Journal of Electrical and Electronic Engineering
2022; 10(4): 170-179
http://www.sciencepublishinggroup.com/j/jeee
doi: 10.11648/j.jeee.20221004.16
ISSN: 2329-1613 (Print); ISSN: 2329-1605 (Online)

Design and Analysis a 36-Pulse Rectifier to Improve the High-Voltage Harmonic Distortion Rate Under *5%* in MRT Systems

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To cite this article:
Chien Hsu Chen, Sheng Chieh Huang. Design and Analysis a 36-Pulse Rectifier to Improve the High-Voltage Harmonic Distortion Rate Under *5%* in MRT Systems. *Journal of Electrical and Electronic Engineering*. Vol. 10, No. 4, 2022, pp. 170-179. doi: 10.11648/j.jeee.20221004.16

Received: August 9, 2022; **Accepted**: August 25, 2022; **Published**: August 31, 2022

Abstract: I have served the Taipei MRT Bureau over than 25 years, and the inductive current harmonics affect the MRT power system, causing the train to malfunction and shorten its service life. Therefore, I am interested in solving this problem. The traditional solution is to use RLC high-pass filter. Its disadvantage is that it will reduce the power of the power supply system and need to do power compensation. This study analyzed the conversion designs of the traditional transformer wiring Δ-Δ-Δ-Δ and 36-pulse rectifier transformers. This type of transformer is used mainly in the industrial sector and features a system stability function. It involves parallel connection of two 18-pulse transformers to rectify 36-pulse DC power sources. The transformers were wire connected using the Δ pattern, which can convert 22 kV AC into 750 V DC. Regarding the two transformers in parallel connection, the primary side was 22 kV three-phase AC and the second, third, and fourth sides were in parallel connection. In addition, 72 diode rectifiers were used to rectify AC into single-phase 750 V DC. The 36-pulse and 24-pulse simulation results were compared and revealed that the power output of the 36-pulse system was greater than that of the 24-pulse system and presented a relatively straight waveform. This indicated that AC harmonics and DC ripples were reduced, verifying that the 36-pulse design is superior to the 24-pulse design.

Keywords: Metro Rapid Transit (MRT), Phase Transformer (PT), Traction Substation (TSS), Zero Sequence Blocking Transformer (ZSBT), Interphase Transformer (IPT)

1. Introduction

Thyristor rectifier is a mature technology and has been widely used in operation. The rectifier limiter combination is usually used to control direct current. Diode rectifiers used for front-end rectification can reduce flicker and increase power. Compared with traditional operation, the rectifier current-limiting system has many operating advantages, such as fast and dynamic rectification response, low output ripple, improved power factor and efficiency. The rectifier-limiter combination includes a rectifier system for high current insulated gate bipolar transistors.

DC power supply is the future research direction, because all countries currently use nuclear power generation as a high-power source, and its output power is AC power. Therefore, to use a large DC power supply, the rectifier is more important, and the research on the high-power rectifier is also more important.

The high-voltage diode rectifier controls the harmonic distortion within 5% and meets the requirements of the 519-2014 - IEEE [1] harmonic standard. At present, the most advanced MRT DC power supply systems in the world all use 24-pulse rectifiers. The measured harmonic rate of a single station of the Taipei MRT system is 0.6394%, which will reach an average value of 7.672% for the entire 12 MRT stations. This kind of rectifier also needs to be equipped with a high-pass filter to eliminate harmonic distortion below 5%, and it will cause the entire power system to drop and reduce the efficiency of the power system. If a 36-pulse rectifier is used, the harmonic rate measured by a single station is 0.37%, as in formula (12), if taking the entire 12 MRT stations, it is only 4.44%, which is within 5% of the harmonics. There is no need to add a high-pass filter, which will naturally not cause the problem of power system power reduction. This paper studies the built-in 36-pulse rectifier, which forms a power transformer through the Δ-ΔΔΔ connection. Because the high-voltage power is transmitted to the low-voltage system, the parallel bridge structure must be adopted. The wiring crosses symmetrically, extending from 72 diode bridges to three single-phase units. In this study, the rectifier transformer uses three diode bridges (nine pins) in parallel. This parallel structure can make 36-pulse configuration AC-DC conversion. Use MATLAB to build a model and simulate the pulse number of the design system to verify the improvement of power supply efficiency and reduce the harmonic distortion in the AC.

DC power system is widely used in industry and transportation sector because of its stable voltage and power output [2]. Harmonic is a power source interference factor caused by rectification, as shown in Figure 1. The generation of harmonics can lead to electromechanical failures, signal errors and control abnormalities. Therefore, mitigating harmonic problems is a long-standing topic. In this research, a rectifier is designed, a 22 kV three-phase AC power supply is input on the primary side, and the Δ-Δ-Δ-Δ connection of a traditional transformer is used. On the other primary side, an AC/DC rectifier with 12-pulse three-phase technology is used, as shown in Figure 2. The parallel 12-pulse high-voltage diode bridge adopts a 36-pulse rectified DC output design, which can provide up to 4000 A of 750 V DC current for the MRT system [3].

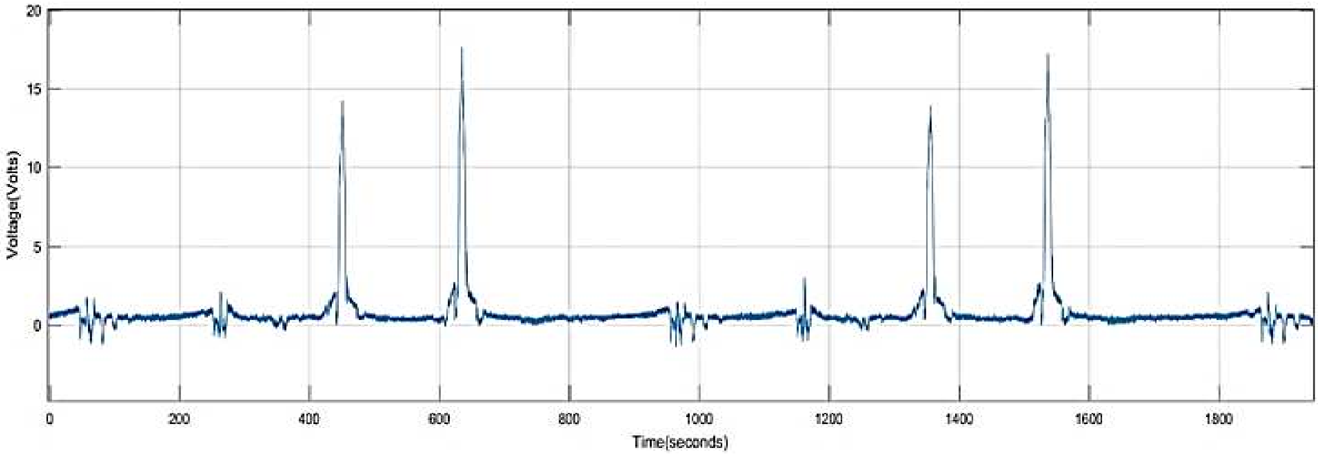

Figure 1. *22kV harmonic voltage measurement diagram.*

The high-voltage diode bridge rectifier of the MRT system adopts the DC rectification method and requires the use of ZSBT. The PT is connected to the ZSBT output, and 36 phase angles are obtained from the second, third and fourth side phase transformers. Under variable load, the total harmonic distortion (THD) of variable current is less than 3%. In DC load development and modeling, the 36-pulse AC/DC transformer conversion design is necessary to create a high-rated current rectifier. In addition, the transformer magnetic field is used to reduce the power supply voltage. It consists of two 18-pulse AC/DC converters connected in parallel, which can meet the 519-2014-IEEE standard. This research discusses the future development of 36-pulse rectifier transformers [4].

2. Mrt Traction Power Discussion

Most countries use 24-pulse DC power sources for MRT traction power. Figure 3 presents the wiring method of 24-pulse waves. The first phase of primary side voltage is sed as the reference zero degree. The voltage phasors of the second and third sides are −7.5°, 22.5°, + 7.5°, and −22.5°. As Table 1 indicates, the angle of the primary side does not vary. Phase shifts exist at the second and third sides. When the voltage difference of the primary side changes, the second and third side phase angles change by 0.25° and 0.75°, respectively. The rated power of the rectifier transformer is 1660 kVA, with the primary side voltage at 22 kV and second and third side voltage at 587 V.

The DC pulse average voltage is calculated as follows:

$$-\frac{\pi}{6} \leqslant \omega \leqslant \frac{\pi}{6}\ ,\ \sqrt{2}\ V_S \cos\omega\ t \tag{1}$$

The three-phase full-wave output average voltage is expressed as follows:

$$V_o = \frac{6}{2\pi}\int_{-\frac{\pi}{6}}^{\frac{\pi}{6}} \sqrt{2}V_S \cos\ \omega t dt = 1.35\ V_S\ ,\ V_S = 587V\ AC \tag{2}$$

High-voltage rectifier diodes consist of four units. The phase shift of each unit is 15°. A cycle contains 360°; therefore, 24 pulse waves can be generated. AC comprises three phase wire voltages, A, B, and C. The primary side based on the A phase wire voltage is at the angle of 0°; the second and third side phase angles/pulses are −7.5°/1, 142.5°/11, +7.5°/2, and 157.5°/12. The primary side based on the B phase wire voltage is at the angle of 120°; the second and third side phase angles/pulses are 112°/9, 262.5°/19, 127.5°/10, and 277.5°/20. The primary side based on the C phase wire voltage is at the angle of 240°; the second and third side phase angles/pulses are 232.5°/17, 22.5°/3, 247.5°/18, and 37.5°/4. When the primary side is moved from 0° to 15°, the second and third sides change from −7.5°/1, 142.5°/11, +7.5°/2, and 157.5°/11 to 52.5°/5, 202.5°/15, 67.5°/6, and 217.5°/16. Therefore, when the primary side changes by 15°, the second and third sides change by 60° along with changes in the four pulse phase sequences. When the primary side changes by 30°, eight pulse sequences are generated at the second and third sides. Because the voltage has three phases, 24 pulses occur, as illustrated in Table 1.

Table 1. *24 pulse wave phase angle change.*

Primary side angle				**Second side, third sided, phase angle / pulse sequence**			
0°	90°	180°	270°	-7.5°/1	142.5°/11	7.5°/2	157.5°/12
15°	105°	195°	285°	52.5°/5	202.5°/15	67.5°/6	217.5°/16
30°	120°	210°	300°	112.5°/9	262.5°/19	127.5°/10	277.5°/20
45°	135°	225°	315°	172.5°/13	322.5°/23	187.5°/14	337.5°/24
60°	150°	240°	330°	232.5°/17	22.5°/3	247.5°/18	37.5°/4
75°	165°	255°	345°	292.5°/21	87.5°/7	307.5°/22	97.5°/8

2.1. Discussion on the 36-Pulse Rectifier Transformer

The DC power source system of the MRT is rectified from the 22 kV AC three-phase voltage to 750 V DC single-phase for power supply. The rectifier transformer phase angles are changed by the phase angles of the phase transformers, as illustrated in Figure 2 [5], If the three phases attain a balance at the primary side (not counted as a single-phase transformer), then the second and third sides of No. 1 and No. 2 machines possess a positive phase sequence, a negative phase sequence, and a zero-phase sequence [6]. The phase difference is 120°, presenting three phase sequence changes. The second, third, and fourth sides of No. 1 and No. 2 machines have an initial angle of 0°. The angle changes from 0° to 350° at intervals of 10°. By adding a phase transformer, the second side presents a phase angle difference of 5° (i.e., −5°) in relation to the primary side. The third side angle is synchronous to the primary side phase angle and no angle difference exists. The fourth side phase angle has a phase angle difference of 5° (i.e., +5°) in relation to the primary side phase angle. Therefore, the phase angle difference between the second, third, and fourth sides phases is 10°. However, the angle difference between the second and fourth sides winding is 10°, and the transformer phase is positioned at every 5° of the sequences. When the primary side changes by 30°, 12 pulse wave sequences are generated at the second, third, and fourth sides. Because the voltage has three phases, 36 pulse waves are generated.

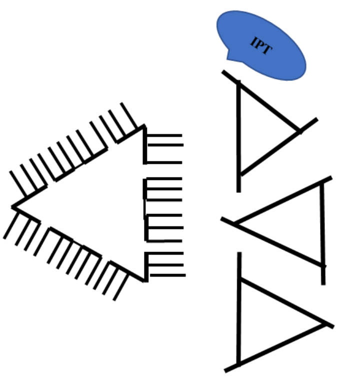

Figure2. *Δ-Δ-Δ-Δ wiring method of 36-pulse rectifier transformer.*

But the difference between the first side winding and the fourth side winding is 15°, the winding on the second side of the machine directs the primary winding with respect to each sequence 5° (ie -5°) the third side winding is synchronized with the first side, there is no angular difference and the second and third side windings are also different from -5°. The wiring on the fourth side directs the first side wiring with respect to each order 15° (ie -15°), but the difference between the third and fourth side windings is -5°, the first and fourth side wiring between them is -10°

The DC pulse voltage formula is:

$$\sqrt{2}\ V_S \cos\omega\ t\ ,\ \frac{\pi}{12} \leqslant\ \omega\ \leqslant \frac{\pi}{12} \tag{3}$$

Its three-phase full-wave output voltage is:

$$V_o = \frac{12}{2\pi}\int_{\frac{\pi}{12}}^{\frac{\pi}{12}} \sqrt{2}\, V_S \cos\ \omega tdt\ = 1.414\ V_S\ ,$$

$$V_S = 587V\ AC \tag{4}$$

The phase voltage at the primary side is used as the reference 0°. The voltage phases of the second, third, and fourth sides of No. 1 and No. 2 machines are −5° and 25°, 0° and 30°, and +5° and −25°, respectively. The primary side angle remains the same. The data are provided in Table 2. Phase shifts are observed at the second, third, and fourth sides. When the primary side tapping voltage difference changes, the second side phase angle changes by 0.25° and the phase angle of the third side changes by 0.75°. The rated power of the rectifier transformer is 1660 kVA with the primary side AC voltage at 22 kV, and second, third, and fourth side AC voltage at 587 V. Because the rectifier diode consists of four battery sets, each phase for each battery represents 10° of phase shifts. With 360° within a cycle, a total of 36 pulses can be generated. At the first stage, based on the 0° primary side line voltage, the second, third, and fourth side phase angles/pulses are −5°/1, 175°/19, 0°/2, 180°/20, + 5°/3, and 185°/21. At the second stage, the primary side line voltage at 120° is used as the basis.

The second, third, and fourth side phase angles/pulses are 55°/7, 235°/25, 60°/8, 240°/26, 65°/9, and 245°/27. At the third stage, the primary side line voltage at 240° is used as the basis. The second, third, and fourth side phase angles/pulses are therefore 115°/13, 295°/31, 120°/14, 300°/32, 125°/15, and 305°/33. When the primary side phase angle is changed from 0° to 10°, the second side phase angles/pulses are changed from −5°/1 and 175°/19 to 25°/4 and 205°/22, respectively.

2.2. Discussion on Δ-ΔΔΔ 36-Pulse Phase Angles [7]

The phase voltage at the primary side is used as the reference 0° [8]. The voltage phases of the second, third, and fourth sides of No. 1 and No. 2 machines are −5° and 25°, 0° and 30°, and +5° and −25°, respectively. The primary side angle remains the same. The data are provided in Table 2. Phase shifts are observed at the second, third, and fourth sides. When the primary side tapping voltage difference changes, the second side phase angle changes by 0.25° and the phase angle of the third side changes by 0.75°. The rated power of the rectifier transformer is 1660 kVA with the primary side AC voltage at 22 Kv.

The second, third, and fourth side AC voltage at 587 V. Because the rectifier diode consists of four battery sets, each phase for each battery represents 10° of phase shifts. With 360° within a cycle, a total of 36 pulses can be generated. At the first stage, based on the 0° primary side line voltage, the second, third, and fourth side phase angles/pulses are −5°/1, 175°/19, 0°/2, 180°/20, + 5°/3, and 185°/21. At the second stage, the primary side line voltage at 120° is used as the basis. The second, third, and fourth side phase angles/pulses are 55°/7, 235°/25, 60°/8, 240°/26, 65°/9, and 245°/27. At the third stage, the primary side line voltage at 240° is used as the basis. The second, third, and fourth side phase angles/pulses are therefore 115°/13, 295°/31, 120°/14, 300°/32, 125°/15, and 305°/33. When the primary side phase angle is changed from 0° to 10°, the second side phase angles/pulses are changed from −5°/1 and 175°/19 to 25°/4 and 205°/22, respectively. The third side phase angles/pulses are changed from 0°/2 and 180°/20 to 30°/5 and 210°/23, respectively. The fourth side phase angles/phases are changed from 5°/3 and 185°/21 to 35°/6 and 215°/24, respectively. Therefore, when the primary side changes by 10°, the second, third, and fourth sides change by 30° and the six pulse sequences are changed. When the primary side changes by 30°, 12 pulse phase sequences are generated at the second, third, and fourth sides. Because the voltage has three phases, a total of 36 pulses are generated naturally, as presented in Table 3.

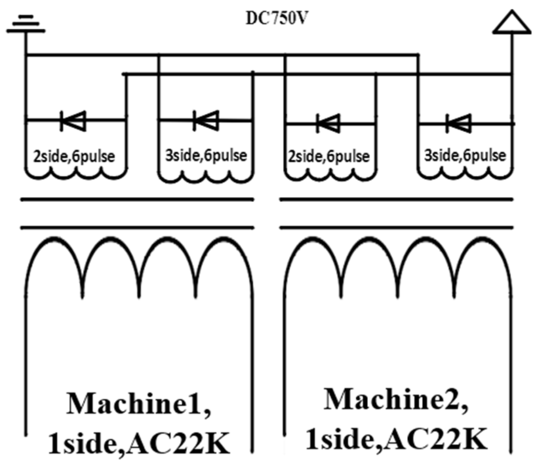

Figure 3. *Circuit diagram of 24-pulse rectifier transformer.*

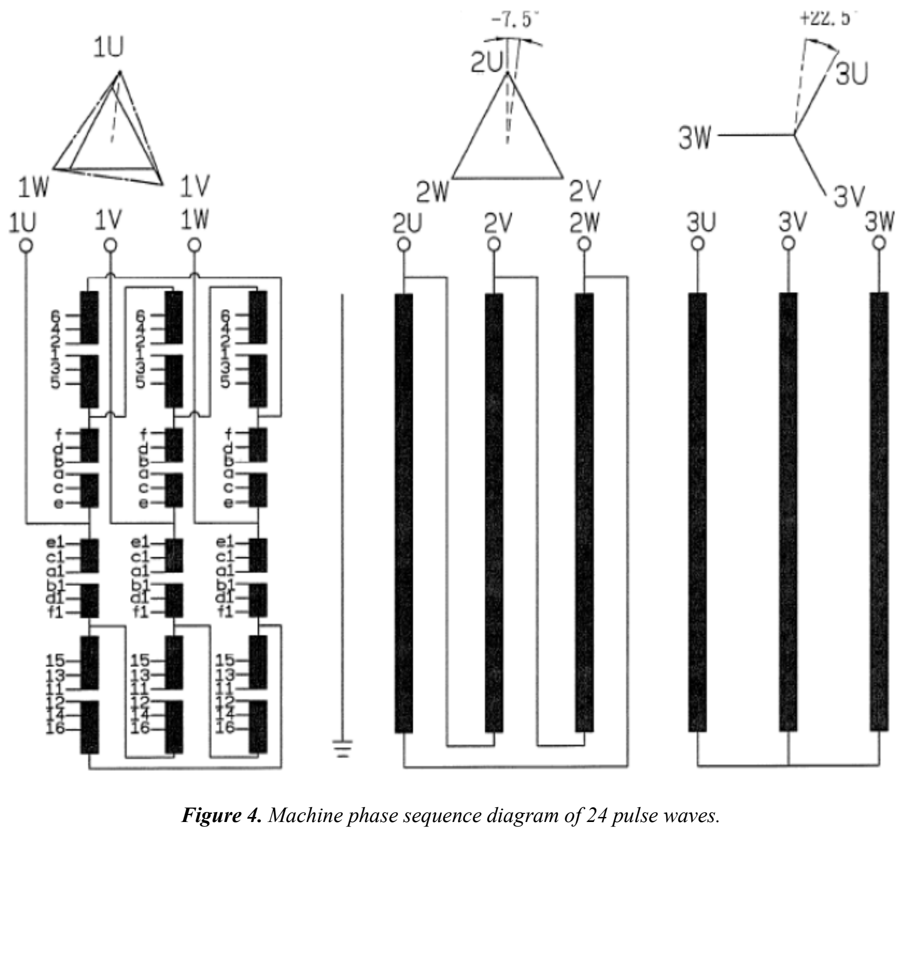

Figure 4. *Machine phase sequence diagram of 24 pulse waves.*

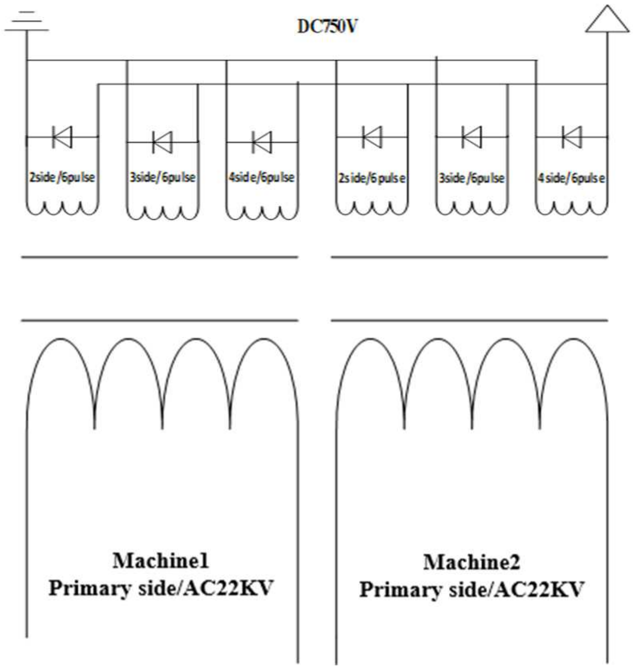

Figure 5. *Circuit diagram of 36-pulse rectifier transformer.*

Vb2c2=587∠-120°V, Vc2a2=587∠120°V

Corresponding to primary side contact point:

a_2b_2 ∥ U_1V_1, b_2c_2 ∥ V_1W_1, c_2a_2 ∥ W_1U_1

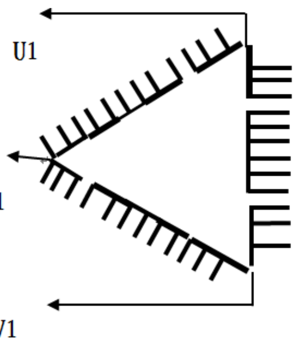

Figure 6. *36 pulse wave primary side wiring diagram.*

According to the data, the line voltage on the secondary side is:

541∠-5°=539-j47 V (position1, tap-change connectors 3-6)

555∠-4.75°=553-j46 V (position2, tap-change connectors 5-3)

569∠-4.5° =567-j45 V (position3, tap-change connectors 2-5)

583∠-4.25°=581-j43 V (position4, tap-change connectors 4-2)

597∠-4 °=596-j42 V (position5, tap-change connectors 1-4)

According to the data, the line voltage on the tertiary side is:

552∠0°=552-j0 V (position1, tap-change connetors 3-6)

566∠-0.25°=556-j2 V (position2, tap-change connectors 5-3)

580∠-0.5° =580-j5 V (position3, tap-change connectors 2-5)

594∠-0.75°=594-j8V (position4, tap-change connectors 4-2)

608∠-1 °=608-j11 V (position5, tap-change connectors 1-4)

According to the data, the line voltage on the quadratic side is:

541∠5°=539+j47 V (position1, tap-change connectors 3-6)

555∠5.25° =553+j51V (position2, tap-change connectors 5-3)

569∠5.5° =566+j55V (position3, tap-change connectors 2-5)

583∠5.75° =580+j58V (position4, tap-change connectors 4-2)

597∠ 6° =594+j62 V (position5, tap-change connectors 1-4)

Based on position 3, the second, tertiary and quadratic side phasors are verified by calculation.

1. Verify the secondary side phasor:

△V=597-583=583-569=569-555=555-541=14V

541∠-5°+ 14∠0.25°=556∠-4.75°V

556∠-4.75°+ 14∠0.25°=569∠-4.5°V

569∠-4.5°+ 14∠0.25°=583∠-4.25°V

583∠-4.25°+ 14∠0.25°=597∠-4°V

Verification is correct

2.Verify the tertiary side phasor:

△V=608-594=594-580=580-566=566-552=14V

552∠0°+ 14∠-0.25°=556∠-0.25°V

556∠-0.25°+ 14∠-0.25°=580∠-0.5°V

580∠-0.5°+ 14∠-0.25°=594∠-0.75°V

594∠-0.75°+ 14∠-0.25°=608∠-1°V

Verification is correct

3. Verify the quadratic side phasor:

△V=597-583=583-569=569-555=555-541=14V

541∠5°+ 14∠-0.25°=556∠4.75°V

556∠4.75°+ 14∠-0.25°=569∠4.5°V

569∠4.5°+ 14∠-0.25°=583∠4.25°V

583∠4.25°+ 14∠-0.25°=597∠4°V

Verification is correct as shown in Table 2.

Table 2. *Brake angle changes.*

Item	Primary side phase shift	Second side phase shift	Third side phase shift	Fourth side phase shift	Primary side voltage	Gate joint
1	0°	−8°	10^0	24°	20900	3-6
2	0°	−7.75°	9.75^0	23.25°	21450	5-3
3	0°	−7.5°	9.5^0	22.5°	22000	2-5
4	0°	−7.25°	9.25^0	21.75°	22550	4-2
5	0°	−7°	9°	21.5	23100	1-4

***Table 3.** 36 pulse wave phase angle changes.*

Primary side angle						secondary, tertiary and quadratic side phase angle / pulse sequence					
0°	60°	120°	180°	240°	300°	-5°/1	175°/19	0°/2	180°/20	5°/3	185°/21
10°	70°	130°	190°	250°	310°	25°/4	205°/22	30°/5	210°/23	35°/6	215°/24
0°	80°	140°	200°	260°	320°	55°/7	235°/25	60°/8	240°/26	65°/9	245°/27
30°	90°	150°	210°	270°	330°	85°/10	265°/28	90°/11	270°/29	95°/12	275°/30
40°	100°	160°	220°	280°	340°	115°/13	295°/31	120°/14	300°/32	125°/15	305°/33
50°	110°	170°	230°	290°	350°	145°/16	325°/34	150°/17	330°/35	155°/18	335°/36

2.3. Calculation of Harmonic Voltage Equation Form Rectifier Output Voltage Value

The Fourier periodic wave is:

$$f(t) = F_0 + \sum_{h=1}^{\infty} f_h(t) = \frac{1}{2} a_0 + \sum_{h=1}^{\infty} \left[a_h \cos(h\omega t) + b_h \sin(h\omega t) \right] \tag{5}$$

An odd function for harmonics

$$a_h = 1, b_h = \frac{2}{\pi} \int_0^{\pi} f(t) \sin(h\omega t) d(\omega t)$$

The rectifier output voltage equation is shown in Table 4:

$$V_{d6k} = 1 + \frac{2}{6n*6nk-1} + \sum_{k=1}^{n=1} cos\, 6\, n\omega t \pm \frac{1}{6n*6nk-1}, n = 1,2,3 \ldots, k = 1,4,9 \ldots \tag{6}$$

***Table 4.** Harmonic voltage equation of the 6N pulse.*

Pulse	Rectifier output voltage equation
6	$Vd\left(1+\frac{2}{6*6k-1}+\sum_{k=1}^{n=1} cos\, 6\, n\omega t \pm \frac{1}{6*6k-1}\right) = V_d \left[1+\frac{2}{35}+cos6\omega t-\frac{1}{35}+cos12\omega t+\frac{1}{143}+cos18\omega t-\frac{1}{323}+\ldots cos6n\omega t\pm\frac{1}{6*6k-1}\right]$ n=1,2,3 … k=1,4,9,16…
12	$Vd\left(1+\frac{2}{12*12k-1}+\sum_{k=1}^{n=1} cos\, 12\, n\omega t \pm \frac{1}{12*12k-1}\right) = V_d \left[1+\frac{2}{143}+cos12\omega t-\frac{1}{143}+cos24\omega t+\frac{1}{575}+cos36\omega t-\frac{1}{1295}+\ldots cos12n\omega t\pm\frac{1}{12*12k-1}\right]$ n=1,2,3 … k=1,4,9,16…
24	$Vd\left(1+\frac{2}{24*24k-1}+\sum_{k=1}^{n=1} cos\, 24\, n\omega t \pm \frac{1}{24*24k-1}\right) = V_d \left[1+\frac{2}{575}+cos24\omega t-\frac{1}{575}+cos48\omega t+\frac{1}{2383}+cos72\omega-\frac{1}{5183}+\ldots cos24n\omega t\pm\frac{1}{24*24k-1}\right]$ n=1,2,3 … k=1,4,9,16…
36	$V_d\left(1+\frac{2}{36*36k-1}+\sum_{k=1}^{n=1} cos\, 36\, n\omega t \pm \frac{1}{36*36k-1}\right) = V_d \left[1+\frac{2}{1295}+cos36\omega t-\frac{1}{1295}+cos72\omega t+\frac{1}{5183}++cos108\omega t-\frac{1}{11663}+\ldots cos36n\omega t\pm 2/(36*36k-1)\right]$ n=1,2,3 … k=1,4,9,16…

Harmonic voltage is proportional to its amplitude, which increases the electric field strength of the medium. The increased electric field strength may increase partial discharge and cause dielectric losses and temperature rise, thereby shortening the lifetime of cables and increasing the occurrence of accidents.

These harmonic-induced hazards are severe. When the harmonic current flows through the surface of a conductor, the skin effect and proximity effect may generate excessive heat on the lines or devices, affecting power transmission. In addition, harmonic currents generate high-frequency electric fields, which increase partial discharge of insulators, substantially increase dielectric losses, raise the temperature, and affect insulator lifetime and devices.

3. Result

Parallel filters are the main method used to inhibit high-order harmonics in the MRT system. Industrial DC power sources originate from 6-pulse rectification systems; when power demand increases, the system is advanced to 12 pulses. MRT systems in Europe and the United States use 12-pulse DC power sources and high-pass filters to filter harmonics.

The Taipei Metro uses a 24-pulse system (Figure 8). The rectifiers can be treated as parallel resonant capacitors. If the rectifiers are not loaded, the THD will be within the 5% standard recommended by 519-2014-IEEE. When the rectifiers are loaded, the THD will exceed 5%. The proposed 36-pulse rectifier [9] can be used to reduce the THD to 5% or lower, as illustrated in Figure 9 [10]. The current harmonic distortion values measured at the 22 kV side at MRT Stations A and B were 1.64% and 2.16%, respectively (Table 5). The THD was 3.8%(have RLC filter). By contrast, the THD of the 36-pulse currents was 0.37%, considerably lower than the 3.8% THD of the 24-pulse currents.

***Table 5.** 24 pulse rectifier harmonic measurement.*

Harmonic series	Harmonic quantity
5	47.56%
7	69.21%
11	93.20%
13	97.06%
17	99.20%
19	99.28%
23	99.70%
25	99.76%

※The harmonic distortion rate of 36 pulse wave is 0.37%, which is much smaller than the harmonic.

(a) (b) (c)

Figure 7. *24-pulse rectifier transformer (a) circuit box (b) diode group (c) transformer.*

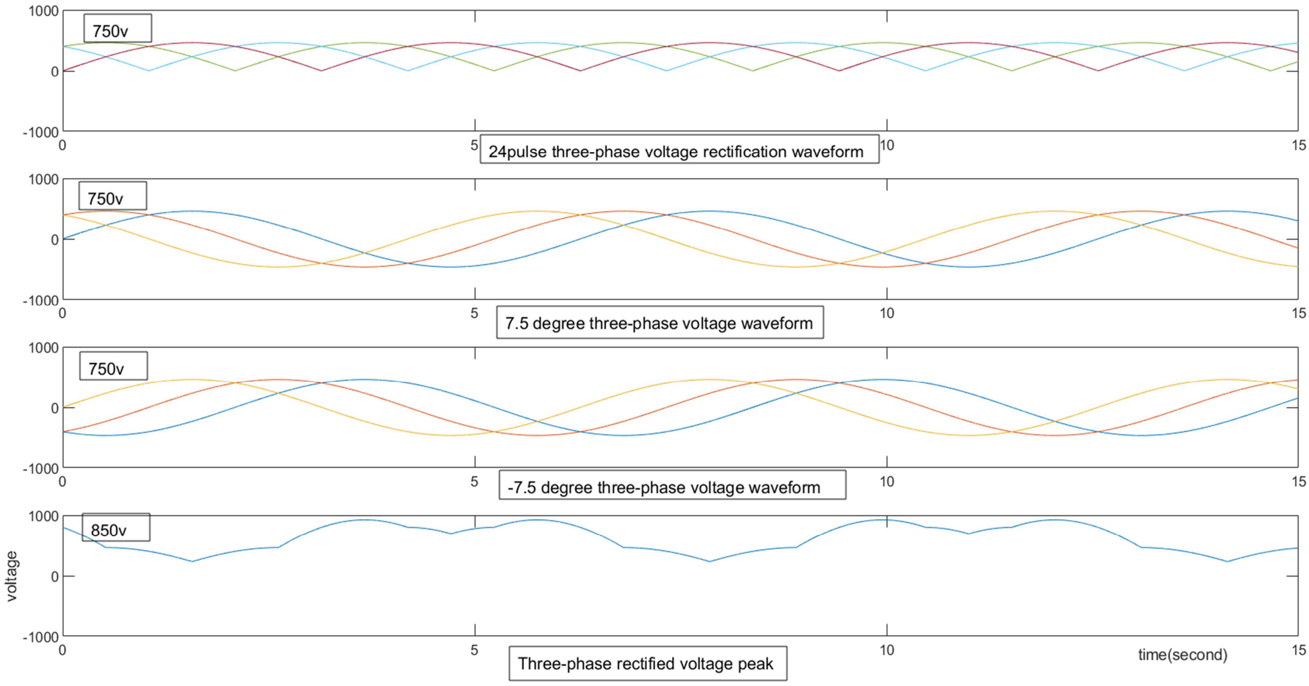

Figure 8. *24-pulse rectification waveform.*

However, high-pass filters pose electrical impedance. Adding an excessive number of high-pass filters may reduce power output and affect the propulsion of electric vehicles. Therefore, MRT systems in mainland China and Taiwan have adopted 24-pulse rectification, as depicted in Figure 7.

Its calculation formula is as follows:

$$K=\sum_{0}^{1} n^2 \tag{7}$$

f_n: the nth harmonic current distribution coefficient.

$\left(\frac{I_n}{I_1}\right)$: I_n is the nth harmonic current; I_1 is the primary harmonic current.

The K factor is defined as above. If the transformer provides a linear load, K = 1. If the transformer provides a non-linear load, K > 1. When K > 1, the value of Imax(pu) decreases. In other words, the output voltage rating of the transformer is reduced and the power is reduced, which in turn reduces the power output due to harmonic loading.

About harmonic improvement equation as follows:

$$\begin{aligned} h(p) &= pk \pm 1 \\ I_h(p) &= \frac{I_1}{h(p)} \end{aligned} \tag{8}$$

h: Harmonic series, p: Rectifier pulse number,
k: Integer, 1,2,3…., I_1: Base frequency current,
I_h: Harmonic series current.

$$\Delta p = \sum_{n=1,3,5\ldots}^{\infty} c(tg\delta)\omega_n U_n^2 \tag{9}$$

$$I_h = I_1\sqrt{1 + 3^2h_3^2 + 5^2h_5^2 + \cdots + (n+1)^2h_{n+1}^2} \quad (10)$$

$$U_n = \sqrt{1 + h_3^2 + h_5^2 + \cdots + h_{n+1}^2} \quad (11)$$

$$K=0.4756^2+0.6921^2+0.932^2+0.9706^2+0.992^2+0.9928^2+0.997^2+0.9976^2=6.47482$$

$$H(24)=6.47482\times 24+1=156.396$$

$$H(36)=6.4782\times 36+1=270.1$$

$$I_h(24)=\frac{1}{156.396}\times 100\% = 0.6394\%$$

$$I_h(36)=\frac{1}{270.1}\times 100\% = 0.37\% \quad (12)$$

Distortion rate of current MRT 24 pulse plus high-pass filter by 3.8% [11].

3.1. Analysis of 36-Pulse Waveform

Positive phase sequences are depicted in Figure 10 [12]. The second, third, and fourth side phase angles of the 36-pulse system begin from −5°, 0°, and 5° and are added with basic positive phase sequence waveform 120° and 0°. Consequently, the basic three-phase waveform of second, third, and fourth sides are 115°, 0°, and −115°.

When the MRT system incorporates 36-pulse rectification to address its harmonics problems, the number of high-pass filters used can be reduced to increase output power, thereby greatly reducing propulsion power loss during peak time.

1) At present, no 36-pulse rectifier has been applied in the MRT system. Numerous technical problems must be overcome before its practical application, as described in Table 5.
2) The MRT system adopts DC power sources and current distortion has a substantial influence on the system; however, the effect of voltage fluctuation is minimal.

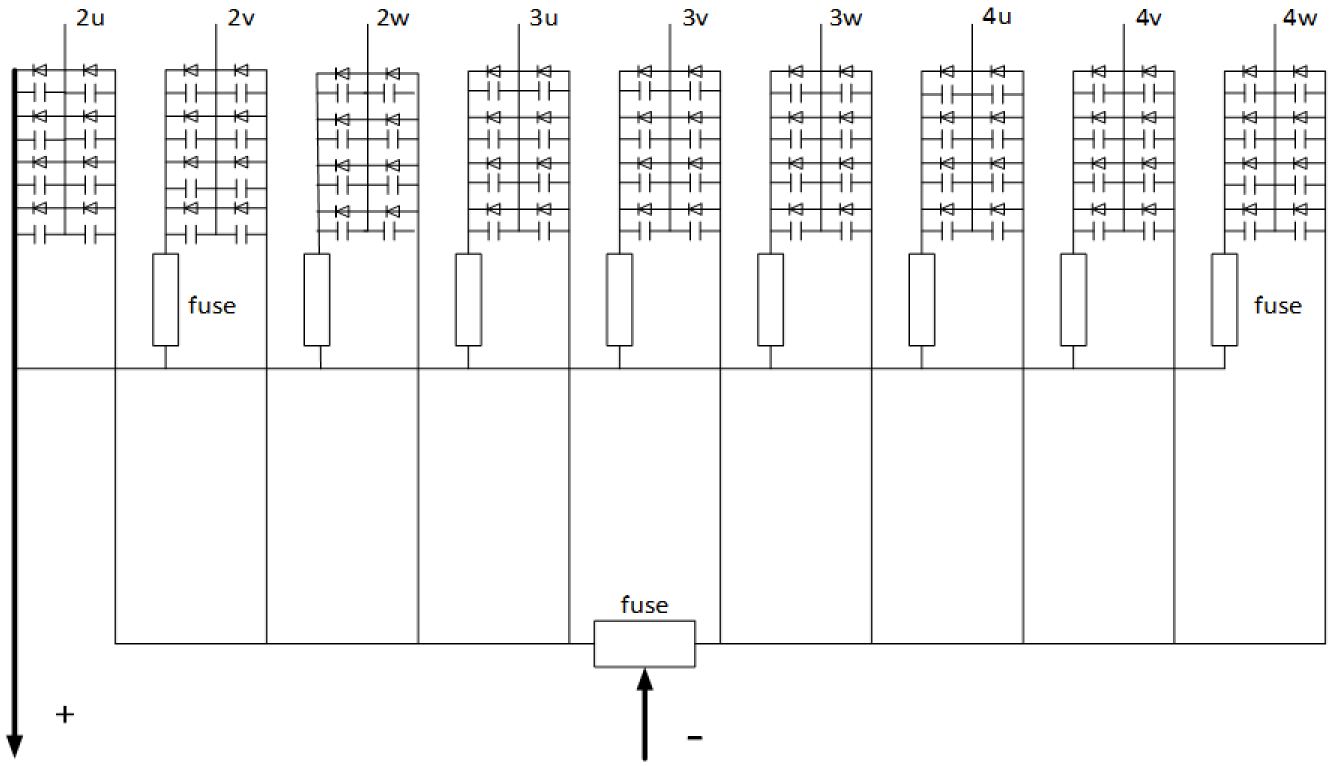

Figure 9. *36 pulse wave high voltage diode layout.*

3.2. 36 Pulse Waveform Analysis

For the positive phase sequence, the second, third and fourth side phase angles of the 36 pulse wave start from -5°, 0° and 5° as shown in Figure 10. plus the basic positive phase sequence waveform 120°, 0°, therefore, second The basic three-phase waveforms on the stage side, the third side and the fourth side are respectively 115°, 0°, -115°.

When the MRT system incorporates 36-pulse rectification to address its harmonics problems, the number of high-pass filters used can be reduced to increase output power, thereby greatly reducing propulsion power loss during peak time [13], Table 7. Specifications of 36-pulse rectifier transformer.

1) At present, no 36-pulse rectifier has been applied in the MRT system. Numerous technical problems must be overcome before its practical application, as described in Table 7.
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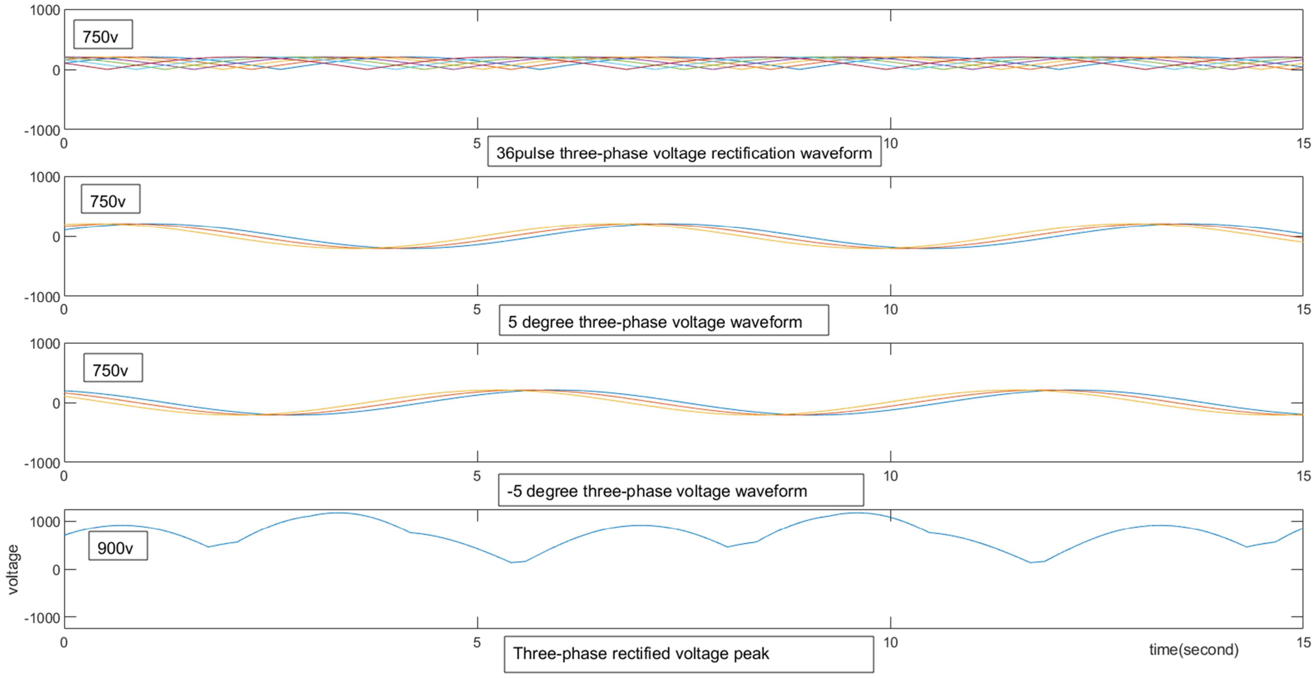

Figure 10. *36-pulse rectification waveform.*

Table 6. *Symbol description list.*

Symbol description list		
Serier	**Symbol**	**Symbol Description**
1	h	Harmonic order
2	ω	Angular frequency
3	n	Positive integer without 0
4	k	Harmonic distortion rate sum of squares
5	C(tgδ)	Conductive material coefficient
6	Un	Harmonic order square sum root mean square value
7	Ihh	h-order harmonic current distortion rate
8	Ih(36)	36-pulse harmonic current total distortion rate

Table 7. *Specifications of 36 pulse rectifier transformer.*

Rated power	Full load DC voltage	Duties	For continuous	For 3 hours	For 1 minute
3000KW	750V		4000A	6000A	12000A
Diode type	Peak off state voltage off diode	Total number of diodes per three phase bridge			
D4000 N22	2200V	54			
Degree of protection	Humidity class	Insulated according to			
IPOO to DIN 40050	F to DIN 40040	VDE 0160 for places of insulation group C to VDE 0110			

4. Discussion

When the 48-pulse rectifier has not been used in the MRT power system, considering the construction cost and harmonic distortion, the 36-pulse rectifier is an option. In addition to the traditional transformer Δ-Δ and Δ-Y wiring, special transformer wiring methods such as Scott, Le-Blanc and Modified-Woodbridge connections can be applied to future MRT circuits. However, compared with the transformer dedicated wiring, the delta-delta-delta-delta wiring has a lower phase angle and generates fewer harmonics in the internal circuit. In addition, the Δ-Δ-Δ-Δ wiring method also has the advantages of more stable system, higher efficiency, simpler harmonic improvement methods, less complicated wiring requirements, and higher output power relative to special transformer wiring. The next step is to study the impact of DC 48 pulse wave and transformer dedicated wiring DC rectifier on the future.

5. Conclusion

Due to the frequency-free transmission of DC, the power transmission distance of DC is shorter than that of AC. The 36-pulse DC voltage is greater than the 24-pulse DC voltage to achieve a longer transmission distance. The measured harmonic rate of a single station of the Taipei MRT system is 0.6394%, and the average harmonic rate of the entire 12 MRT stations is 7.672%. If a 36-pulse rectifier is used, the measured harmonic rate of a single station is

0.37%. If the entire 12 MRT stations are taken, it is only 4.44%, which is within 5% of the harmonics. There is no need to add a high-pass filter. The wave rate is improved by 3.232%, which naturally will not cause the problem of power system power reduction.

A high-pass filter must be added to the 24-pulse rectifier, which requires additional power compensation. The ensuing power loss reduces the power output. The advantage of the 36-pulse rectifier is that the harmonics are reduced after rectification, and the output power is greater. The use of 36-pulse rectifiers eliminates the need for high-pass filters and solves the problem of harmonic distortion.

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Biography

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