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(Reduction Harmonics in Double Connected Modified Current Source Inverter by Switching Taps on Auto Transformer)

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Abstract

An effective method for reducing the harmonics in double connected modified current source inverter[MCSI] by switching taps on auto transformer is presented in this paper.

The proposed system operates as like a 24 step MCSI by adding only tap changing auxiliary circuit which consists of several taps and static switching elements to the 12 step multiple inverter, which is double connected three-phase six-step MCSI with an auto transformer. The basic theories of the proposed inverter systems for analyzing the output waveforms are described.

And to optimize the effectiveness of the harmonic reduction, the optimum turn ratio and the tap changing control angle of auto transformer are decided by digital simulation and its validity is verified by experiment.

Although the construction of the proposed inverter is very simple, it is clarified that the output waveform of the inverter is almost the same as that of the conventional 24 step multiple inverter under the optimum condition.

1. Introduction

A current source inverter has many advantages compared with a voltage source inverter, such as simple structure, high reliability, easy overcurrent protection, strong commutation capability, and so on. But a current source inverter may exert a high voltage stress to its components and motor and can drive only one induction motor, which is not economical in several applications [1)~3)]

For this reason, a modified current source inverter[MCSI] shown Fig. 2 was proposed[3)]. The MCSI retains all the good features of the current source inverter mentioned above and overcomes its shortcomings. It also has some features of the voltage source inverter which can drive induction motors in parallel.

However, the harmonics involved in the output waveforms of these inverters have often caused the burning of the capacitor which is adopted for improving the power factor, the mis-action of protective relay and the torque ripple in the motor, especilly at the lower frequency, etc.

It is an effective countermeasure for this problem to increase the pulse number by means of multi-sequential or multi-parallel connections. However,

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these methods result in considerable increase in the cost and the size of the inverter system because of necessity of phase shifting transformers, such as zig-zag or fork connections and numerous switching elements[4),5)].

It is the most important thing for practical use to design the system itself simply and to get the reducing effect of harmonics on equal to these methods.

Therefore this paper presents an effective method for reducing the harmonics in double connected MCSI by switching taps on auto transformer. The proposed system operates as like a 24 step MCSI by adding only tap changing auxiliary circuit which consists of several taps and static switching elements to the 12 step multiple inverter, which is the double connected three-phase six-step MCSI with an auto transformer.

And to optimize the effectiveness of the harmonic reduction, the optimum turn ratio and the tap changing control angle of auto transformer are decided by digital simulation and its validity is verified by experiment.

Although the construction of the proposed inverter is very simple, it is clarified that the output waveform of the inverter is almost the same as that of the conventional 24 step multiple inverter under the optimum condition.

2. Multiple inverter

Fig. 1(a) shows the proposed circuit construction in this paper, which is applied to the double connected 12 step MCSI.

The proposed inverter operates as like a 24 step MCSI by the tap changing auxilily circuit consisting of auto transformer with three-taps distributed symmetrically for the midpoint and two static switching elements connected to the auto transformer.

We will discuss the theory of this system under the following assumptions.

- Both the main output transformers and the auto transformer are ideal. That is, the exciting currents and leakage inductance for these can be regarded as zero.
- Forward drops of static switching elements are negligible.
- Commutations are completed instantly.

2.1 Unit inverter

As shown in Fig. 2, the unit inverter used in the propoed system is a MCSI[3)].

The MCSI is developed from the conventional current source inverter by adding freewheeling diodes D_1'-D_6', smoothing capacitor C_0, and inductances

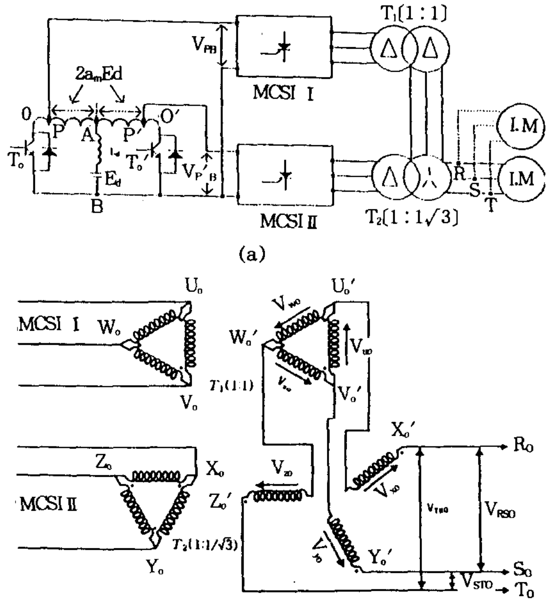


Fig. 1. Circuit construction of proposed inverter (a) and connection of its AC main output transformer (b)

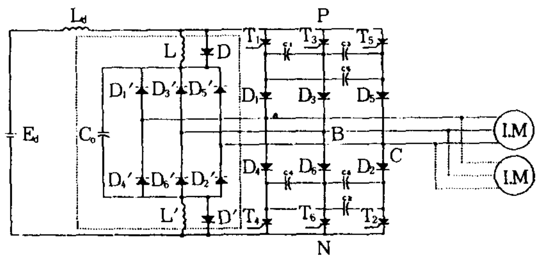


Fig. 2. Modified current source inverter

L and L′ to the current source inverter.

The function of the freewheeling diodes D_1'-D_6', and inductances L and L′ is to provide a path for reactive current of load. Diodes D and D′ can provide a freewheeling path for the current in L and L′ after commutation, which improved the output voltage waveform.

When freewheeling diodes are conducting in the MCSI, the output voltage is clamped to the smoothing capacitor voltage and when thyristors are conducting, the output voltage is equal to the dc input voltage. The smoothing capacitor voltage is equal to the DC input voltage. So the output voltage waveform is quasi-square similar to the voltage source inverter.

2.2 Double connected 12 step MCSI

If the auto transformer and two static switching elements are removed and input terminals P and P′ of MCSI Ⅰ, Ⅱ and terminal A of the DC input voltage in Fig. 1(a) are connected directly, then this system is changed to the double connected three-phase bridge inverter, that is, 12 step MCSI.

As shown in Fig. 1(a), output terminals of MCSI Ⅰ, Ⅱ are connected to primary windings[delta and delta connection] of the main output transformers [T_1,T_2], respectively. And secondary windings of these transformers are connected in series as shown in Fig. 1(b) and then connected to the loads of this inverter, such as induction motor.

The output voltage of MCSI Ⅰ differs from that of MCSI Ⅱ by 30°. So totally we can regard this inverter system as 12 step multiple inverter. And for balance of the output voltages of MCSI Ⅰ, Ⅱ let the turn ratios of the main output transformers T_1 and T_2 be 1 : 1[delta and delta connection] and 1 : $1/\sqrt{3}$[delta and open star connection], respectively.

First, in order to discriminate each voltage in the case of the double connected 12 step MCSI from that of the proposed inverter, let us add the subscript "0" to each voltage as like this $V_{RS} \rightarrow V_{RSO}$, $V_u \rightarrow V_{UO}$, $V_X \rightarrow V_{XO}$, $V_Y \rightarrow V_{YO}$, ⋯ etc.

Here, each thyristor of MCSI Ⅰ, Ⅱ is cnducted during 120° and the output voltage values of MCSI Ⅰ, Ⅱ are E_d and $E_d/\sqrt{3}$, respectively. And Fig. 3 (a)~(c) show the waveforms of V_{UO}, V_{XO}, V_{YO}.

From the connection of the main output transformer as shown Fig. 1(b), we have Eq. (1) easily.

$$V_{RSO} = V_{UO} + V_{XO} - V_{YO} \quad (1)$$

And from Eq. (1), the waveshape of V_{RSO} is constructed to 12 step as shown in Fig. 3(d). From this equation, the step values of V_{RSO}[1/4period] are follows :

Period	step value
$0° \leq \theta < \pi/6$	$V_{RSO} = E_d/\sqrt{3}$
$\pi/6 \leq \theta < \pi/3$	$V_{RSO} = (1+\sqrt{3})E_d/\sqrt{3})$
$\pi/3 \leq \theta \leq \pi/2$	$V_{RSO} = (2+\sqrt{3})E_d/\sqrt{3})$

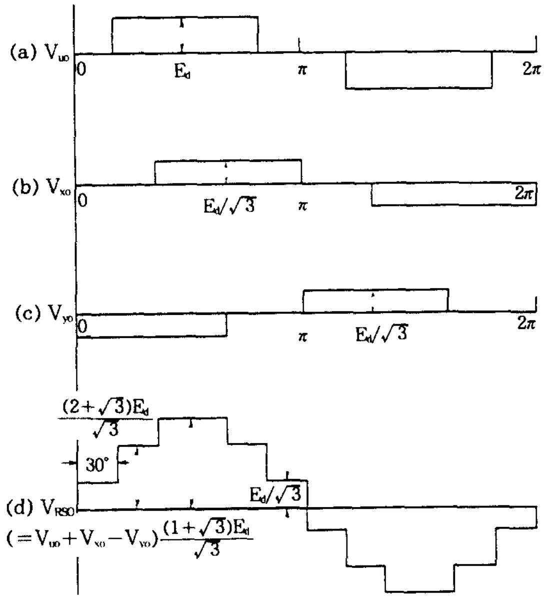


Fig. 3. Graphical analysis of wave forms of outout voltage in double connected 12 step MCSI

3. The proposed inverter

The inverter apparatus shown in Fig. 1(a) operates as like a 24 step MCSI by the tap changing auxiliary circuit.

Now let the conducting states of static switching elements T_0 and T_0' be mode p and p'. As shown in Fig. 4(a), the order and the control angle of tap changing mode are essential to operate the tap changing auxiliary circuit effectively.

That is, in case $V_{PA}(=V_{AP}')>0$, the order of tap changing mode may be mode p→mode p' [let the control angle of tap changing mode p→p' be β], and $V_{PA}(=V_{AP}')<0$, mode p'→mode p[let the control angle of tap changing mode p'→p be $\beta+30°$]

For the input DC voltage, we obtain

$$V_{PB}=E_d+V_{PA},\ V_{P'B}=E_d-V_{AP'} \quad (2)$$

And from the turn ratio of the auto transformer and the tap changing mode, we obtain

$$\text{Mode p}\ :\ V_{PA}(=V_{AP}')=-2a_mE_d \quad (3)$$

$$\text{Mode p}'\ :\ V_{PA}(=V_{AP}')=\ 2a_mE_d$$

(where the turn ratio of the auto transformer $a_m =N_{PA}/N_{OO}'=N_{AP}'/N_{OO}'$)

The $V_{PA}(=V_{AP}')$ produced by the tap changing auxiliary circuit is the rectangular wave as shown in Fig. 4(b). This voltage plays an important role in reducing the harmonics involved in AC output voltages.

From Eq. (2) and (3), V_{PB} and $V_{P'B}$ can be represented as

$$\text{Mode p}\ :\ V_{PB}=(1-2a_m)E_d,\ V_{P'B}=(1+2a_m)E_d \quad (4)$$

$$\text{Mode p}'\ :\ V_{PB}=(1+2a_m)E_d,\ V_{P'B}=(1-2a_m)E_d \quad (5)$$

Let us substitute the subscript "m" for "o" to discriminate the $V_{PA}(=V_{PA}')$ from the output voltage of double connected 12 step MCSI, $V_{RSO}\rightarrow V_{RSm}$, $V_{uo}\rightarrow V_{um}$, $V_{xo}\rightarrow V_{xm}$, $V_{yo}\rightarrow V_{ym}$, … etc.

Then the waveshapes of these components are the part of the broken lines as shown in Fig. 4(c)−(e). And as shown in Fig. 4(f), the component of the output voltage v_{RSm} due to the performance of the tap changing auxiliary circuit can be obtained as follows.

$$V_{RSm}=V_{um}+V_{xm}-V_{ym} \quad (6)$$

From this equation the step values of V_{RSm}[1/4 period] are as follows :

Period	Step Value
$0°\leq\theta<\pi/12$	$V_{RSm}=-2a_mE_d/\sqrt{3}$
$\pi/12\leq\theta<\pi/6$	$V_{RSm}=\ 2a_mE_d/\sqrt{3}$
$\pi/6\leq\theta<\pi/4$	$V_{RSm}=-2(1-1\sqrt{3})a_mE_d$
$\pi/4\leq\theta<\pi/3$	$V_{RSm}=\ 2(1-1\sqrt{3})a_mE_d$
$\pi/3\leq\theta<5\pi/12$	$V_{RSm}=-2(2/\sqrt{3}-1)a_mE_d$
$5\pi/12\leq\theta\leq\pi/2$	$V_{RSm}=\ 2(2\sqrt{3}-1)a_mE_d$

Therefore, the output voltage V_{RS} in Fig. 1(a) can be obtained by adding Fig. 3(d) and Fig. 4(f) as shown in Fig. 4(g). That is,

$$V_{RS}=V_{RSO}+V_{RSm} \quad (7)$$

From Eq. (7) the step values of V_{RS}[1/4 period] are as follows :

Period	Step Value
$0°\leq\theta<\pi/12$	$V_{RS}=(1-2a_m)E_d/\sqrt{3}$
$\pi/12\leq\theta<\pi/6$	$V_{RS}=(1+2a_m)E_d/\sqrt{3}$
$\pi/6\leq\theta<\pi/4$	$V_{RS}=[(1+\sqrt{3})+2(1-\sqrt{3})a_m]E_d/\sqrt{3}$
$\pi/4\leq\theta<\pi/3$	$V_{RS}=[(1+\sqrt{3})-2(1-\sqrt{3})a_m]E_d/\sqrt{3}$
$\pi/3\leq\theta<5\pi/12$	$V_{RS}=[(2+\sqrt{3})-2(2-\sqrt{3})a_m]E_d/\sqrt{3}$
$5\pi/12\leq\theta\leq\pi/2$	$V_{RS}=[(2+\sqrt{3})+2(1-\sqrt{3})a_m]E_d/\sqrt{3}$

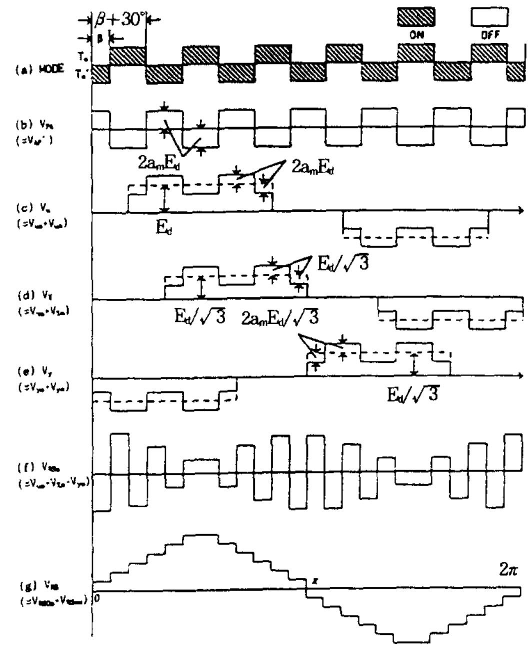


Fig. 4. Graphical analysis of waveforms of output voltage in 24 step MCSI

4. Simulation

As shown in Fig. 3(d), the output voltage V_{RSO} in the case without the tap changing auxiliary circuit is formed into 12 step a cycle. Therefore, from the Fourier analysis for the voltage, we obtained the following.

$$V_{RSO}=\frac{4\sqrt{3}E_d}{\pi}\left[\sin(\theta-\alpha)+\frac{1}{2}\sum_{k=1}^{\infty}\frac{1+(-1)^k}{6k\pm1}\sin(6k\pm1)(\theta-\alpha)\right] \quad (8)$$

(where, $k=1, 2, 3\cdots\cdots$)

And from Fig. 4(f), the Fourier analysis for the output voltage V_{RSm} due to the performance of the tap changing auxiliary circuit is as follows :

$$V_{RSm}=\frac{4\sqrt{3}E_d}{\pi}\left[\sqrt{A_1^2+B_1^2}\sin(\theta-\alpha+\phi1+\sum_{k=1}^{\infty}\frac{1}{12k\pm1}\sqrt{A^2_{12k\pm1}+B^2_{12k\pm1}}\sin(\theta-\alpha+\phi_{12k\pm1})\right] \quad (9)$$

where, $A_n=a_m c_n \cos n(5\pi/12+\beta)$

$B_n=a_m[c_n \sin n(5\pi/12+\beta)-2]$

$C_n=8\sin(n\pi/12)$

$\phi_n=\frac{1}{n}\tan^{-1}(A_n/B_n)$

$n=1$ or $12k\pm1(k=1, 2, 3\cdots)$

The output voltage V_{RS} in 24 step MCSI can be obtained by substituting Eq. (8) and Eq. (9) into Eq. (7)

Here, we are going to investigate the distortion factor μ of output voltage V_{RS} in the following equation :

$$\mu=\sqrt{\sum_{n(n>1)}^{\infty}V_{RSn}^2/V_{RS1}} \quad (10)$$

Where V_{RSn} and V_{RS1} are the effective values of the n-th harmonic component and the fundamental component in output voltage, respectively.

From Eq. (8), (9), (10), the distortion factor μ of V_{RS} becomes the function of Eq. (11).

$$\mu=\mu(a_m, \beta) \quad (11)$$

Then the optimum values of a_m and β for minimizing the distortion factor μ can be found from Eq. (11) by the aid of computer as shown in Fig. 5.

That is, the turn ratio of auto transformer $a_m=\sqrt{0.2456}$ and the control angle $\beta=15^\circ$ are the optimum values for minimizing μ in output voltage V_{RS}.

Moreover, it should be noted that $\mu=6.89(\%)$ under the above optimum conditions can be de-

Table 1. Harmonic components involved in output voltage

Harmonic order	Rate of harmonic components V_{RSn}/V_{RS1}[%]				
	Multiple inverter		Tap changing control		
n	12 step	24 step	$a_{m1}=0.1$, $\beta_1=8^\circ$	$a_{m1}=0.2456$, $\beta_1=8^\circ$	$a_{m1}=0.2456$, $\beta_1=15^\circ$
11	9.09	–	7.89	6.24	2.4×10^{-3}
13	7.69	–	5.00	1.30	2.06×10^{-3}
23	4.30	4.35	2.37	3.39×10^{-1}	4.35
25	4.00	4.00	2.37	1.20×10^{-1}	4.00
35	2.86	–	2.13	1.10	7.65×10^{-4}
37	2.70	–	2.57	2.40	7.24×10^{-4}
47	2.13	2.13	2.18	2.25	2.13
49	2.04	2.04	1.91	1.73	2.04
59	1.69	–	1.30	7.60×10^{-1}	4.54×10^{-4}
61	1.64	–	0.94	3.05×10^{-1}	4.39×10^{-4}
71	1.41	1.41	0.76	1.25×10^{-1}	1.41
73	1.37	1.37	0.91	2.96×10^{-1}	1.37
Distortion factor[%]	15.2	6.89	11.06	7.52	6.89

creased to about half as compared with μ=15.2(%) under double connected 12 step MCSI. Fig. 6 and Fig. 7 show waveform of output voltage and harmonic spectrum in case a_m=0.2456 and β=15°, respectedly.

And the harmonic components involved in the output voltage of the proposed inverter are nearly equal to those of the conventional 24 step multiple inverter as shown Table 1.

5. Experimental results

By adopting the results of the above optimum condition in the proposed apparatus, we have ob-

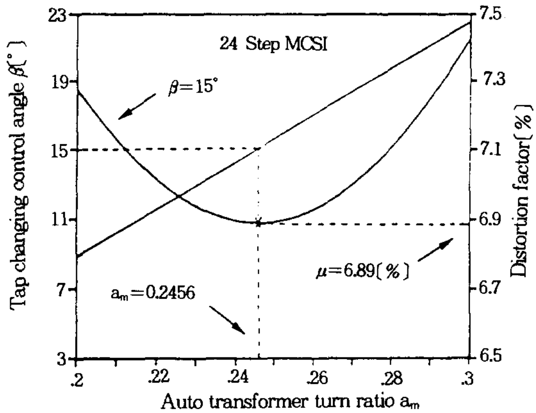
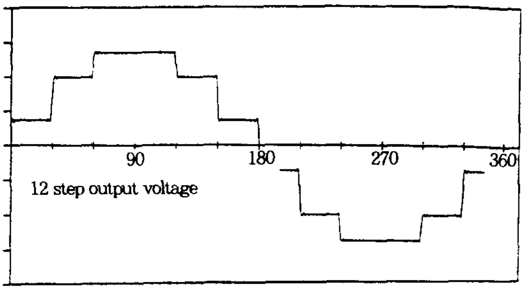
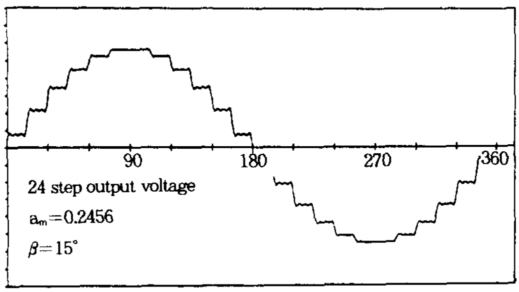


Fig. 5. Distortion factor curve versus turn ratio and tap changing control angle

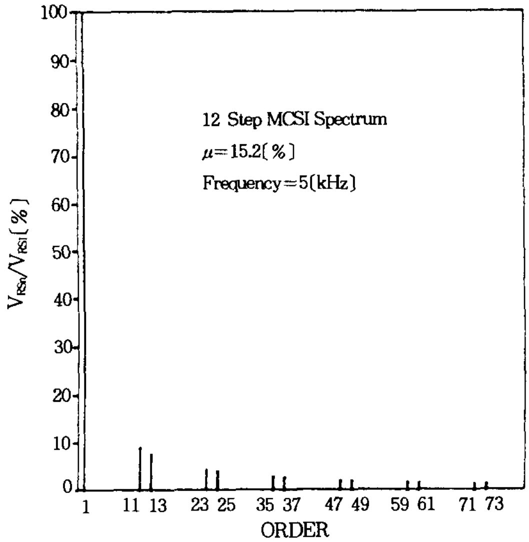


(a) Waveform of 12 step output voltage

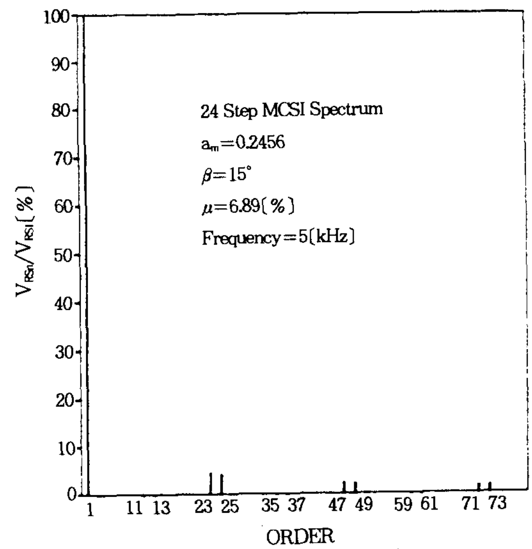


(b) Waveform of 24 step output voltage

Fig. 6. Waveform of output voltage in case a_m=0.2456, β=15°



(a) Harmonic spectrum of 12 step inverter



(b) Harmonic spectrum of 24 step inverter

Fig. 7. Harmonic spectrum in case a_m=0.2456, β=15°

tained the experimental results as shown in Fig. 8~11.

The parameters of motor and circuit used in the experiment are as follows :

- Rated power : 1〔HP〕
- Rated voltage : 150〔V〕
- Main transformer : 3〔kVA〕
- Rated speed : 1,710〔rpm〕
- Rated current : 4.2〔A〕
- Commutating capacitor : 9〔μF〕

Fig. 8(a) and Fig. 8(b) show the oscillograms of the output voltages of 12 and 24 step MCSI for the condition of two induction motors operating in parallel. From which it can be seen that the output voltage of 24 step MCSI is more closer to sinusoidal wave than that of the 12 step MCSI without the tap changing auxiliary circuit. Fig. 9 shows the base driving signal of the switching elements T_0 and T_0' in the tap changing auxiliary circuit. Fig. 10 shows the waveform of commutation capacitor voltage in 24 step MCSI. Fig. 11 shows the auto transformer voltage V_{PA} by the performance of the tap changing

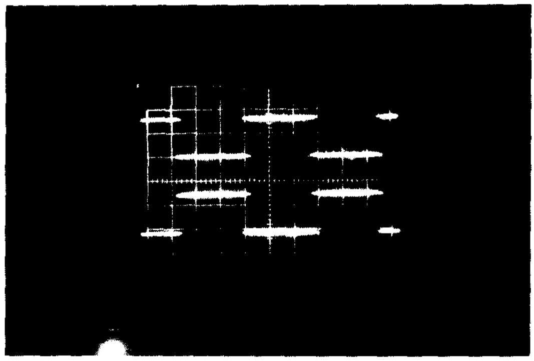
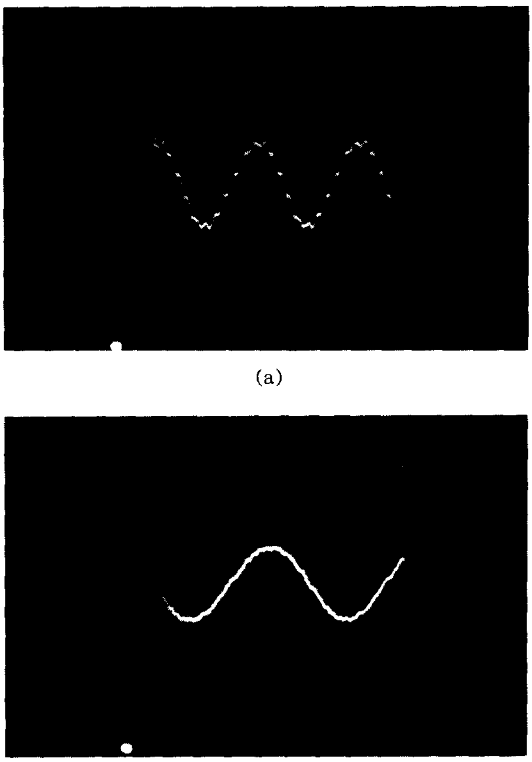


Fig. 9. The base driving signal of To and to′



(a)

(b)

Fig. 8. Waveform of the output voltages of 12 and 24 step MCSI〔50V/div〕

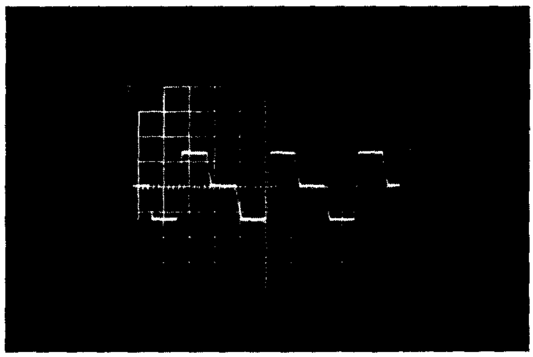


Fig. 10. Waveform of commutating capacitor voltage〔100V/div〕

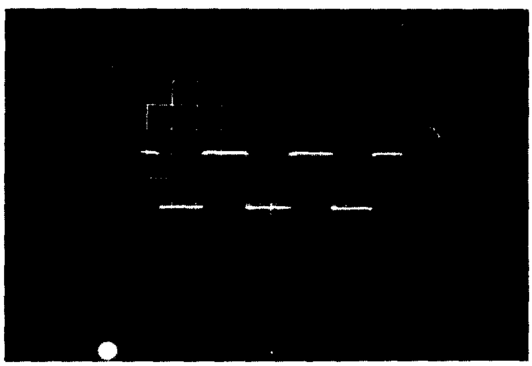


Fig. 11. The voltage waveform of auto transformer V_{PA}〔50V/div〕

auxiliary circuit.

6. Conclusion

An effective method for reducing the harmonics in double connected MCSI by switching taps on auto transformer is presented in this paper.

The basic theories of the proposed inverter are explained by the graphical analysis, and the optimum parameters of this circuit are searched. And the distortion factor of the proposed inverter under the optimum values $a_m=0.2456$, $\beta=15^\circ$, is $\mu=6.89(\%)$, this value can be decreased to about half compared with $\mu=15.2(\%)$, the distortion factor of double connected 12 step MCSI.

And it has been clarified that the distortion factor of the proposed inverter under the optimum parameters is nearly eual to that of the conventional 24 step multiple inverter.

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