Study on the Double Connection of Modified Bridge Rectifier with Power Factor Improvement

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Keywords: double converter, power factor, firing angle, harmonic, voltage-waveforms

The conventional phase-controlled bridge rectifier has some disadvantages, for instance, generation of harmonics and increasing reactive power when operated at high firing angles, as a result, line power factor is lower. On the contrary, the modified bridge rectifier is successfully applied to industrial plants because it offers the advantages of high-power factor and reduced reactive power. In order to satisfy the application on high power load, this paper introduced a double connection scheme of the modified bridge rectifier with power-factor improvement.

The modified double connection converter, as shown in Fig. 1, is composed of a vectiformer RTM and two rectifiers with three-phase four-wire bridge. Among them, the rectifier is to provide two groups AC power source with 15° phase-difference; these two modified rectifiers may be connected by series or parallel for the application on high-voltage or larger-current load. This double converter adopted the Equidistant-Firing-Control for thyristors, i.e., main thyristors are triggered at 60° intervals each other, moreover, these thyristors on the neutral wire are conducted to delay 30° than corresponding main thyristor, respectively. The operation of the double converter is divided into two modes of the rectifying and the inverting, according to the different positions of firing angle α , that is, the area I of $0^\circ \leq \alpha \leq 105^\circ$ is the rectification mode, the area II of $105^\circ < \alpha \leq 180^\circ$ is the inversion mode. When main thyristor is triggered to conduct, the load terminal voltage is the corresponding line voltage. After line voltage is smaller than phase voltage, the load terminal voltage is transferred to the phase voltage, once the thyristor on the neutral wire is triggered. Thereby, the load terminal voltage is a twenty-four-pulse of DC voltage each cycle. Since the rectify pulse number increased in the double converter, that dc voltage distortion is lower. In the inverting mode, the inverting angle must be limited, in order to ensure the safety commutation. Naturally, because the thyristor of neutral wire switched on, the ac current is transferred to neutral wire. Therefore, the commutation overlap of the double converter is not happen so long as the overlap angle γ is smaller than $\pi/6$. This is an advantage of the double converter.

This double converter offers these advantages of higher power factor, lower dc voltage distortion, reduced apparent power when compared with the conventional twelve-pulse converter. Although $(6n \pm 1)$ order ac line current harmonics generated on ac side, but the magnitudes are lower than with the conventional converter. The theoretical analyses, mathematical models and the experimental data proved that performance of the modified double converter is superior to the conventional double converter.

Fig.1. Double connection of the modified bridge converter

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A double converter of modified three-phase bridge full-controlled rectifier with improved power factor is presented and analyzed for its commutation processes and operating condition. Both the mathematical model and the minimum inverting angle for safety commutation are derived. A comparison is carried on with the conventional twelve-pulse bridge. The waveforms and data tested from the experimental converter agree with the theoretical analysis.

Keywords: double converter, power factor, firing angle, harmonic, waveform

1. Introduction

At present, full-controlled power electron element, e.g. GTR, IGBT and MOSFET, etc. have although already found wide application in converter unit, but thyristor is still used in high-power equipment such as electric-drive, electrolysis, electroplating and power transfer, because of its high-capacity, high-reliability and easily control. However, main disadvantages of the thyristor phase-controlled rectifier are the generation of harmonics and increasing reactive power when the firing angle is augmented, as a result, power factor is lower.

For this purpose, Stefanovic presented the modified bridge converter with power factor improvement⁽¹⁾, this three-phase four-wire bridge rectifier was successfully applied to controllable rectify equipment⁽²⁾. The operated result indicates that the power factor in the modified bridge rectifier is above the conventional bridge rectifier, while the reactive power is reduced.

In order to satisfy the requirement of the case on high power applications, it is necessary to probe into the double connection of the modified bridge rectifier presented in Ref. (1). Therefore, this paper introduced a double converter of this modified bridge rectifier. It will be demonstrated that the double converter is superior to the conventional twelve pulse bridge converter in the power factor through the theoretical analyses, mathematical models and experimental data, while the reactive power and the rms input current are much less than the latter.

Fig. 1 shows the double converter of the modified bridge rectifier discussed in this paper. As shown in Fig. 1, the double converter is composed of a rectifier RTM, modified rectifier RB₁ and RB₂, and a load. Among them, both rectifier RB₁ and RB₂ are all the three-phase four-wire bridge. This double converter can be classified to the series or the parallel connection converter, according to whether these two

Fig. 1. Double connection of the modified bridge converter

rectifiers are connected by series or the parallel. The former type is used in the high-voltage load as Fig. 1(a), but the latter type is used in the large-current load as shown in Fig. 1(b). Of course, the parallel connecting double converter will require a reactor BR so as to balance DC voltage between the two rectifiers. In this paper, the double converter is presented and discussed by the series connection type for example.

2. Rectifier

In this double converter, the function of the rectifier is to provide input power source with twelve-phase for every rectifier respectively, moreover, the input voltage V_A should be led the V_B by 15° . Based on the above demands, a transformer with three-phase four-windings is adopted, its structure is shown in Fig. 2(a). The primary three-phase windings may be connected to Y or Delta connection. The secondary windings may be divided into two groups. Among them, both M_{A1} and M_{A2} windings should be connected to

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Fig. 2. Construction of rectifier

the zigzag-star-connection with neutral point, ac voltage V_A supplies for the rectifier RB_1 , while M_B winding must be connected in Star-connection with neutral point, the ac voltage provides for the rectifier RB_2 . The voltages vectogram of the secondary windings is shown in Fig. 2(b), M_{A1} winding should be equal to $0.82M_B$ winding; M_{A2} should be equal to $0.3M_B$. The above relationships may be found by the Sine-law, for example, the voltage relationships on the V_{21} phase, as follows

$$V_{X1} = \frac{\sin 45^\circ}{\sin 120^\circ} V_B = 0.82V_B, \quad V_{Z2} = \frac{\sin 15^\circ}{\sin 120^\circ} V_B = 0.3V_B$$

3. Operating Analysis of the Rectifying Mode

The operating process of the double converter is divided into the two modes of the rectifying and the inverting. This section analyses an operating process in the rectifying mode. In order to simplify the analysis process, here will be assumed specially as follows:

- (1) The input ac power source waveforms are sinusoidal.
- (2) The dc load current is steady, load inductance is infinitely great, and ac power source impedance is approximately zero.
- (3) Both the "ON-OFF" times and the "ON" status drop of voltage in thyristor are neglected.
- (4) The commutation inductance is neglected.

Here, the equidistant-firing-control for thyristor in this double converter is adopted to simplify the control algorithm. The firing pulse scheme is shown as Fig. 4.

When the firing angle α changed between $0^\circ \sim 105^\circ$, this double converter is situated in the rectification mode. According to the different positions of the firing angle α , the rectification mode is also divided into two areas, e.g. the area I of $0^\circ \leq \alpha \leq 30^\circ$ and the area II of $30^\circ < \alpha \leq 105^\circ$. Since the commutation process and mathematical models are different, the operating process of the two areas should be analyzed respectively.

3.1 Operation of Reactification in Area I In this area, because the input line voltages are always larger than the phase voltages, these thyristors of the neutral-point do not conduct. At this moment, the operating condition on the double converter is similar to the conventional twelve-pulse bridge. In Fig. 3 both RB_1 rectifier's T_{11} , T_{16} and RB_2 rectifier's T_{25} , T_{26} are triggered to conduct at ωt_1 when $\alpha = 30^\circ$, the input ac voltage V_{UV1} and V_{WV2} loaded to the load through both rectifiers RB_1 and RB_2 , separately. Thus,

Fig. 3. DC terminal voltage and line current when $\alpha = 30^\circ$

the dc voltage V_{dI} on the load is $V_{dI} = V_{UV1} + V_{WV2}$. At ωt_2 , these T_{21} and T_{26} on RB_2 are triggered to conduct; the output voltage of RB_2 is transferred from V_{WV2} to V_{UV2} . Thus, the load voltage becomes $V_{dI} = V_{UV1} + V_{UV2}$. At ωt_3 , T_{18} of RB_1 is triggered, but no conducting, because of $V_{UV1} > V_{U1}$. Thus, both T_{11} and T_{16} on RB_1 will be continued to conduct, the load voltage is still $V_{UV1} + V_{UV2}$. Until ωt_5 , T_{12} of RB_1 is triggered to conduct, T_{16} turned off. Thus, the load terminal voltage is changed to $V_{dI} = V_{UW1} + V_{UV2}$. Therefore, in this area, the load voltage V_{dI} is a dc voltage with twelve-pulse at a cycle. Thus, the dc average voltage on the load can be calculated by one-sixth cycle.

If using $V_{U1} = \frac{\sqrt{2}}{\sqrt{3}} V_{2l} \sin \omega t$ for a reference, then

$$\begin{aligned} V_{UV1} &= \sqrt{2} V_{2l} \sin \left(\omega t + \frac{\pi}{6} \right) \\ V_{UV2} &= \sqrt{2} V_{2l} \sin \left(\omega t + \frac{\pi}{12} \right) \\ V_{WV2} &= \sqrt{2} V_{2l} \sin \left(\omega t + \frac{5\pi}{12} \right) \end{aligned}$$

Therefore, the dc average voltage on the load in the area I is given by

$$\begin{aligned} V_{dI} &= \frac{3\sqrt{2}V_{2l}}{\pi} \left\{ \int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{4}+\alpha} \left[\sin \left(\omega t + \frac{\pi}{6} \right) + \sin \left(\omega t + \frac{5\pi}{12} \right) \right] d\omega t \right. \\ &\quad \left. + \int_{\frac{\pi}{4}+\alpha}^{\frac{\pi}{2}+\alpha} \left[\sin \left(\omega t + \frac{\pi}{6} \right) + \sin \left(\omega t + \frac{\pi}{12} \right) \right] d\omega t \right\} \\ &= \frac{6\sqrt{2}V_{2l}}{\pi} \cos \alpha(V) \dots \dots \dots (1) \end{aligned}$$

The rms input current is

$$\begin{aligned} I_{UI} &= \left\{ \frac{1}{\pi} \left[\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{4}+\alpha} \left(\frac{2}{\sqrt{3}} I_d \right)^2 d\omega t + \int_{\frac{\pi}{4}+\alpha}^{\frac{\pi}{2}+\alpha} \left(\frac{3}{\sqrt{3}} I_d \right)^2 d\omega t \right. \right. \\ &\quad \left. \left. + \int_{\frac{7}{12}\pi+\alpha}^{\frac{5}{6}\pi+\alpha} \left(\frac{4}{\sqrt{3}} I_d \right)^2 d\omega t + \int_{\frac{5}{6}\pi+\alpha}^{\frac{11}{12}\pi+\alpha} \left(\frac{3}{\sqrt{3}} I_d \right)^2 d\omega t \right. \right. \\ &\quad \left. \left. + \int_{\frac{11}{12}\pi+\alpha}^{\frac{3}{2}\pi+\alpha} \left(\frac{2}{\sqrt{3}} I_d \right)^2 d\omega t \right] \right\}^{\frac{1}{2}} \\ &= 2I_d \sqrt{\frac{5}{8}}(A) \dots \dots \dots (2) \end{aligned}$$

where, I_d is the dc average current on the load.

Thus, gives the total input power factor

$$PF_I = \frac{V_{dI} I_d}{\sqrt{3} V_{2l} I_{UI}} = 0.986 \cos \alpha \dots \dots \dots (3)$$

It is known in the above analysis that, during the area I, both operating condition and mathematical model of the double converter are the same as a conventional twelve-pulse bridge. The conduction period of the thyristor is $2\pi/3$.

3.2 Operation of Rectification in Area II When α is larger than 30° , whenever the line voltage is smaller than the phase voltage, the neutral points thyristors on both RB₁ and RB₂ should be conduct, once its gate is loaded with a firing pulse. Thus, the dc voltage on the load is imported from line voltage to corresponding phase voltage, and the thyristor on the main bridge is beforehand switched off. For example, consider the operation along the load voltage waveform v_{dII} , in Fig. 4. Suppose ωt_1 moment, these T₁₁, T₁₆ and T₂₇, T₂₆ conduct, respectively, the load voltage is $V_{dII} = V_{UV1} + V_{-U2}$. At ωt_2 partitioned off 15° , T₂₁ is fired to conduct. Because of $V_{UV2} > V_{-U2}$ now, T₂₇ is commutated to T₂₁, T₂₇ is turned off. Thus, the load voltage becomes $V_{dII} = V_{UV1} + V_{UV2}$. At ωt_3 apart from ωt_1 with 30° , RB₁ rectifier's T₁₈ is triggered. Because of $V_{U1} > V_{UV1}$, T₁₆ is commutated to T₁₈, T₁₆ is beforehand switched off. Thus, the load voltage becomes $V_{dII} = V_{U1} + V_{UV2}$. To ωt_4 moment, T₂₆ is commutated to T₂₈, the load voltage becomes $V_{dII} = V_{U1} + V_{U2}$. Therefore, in this area, the load voltage V_{dII} is a twenty-four-pulse of the dc voltage each cycle; the conduction period of the main bridge thyristor is $\pi/2$.

Fig. 5 show the waveforms of both load voltage V_d and input ac current i_u , when $\alpha = 90^\circ$. The dc average voltage of the load is calculated as below.

If using $V_{U1} = \frac{\sqrt{2}}{\sqrt{3}} V_{2l} \sin \omega t$ for a reference again, see the Fig. 4, each synthetic voltage is expressed as follows respectively.

$$\begin{aligned} V_1 &= (V_{UV1} + V_{-V2}), & V_2 &= (V_{UV1} + V_{UV2}), \\ V_3 &= (V_{U1} + V_{UV2}), & V_4 &= (V_{U1} + V_{U2}). \end{aligned}$$

Therefore, the dc average voltage in area II is given by

$$\begin{aligned} V_{dII} &= \frac{3\sqrt{2}V_{2l}}{\pi} \left(\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{4}+\alpha} V_1 d\omega t + \int_{\frac{\pi}{4}+\alpha}^{\frac{\pi}{3}+\alpha} V_2 d\omega t \right. \\ &\quad \left. + \int_{\frac{\pi}{3}+\alpha}^{\frac{5}{12}\pi+\alpha} V_3 d\omega t + \int_{\frac{5}{12}\pi+\alpha}^{\frac{\pi}{2}+\alpha} V_4 d\omega t \right) \\ &= \frac{3\sqrt{2}V_{2l}}{\pi} \left(1 + \frac{1}{\sqrt{3}} \right) \cos(\alpha - 15^\circ)(V) \dots \dots \dots (4) \end{aligned}$$

The corresponding rms value of input current I_{UII} is

$$\begin{aligned} I_{UII} &= \left\{ \frac{1}{\pi} \left[2 \int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{4}+\alpha} \left(\frac{I_d}{\sqrt{3}} \right)^2 d\omega t + 2 \int_{\frac{\pi}{4}+\alpha}^{\frac{\pi}{3}+\alpha} \left(\frac{2}{\sqrt{3}} I_d \right)^2 d\omega t \right. \right. \\ &\quad \left. \left. + 2 \int_{\frac{\pi}{3}+\alpha}^{\frac{5}{12}\pi+\alpha} \left(\frac{3}{\sqrt{3}} I_d \right)^2 d\omega t + 2 \int_{\frac{5}{12}\pi+\alpha}^{\frac{\pi}{2}+\alpha} \left(\frac{4}{\sqrt{3}} I_d \right)^2 d\omega t \right] \right\}^{\frac{1}{2}} \\ &= 2I_d \sqrt{\frac{5}{12}} (A) \dots \dots \dots (5) \end{aligned}$$

On the contrary, both dc average voltage and input current of the parallel connecting converter is, respectively, given by

Fig. 4. dc terminal voltage and ac line current, when $\alpha = 60^\circ$

Fig. 5. dc terminal voltage and ac line current when $\alpha = 90^\circ$

Fig. 6. Power factor and power relationship curves

$$\begin{aligned} V_{dII} &= \frac{3\sqrt{2}V_{2l}}{2\pi} \left[\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{4}+\alpha} V_1 d\omega t + \int_{\frac{\pi}{4}+\alpha}^{\frac{\pi}{3}+\alpha} V_2 d\omega t \right. \\ &\quad \left. + \int_{\frac{\pi}{3}+\alpha}^{\frac{5}{12}\pi+\alpha} V_3 d\omega t + \int_{\frac{5}{12}\pi+\alpha}^{\frac{\pi}{2}+\alpha} V_4 d\omega t \right]^{\frac{1}{2}} \\ &= \frac{3\sqrt{2}V_{2l}}{2\pi} \left(1 + \frac{1}{\sqrt{3}} \right) \cos(\alpha - 15^\circ)(V) \\ I_{UII} &= I_d \sqrt{\frac{5}{12}} (A) \end{aligned}$$

Therefore, the input power factor in area II is given by

$$PF_{II} = \frac{V_{dII} I_d}{\sqrt{3} V_{2l} I_{UII}} = 0.984 \cos(\alpha - 15^\circ) \dots \dots \dots (6)$$

Fig. 6(a) shows the curves of the dc voltage versus the power factor on both this double converter and the conventional twelve-pulse bridge, it is seen that power factor of the former is superior to the latter. C denotes conventional converter. M denotes modified converter in every figure.

Fig. 7. dc terminal voltage and ac line current when $\alpha = 120^\circ$

4. Operating Analysis of the Inversion Mode

Known from Eq. (4), when $\alpha = 105^\circ$, the dc terminal average voltage is equal to zero, similarly, when $\alpha > 105^\circ$, the double converter get into the inversion mode.

4.1 Operating Process Analysis Fig. 7 shows the waveforms of both the load terminal voltage $V_{d\beta}$ and input ac current i_u when $\alpha = 120^\circ$. Here, it is assumed that a dc source $E_{d\beta}$ is existed in the load side. Therefore, at ωt_1 , both RB₁ rectifier's T₁₁, T₁₆ and RB₂ rectifier's T₂₇, T₂₆ are all triggered to conduct, the load voltage becomes $V_{d\beta} = -(V_{UV1} + V_{V2})$. At ωt_2 , because of $|V_{V2}| < |V_{UV2}|$, T₂₁ is triggered to conduct, T₂₇ is switched off, the load voltage $V_{d\beta} = -(V_{UV1} + V_{UV2})$. At ωt_3 , because of $|V_{U1}| < |V_{U2}|$, T₁₆ is commutated to T₁₈, $V_{d\beta} = -(V_{U1} + V_{U2})$. Thus, the load terminal voltage $V_{d\beta}$ is a negative dc voltage with twenty-four-pulse within a cycle. The current I_d flows from the load side to the electric network side, so long as $|V_{d\beta}| < |E_{d\beta}|$, the inversion operation is realized.

In order to find the power factor of inverting area, suppose that β is a firing angle of inverting mode, and $\pi = \alpha + \beta$. Thus, inserting $\alpha = \pi - \beta$ into Eq. (4), gives the dc average voltage on the inversion area

$$V_{d\beta} = -2.2V_{2l} \cos(\beta + 15^\circ)(V) \dots \dots \dots (7)$$

The rms value of input current is the same as Eq. (5). Therefore, the power factor in the inversion area is

$$PF_\beta = \frac{V_{d\beta} I_d}{\sqrt{3} V_{2l} I_{U11}} = -0.984 \cos(\beta + 15^\circ) \dots \dots \dots (8)$$

The relationship of the input power factor with dc average voltage is shown as Fig. 6(a). Obviously, the absolute value of the power factor in inversion mode on the double converter is larger than the conventional twelve-pulse bridge.

4.2 Limitation of The Inversion Angle In the inversion area, the commutation process of thyristor is different with the rectification area, the phenomenon of the free-wheeling will easily happen, the reasons are:

1) Because four thyristors of the neutral point N₂₁ and N₂₂ are partitioned each other by 60° to conduct, these thyristors T₁₇ and T₁₈ or T₂₇ and T₂₈ will probably occur series conduction when commutation overlap angle $\gamma > 30^\circ$, thus, the dc side will be short-circuited, that is, $V_{d\beta} = 0$.

2) When $\alpha \geq 150^\circ$, these thyristors on both RB₁ and RB₂ may be unable normally to commutate at the commutation

point. For example, RB₁ rectifier's T₁₂ is triggered, T₁₈ will be commutated to T₁₂. But, because of $|V_{UW1}| > |V_{U1}|$, T₁₂ bores a reverse voltage, and does not conduct. Thus, both T₁₁ and T₁₈ will be continued to conduct, similarly, both T₂₁ and T₂₈ on the rectifier RB₂ will be continued to conduct too.

Once that T₁₇ and T₂₇ are triggered to conduct, four thyristors on the neutral point formed series conducting. Thus, the double converter entered into the state of the free-wheeling. The free-wheeling state is not suitable for AC/DC adjustable speed systems, it will cause the torque pulsing or the commutating failure. Therefore, the inversion angle must be also limited in this double converter.

Obviously, the inversion angle $\beta_{\min}$ has concerned with both the commutation overlap angle γ and the thyristor switching off time ε . Because those thyristors on the neutral point possibly appear direct connecting when $\alpha = 150^\circ$, thus, the γ and ε should be considered in the minimum inversion angle.

Suppose $\alpha_{\max} \leq 150^\circ - \gamma - \varepsilon$.

Inserting $\alpha = \pi - \beta$ into above equation, and let $\beta \geq \gamma$, consequently,

$$\beta_{\min} \geq 30^\circ + \gamma + \varepsilon$$

where, normally ε is about $4^\circ \sim 5^\circ$. Therefore, the minimum inversion angle of this double converter is given by

$$\beta_{\min} \geq 34^\circ + \cos^{-1} \left(\cos \alpha - \frac{\sqrt{2} I_d X_B}{V_\phi} \right) + \alpha, (\text{degree})$$

where, X_B – rectifier leakage reactance, (henry)

I_d – dc load current, (ampere)

V_ϕ – rectifier secondary phase voltage, (volt)

5. Power Relationship

According to above analysis, when thyristors of the neutral points not conduct, the operating state of this converter is the same as a conventional twelve-pulse bridge. When those thyristors are put into working, these main bridge's thyristors are beforehand switching off, the ac current is transferred to the neutral wire. Thus, the power factor for this converter is improved by reducing the conduction period for each phase. Thereby, the power relationship of the double converter is divided into two parts.

(1) When $\alpha \leq 30^\circ$, the state on this converter is alike with the conventional twelve-pulse bridge. Thus, the power relationship of each phase is given by

$$\begin{cases} S_I = 2 \sqrt{\frac{5}{8}} I_d V_\phi & (VA) \\ Q_I = 2 \sqrt{\frac{5}{8}} I_d V_\phi \sin(\alpha) & (Var) \dots \dots \dots (9) \\ P_I = 2 \sqrt{\frac{5}{8}} I_d V_\phi \cos(\alpha) & (W) \end{cases}$$

(2) When $30^\circ < \alpha \leq 150^\circ$, because these thyristors on neutral points put into operating, right now, this double converter is alike with the twenty-four-pulse bridge converter, it's power relationship per phase is given by

$$\begin{cases} S_{II} = 2 \sqrt{\frac{5}{12}} I_d V_\phi & (VA) \\ Q_{II} = 2 \sqrt{\frac{5}{12}} I_d V_\phi \sin(\alpha - 15^\circ) & (Var) \dots\dots\dots (10) \\ P_{II} = 2 \sqrt{\frac{5}{12}} I_d V_\phi \cos(\alpha - 15^\circ) & (W) \end{cases}$$

For convenient comparison, here, the dc terminal voltage is used for variables. Thus, the normalized do voltage is

$$V_o = \frac{V_{dII}}{V_{dmax}} \dots\dots\dots (11)$$

The normalized apparent power is

$$S_o = \frac{S_{II}}{S_I} \dots\dots\dots (12)$$

The normalized reactive power is

$$Q_o = \frac{Q_{II}}{Q_I} \dots\dots\dots (13)$$

Thus, the power relationship curves for this converter are shown as Fig.6(b). It is seen that the double converter is different from the single bridge rectifier described in (1), the apparent power of this converter does not changed with the firing angle α varying, but the reactive power is correspondingly increased when the dc voltage is reduced. It should be noted that the power relationship for this converter is alike to the conventional twelve-pulse bridge when $\alpha < 30^\circ$. On the contrary, when $\alpha > 30^\circ$, both the apparent power and the reactive power are all reduced. This is an advantage for this converter.

6. Harmonics

The harmonics of both dc terminal voltage and ac line current in this double converter should be divided into two areas to discuss. The assumptions made in above state are used here.

6.1 Harmonics of the AC Line Current The harmonic expression for ac line current requires finding the rms value of the ac line current in the rectifying mode. As is shown in Figs. 3 or 4, the ac line current i_u is an odd function because it was symmetrized to the zero-point on the axis of coordinate, consequently, that had not the cosine content. Here, the rms value is found to the current i_u in Fig. 3, obtained that the harmonic expression of the ac line current in $0^\circ \sim 30^\circ$ area is

$$\begin{aligned} i_u(t)_I = & \frac{\sqrt{3}I_d}{\pi} \left[\left(2 + \frac{\sqrt{2}}{2} + \frac{\sqrt{6}}{2} \right) \sin \omega t + \frac{1}{5} \left(2 - \frac{\sqrt{2}}{2} + \frac{\sqrt{6}}{2} \right) \sin 5\omega t \right. \\ & + \frac{1}{7} \left(2 + \frac{\sqrt{2}}{2} - \frac{\sqrt{6}}{2} \right) \sin 7\omega t + \frac{1}{11} \left(2 - \frac{\sqrt{2}}{2} - \frac{\sqrt{6}}{2} \right) \sin 11\omega t \\ & + \frac{1}{13} \left(2 - \frac{\sqrt{2}}{2} - \frac{\sqrt{6}}{2} \right) \sin 13\omega t + \frac{1}{17} \left(2 + \frac{\sqrt{2}}{2} - \frac{\sqrt{6}}{2} \right) \sin 17\omega t \\ & \left. + \frac{1}{19} \left(2 - \frac{\sqrt{2}}{2} + \frac{\sqrt{6}}{2} \right) \sin 19\omega t + \frac{1}{23} \left(2 + \frac{\sqrt{2}}{2} + \frac{\sqrt{6}}{2} \right) \sin 23\omega t \dots \right] \end{aligned} \dots\dots\dots (14)$$

From Fig. 4. the harmonic expression in $30^\circ \sim 150^\circ$ area is found

(a) AC current harmonics

(b) DC terminal voltage harmonics

Fig. 8. Harmonic curves

$$\begin{aligned} i_u(t)_{II} = & \frac{\sqrt{3}I_d}{\pi} \left[\left(1 + \frac{1}{\sqrt{3}} + 2\sqrt{\frac{2}{3}} \right) \sin \omega t + \frac{1}{5} \left(1 - \frac{1}{\sqrt{3}} + 2\sqrt{\frac{2}{3}} \right) \sin 5\omega t \right. \\ & + \frac{1}{7} \left(1 - \frac{1}{\sqrt{3}} - 2\sqrt{\frac{2}{3}} \right) \sin 7\omega t + \frac{1}{11} \left(1 + \frac{1}{\sqrt{3}} - 2\sqrt{\frac{2}{3}} \right) \sin 11\omega t \\ & + \frac{1}{13} \left(1 + \frac{1}{\sqrt{3}} - 2\sqrt{\frac{2}{3}} \right) \sin 13\omega t + \frac{1}{17} \left(1 + \frac{1}{\sqrt{3}} + 2\sqrt{\frac{2}{3}} \right) \sin 17\omega t \\ & \left. + \frac{1}{19} \left(1 + \frac{1}{\sqrt{3}} - 2\sqrt{\frac{2}{3}} \right) \sin 19\omega t + \dots \right] \dots\dots\dots (15) \end{aligned}$$

The ac line current in this converter appeared the harmonic components with 5th, 7th, 19th etc. from the above two equations. Fig. 8(a) presents a comparison of the ac line current harmonic for this double converter and the conventional converter. It can be seen that both 5th and 7th harmonic components of the former are much lower. Simultaneously, illustrate that the ac input current of the double converter does not changed when the dc terminal voltage varying. The order of harmonic in two areas never changed, merely, the magnitude is somewhat different, that is, the magnitude is reduced when those thyristors on the neutral points conducting. This feature is different with the single bridge converter described in Ref. (1).

6.2 Harmonics of the DC Terminal Voltage The calculation for the harmonics of the terminal voltage is more complicated, it requires to analyse the rectified voltage. Here, the Harmonic-Series-Superimposition-Method is used to drive.

(1) Harmonic Component of the DC Terminal Voltage on Area I

In area I, because these thyristors on the neutral points does not operate, the state of the double converter is similar to the

conventional converter. The dc terminal voltage is composed with two groups of six-pulse voltage, moreover, the phase-difference of corresponding ac input voltage is 15° . Therefore, the harmonic expression of the dc terminal voltage is given by

$$V_d(t)_I = \frac{3\sqrt{2}I_d}{\pi} \left[\cos\alpha + \left(\frac{2}{5^2} + \frac{2}{7^2} - \frac{4\cos 2\alpha}{5*7} \right)^{\frac{1}{2}} \cos\left(6\omega t + \frac{\pi}{4}\right) + \left(\frac{2}{17^2} + \frac{2}{19^2} - \frac{4\cos 2\alpha}{17*19} \right)^{\frac{1}{2}} \cos(18\omega t) + \left(\frac{4}{23^2} + \frac{4}{25^2} - \frac{8\cos 2\alpha}{23*25} \right)^{\frac{1}{2}} \cos\left(24\omega t - \frac{\pi}{2}\right) + \dots \right] \quad (16)$$

It may be seen from Eq. (16) that the 12th harmonic component for the voltage harmonics in area I is disappeared, but both 6th and 18th harmonic components are appeared.

(2) Harmonic Component of the Terminal Voltage on Area II

In area II when those thyristors on the neutral points are putting into operation, the dc terminal voltage is changed to a dc voltage with twenty-four-pulse. This dc voltage may be divided into two line voltage with six-pulse, respectively, and two phase voltage with six-pulse, moreover, the corresponding ac input voltages are 15° apart in the phase, the magnitude differ by $\sqrt{3}$. Therefore, through superimposing for these four harmonics of the dc voltage with six-pulse, the harmonic expression for dc terminal voltage in area II can be obtained.

Fig. 8(b) shows the characteristics relationship between the dc voltage harmonics and the firing angle α in this converter. From Fig. 8(a), when these thyristors on the neutral points are operated, The magnitudes of the voltage harmonics for this converter is not greater than the conventional converter, although the dc terminal voltage appeared both 6th, 8th harmonic components.

$$V_d(t)_{II} = \frac{6\sqrt{2}V_{2l}}{\pi} \left[\left(1 + \frac{\sqrt{3}}{3} \right) \cos(\alpha - 15^\circ) + \left(1 - \frac{\sqrt{3}}{3} \right) \left(\frac{1}{5^2} + \frac{1}{7^2} - \frac{2\cos 2(\alpha - 15^\circ)}{5*7} \right)^{\frac{1}{2}} \sin 6\omega t + \left(1 - \frac{\sqrt{3}}{3} \right) \left(\frac{1}{11^2} + \frac{1}{13^2} - \frac{2\cos 2(\alpha - 15^\circ)}{11*13} \right)^{\frac{1}{2}} \sin 12\omega t + \left(1 - \frac{\sqrt{3}}{3} \right) \left(\frac{1}{23^2} + \frac{1}{25^2} - \frac{2\cos 2(\alpha - 15^\circ)}{23*25} \right)^{\frac{1}{2}} \sin 24\omega t \dots \right] \quad (17)$$

7. Discussion

Both theoretical analysis and mathematical model indicate that for the same input power, the modified double converter operates with better power-factor and lower voltage distortion comparing the conventional bridge. Obviously, because these auxiliary thyristors on the neutral points are fired to conducting, those main thyristors are beforehand switched off, the ac current is transferred to the neutral wire. Since

dc terminal voltage waveforms	$\alpha(\text{rad})$	$V_d(\text{V})$	PF_M	PF_C
0°	456	0.986	0.986
30°	401	0.95	0.853
45°	319	0.85	0.7
60°	260	0.7	0.5
75°	182	0.5	0.25
90°	95	0.25	0
97.5°	36	0.13	0
135°	-172	-0.5
120°	-95	-0.254	

Fig. 9. the load waveforms and data of experiment tested

the conduction period for each phase is decreased, the total apparent power is reduced. Example: In this experimental system, the converter used two dc motors for the test of series-connecting operation, the data of each dc motor are $P_N = 2.2 \text{ KW}$, $V_N = 220 \text{ V}$, $I_N = 12 \text{ A}$, $n_N = 1500 \text{ r/m}$. While operating, the total apparent power is 3.3 KVA, PF_C is 0.41, supplied by the conventional bridge, and then, that is 2.68 KVA, PF_M is 0.59, supplied by the modified double converter. When both motors are turned on 750 r.p.m., it is evident that, the latter apparent power is decreased by 0.62 KVA; namely, the saving-power is about 19%.

Although, the secondary windings of the rectifier added winding M_{A2} , the secondary turns is decreased by 37% with the conventional bridge in a Delta-connected. Similarly, because input rms current is reduced by 18.4%, the capacity of the rectifier is reduced by 18.4% than the conventional bridge, too. Although additional four auxiliary thyristors might cost more equipment expenses, the inductance value of smoothing reactor L_d is only 57.7% of the conventional bridge, due to the increasing of dc voltage pulses. The harmonic values in ac input current do not vary with the change of firing-angle α .

Fig. 9 shows the dc terminal voltage waveforms of the modified double converter in this experimental process. It may be shown that the experimental result accord with theoretical analysis.

8. Conclusion

The results of both theory and experiment has proved that the modified bridge converter presented by Stefanovic⁽¹⁾ can be fully operated with series or parallel connecting, it not only offers the advantages of higher power-factor, lower harmonic distortion, but also reduced apparent power when compared with twelve-pulse bridge converter, in addition, its cost is even lower than the conventional bridge, because both the capacity of the rectifier and the inductance value

of the smoothing reactor are decreased, moreover, since the equidistant-firing-control is used in this converter, the control scheme is very simple.

Obviously, this double converter should be suited to the large-capacity DC or AC adjustable speed drive and the higher-power rectify system used phase-controlled, especially it is available for those equipments, which operated in high-firing angle for a long time.

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