A Novel Nine-Switch Inverter for Independent Control of Two Three-phase Loads

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***Abstract*— Industrial applications require large numbers of motors. For example, motors are used to manipulate industrial robots, an electric vehicles with in-wheel motors and electric trains. Two methods exist for controlling PM motors providing an inverter to control each motor, and connecting the motors in parallel and driving them with a single inverter. The first method makes an experimental apparatus complex and expensive; the second does not allow independent control of each motor because of differences in rotor angle between the two motors. Thus, we propose a novel *nine-switch inverter* that can independently control two three-phase loads. This paper introduces the structure of the *nine-switch inverter*, which is made from nine switches. The validity of the proposed inverter is verified through simulations and experiments.**

I. Introduction

The permanent magnet (PM) motor is finding widespread application because of its good efficiency. In particular, a variety of these motors are needed for factory applications, such as manipulating industrial robots. There are two methods of controlling dual PM motors: providing two separate inverters to drive each motor, and connecting the two motors in parallel and driving them with a single inverter. The first method increases the complexity and cost of the experimental apparatus. The second method cannot provide independent control of the two motors. Thus, we propose a novel *nine-switch inverter* that independently controls two three-phase loads. A similar concept called the five-leg inverter has been reported. This approach uses 10 switches, and its operational principle is verified through simulations[1].

This paper proposes a *nine-switch inverter* made from nine switches. This inverter eliminates three switching devices from the dual three-phase inverter[2][3][4][5]. The validity of the proposed inverter is verified through simulations and experiments.

II. Structure of the *Nine-Switch* Inverter

A. Basic Concept

Figure 1 shows the structure of the proposed *nine-switch inverter*, which consists of two three-phase inverters combined with three common switches (UM, VM, and WM). The upper portion in Fig. 1 is called *Inv1*, and the lower part is called *Inv2*. *Inv1* consists of switches UH, VH, WH, UM, VM, and WM, and *Inv2* consists of the switches UM, VM, WM, UL, VL, and WL.

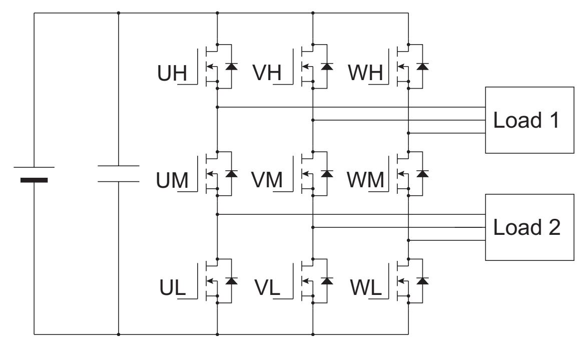

Fig. 1. Main circuit of proposed *nine-switch inverter*.

A pulse-width modulator (PWM) generates gate signals for *Inv1* and *Inv2*, as shown in Fig. 2. This PWM modulator has a unique carrier waveform. From this waveform, a reference for *Inv2* is lower than *carrier2* if the PWM modulation for *Inv1* is calculated. Moreover, the *Inv1* reference exceeds *carrier1* if the PWM modulation for *Inv2* is calculated. Therefore, switches UL, VL, and WL are in the ON state when *Inv1* is driven (mode1) and switches UH, VH, and WH are in the ON state when *Inv2* is driven (mode2). Figure 3 shows the state of each mode.

B. Method of Realization

The *Carrier1* and the *carrier* in Fig. 2 can be combined when generating the gate signals. Therefore, the PWM modulation of *Inv1* is calculated at the upper part of a triangular wave, and the PWM modulation of *Inv2* is calculated at its lower part, as shown in Fig. 4. Let a U-phase voltage reference for *Inv1* be V_{u1}^{ref}, and a U-phase voltage reference for *Inv2* be V_{u2}^{ref}. Assume that V_{u1}^{ref} and V_{u2}^{ref} are given by

$$V_{u1}^{ref} = A_1 \sin(2\pi f_1 t + \phi_1) \quad (1)$$

$$V_{u2}^{ref} = A_2 \sin(2\pi f_2 t + \phi_2) \quad (2)$$

where A_1, A_2 are amplitudes, f_1, f_2 are frequencies, and ϕ_1, ϕ_2 are phases. A general modulation rate, m, is given by

$$m = \frac{V^{ref}}{E/2} \quad (3)$$

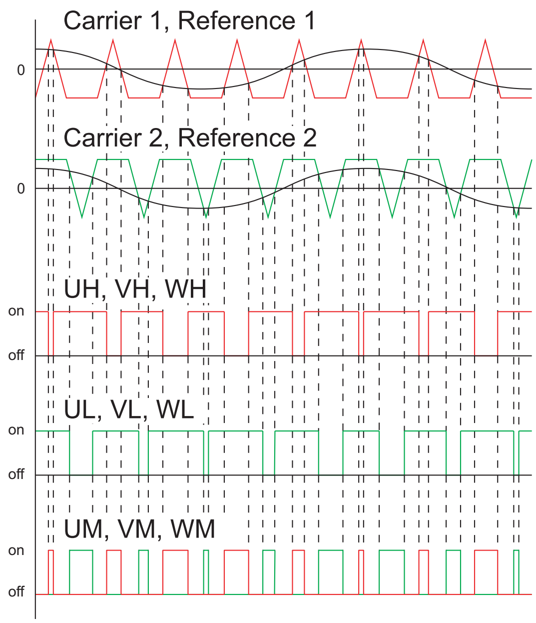

Fig. 2. Principle of operation.

where E is a dc source voltage. An offset, $E/4$, is added to the reference in (1) and an offset $-E/4$ is added to the reference in (2) when calculating the proposed PWM modulation. Therefore,

$$m_{1u} = \frac{V_{u1}^{ref} + E/4}{E/2} = \frac{V_{u1}^{ref}}{E/2} + \frac{1}{2} \tag{4}$$

$$m_{2u} = \frac{V_{u2}^{ref} - E/4}{E/2} = \frac{V_{u2}^{ref}}{E/2} - \frac{1}{2}. \tag{5}$$

From these transformations, the range of the references for *Inv1* and *Inv2* become $-E/4 \leq V_{u1}^{ref} \leq E/4$ and $-E/4 \leq V_{u2}^{ref} \leq E/4$, respectively. The gate signals for the switches UH, VH, and WH are positive logic values generated by the reference for *Inv1* and the upper part of the carrier. The gate signals for switches UL, VL, and WL are negative logic values generated by the reference of *Inv2* and the lower part of the carrier. The gate signals for the switches UM, VM, and WM are reversed values generated by the logical OR value of the gate signals for switches UH, VH, WH and UL, VL, WL, as shown in Fig. 5.

III. Improving Voltage Utilization

The *nine-switch inverter* shares one dc voltage source between *Inv1* and *Inv2*. Therefore, voltage utilization for *Inv1* and *Inv2* is 50%. However, this section proposes a method of improving voltage utilization. Each inverter's use of the voltage source changes with its reference value. Let the distribution rate of voltage utilization be α $(0 \leq \alpha \leq 1)$. First, we derive an equation for a single phase. α is given by

$$\alpha = \frac{A_1}{A_1 + A_2}. \tag{6}$$

An offset using this α is added to the variations of the reference for *Inv1* and *Inv2*. The offsets are decided as modulation

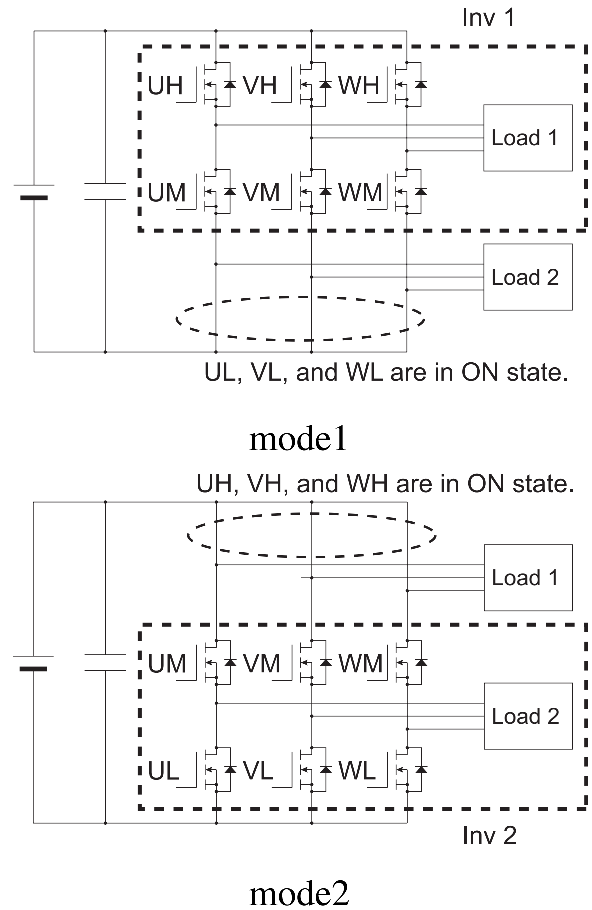

Fig. 3. Operation mode (mode1 and mode2).

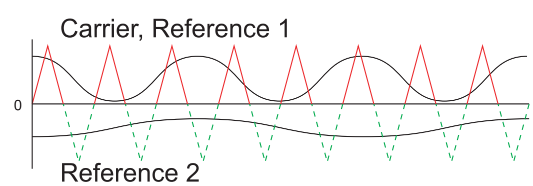

Fig. 4. PWM modulation of the novel inverter.

rates located on the center of the divided carrier. Thus, each offset is given by

$$\mathit{offset}_1 = 1 - \alpha \tag{7}$$

$$\mathit{offset}_2 = -\alpha. \tag{8}$$

Therefore, the modulation rate of the U-phase is given by

$$m_{1u} = \frac{V_{u1}^{ref}}{E/2} + 1 - \alpha \tag{9}$$

$$m_{2u} = \frac{V_{u2}^{ref}}{E/2} - \alpha. \tag{10}$$

Next, we derive an equation for three-phase operation. The maximal value of each absolute of the three-phase reference is represented by r_1 and r_2. Finally, the rate of apportionment

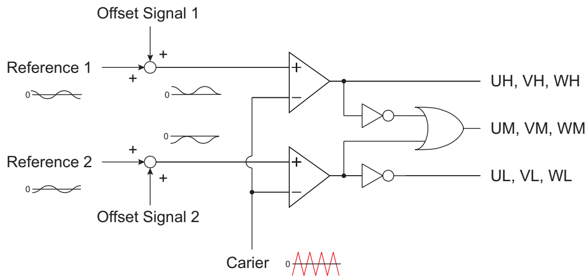

Fig. 5. Method of generation gate signals.

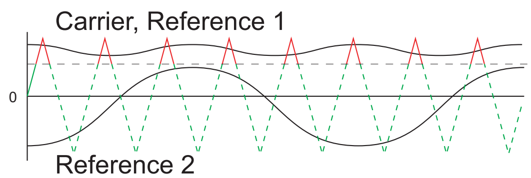

Fig. 6. PWM modulation with the distribution rate of voltage utilization.

α and the modulation rate are given by

$$\alpha = \frac{|r_1|}{|r_1| + |r_2|} \tag{11}$$

$$\mathbf{m_1} = \frac{\mathbf{V_1^{ref}}}{E/2} + (1-\alpha)\mathbf{e} \tag{12}$$

$$\mathbf{m_2} = -\frac{\mathbf{V_2^{ref}}}{E/2} - \alpha\mathbf{e} \tag{13}$$

where

$$\mathbf{V_i^{ref}} = \begin{bmatrix} V_{ui}^{ref} & V_{vi}^{ref} & V_{wi}^{ref} \end{bmatrix}^T \tag{14}$$

$$\mathbf{m_i} = \begin{bmatrix} m_{ui} & m_{vi} & m_{wi} \end{bmatrix}^T \tag{15}$$

$$\mathbf{e} = \begin{bmatrix} 1 & 1 & 1 \end{bmatrix}^T \tag{16}$$

$$i = 1, 2\ ;\ -1 \leq m_i \leq 1.$$

This method can improve voltage utilization of either *Inv1* or *Inv2*. Figure 6 shows PWM modulation with the distribution rate of voltage utilization. Figure 7 shows a block diagram of the circuit that establishes the modulation rate.

IV. Simulation

A simulation performed to verify the validity of the proposed inverter. In this simulation, we impose a different reference on each inverter. The reference for *Inv1* is a three-phase sine wave with an amplitude of 10 [V] and a frequency of 320 [Hz], and the reference for *Inv2* is a three-phase sine wave with an amplitude of 10 [V] and a frequency of 640 [Hz]. A three-phase LR load is connected to each inverter. Table I shows the simulation parameters. Figure 8 gives the U-phase current of *Inv1* and Fig. 9 gives the U-phase current of *Inv2*. These results indicate that the *nine-switch inverter* can independently control amplitude and frequency for two loads.

TABLE I
Parameters of simulations.

DC source voltage	E	40 [V]
Frequency of the carrier	f	10 [kHz]
Resistance	R	47 [Ω]
Inductance	L	15000 [μH]

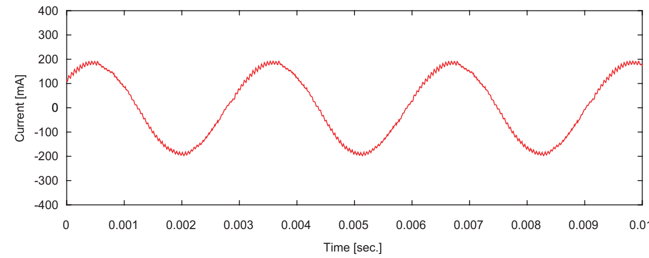

Fig. 8. Simulated current of *Inv1* (U-phase). The reference for *Inv1* is a three-phase sine wave with an amplitude of 10 [V] and a frequency of 320 [Hz].

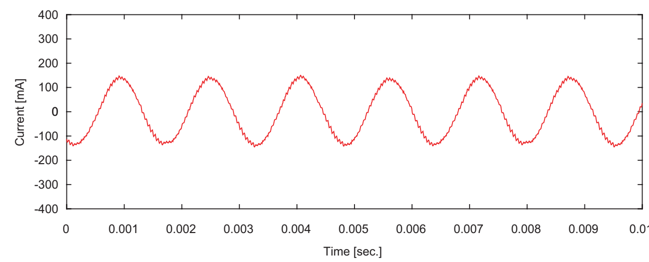

Fig. 9. Simulated current of *Inv2* (U-phase). The reference for *Inv2* is a three-phase sine wave with an amplitude of 10 [V] and a frequency of 640 [Hz].

V. Experiment

A. Experiment Using LR Loads

We conducted an experiment to verify the inverter's operation. The parameters of the experimental system are the same as for the simulation. The reference for *Inv1* is a three-phase sine wave with an amplitude of 10 [V] and a frequency of 320 [Hz]; the reference for *Inv2* is a three-phase sine wave with an amplitude of 10 [V] and a frequency of 640 [Hz]. Figure 10 shows the U-phase current for *Inv1*, and Fig. 11 shows the U-phase current for *Inv2*. These results demonstrate that the *nine-switch inverter* independently controls amplitude and frequency for two loads. However, the current waves have some ripples.

1) Independence of Inv1 and Inv2: To verify independent control, we conducted an experiment with different references for *Inv1* and *Inv2*. In this experiment, the reference for *Inv1* is a three-phase sine wave with an amplitude of 20 [V] and a frequency of 320 [Hz], while the reference for *Inv2* is zero volts. Figure 12 shows the U-phase current for *Inv1*, and Fig. 13 shows the U-phase current for *Inv2*. Figure 12 shows that *Inv1* is driven correctly. However, as shown in Fig. 13, the current of *Inv1* interferes with *Inv2* by less than 1%. In the future, we will examine the improvement of the ripple

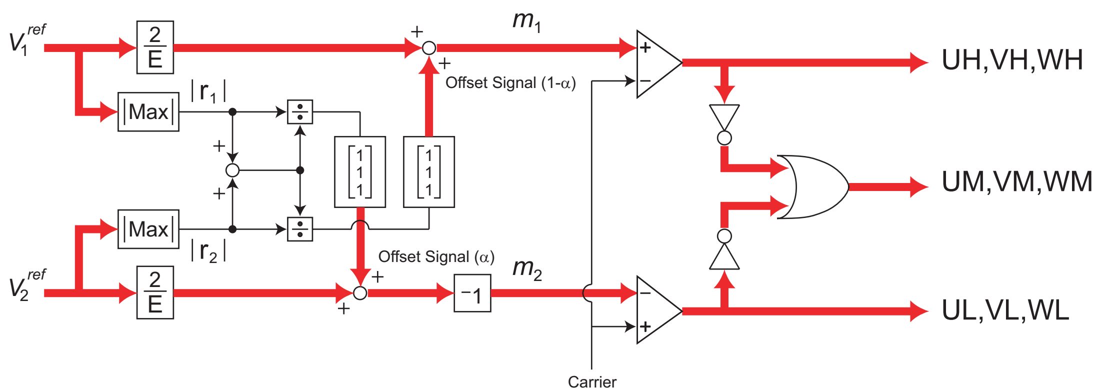

Fig. 7. Block diagram of establishment of modulation rate.

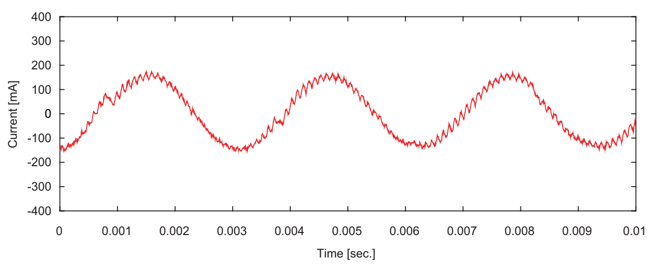

Fig. 10. Measured current of *Inv1* (U-phase). The reference for *Inv1* is a three-phase sine wave with an amplitude of 10 [V] and a frequency of 320 [Hz].

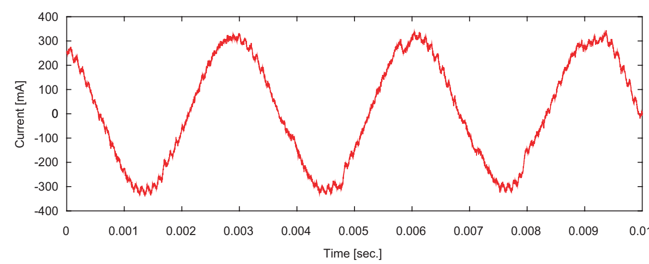

Fig. 12. Measured current of *Inv1* (U-phase). The reference for *Inv1* is a three-phase sine wave with an amplitude of 20 [V] and a frequency of 320 [Hz].

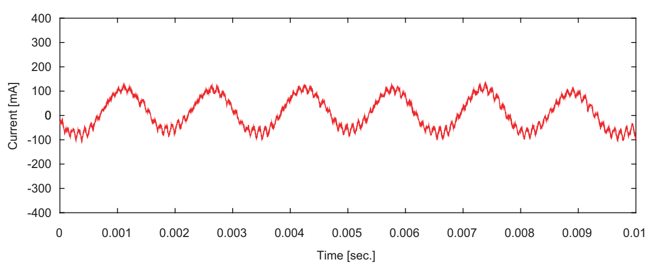

Fig. 11. Measured current of *Inv2* (U-phase). The reference for *Inv2* is a three-phase sine wave with an amplitude of 10 [V] and a frequency of 640 [Hz].

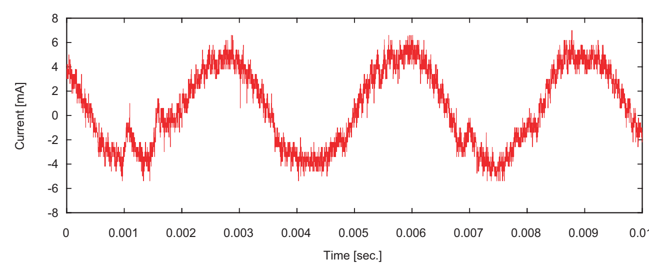

Fig. 13. Measured current of *Inv2* (U-phase). The reference for *Inv2* is zero volts.

amplitude and inverter interference.

B. Experiment Using Permanent Magnet Synchronous Motor

We conducted an experiment that connected two permanent magnet synchronous motors as loads. These motors had a rated output of 60 [W]. In this experiment, the *Inv1* reference is a three-phase sine wave with a frequency of 50 [Hz] and the reference for *Inv2* is a three-phase sine wave with a frequency of 30 [Hz]. These motors are driven with the frequencies of *Inv1* and *Inv2*. Line voltages of the U-V phase and W-V phase for *Inv1* are shown in Fig. 14 and those for *Inv2* are shown in Fig. 15. These results confirm that the *nine-switch inverter* can independently control two motors.

VI. Conclusion

This paper proposes a *nine-switch inverter* and a PWM method that can independently control two three-phase loads.

The simulations and the experiments were performed to verify the validity of the proposed inverter. The results confirmed that the *nine-switch inverter* can independently control amplitude and frequency for two three-phase loads, and parmanent-magnet synchronous motors; however, there is some ripple amplitude, and slight interference between *Inv1* and *Inv2*. Work is needed to improve of the interference problem.

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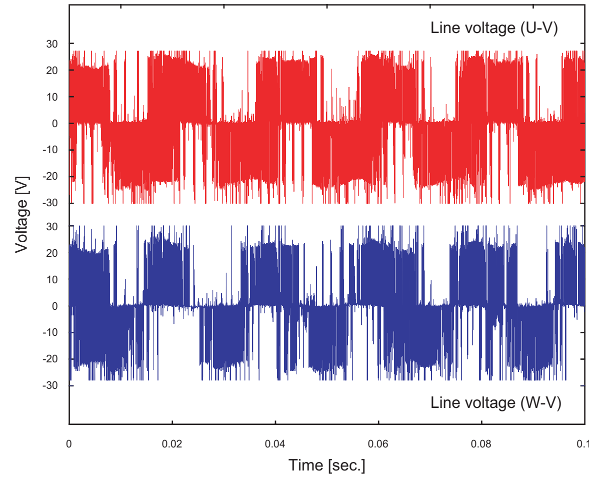

Fig. 14. Line voltage of U-V phase and W-V phase; *Inv1*.

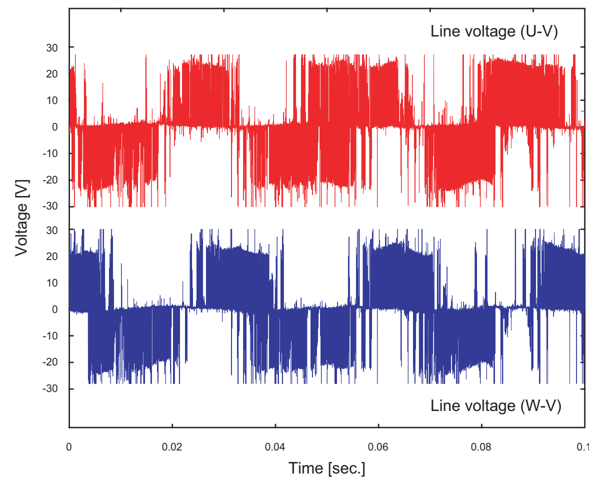

Fig. 15. Line voltage of U-V phase and W-V phase; *Inv2*.