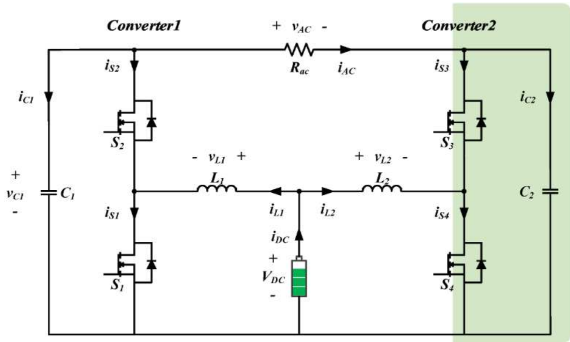
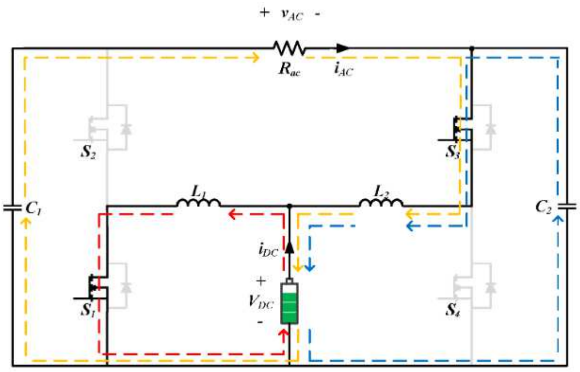
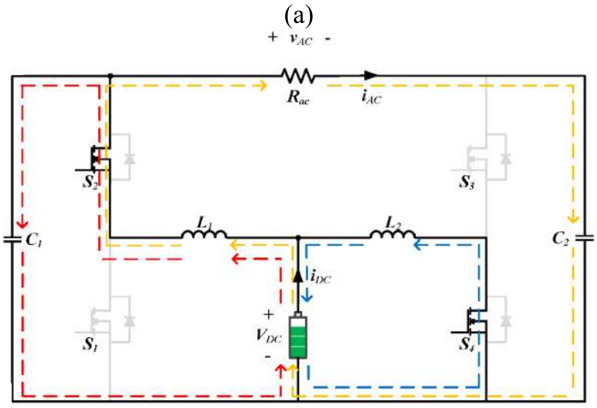


Fig. 6. The SSDB inverter model.

This SSDB inverter switching frequency is high than the SSDB inverter output voltage frequency, so the SSDB inverter work is repeated charge and discharge during the output frequency area. The SSDB inverter work states are shown in Fig. 7. Fig. 7 (a) and Fig. 7 (b) show the SSDB inverter work states of Mode-I and Mode-II, this part displays the positive half waveform. Fig. 7 (c) and Fig. 7 (d) show the SSDB inverter work states of Mode-III and Mode-IV, this part displays the negative half waveform.



(a)



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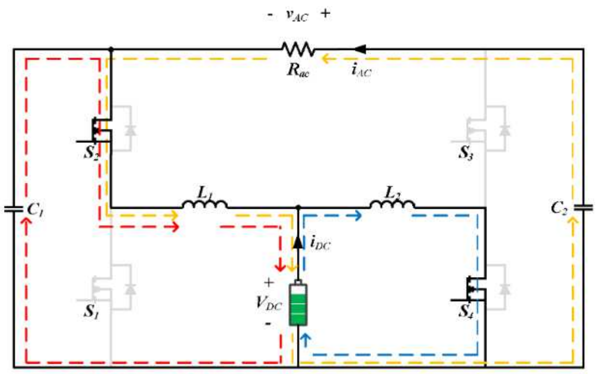
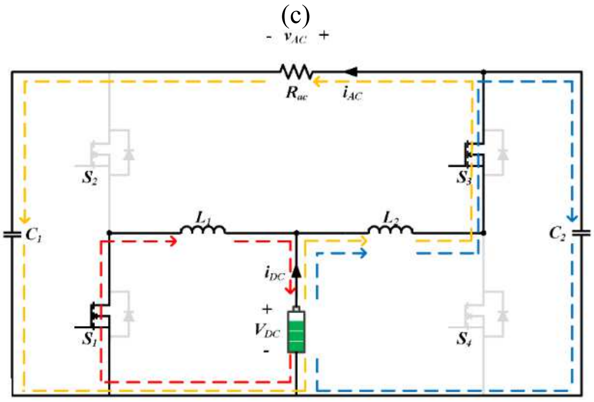


(c)



(d)

Fig. 7. The SSDB inverter work states: (a) Mode-I; (b) Mode-II; (c) Mode-III; (d) Mode-IV.

III. The Control Method Analysis

A. The sinusoidal PWM Control applies SSDB Inverter

Many inverter control strategies, but the classic control strategy is the sinusoidal PWM. This control method usually uses for the step-down inverter.

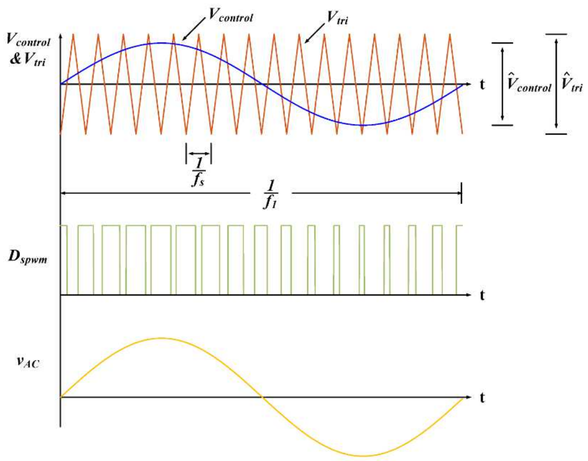


Fig. 8. The relationships between the control signal, duty cycle, and output AC voltage in a step-down inverter with a classic sinusoidal PWM control method.

The relationships between the control signal, duty cycle, and output AC voltage in a step-down inverter with a classic sinusoidal PWM control method are shown in Fig. 8. The *sinusoidal PWM* duty cycle produces from compare of the voltage control signal and the triangle wave.

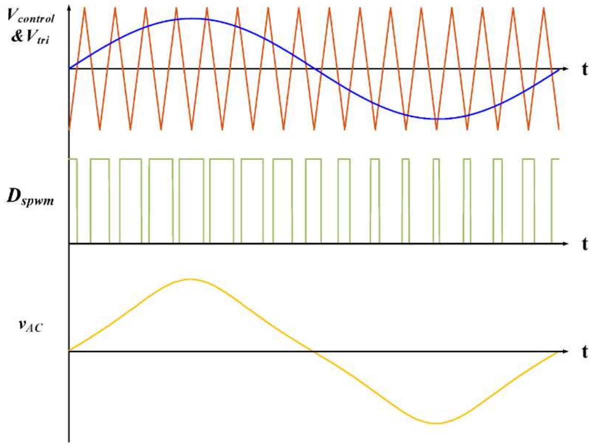


Fig. 9. The relationships between the control signal, duty cycle, and output AC voltage in an SSDB inverter with a classic sinusoidal PWM control method.

This amplitude modulation index m_a from comparing the voltage control signal and the triangle wave. This m_a can judge the duty cycle, as below.

$$D_{spwm}(t) = \frac{1}{2} + \frac{V_{control}(t)}{2} = \frac{1}{2} + \frac{m_a \sin \omega t}{2} \tag{1}$$

The sinusoidal PWM is mainly apple to a step-down inverter, the gain M < 1, ie is $m_a/2$. The gain M and duty cycle re-permutation are shown in (2) and (3).

$$M = \frac{v_{AC}}{V_{DC}} = \frac{1}{2} m_a = \frac{1}{2} \frac{\hat{V}_{control}}{\hat{V}_{tri}} \tag{2}$$

$$\begin{aligned} D_{spwm}(t) &= \frac{1}{2} + \frac{V_{control}(t)}{2} = \frac{1}{2} + \frac{m_a \sin \omega t}{2} \\ &= \frac{1}{2} + \mathrm{M}\sin\omega t = \frac{1}{2} + \frac{v_{AC}(t)}{V_{DC}} \end{aligned} \tag{3}$$

Assuming the input DC source has stable, the voltage value is constant. From Eqs. (1)-(3) know the voltage control signal change, then the duty cycle, output AC voltage, and gain M change together. So the voltage control signal affects the inverter output AC voltage, and the duty cycle and gain M have a linear relationship with a voltage control signal.

The relationships between the control signal, duty cycle, and output AC voltage in an SSDB inverter with a classic sinusoidal PWM control method are shown in Fig. 9. We can find that the inverter output AC voltage waveform will have a distortion issue.

B. Modified sinusoidal PWM Control Method Explain

The proposed modified sinusoidal PWM duty cycle equation is below to enhance the SSDB inverter output AC voltage's power quality.

$$D_{modified\_spwm}(\mathrm{t}) = \frac{v_{AC}(t) - 2V_{DC} + \sqrt{v_{AC}^2(t) + 4V_{DC}^2}}{2v_{AC}(t)} \qquad (4)$$

In this study, we obtain Eq. (4), the controller output duty cycle lets drive the SSDB inverter via Eq. (4), then this inverter output AC voltage's power quality is good.

$$V_{control}(t) = \frac{-2V_{DC} + \sqrt{v_{AC}^2(t) + 4V_{DC}^2}}{v_{AC}(t)} \qquad (5)$$

Figure 10 shows the conventional sinusoidal PWM control method and the proposed modified sinusoidal PWM control method. Fig. 10(a) displays the SSDB inverter output AC voltage and Fig. 10(b) illustrates the voltage control signal. The proposed modified sinusoidal PWM control method's power quality is better than the conventional sinusoidal PWM control method, and the proposed control method's duty cycle can be automatically adjusted to improve power quality.

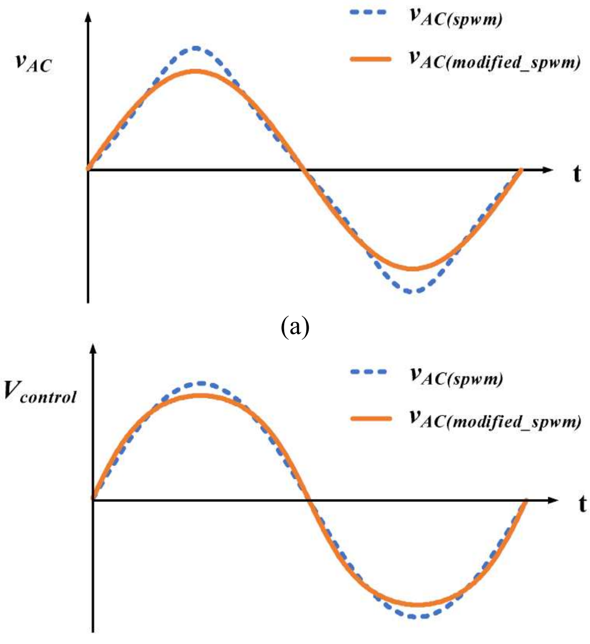


Fig. 10. Conventional sinusoidal PWM control method and the proposed modified sinusoidal PWM control method: (a) The SSDB inverter output AC voltage and (b) voltage control signal.

IV. Simulation And Experimental Results

Figure 11 displays the SSDB inverter's system architecture diagram. Fig. 12 shows the SSDB inverter's experiment platform. The battery module from the cells in 16 series and 3 parallel, among cells is produced by phoenix battery corporation. The battery module outputs a DC voltage of 33.5V to 58.5 V, the SSDB inverter rate power is 1 kW, the switching frequency is 20 kHz, and the value of the inductor both are 120 μH, respectively two capacitors value both are 12 μF.

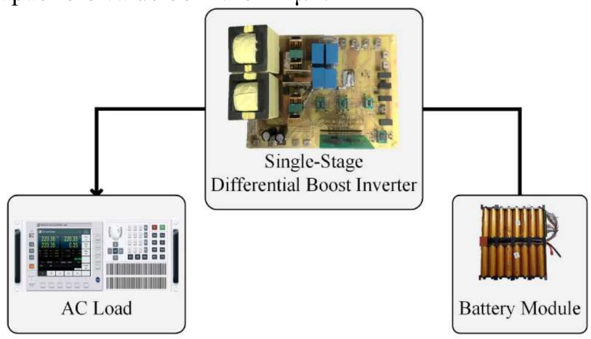


Fig. 11. The SSDB inverter's system architecture diagram.

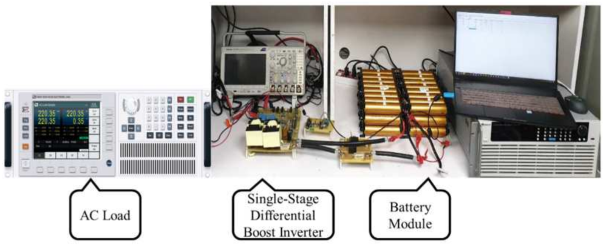


Fig. 12. The SSDB inverter's experiment platform.

The proposed modified sinusoidal PWM and conventional sinusoidal PWM for the 1 kW SSDB inverter that uses the MATLAB simulations and experimental results further verify the proposed modified sinusoidal PWM power quality is better than the conventional sinusoidal PWM.

Figure 13 shows the voltage control signal simulation comparison between the conventional sinusoidal PWM and the proposed modified sinusoidal PWM. We can find out that the proposed modified sinusoidal PWM's voltage control signal is not a sine wave.

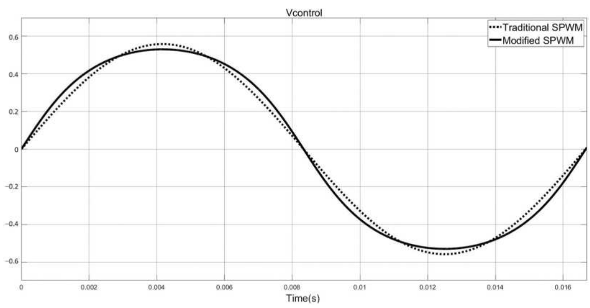
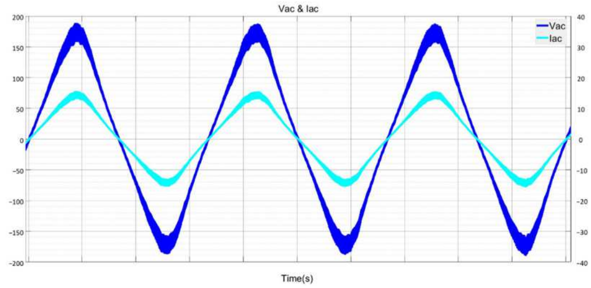
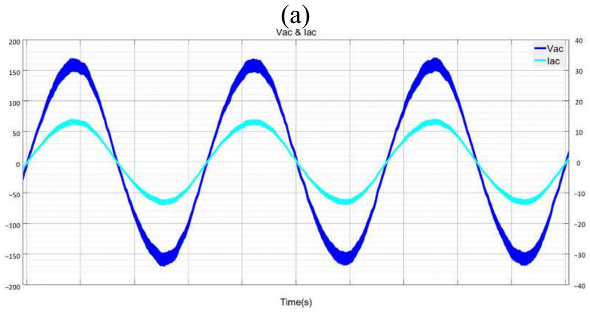


Fig. 13. The voltage control signal simulation comparison between the conventional sinusoidal PWM and the proposed modified sinusoidal PWM.

The simulation results of the SSDB inverter (1 kW) output AC voltage and current waveforms as shown in Fig. 14. Fig. 14 (a) shows the conventional sinusoidal PWM control method. Fig. 14 (b) displays the proposed modified sinusoidal PWM control method. We very clearly find out the SSDB inverter output AC voltage and current waveforms, the proposed modified sinusoidal PWM control method power quality is better than the conventional sinusoidal PWM control method.

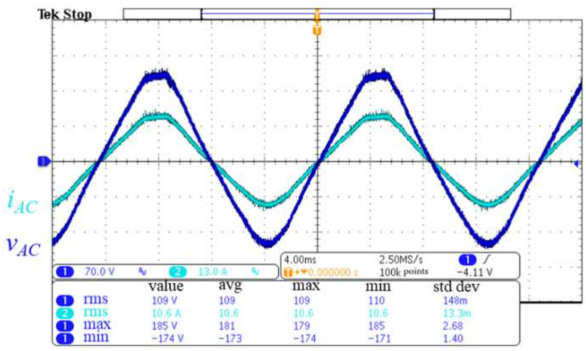


(a)

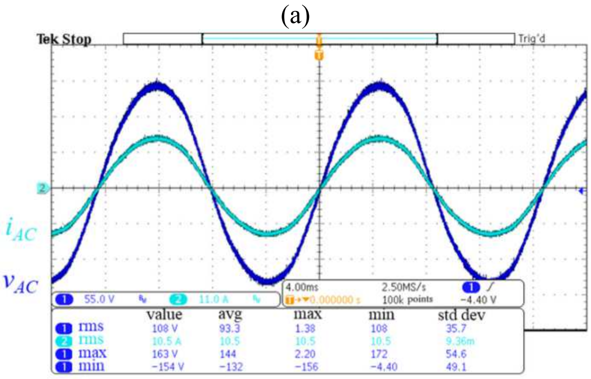


(b)

Fig. 14. The simulation results of the SSDB inverter (1 kW) output AC voltage and current waveforms: (a) the conventional sinusoidal PWM control method and (b) the proposed modified sinusoidal PWM control method.



(a)

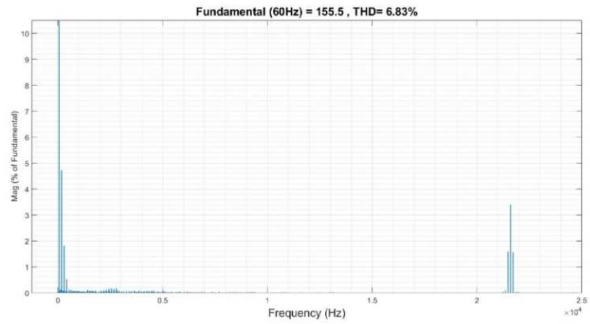


(b)

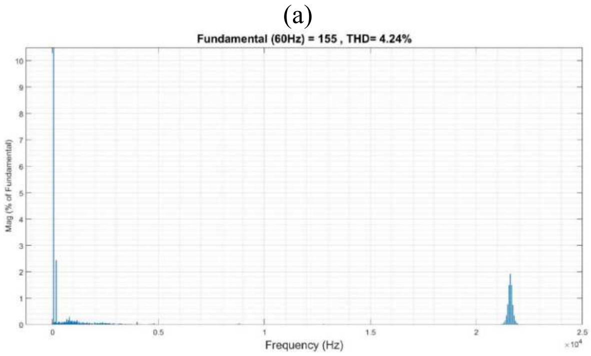
Fig. 15. The test results of the SSDB inverter (1 kW) output AC voltage and current waveforms: (a) the conventional sinusoidal PWM control method and (b) the proposed modified sinusoidal PWM control method.

The experimental results of the SSDB inverter (1 kW) output AC voltage and current waveforms as shown in Fig. 15. Fig. 15 (a) shows the conventional sinusoidal PWM control method. Fig. 15 (b) displays the proposed modified sinusoidal PWM control method. The SSDB inverter output AC voltage and current waveforms, the proposed modified sinusoidal PWM control method power quality is better than the conventional sinusoidal PWM control method (as Fig .14).

The simulation results of the SSDB inverter (1 kW) output AC voltage THD as shown in Fig. 16. Fig. 16(a) shows the conventional sinusoidal PWM control method that THD = 6.83 %. Fig. 16 (b) the proposed modified sinusoidal PWM control method that THD = 4.24 %. So the proposed modified sinusoidal PWM control method THD is better than the conventional sinusoidal PWM control method.



(a)



(b)

Fig. 16. The simulation results of the SSDB inverter (1 kW) output AC voltage THD: (a) the conventional sinusoidal PWM control method and (b) the proposed modified sinusoidal PWM control method.

V. CONCLUSIONS

The conventional sinusoidal PWM control method is applied to the SSDB inverter, the SSDB inverter outputs AC voltage and the current waveform will be distorted. This study proposed a modified sinusoidal PWM control method for the SSDB inverter. The SSDB inverter outputs AC voltage and the current waveform has good quality, and that is because the voltage control signal with automatic adjustment. This study's simulation and experimental results show that the proposed modified sinusoidal PWM control method THD is better than the conventional sinusoidal PWM control method.

Acknowledgment

This research was funded by the National Science and Technology Council, Taiwan, grant number MOST 111-2221-E-003-012. This work was also supported by the National Taiwan Normal University Subsidy Policy for International Collaboration and Research Projects.

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