High Efficiency Three-Phase Inverter for Motor Drive using HEECS Chopper

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***Abstract*— This paper proposed a new high efficiency three-phase inverter used as a motor drive. The inverter consists of three HEECS choppers and two batteries as the dc sources. From the results of the experiment, a conversion efficiency of up to 99.5% was measured around 2 kW output.**

***Keywords*— High efficiency, three-phase inverter, motor drive, multilevel inverter**

I. Introduction

The advent of wide-gap power semiconductor devices has led to the emergence of reported examples of highly efficient inverter operation in multilevel circuit systems[1-10]. In [1-4], the output waveform is a sinusoidal wave with little distortion, assuming that the output is connected to the power system, while in [5, 6], the motor is driven by a PWM waveform. The authors reported a single-phase inverter (HEECS inverter (High Efficiency Energy Conversion System)) with a high efficiency of over 99.7% by making the multilevel DC voltage non-uniform[3]. This circuit system is single-phase and includes an LC filter because it is for grid connection. In this paper, we report the development of this circuit to a three-phase inverter for motor drive.

The proposed circuit, called a three-phase HEECS inverter, consists of a three-phase inverter using three multilevel high-efficiency buck choppers (called HEECS choppers), which constitute a high-efficiency dual-supply HEECS single-phase inverter[3]. This new circuit topology is new and is expected to have high efficiency, so the efficiency is measured experimentally by connecting it to resistive loads[7,8] and motor loads. Chapter 2 outlines the single-phase HEECS inverter, and Chapter 3 shows the proposed three-phase inverter, Chapter 4 reports various experimental results, Chapter 5 is a discussion, and 6 is a conclusion.

II. Operation of the Two Battery HEECS Chopper

Fig.1 shows the circuit diagram of a dual-supply single-phase HEECS inverter and its typical waveforms[3]. The dual-supply HEECS chopper is a high-efficiency step-down chopper with two power supplies, E_1 and E_2, as inputs, and outputs voltages in three operating modes as shown in Fig. 2.

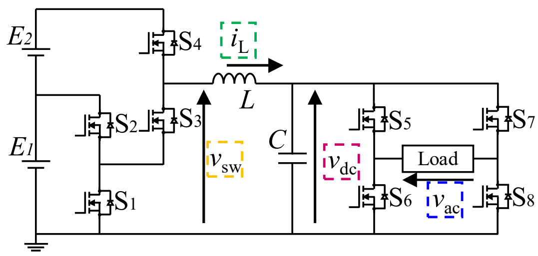
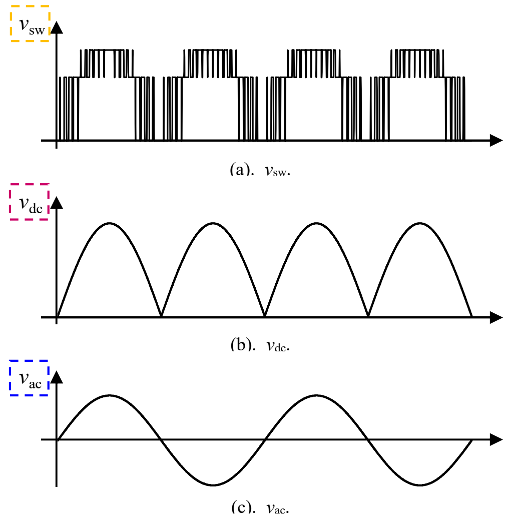


Fig. 1-a. Two battery HEECS inverter.

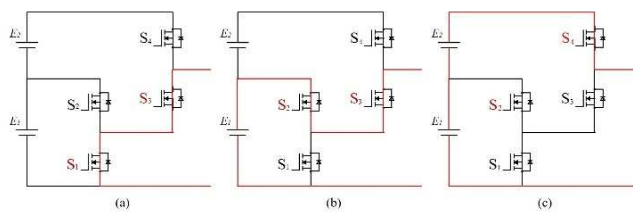


(a). v_{sw}.

(b). v_{dc}.

(c). v_{ac}.

Fig. 1-b Illustration of three waveforms at circuit points in Fig. 1.



(a) (b) (c)

Fig. 2. Operation of 2-battery HEECS chopper

III. NEW PROPOSED CIRCUIT: THREE-PHASE VOLTAGE TYPE HEECS INVERTER [7].

The proposed three-phase inverter is composed of three legs of HEECS chopper as shown in Fig.3. Phase voltage command of each leg is a sinusoidal wave with DC offset without crossing zero as shown in Fig.4. As a modulation method, carrier offset modulation (carrier disposition method) is adopted. Furthermore, the command value of each leg is shifted by 120° in phase to obtain the line voltage of three phases. The modulation method of the existing HEECS inverter [3] can be used without modification.

IV. EXPERIMENTS [8]

In this section, the resistive load experiment using the proposed inverter and the induction motor drive experiment are performed using the device from reference [3] with DSP as the controller. The circuit constants for each experiment are shown in Table.1. In the following, the losses under resistive and inductive loads are measured.

A. Resistive load experiment

Experiments were conducted when the output of the proposed inverter was a resistive load connected to an LC filter and Y-connection as shown in Fig. 3. In the resistive load experiment, the experimental condition[3] of the HEECS single-phase inverter was followed, where $E = E_1 + E_2 = 200 + 200$ V = 400 V. The circuit constants are shown in Table 1, and the experimental waveforms at the steady-state output of 1.8 kW in Fig.5 show that the line voltage between phases u and v is sinusoidal. The conversion efficiency of the inverter when the load is an AC electronic load and the inverter output is varied from 1.4 kW to 3.2 kW is shown in Fig. 6. The power was measured using a PW6001 (Hioki), and the losses were measured using the direct method in [3], where the losses are calculated from the difference between the input and output power. The maximum conversion efficiency of 99.57% was measured around $E_1 = E_2 = 200$ V and 2.2 kW output[8].

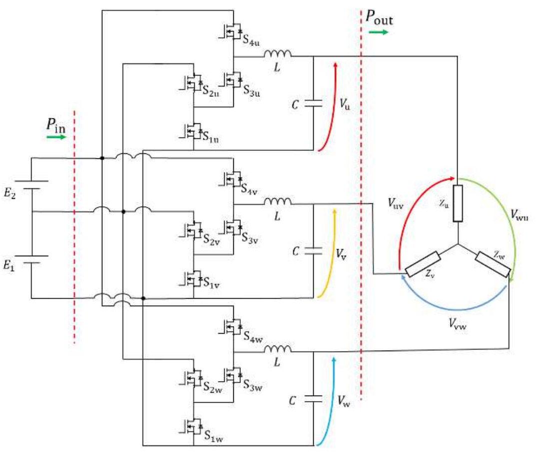


Fig. 3. Configuration of 2 battery HEECS 3-phase Inverter

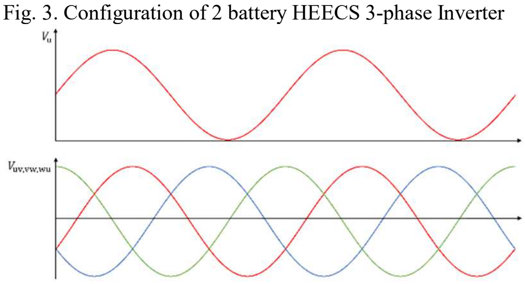


Fig.4 Waveform of 2 battery HEECS 3-phase Inverter

Table.1 Circuit parameters

	Parameters	Value
	S1~S4	SCT3017AL (Rohm)
	Dead Time	200 ns
Resistive Load	E (E_1+E_2)	400 V
	L	1.25 mH
	C	8 μF
	PWM Carrier Frequency (fs)	20 kHz
IM drive	E_1	175 V
	E_2	175 V
	IM	(VTFO-LK 4P 1.5KW) (HITACHI)
	PMM	MM-CF352 (MITSUBISHI)

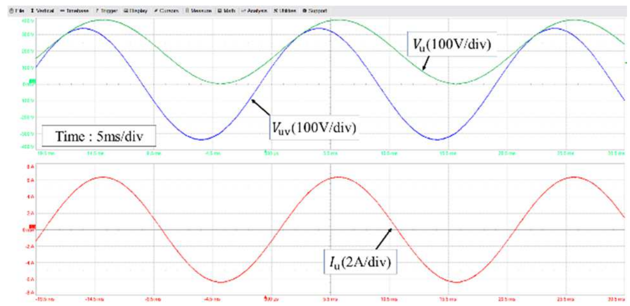


Fig. 5. Experimental waveform of V_u, V_{uv}, and I_u (Pout=1.8 kW, Resistive load)

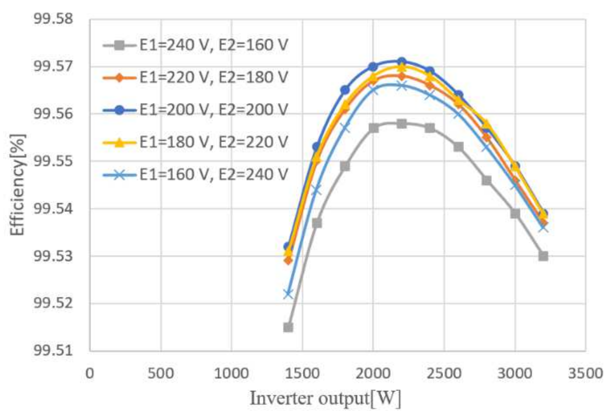


Fig. 6. Measured efficiency of proposed inverter (Resistive load, direct method[3])

B. Experiment of three-phase induction motor drive

The experimental results are shown when the LC filter is removed from the pure resistance load experiment and the load is a general-purpose three-phase cage-type induction motor. The experimental circuit configuration is shown in Fig. 7. The induction motor is directly connected to a permanent magnet synchronous motor, and the power generated by the synchronous motor is released to the electronic load. By adjusting the parameters of the electronic load, the rotating load is adjusted. In the motor drive experiment, the supply voltage was lowered to E1 = E2 = 175 V than in the resistive load experiment because the efficiency was best when E1 = E2 based on the results of the resistive load experiment and because the motor with a rated voltage of 3Φ-200 V was used. The motor was driven by open loop control with constant V/f. The voltage across the motor terminals at 50Hz, 200V, and 1500W input power is shown in Fig. 8, and the line current is shown in Fig. 9. Table. 2 shows the results of the induction motor drive experiment, and Fig. 10 shows the power conversion efficiency of the inverter when a three-phase 200 V, 50 Hz PWM output is applied to the motor and the output power of the inverter is varied from no load to 2.1 kW. A power conversion efficiency of more than 99.5% was measured around the rated power of the motor. Fig. 11 shows the transition of the power conversion efficiency when the PWM carrier frequency is decreased from 20 kHz to 14 kHz around the rated power of the motor. It can be observed that the losses decrease in proportion to the decrease in the carrier frequency for the same power.

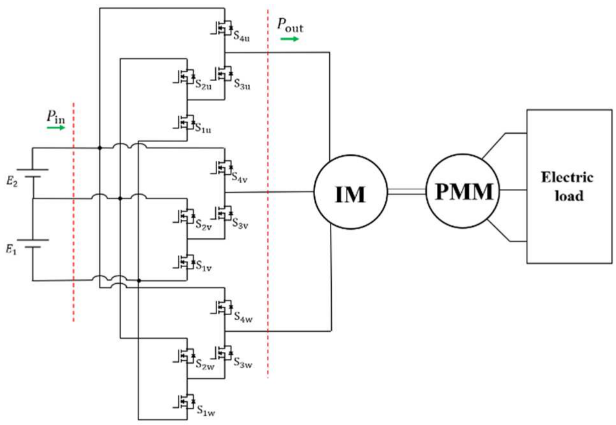


Fig. 7. IM drive with proposed inverter

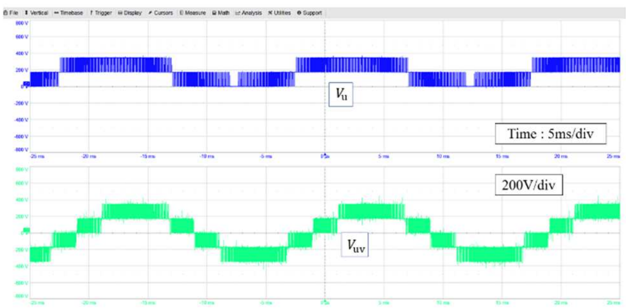


Fig. 8. Experimental waveform of V_u and V_{uv}

(Pout = 1.5 kW, IM drive)

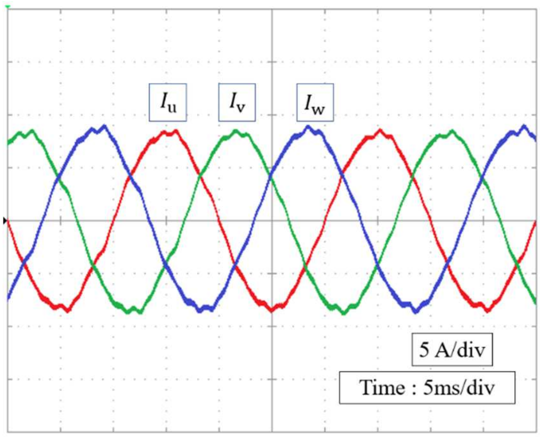


Fig. 9. Experimental waveform of current

(Pout = 1.5 kW, IM drive)

Table.2 Experimental result of IM drive (fs=20 kHz)

Pin [W]	Pout [W]	Rotations of IM [rpm]	Slip [%]	Power Factor	Efficiency (Inverter) [%]
217.49	212.52	1496	0.27	0.16	97.72
304.67	299.72	1494	0.41	0.22	98.38
504.41	499.43	1489	0.76	0.36	99.01
704.94	699.80	1483	1.12	0.48	99.27
906.52	901.03	1478	1.49	0.57	99.40
1106.81	1100.82	1472	1.87	0.64	99.46
1306.87	1300.23	1466	2.26	0.69	99.49
1508.41	1501.02	1460	2.67	0.74	99.51
1708.95	1700.70	1453	3.13	0.77	99.52
1909.19	1900.03	1446	3.58	0.79	99.52
2109.80	2099.63	1439	4.05	0.81	99.52

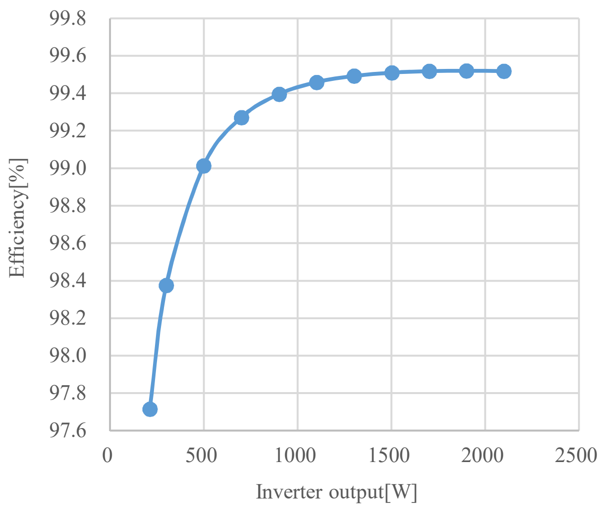


Fig. 10. Measured efficiency of proposed inverter

(IM drive, direct method[3])

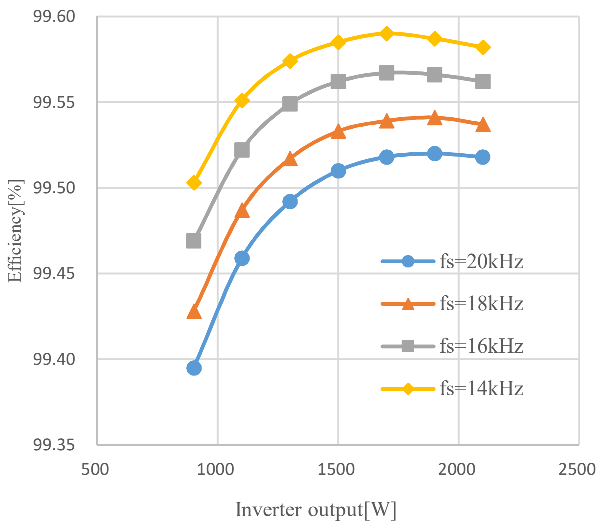


Fig. 11. Measured efficiency of proposed inverter

(IM drive. direct method[3])

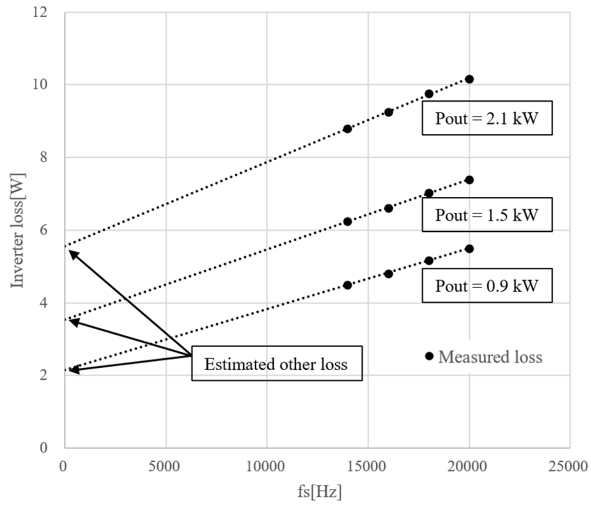


Fig. 12. Examples of how to estimate switching loss

(IM drive)

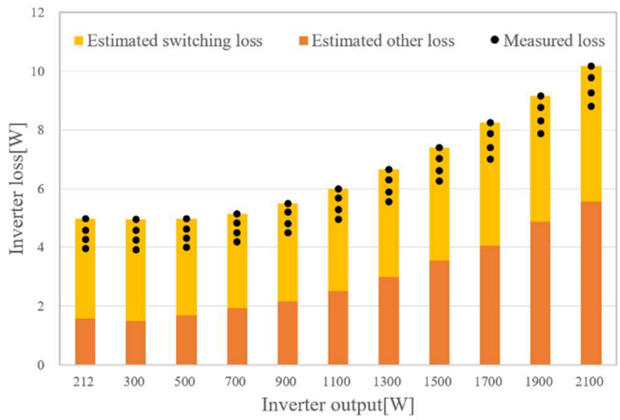


Fig. 13. Estimated loss breakdown of proposed inverter

(IM drive)

V. Discussion

A. Estimation of switching loss and conduction loss

The motor drive by the proposed three-phase inverter is performed in a circuit where the unfolding circuit and LC filter are removed from the two battery HEECS single-phase inverter. Therefore, most of the losses in the proposed inverter are switching losses and conduction losses of power devices. Since the switching loss is generally proportional to the carrier frequency, it is possible to estimate the switching loss from the experimental results when the carrier frequency is changed. From Fig.11, Fig.12 and reference [3], losses are estimated as shown in Fig.13. Although this experiment was conducted without changing the circuit configuration of the chopper used in the two battery HEECS single-phase inverter, it is believed that further improvement of efficiency and shift of the maximum efficiency point is possible by using power devices with different on-resistance and switching losses.

B. Comparison with two battery HEECS single-phase inverter

The proposed three-phase inverter is based on the chopper part of the two battery HEECS single-phase inverter [3], but it has various differences. One of the advantages of the proposed three-phase inverter is that it does not have a unfolding circuit as shown in Fig. 1, so it can operate regardless of the load power factor and the LC filter can be omitted in the case of motor drive. On the other hand, since the DC voltage utilization ratio is inferior to that of a single-phase inverter, the current increases at the same output, resulting in an increase in conduction loss. In addition, if an LC filter is used, the current bidirectionally flows in L in the proposed inverter while it flows only in one direction in the HEECS single-phase inverter, which may lead to an increase in the hysteresis loss in L. For such reasons, different optimizations are required to improve the efficiency despite having a common circuit configuration.

VI. Conclusion

In this paper, a three-phase HEECS inverter circuit using a high efficiency two battery HEECS chopper is proposed, and its efficiency characteristics are investigated by conducting two types of experiments. The efficiency characteristics of the proposed circuit are investigated by conducting two types of experiments. In addition, the losses are discussed. From the results of the resistive load experiment and the motor drive experiment, a high conversion efficiency of more than 99.5 % was measured at a load of about 2 kW. This three-phase HEECS inverter will enable high-efficiency three-phase power conversion and will contribute to energy saving. More accurate measurements[9,10], higher efficiency and modification of the modulation method[11] are currently under investigation. In addition, the high efficiency of small-capacity three-phase inverters with an output of a few kW may contribute to the study of energy saving in air-conditioning equipment and electric vehicles (EVs) under light loads.

APPENDIX PHOTO OF EXPERIMENTAL SET-UP

The photos of the motor drive (IM+PMM) and a proto-type of a three phase HEECS inverter are shown in Fig. A and Fig. B. The used motors in Fig. A are (1) Induction motor (1.5 kW, VOFO-LK 4P, Hitachi) and (2) Permanent Magnet Synchronous Motor (3.5 kW, MM-CF353 Mitsubishi).

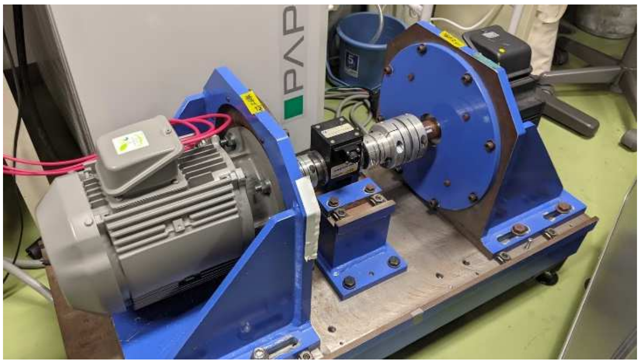


Fig. A. IM and PMM at experiment

Fig. B. HEECS chopper (u-phase leg)

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