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Analysis of 12 Pulse Phase Control AC/DC Converter

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Abstract - In this paper, the unbalanced current in the 12-pulse phase control AC/DC converters was studied. The 12-pulse Δ-Y type AC/DC converter will keep a balanced voltage with 30° phase shifted at the low coupling coefficient condition. But an unbalanced current will be obtained in the 12-pulse autotransformer phase shift AC/DC converter at the low coupling coefficient condition. The theoretical phasor analysis of the unbalanced current was presented and a feedback controller was designed to overcome this problem. Finally, a 3 kW 12-pulse autotransformer phase shifted AC/DC converter was implemented to demonstrate the theoretical analysis.

Keywords : 12 Pulse AC/DC Converter, Phase Controller, Autotransformer

I. INTRODUCTION

In recent years, the harmonics in the power system are serious due to the widely applications of the electronic equipments in which the AC/DC converter are usually used. Therefore, it is an important topic to reduce harmonic components in the AC/DC converter. The harmonic problems can be solved by using the active filters which are usually operated at high switching frequency and are not suitable for high power applications. The power factor and harmonic components of the utility input line current can be improved by the poly-pulse AC/DC converter. Choi[1] proposed an autotransformer-connected 12-pulse AC/DC converter to obtain high power factor and low harmonic distortion. The required capacity of the power transformer can be reduced by about 80 percent in the autotransformer-connected 12-pulse AC/DC converter in comparison with the Δ-Y connected AC/DC converter. However, an unbalanced current might be obtained at the 12-pulse autotransformer connected AC/DC converter due to the unsymmetrical phase shifted. In this paper, the phasor analysis method is used to verify the unsymmetrical phase shift in the autotransformer connected 12-pulse AC/DC converter. Also, a balanced current can be obtained by using the thyristors controlled rectifiers with a feedback controller. The computer simulations and experimental results are performed to verify the theoretical analysis.

II. 12-PULSE AC/DC CONVERTER

The conventional 12-pulse AC/DC converters are shown in Fig.1a and Fig.1b. The power factor and harmonic components of the utility input line current can be improved by shifting the input voltages 30° in the Δ-Y connected AC/DC converter as well as in the autotransformer phase-shifted AC/DC converter. But the output voltages of these AC/DC converters are not controllable. The output voltage of the 12-pulse AC/DC converter can be controlled by using the thyristors instead of diodes. The 12-pulse phase control AC/DC converters with Δ-Y isolated transformer and autotransformer connected are shown in Fig. 2 and Fig. 3, respectively. Fig. 4 and Fig. 5 show the equivalent circuit and the per phase voltage phasor diagram of the Δ-Y isolated transformer AC/DC converter. Fig. 5 illustrates that the voltage V_2 lags V_1 in the inductive load condition when the coupling coefficient is less than unity. The voltages v'_{R1} and v'_{R2} have the same amplitude and the phase angle between v'_{R1} and v'_{R2} is kept at a balanced 30° . Fig.6 shows the IsSpice simulation waveforms of v_{R1}, v'_{R1}, v_{R2} and v'_{R2} in the Δ-Y AC/DC converter with inductive load. A balanced current can be obtained when the thyristors are triggered with any firing angles. A simplified per phase circuit and equivalent circuit of autotransformer connected AC/DC converter are shown in Fig.7 and Fig.8, respectively.

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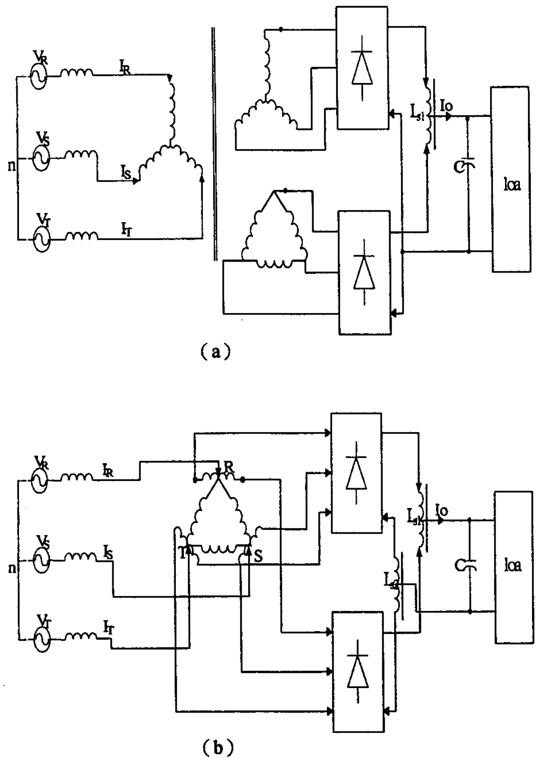


Fig. 1. Conventional 12-pulse AC/DC converter.
(a) Δ-Y isolated transformer.
(b) Autotransformer phase shifted.

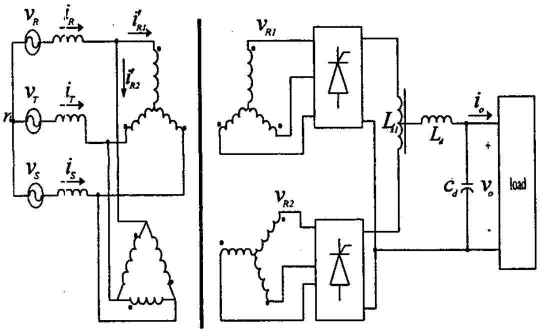


Fig. 2. 12-pulse phase control Δ-Y connected AC/DC converter.

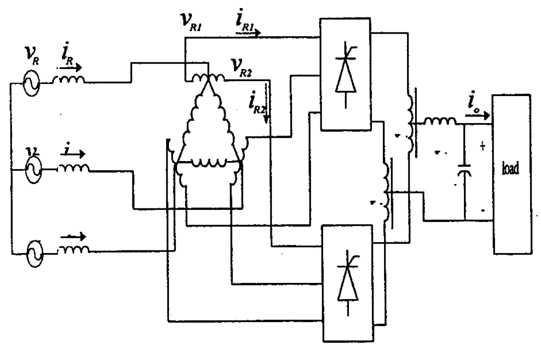


Fig. 3. 12-pulse phase control autotransformer connected AC/DC converter.

From Fig. 7, the following equations can be derived

$$v_{ST} = L_1\frac{di_S}{dt} - M_1\frac{di_{R2}}{dt} + M_2\frac{di_{R1}}{dt} \quad (1)$$

$$E_A = M_1\frac{di_S}{dt} - L_2\frac{di_{R2}}{dt} + M_3\frac{di_{R1}}{dt} \quad (2)$$

$$E_B = M_2\frac{di_S}{dt} - M_3\frac{di_{R2}}{dt} + L_3\frac{di_{R1}}{dt} \quad (3)$$

where L_1, L_2 and L_3 are self-inductance
M_1, M_2 and M_3 are mutual-inductance

From Fig. 8, the following equations can be derived

$$v_{ST} = (L_a + L_b)\frac{di_S}{dt} - \frac{L_b}{a}\frac{di_{R2}}{dt} + \frac{L_b}{a}\frac{di_{R1}}{dt} \quad (4)$$

$$E_A = \frac{L_b}{a}\frac{di_S}{dt} - (\frac{L_b}{a^2} + L_c)\frac{di_{R2}}{dt} + \frac{L_b}{a^2}\frac{di_{R1}}{dt} \quad (5)$$

$$E_B = \frac{L_b}{a}\frac{di_S}{dt} - \frac{L_b}{a^2}\frac{di_{R2}}{dt} + (\frac{L_b}{a^2} + L_d)\frac{di_{R1}}{dt} \quad (6)$$

By assuming $L_2 = L_3$, $M_1 = M_2$, the inductance L_b, L_b, L_c and L_d can be expressed as

$$L_a = (1-K)L_1 \quad (7)$$

$$L_b = KL_1 \quad (8)$$

$$L_c = L_d = (1-K)L_2 \quad (9)$$

and

$$E_A = \frac{1}{a}(v_{ST} - i_S j\omega L_a) - i_{R2} j\omega L_c \quad (10)$$

$$E_B = \frac{1}{a}(v_{ST} - i_S j\omega L_a) + i_{R1} j\omega L_c \quad (11)$$

$$v'_{R1} = v_R - E_B = v_{R1} + j\omega L_c(ai_S - i_{R1}) \quad (12)$$

$$v'_{R2} = v_R + E_A = v_{R2} - j\omega L_c(ai_S + i_{R2}) \quad (13)$$

By ignoring the excitation current i_e, Equation (12) and (13) become

$$v'_{R1} = v_{R1} + j\omega L_c(i_{R2} - 2i_{R1}) \quad (14)$$

$$v'_{R2} = v_{R2} - j\omega L_c(2i_{R2} - i_{R1}) \quad (15)$$

From (14) and (15), the phasor diagram analysis can be used to compute the autotransformer connected output voltage v'_{R1} and v'_{R2}. Fig. 9a and Fig. 9b show the phasor diagrams of v'_{R1} and v'_{R2} with inductive load and resistive load. Due to the effect of the leakage inductance of the autotransformer, the practical voltage v'_{R1} will lag the ideal output voltage v_{R1}. However, the practical output voltage v'_{R2} will lead the ideal voltage v_{R2}. Thus, the voltage amplitudes of v'_{R1} and v'_{R2} are not equal and the phase shift between v'_{R1} and v'_{R2} cannot be kept at 30°. The output voltages, v'_{R1} and v'_{R2}, in the autotransformer connected AC/DC converter with inductive load and resistive load are shown in Fig. 10a and Fig. 10b, respectively. They also depict the unequal amplitudes and unbalanced phase shifted between v'_{R1} and v'_{R2}. This phenomenon will cause unequal conducting time in each paralleled 6-pulse AC/DC converter at the same firing angle conditions. The output current of v'_{R1} will be increased and the output current of v'_{R2} will be decreased so that the interphase reactor might be saturated with the unbalanced dc current. The unbalance current will become more serious at the low coupling coefficient or large firing angle conditions.

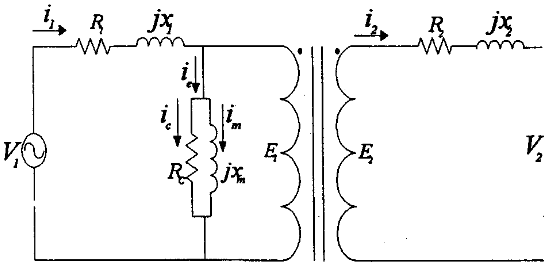


Fig. 4 Equivalent circuit diagram of Δ-Y transformer AC/DC converter.

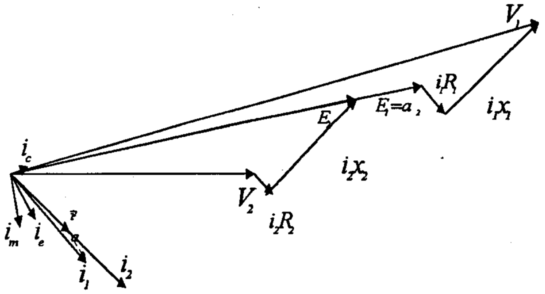


Fig. 5 Phasor diagram of Δ-Y transformer AC/DC converter with inductive load

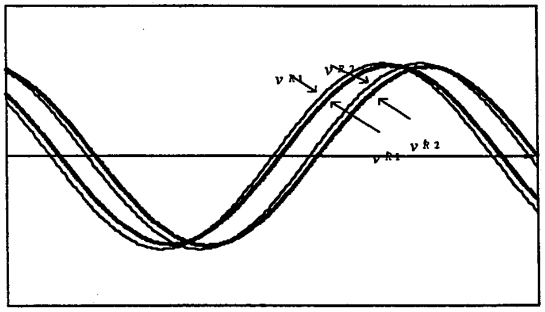


Fig. 6 Computer simulation of v_{R1}, v'_{R1}, v_{R2} and v'_{R2} in Δ-Y transformer AC/DC converter with inductive load

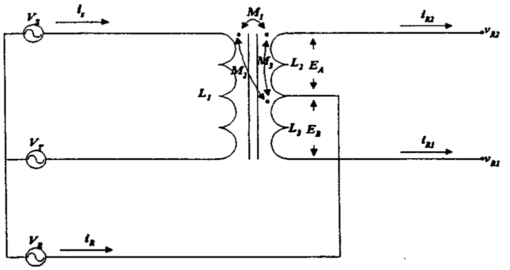


Fig. 7 Simplified per-phase circuit of the autotransformer connected AC/DC converter.

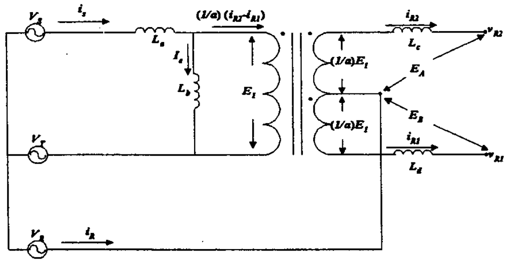
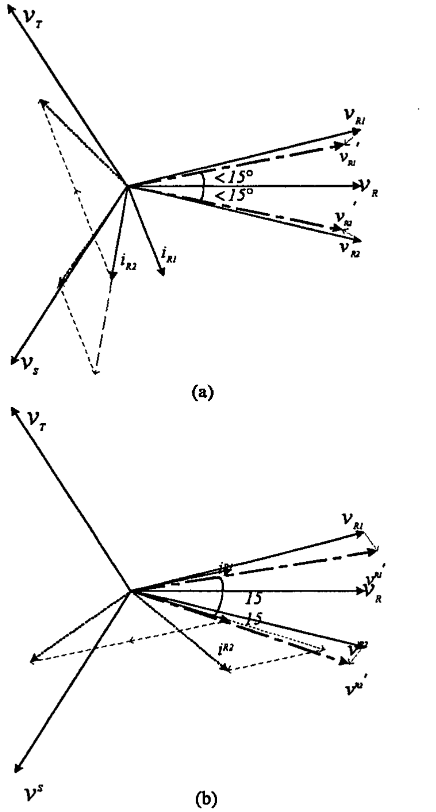


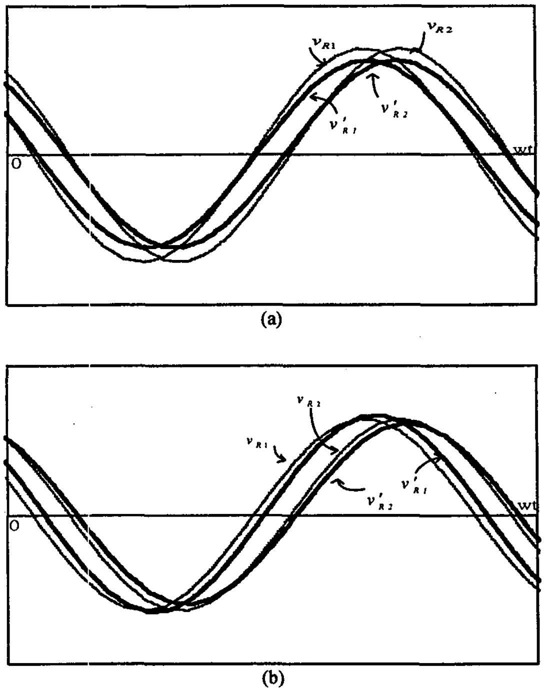
Fig. 8 Equivalent circuit of autotransformer connected AC/DC converter.



(a)

(b)

Fig. 9 Phasor diagram of autotransformer connected AC/DC converter with (a) inductive load. (b) resistive load.



(a)

(b)

Fig. 10 Autotransformer connected AC/DC converter output voltage v_{R1}, v'_{R1}, v_{R2} and v'_{R2} (a)inductive load (b)resistive load

III. SIMULATION RESULTS

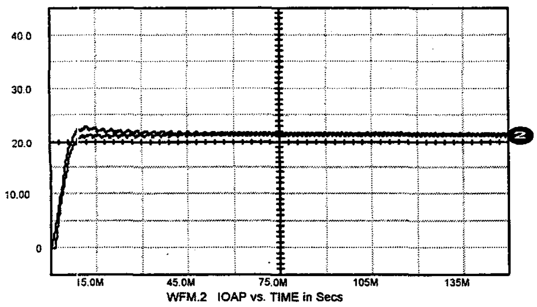


Fig. 11 The output current i_{o1} and i_{o2} of 12-pulse phase control Δ-Y type transformer AC/DC converter with K=0.96 and $\alpha = 30^\circ$

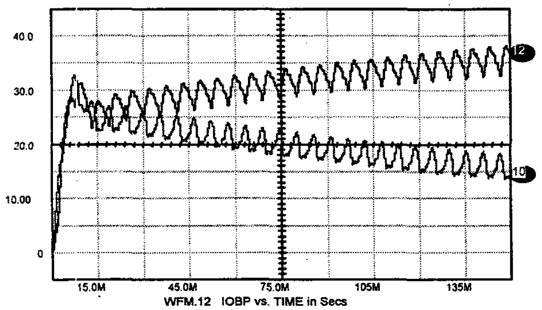


Fig. 12 The output current i_{o1} and i_{o2} of 12-pulse autotransformer phase shift AC/DC converter with K=0.96 and $\alpha = 30^\circ$.

Fig. 11 (a) and (b) show the output voltages and currents of two six-pulse converters in the isolated transformer Δ-Y phase control AC/DC converter. They depict the balanced current in each six-pulse converter. The output voltages and currents of each six-pulse converter in the 12-pulse autotransformer connected AC/DC converter are shown in Fig. 12 (a) and (b). Fig. 12 (a) depicts that a severe problem will occur during thyristor commutation interals. Also, the current supplied by each six-pulse converter has a serious unbalanced problem. The unbalanced circulating current problem can be overcome by using a feedback controller[7] to adjust the firing angle in of each 6-pulse AC/DC converter. The block diagram of the feedback controller is shown in Fig. 13. A balanced output current of each 6-pulse AC/DC converter can be obtained and is shown in Fig. 14. Finally, a 3 kW 12-pulse autotransformer connected AC/DC converter is implemented with feedback controller in the laboratory. Fig. 15 shows the output currents of two 6-pulse AC/DC converters. It illustrates that a severe unbalanced current between the two AC/DC converters outputs. The output currents of two 6-pulse AC/DC converter with feedback controller is shown in Fig.16. It depicts a balanced output currents are provided by two 6-pulse AC/DC converter.

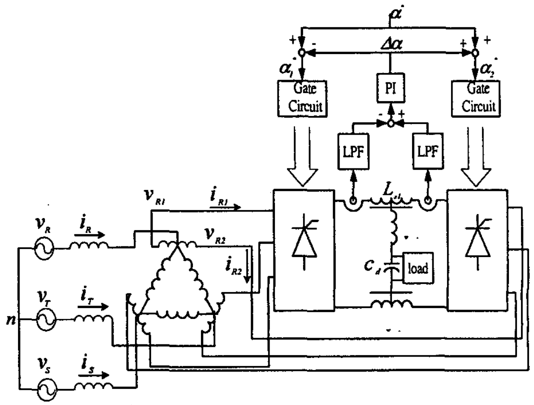


Fig. 13 Block diagram of controller

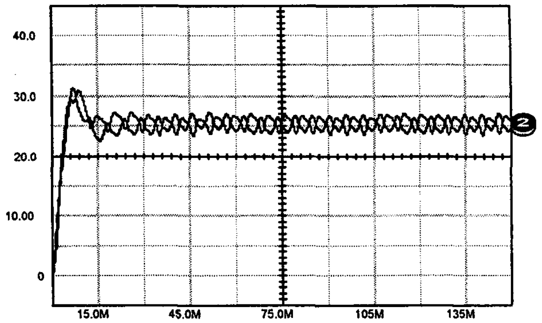


Fig. 14 The output current of 12-pulse autotransformer connected AC/DC converter with the controller

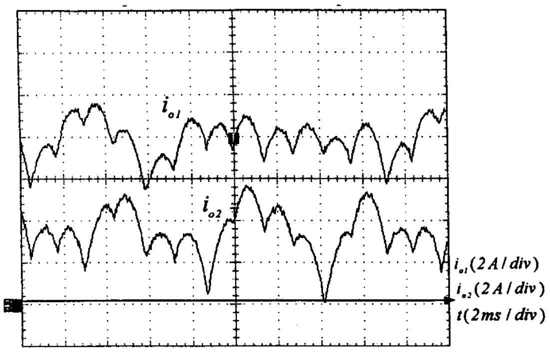


Fig. 15 Experimental results for a resistive load without controller.

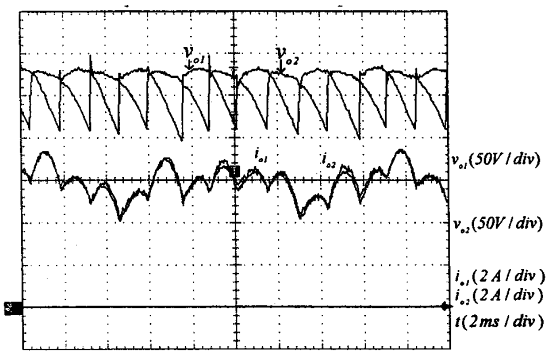


Fig. 16 Experimental results for a resistive load with controller

IV. CONCLUSIONS

In this paper, the 12-pulse phase control AC/DC converters with Δ-Y type and autotransformer type are analyzed and studied. The theoretical analysis is presented and the computer simulation results are performed. The 12-pulse Δ-Y type AC/DC converter can function well under any firing condition. However, a serious unbalanced circulation current exists in the autotransformer connected AC/DC converter at the non-unity coupling coefficient conditions. Finally, a 3 kW 12-pulse autotransformer phase controlled AC/DC converter was implemented to demonstrate the theoretical analysis.

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