A Novel Control Strategy of the Inverter with Sinusoidal Voltage and Current Outputs

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ABSTRACT

The authors have proposed a novel inverter with sinusoidal voltage and current outputs.[1][2]

In the novel inverter, the design of a high-pass filter inserted in the feed-back circuit largely influences the output waveforms. In this paper, the authors show a solution to the design problem of the high-pass filter, applying a rotating coordinate transformation.

1. INTRODUCTION

An ideal inverter should have sinusoidal voltage and current outputs. Generally, output voltages of a voltage-source PWM inverter contain high level switching frequency harmonics due to the PWM operation, while output currents are kept nearly sinusoidal. High level harmonics contained in output voltages of a voltage-source inverter cause acoustic noises, iron losses and electromagnetic interferences. An L-C filter was used to suppress the switching frequency harmonics; however, there is reason to fear resonance in the L-C filter. Therefore, the authors here propose a novel control system applying a rotating coordinate transformation to suppress the resonance.

2. CONVENTIONAL SYSTEM

2.1 Conventional system

Fig.1 shows a diagram of the conventional system for the inverter with sinusoidal voltage and current outputs, proposed by the authors. The system is composed of a voltage-source PWM inverter, an L-C filter and a voltage feed-back loop.

Generally, output voltages of a voltage-source PWM inverter contain high level switching frequency harmonics due to the PWM operation. Switching frequency harmonics in the output voltages are removed by the inserted L-C filter in the output side of the inverter. Therefore, output voltages of the inverter turn out sinusoidal waveforms. However, when load currents contain harmonics of L-C filter resonance frequency, the L-C filter resonates to the harmonics, and they appeared in the load voltages. Accordingly, in order to remove harmonics of the L-C filter resonance frequency, the authors add a voltage feed-back loop as shown in Fig.1. If the voltage feed-back circuit operates adequately, and all harmonics in the load-side voltage are cancelled, then output voltages are kept in sinusoidal waveform. That is, the feed back loop behaves just like an active filter.

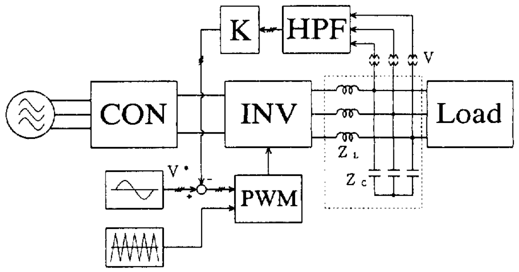

Fig. 1 Diagram of Conventional System

2.2 Simulation results

Fig.2 shows simulation results of the conventional system shown in Fig.1. Simulation conditions are shown in Table 1. It is assumed that the inverter is an ideal one, that is, dead times to avoid an arm break-through are neglected.

Fig.2 (a) shows simulation results at output frequency 20Hz, (b) shows results at 50Hz and (c) show results at 250Hz. Output voltages of the inverter become sinusoidal waveforms in each results, that is, output waveforms are improved.

Table 1 Simulation conditions

Main Circuit	DC Voltage		280	[V]
	L-C Filter	L	0.37	[mH]
		C	20	[μF]
	Load		Non-Load	
Control Circuit	Fundamental Component	Frequency	20,50,250	[Hz]
		Amplitude	7	[V]
	Carrier	Frequency	16	[kHz]
		Amplitude	8	[V]
	High-pass Filter	Cut-off	700	[Hz]
		K	3	

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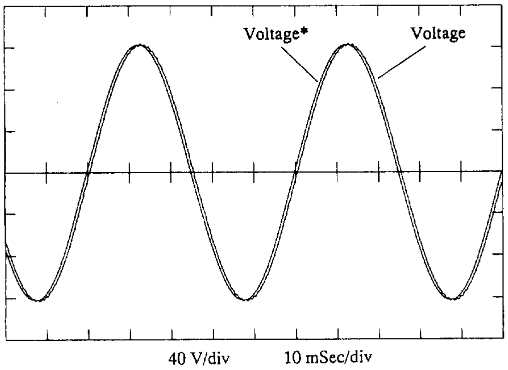


Fig. 2 (a) Simulation Results of Conventional System at 20Hz

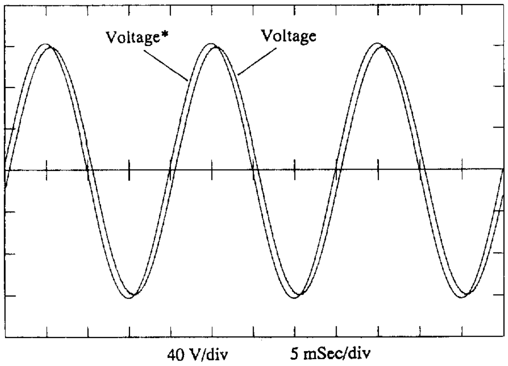


Fig. 2 (b) Simulation Results of Conventional System at 50Hz

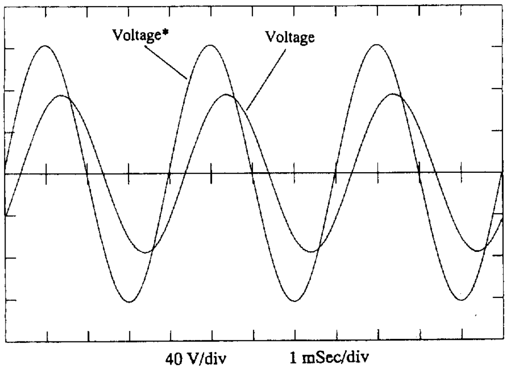


Fig. 2 (c) Simulation Results of Conventional System at 250Hz

2.3 Experimental results

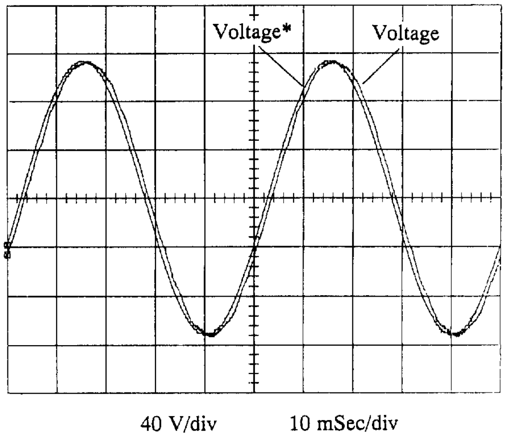


Fig. 3 (a) Experimental Results of Conventional System at 20Hz

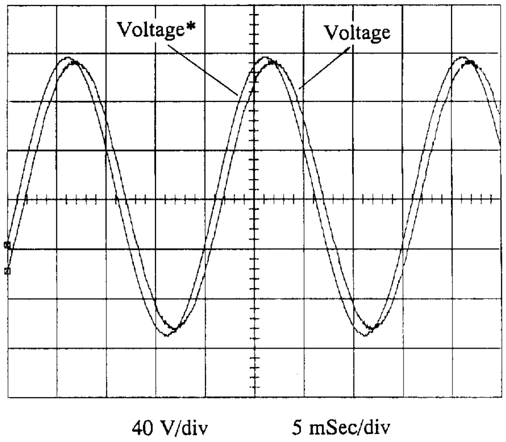


Fig. 3 (b) Experimental Results of Conventional System at 50Hz

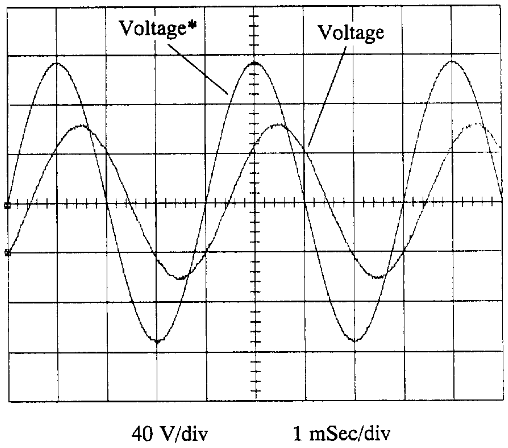


Fig. 3 (c) Experimental Results of Conventional System at 250Hz

Fig.3 shows experimental results of the conventional system shown in Fig.1. Experimental conditions are shown in Table 2. Output voltage shows good coincidence with reference voltage at 20Hz and 50Hz. However, at 250 Hz, output voltage is largely delayed and reduced in the output voltage amplitude the same as the simulation results. Therefore, the delay and amplitude reduction of the output voltage are essential problems of the conventional system shown in Fig. 1.

Table 2 Experimental conditions

Main Circuit	DC Voltage		280 [V]
	L-C Filter	L	0.37 [mH]
		C	20 [μF]
	Load		Non-Load
Control Circuit	Fundamental Component	Frequency	20,50,250 [Hz]
		Amplitude	7 [V]
	Carrier	Frequency	16 [kHz]
		Amplitude	8 [V]
	High-pass Filter	Cut-off	700 [Hz]
		K	3
	Died Time		1 [μSec]

2.4 An analysis of the output characteristics on the system

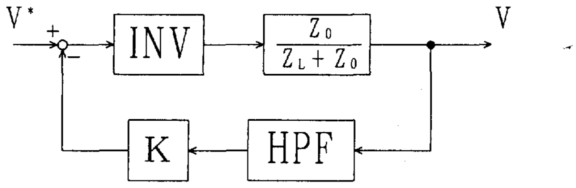


Fig. 4 Block Diagram of Feed-back Loop

Fig.4 shows the block diagram of the system shown in Fig.1. Where Z_L is an impedance of L in L-C filter, Z_0 is a parallel impedance of C in L-C filter and load. In Fig.4, assuming that V* is reference voltage, V is output voltage and the inverter is ideal one (gain = 1), voltage transfer function can be calculated as follows ;

$$V = \frac{Z_0}{Z_L + Z_0}\left(V^* - K\frac{s}{s+\omega_C}V\right)$$

Then,

$$V\left(1+\frac{Z_L}{Z_0}+K\frac{s}{s+\omega_C}\right)=V^*$$

$$\frac{V}{V^*}=\frac{1}{1+\frac{Z_L}{Z_0}+K\frac{s}{s+\omega_C}} \qquad (1)$$

Bode diagrams of the voltage transfer function of the conditions shown in Table 1 are calculated by the equation (1), and it is shown in Figs. 5 and 6.

Fig.5 shows the bode diagram in the case of the L-C filter alone. In Fig.5, the switching frequency harmonics are reduced adequately by the L-C filter. On the other hand, an L-C filter has its own resonant frequency; therefore, when a load current contains an L-C filter resonance frequency component, the resonance frequency harmonic distorts the load voltages because of the resonance of the L-C filter.

Fig.6 shows the bode diagram in the case when the voltage feed-back control circuit is added. By voltage feed-back control, L-C filter resonance is suppressed effectively. But, accompanied by the increase of the inverter output frequency, output voltage of the inverter is delayed and reduced as shown in Fig.6.

These problems are caused by a high-pass filter inserted in the feed-back loop. Accompanied by the inverter output frequency, a high-pass filter can not remove the fundamental component perfectly. As the result, a small fundamental component is fed back, which causes a delay and decrease of output voltage. Accordingly, the design of the high-pass filter is most important for the sake of characteristic improvement of the inverter with sinusoidal voltage and current outputs.

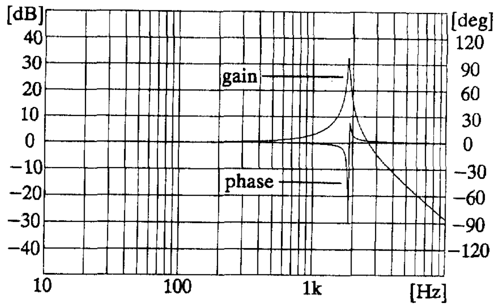


Fig. 5 Bode Diagram (L-C Filter Alone)

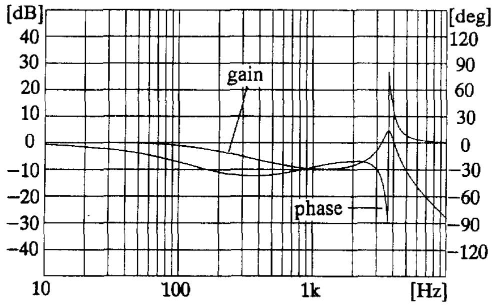


Fig. 6 Bode Diagram of Conventional System

3. PROPOSED SYSTEM USING COORDINATE TRANSFORMATION METHOD

3.1 Proposed system

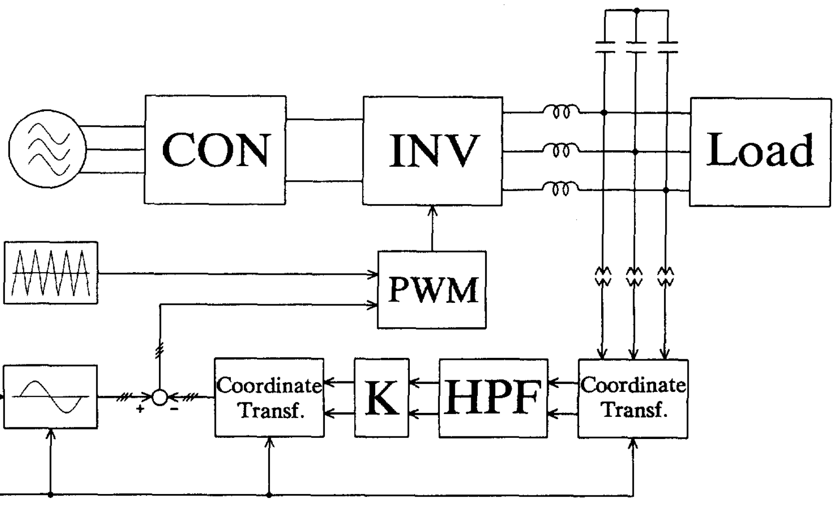
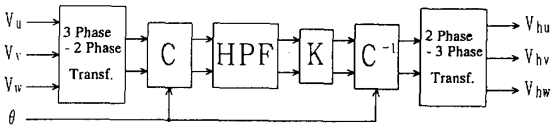


Fig. 7 Diagram of Coordinate Transformation System

To improve the design problem of the high-pass filter, the authors propose the coordinate transformation System shown in Fig.7. This system is composed of a voltage-source PWM inverter, an L-C filter and the voltage feed-back loop the same as a conventional inverter. The feed-back loop in Fig.7 contains two coordinate transformations. The first coordinate transformation is connected to the input side of the high-pass filter HPF, and the second coordinate transformation is connected to the output side of gain K.

Fig.8 shows the control diagram of the feed-back loop. The first coordinate transformation consists of 3 phase to 2 phase transformation and rotating transformation at a fundamental angular velocity of the 3 phase reference voltages. The second coordinate transformation is inverse transformation of the first coordinate transformation.

In Fig.8, detected 3 phase output voltages are transformed through the 3 phase to 2 phase transformation and the rotating coordinate transformation, and they are input to the high-pass filter and gain K, then transformed inversely by the second coordinate transformation. Finally, they are fed back and compared with the 3 phase reference voltages. Fundamental components of 3 phase output voltages on rotating coordinates are expressed by a DC component regardless of output frequency. Accordingly, the fundamental components are perfectly suppressed by the high-pass filter. That is, the high-pass filter inserted in the feed-back loop does not cause any delay and decrease of the output voltages of the inverter.



Where

3 Phase - 2 Phase Transf. : $\sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}$

2 Phase - 3 Phase Transf. : $\sqrt{\frac{2}{3}}\begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}$

C : $\begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$

C^{-1} : $\begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$

Fig. 8 Control Block Diagram of Feed-Back Loop

3.2 Simulation results

Fig.9 shows the simulation results of the coordinate transformation system. Simulation conditions are shown in Table 1. Output voltages coincide well with reference voltage at 20Hz, 50Hz and 250Hz respectively; that is, output voltage waveforms are improved largely by coordinate transformation method.

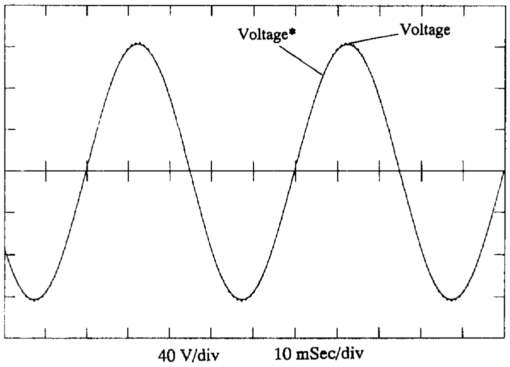


Fig. 9 (a) Simulation Results of Proposed System at 20Hz

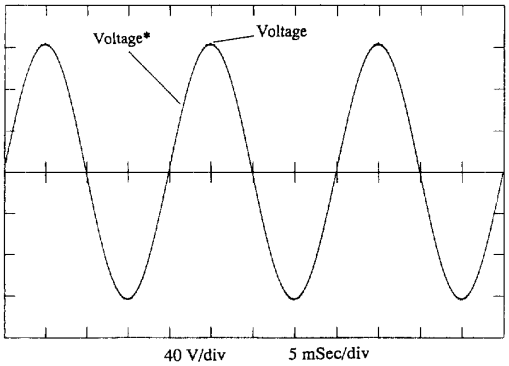


Fig. 9 (b) Simulation Results of Proposed System at 50Hz

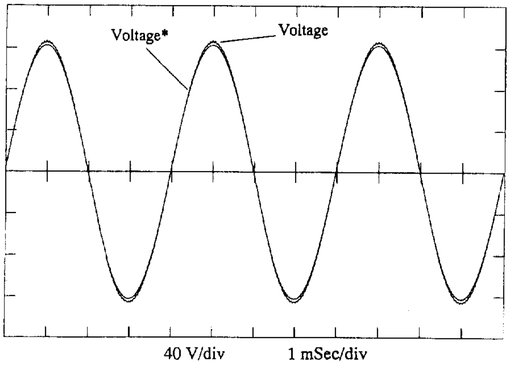


Fig. 9 (c) Simulation Results of Proposed System at 250Hz

3.3 Experimental results

Fig.10 shows the experimental results of the coordinate transformation system. Experimental conditions are shown in Table 2. Output voltages coincide well with reference voltage at 20Hz, 50Hz and 250Hz respectively, the same as the simulation results. At 250Hz, the output voltage of the inverter is largely delayed and reduced in case of the conventional method; however, they are largely improved by the coordinate transformation method.

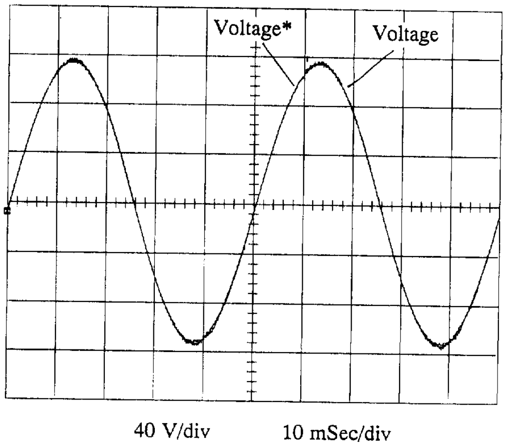


Fig. 10 (a) Experimental Results of Proposed System at 20Hz

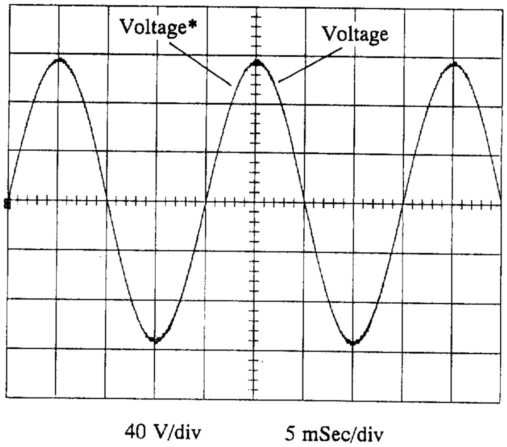


Fig. 10 (b) Experimental Results of Proposed System at 50Hz

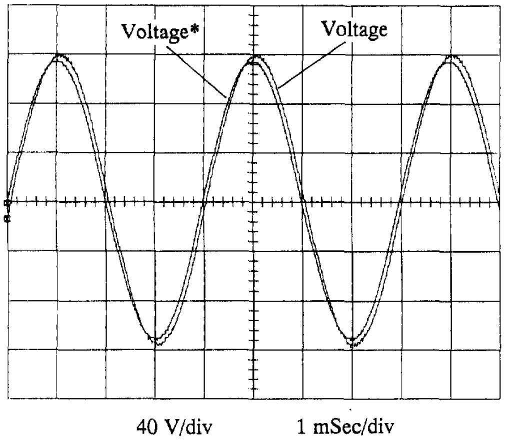


Fig. 10 (c) Experimental Results of Proposed System at 250Hz

4. CONCLUSION

A conventional system can operate without difficulty within 50Hz. However, with accompanying increases of the output frequency, output voltages are largely delayed and reduced by a high-pass filter inserted in the feed-back loop. The authors proposed to apply coordinate transformation to a high-pass filter inserted in the feed-back loop, and theoretical analysis, simulations and experiments showed satisfactory results. As a result, the proposed system has realized the ideal filter which can suppress fundamental frequency components perfectly, and characteristics of the inverter with sinusoidal voltage and current outputs are greatly improved.

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