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Chapter

Five-Phase Line Commutated Rectifiers

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Abstract

Multiphase systems including multiphase generators or motors, especially fivephase, offer improved performance compared to three-phase counterpart. Fivephase generators could generate power in applications such as, but not limited to, wind power generation, electric vehicles, aerospace, and oil and gas. The five-phase generator output requires converter system such as AC-DC converters. This chapter introduces the basic construction and performance analysis for uncontrolled/controlled five-phase line commutated rectifier guided by numerical examples. This rectifier is suitable for wind energy applications to be the intermediate stage between five-phase generator and DC load or inverter stage. The filtration for AC side and effects of source inductances are detailed in other references. Here, this chapter gives the reader a quick idea about the analysis and performance of multiphase line commutated rectifiers and specifically five phase.

Keywords: five phase, multiphase generators, wind turbine, controlled and uncontrolled rectifiers, AC-DC converters, line commutated rectifiers

1. Introduction

Nowadays, energy generation using renewable energy sources is considered as contemporary issue. Many countries are experiencing economic pressures because of the reduction in oil prices. Moreover, energy that is produced by burning fossil fuels is mainly responsible for the global air pollution problem, and consequently, it is not environmentally friendly. As a consequence, many countries are impelled to concentrate on renewable energy sources including generation, management, and planning. Renewable energy share, of the total energy consumption by the end of 2016, is 24.5% where it was 3.3% in 2010 [1]. This number is tremendously increasing each year. Accordingly, most research institutes foster research in the energy sector to go to clean and green energy generation. From renewable energy sources, wind energy is considered to be a pillar using appropriate generator. By the end of 2016, 29 countries have more than 1 GW in operation from wind energy, and the total capacity generated for the world is 487 GW. Only in 2016 a 23.4 GW is added due to wind energy generation [1]. Incontrovertibly, wind power becomes a big industry and a big topic for research. It includes mechanical parts and electrical parts. Accordingly, a generator that converts wind mechanical power to electrical power is a must. But, the power generated using wind turbines is not constant and could fluctuate. Also, the load profile fluctuates with respect to time. To accomplish

this, specially designed power systems for meeting these demands are built which can feed these drastic load changes. In all cases, the generator output voltage should be rectified. Owing to the numerous advantages when compared to its three-phase counterpart such as high fault-tolerant capability, five-phase direct-drive permanent magnet generators are a key area of focus in power generation with renewable and wind energy systems [2–6]. Hence, the generator output requires a converter, such as an AC-DC rectifier, to match load requirements. Rectifiers are broadly classified into two types, namely, line-commutated rectifiers (LCRs) and power factor control rectifiers. LCRs are either uncontrolled (using diodes) or controlled (using thyristors). This type of rectifiers operates on power frequency or generated frequency and has the advantages of simple construction and low cost. In a controlled LCR, the DC-link voltage can be controlled by adjusting the firing angle, thus facilitating high power capability, easy control, and a simple gating system [7, 8]. However, LCRs still have a low input power factor, high input current total harmonic distortion (THD), and unidirectional current flow [9, 10]. To address such problems, power factor control rectifiers, which operate at a high switching frequency, such as pulse-width modulated (PWM) rectifiers are used where the filter size for PWM rectifiers is smaller owing to the higher switching frequencies [9, 11, 12]. However, one of the main drawbacks of using PWM rectifiers is the limitation of the switch current and voltage, which restricts the use of such rectifiers in high-power-scale applications [3, 5, 13, 14].

This chapter introduces uncontrolled/controlled line-commutated five-phase rectifier as we target high-power wind energy applications. The study includes the analysis of both AC side and DC side. Moreover, the gating signal generation is introduced. The study includes ideal source to represent the PM generator. Effect of source inductance and filtration of AC side are introduced in Refs. [3, 5].

2. Five-phase source

The phase voltage of the five-phase source, which is the output of the five-phase generator, can be written as

$$v_{jn} = V_{ph_{max}} \sin \left(\omega t - \frac{2\pi k}{5}\right)$$
 (1)

where *j* represents phases *a*, *b*, *c*, *d*, and *e*, respectively, and *k* equals 0, 1, 2, 3, and 4, respectively. The five-phase source has two line voltages (adjacent and nonadjacent) [3, 5]. The line voltages can be calculated using phasor diagram shown in **Figure 1**.

The line voltage for adjacent phases has amplitude 1.1756 V_{ph_max} and leads to the phase voltage by 54°; see **Figure 1a**. The line voltage for nonadjacent phases has amplitude 1.902 V_{ph_max} and leads to the phase voltage by 18°; see **Figure 1b**.

Example 1: For a 200 V (peak value-phase voltage) five-phase source, calculate and plot the phase and line voltage waveforms.

Solution

Phase voltages are

$$v_a = 200 \sin (\omega t), \quad v_b = 200 \sin \left(\omega t - \frac{2\pi}{5}\right), \quad v_c = 200 \sin \left(\omega t - \frac{4\pi}{5}\right),$$

 $v_d = 200 \sin \left(\omega t + \frac{4\pi}{5}\right), \quad v_e = 200 \sin \left(\omega t + \frac{2\pi}{5}\right) \quad V$



Phasor diagram for five-phase source: (a) line voltage for adjacent phases and (b) line voltage for nonadjacent phases.



Figure 2.

Phase voltage, adjacent line voltage, and non-adjacent line voltage.

Figure 2 shows the line voltages for adjacent and non-adjacent phase voltages. The line voltage for adjacent phases is

$$v_{ab} = 200^* 1.1756 \sin \left(\omega t + \frac{3\pi}{10}\right) = 235.12 \sin \left(\omega t + \frac{3\pi}{10}\right) V$$

The line voltage for nonadjacent phases is

$$v_{ac} = 200^* 1.902 \sin \left(\omega t + \frac{\pi}{10}\right) = 380.4 \sin \left(\omega t + \frac{\pi}{10}\right) V$$

3. Uncontrolled five-phase rectifier

The five-phase uncontrolled rectifier is shown in **Figure 3**. It consists of 10 diodes where the load is fed from five-phase half wave connection, five switches D1-D5, and return path being via another half wave connection, five switches D6-D10, to one of the five supply lines.

The load voltage or output DC voltage can be calculated by the addition of the two five-phase half-wave voltages, relative to the supply neutral point *n*, appearing at the positive and negative sides of the load, respectively. The voltage is 10 pulses in nature having its maximum instantaneous value of that of line voltages for nonadjacent phases and leads the phase voltage by $\pi/10$. The load voltage follows in turn 10 sinusoidal voltages during one cycle, those being v_{ac} , v_{ad} , v_{bd} , v_{be} , v_{ce} , v_{ca} , v_{da} , v_{db} , v_{eb} ,



and v_{ec} . The average voltage can be calculated with the aid of **Figure 4**. The repeated period accommodates 36° and the limits are -18° to $+18^{\circ}$.

The average or mean load voltage can be calculated as

$$V_{mean} = \frac{1}{\pi/5} \left[\int_{-\frac{\pi}{10}}^{\frac{\pi}{10}} 1.902 V_{ph_{max}} \cos \omega t \, d\omega t \right]$$
(2)

$$V_{mean} = 1.87 V_{ph_max} \tag{3}$$

The waveform of supply voltage (phase voltage), positive voltage with respect to neutral (V_P), negative voltage with respect to neutral (V_N), load voltage, diode 1 voltage, diode 1 current, and supply current are shown in **Figure 5** parts 'a' to 'e'. The peak reverse voltage for one diode is the line voltage of nonadjacent phases and as indicated in **Figure 5c**.

The ripple voltage for DC side is



Figure 4. *The load voltage limits.*



Figure 5.

Five-phase uncontrolled rectifier waveforms: (a) supply voltage, positive voltage with respect to neutral VPN, and negative voltage with respect to neutral VNN, (b) output voltage waveform, (c) diode 1 current, (d) diode 1 current, and (e) supply current for phase 'a'.

The DC-side harmonics are generated at 10kf, where *f* is the fundamental frequency of the AC source or generated power frequency and *k* equals (1, 2, 3, etc.). The lowest order harmonic represents 2.1% of the average DC value as shown in **Figure 6**.

The supply current is a quasi-square wave in its nature as shown in **Figure 4e**. The load current is constant as the load is considered highly inductive. Switch current operates for only $2\pi/5$ from one cycle; accordingly, the switch average current can be calculated as in Eq. (5) which represents 20% of the DC-link current.



This means five-phase rectifier could have switches with lower ratings than three-phase counterpart which feed the same load as the average value of switch current in three-phase system is 33.3% [8, 15]. Part 'e' in **Figure 5** shows that supply current is a quasi-square wave where input current comprises $2\pi/5$ alternating polarity blocks, with each phase displaced to others by $2\pi/5$. The input phase current can be expressed as [5, 8, 11, 15].

$$i_{s}(t) = \sum_{n=1, 3, 5, \dots}^{\infty} \frac{4I_{dc}}{n\pi} \sin \frac{n\pi}{5} \sin (n\omega t)$$
 (6)

Substituting n = 5 (or any odd multiple of 5) into Eq. (6) results in $i_{s5}(t) = 0$. The fundamental input current (n = 1) is

$$i_{s1}(t) = 0.7484 I_{dc} \sin(\omega t)$$
 (7)

and rms value of fundamental current is

$$I_{s1} = 0.529 I_{dc}$$
 (8)

The rms value of supply current is calculated as



Figure 6. *Harmonic spectrum for load voltage percentage of average DC value.*

The harmonic contents of the supply current normalized to the fundamental component (I_{sn}/I_{s1}) are shown in **Figure 7**. The harmonic factor (HF_n) is defined as

$$HF_n\% = \frac{I_{sn}}{I_{s1}} 100$$
 (10)

Example 2: A 240 V, 50 Hz, five-phase uncontrolled rectifier is connected to highly inductive load and takes 25 A. Calculate:

b.The value of lowest order harmonic in DC side

c. Maximum and minimum DC side voltage and voltage ripple

d. The root mean square value of supply current

e. The root mean square value of the supply current fundamental

f. The third, fifth, and seventh harmonic factors for supply current

Solution

a. Average load voltage

Figure 8 shows the load voltage and supply voltage for the uncontrolled rectifier when the supply voltage has phase and rms value of 240 V.



Figure 8. *Phase voltages and load voltage.*

a. The average voltage is calculated using Eq. (3):

$$V_{mean} = 1.87 V_{ph max} = 1.87^* 240^* \sqrt{2} = 634.7 V_{ph max}$$

b. The value of lowest harmonic of DC-side voltage is 2.1% of average DC value and occurs at 10 times the supply voltage frequency, i.e. 500 Hz:

Lowest order harmonic = $0.021^{*}634.7 = 13.32$ *V*

c. The maximum voltage in DC side is the peak value of line voltage for nonadjacent phases:

$$V_{\text{max}} = 1.902 V_{ph_{\text{max}}} = 1.902^* 240 \sqrt{2} = 645.5 V_{ph_{\text{max}}}$$

The minimum voltage in DC side is the value of line voltage for nonadjacent phases at angle 18°:

$$V_{\rm max} = 1.902 V_{ph \rm max} \cos 18 = 613.96 V$$

The percentage of ripple voltage can be calculated using Eq. (4):

$$\text{\%Voltage ripple} = \frac{Maximum \ value - Minimum \ value}{V_{mean}} \text{*}100 = \frac{645.6 - 613.96}{634.7} \text{*}100 = 4.98\%$$

d. The rms of supply current is calculated using Eq. (9):

$$I_s = 0.6324 I_{dc} = 15.81 A$$

e. The root mean square value of supply current fundamental is calculated using Eq. (8):

$$I_{s1} = 0.529 I_{dc} = 0.529^* 25 = 13.225 A$$

f. The third harmonic of supply current represents 53.9% of the fundamental = 7.13 A:

The fifth harmonic of supply current = 0.

The seventh harmonic of supply current represents 23.1% of the fundamental = 3.05 A.

Example 3: A highly inductive DC load requires 100 A at 475 V. Give design details for the diode requirement using uncontrolled five-phase full-wave rectifier. Solution

The required load voltage is 475 V; hence the supply voltage can be calculated using Eq. (3):

$$V_{mean} = 1.87 V_{ph_{max}} = 475 = 1.87 V_{ph_{max}}$$

:. $V_{nh_{max}} = 254 V$

The required rms value of phase voltage is $179.6 \cong 180$ V. The line voltage of nonadjacent phases is

$$V_L = 1.902 V_{ph \max} = 1.902^* 179.6^* \sqrt{2} = 483 V_L$$

Hence, the peak reverse voltage is 483 V. Hence, each diode should withstand maximum voltage of 483 V and 100 A.

4. Fully controlled five-phase rectifier

The five-phase fully controlled rectifier is similar to the uncontrolled rectifier, but it has 10 thyristors instead of diodes as shown in **Figure 9**. The challenge with five-phase controlled rectifier is gating signal generation where the development and implementation of gating signals algorithm use nonadjacent line voltages. Delaying the commutation of thyristors for a certain firing delay angle ' α ' controls the mean load voltage.

Figure 1 illustrates how to get DC-load voltage or mean voltage from five-phase source using five-phase controlled rectifier. Figure 10a shows the phase voltages, positive voltage with respect to neutral point, and negative voltage with respect to neutral point. Figure 10b shows the gating signals for the small firing angle α . The load voltage or output voltage can be calculated by the addition of the two fivephase half-wave voltages, relative to the supply neutral point *n*, appearing at the positive and negative sides of the load, respectively. As shown in Figure 10c, the voltage is 10 pulses in nature, labeled from '1' to '10' like uncontrolled rectifier. When v_a is the most positive phase that the thyristor, T1 conducts (T1–T5 are connected to the positive terminals, and *T6–T10* are connected to negative terminals), and during this period, v_c is the most negative with thyristor T8, conducting until v_d becomes more negative, when the current in T8 commutates to T9. The next firing pulse will be to thyristor T9, and T1 is still conducting until phase b has the most positive value and is fired by *g*2, where *T*9 is still conducting, and so forth. The load voltage follows, in turn, with 10 sinusoidal voltages during one cycle, those being v_{ac} , v_{ad} , v_{bd} , v_{be} , v_{ce} , v_{ca} , v_{da} , v_{db} , v_{eb} , and v_{ec} . For the period labeled '1' in **Figure 9c**, phase *a* is the most positive and conducting, when *g*1 is applied to *T*1, while at the same time, phase *c* is conducted when *g*8 is applied to *T*8. Consequently, the load voltage ($v_{ac} = v_a - v_c$) is plotted with respect to the reference of the intersection point between phase *a* and phase *c*. Phase *c* is commutated with phase *d* for the period labeled '2', and thus, the load voltage is $(v_{ad} = v_a - v_d)$ and plotted with respect to the reference of the intersection point between phase a and phase d, where the load voltage, in turn, follows the phase voltage. Figure 10d and e shows currents in *T1* and *T6*, respectively. **Figure 10f** shows the supply current of phase 'a', which is the addition of *T1* and *T6* currents. The supply current is a quasi-square wave in nature. The supply current, the rms value of supply current, and rms value of fundamental supply current are identical to the uncontrolled rectifier case as given by Eqs. (7)–(10). Figure 10g shows the voltage across T1 which can be explained using Figure 11. The period is labeled by '2' (Figure 10g) and shows that



Figure 9. *Five-phase controlled line commutated rectifier.*



Figure 10.

Five-phase rectifier waveforms: (a) supply voltage, positive voltage with respect to neutral VPN, and negative voltage with respect to neutral VNN, (b) gating signals for firing angle α° , (c) output voltage waveform, (d) thyristor 1 current, (e) thyristor 6 current, (f) supply current for phase 'a', and (g) thyristor 1 voltage.

the voltage across the thyristor is near zero, owing to decrease in the thyristor voltage, while the period labeled by '3' (**Figure 10g**) shows that the voltage across *T1* can be calculated as v_{ba} , which has a maximum value of $1.1756V_{ph_max}$, and the waveform reference point is the intersection between phases *a* and *b*. This period is explained using **Figure 11a**. The period label in 4 (**Figure 10**) is explained with the aid of **Figure 11b**. The switch has a constraint design that it should withstand during the off periods' peak reverse voltage (*PRV*) of $1.902V_{ph_max}$ (line voltage for nonadjacent phases).

The mean load voltage can be evaluated with the aid of **Figures 10c** and **12** where it shows one pulse of the output load voltage:



Circuits calculates voltage across switch T1: (a) equivalent circuit for the period labeled 3 in **Figure 10g** and (b) equivalent circuit for the period labeled 4 in **Figure 10g**.



Figure 12. One pulse of the load voltage for uncontrolled five-phase rectifier.

$$V_{mean} = \frac{1}{2\pi/10} \int_{\frac{\pi}{10}+\alpha}^{\frac{\pi}{10}+\alpha} 1.902 V_{ph_{max}} \cos(\omega t) d\omega t$$
(11)
$$V_{mean} = 1.87 V_{ph_{max}} \cos(\alpha)$$
(12)

The angle between the fundamental input current and fundamental input phase voltage, ϕ , is called the displacement angle. The displacement factor is defined as [3, 5, 16].

$$DPF = \cos \phi_1 = \cos(\alpha) \tag{13}$$

The supply power factor is defined as the ratio of the supply power delivered P to apparent supply power S [16]:

$$pf = \frac{P}{S} \tag{14}$$

In the case of non-sinusoidal current and voltage, the active input power to the converter delivered by the five-phase source (e.g. output of wind turbine generator) is

$$P_{in} = \frac{5}{2\pi} \int_{0}^{2\pi} v_{s1}(t) \ i_{s1}(t) \ d\omega t = 5 \ V_{s1} \ I_{s1} \ \cos \phi_1$$
(15)

where V_{s1} and I_{s1} are the rms values of the fundamental components of the input phase voltage and current, respectively. The apparent power is given by

$$S = 5 V_{s-rms} I_{s-rms}$$
(16)

where V_{s-rms} and I_{s-rms} are the rms values of the input phase voltage and current, respectively. The displacement factor (*DPF*) of the fundamental current was obtained in Eq. (13). By substituting (13), (15), and (16) into (14), the power factor can be expressed as

$$pf = \frac{V_{s1}I_{s1}\cos\phi_1}{V_{s-rms}I_{s-rms}} \tag{17}$$

if the source is pure sinusoidal supply $V_{s1} = V_{s-rms}$. The output power (load power) can be calculated using

$$P_{out} = \frac{1}{T} \int_{0}^{T} v(t) i(t) dt = V_{mean} I_{mean}$$
(18)

The efficiency is

$$\eta = \frac{P_{out}}{P_{in}} \tag{19}$$

The total harmonic distortion, *THD*, is given by [3, 5, 15]

$$THD = \frac{\sqrt{I_s^2 - I_{s1}^2}}{I_{s1}}$$
(20)

For a five-phase rectifier, the *THD* is 65.5%.

Example 4: A five-phase fully controlled rectifier is fed from 220 V (phase value), 50 Hz AC source. The DC load is highly inductive and requires 100 A at 475 V. Give design details for the thyristor requirement and the required firing angle. What is maximum DC load voltage that the converter can deliver to the load?

Solution

The required load voltage is 475 V and the supply voltage is 220 V. The firing angle can be calculated using Eq. (12):

$$V_{mean} = 1.87 V_{ph_max} \cos \alpha = 475 = 1.87^* 200^* \sqrt{2} \cos \alpha$$

$$\therefore \ \cos \alpha = 0.8998$$

$$\therefore \ \alpha = 26.1^\circ$$

The peak line voltage of nonadjacent phases is

$$V_L = 1.902 V_{ph_{max}} = 1.902^* 220^* \sqrt{2} = 591.8 V_{ph_{max}}$$

Hence, the peak reverse voltage is \cong 592 V. Hence, each thyristor should withstand maximum voltage of 592 V and 100 A.

The maximum possible DC load voltage is when α is adjusted to zero:

$$V_{mean} = 1.87 \, V_{ph} \,_{
m max} = 1.87^* 220^* \sqrt{2} = 581.8 \,$$
 V

Example 5: A five-phase fully controlled rectifier is fed from 230 V (phase value), 15 Hz AC source. The load is 45 Ω resistance and 1 H inductance (highly inductive load). Calculate for firing angle 36°, the converter power factor. Simulate your converter.

Solution The mean lo

mean load voltage is

$$V_{mean} = 1.87 V_{ph_{max}} \cos \alpha = 1.87^* 230^* \sqrt{2} \cos 36 = 492 V$$

The load current is

$$I_{mean} = \frac{V_{mean}}{R} = \frac{492}{25} = 19.68 \ \Omega$$

From Eq. (8), the rms value for fundamental supply current is 10.41 A. The angle of fundamental current is the firing angle. From Eq. (9), the rms value of supply current is 12.44 A. The power factor is calculated using Eq. (17):

$$pf = \frac{V_{s1}I_{s1}\cos\phi_1}{V_{s-rms}I_{s-rms}} = \frac{230^*10.41^*\cos(36)}{230^*12.44} = 0.677$$

The load voltage and supply current are shown in **Figure 13**. It should be noted that as the firing angle is 36°, the load voltage shown in **Figure 13a** starts for phase 'a' at 90° which equals 54°, the intersection point between two adjacent phases, and 36° which is the firing angle. The supply current for phase 'a' is shown in **Figure 13b**. Switch 1 accommodates 72° and starts at 90°. Switch 6 is shifted 180° for the same phase.

5. Gating pulse generation

A pulse generator synchronized on the source voltage provides the trigger pulses for the 10 thyristors that construct the 10-pulse rectifier. The pulses are generated by α degrees after increasing zero crossings of the commutation voltages which is indicated in **Figures 10a** and **12**. The input to the gating signal generator is 10 signals represent five-line voltages for nonadjacent phases and its inverted signals, and multiplexed, then determines the zero-crossing point and counts the delay angle α and hence applies the pulse for the specified switch through gate drive circuits as shown in **Figure 14**. A double-pulse technique is used to ensure that the specified gate signal fires its own thyristor [3, 5].

A sample of gating signal generation is shown in **Figure 15** where an example for gating signal generator output with delay angle 36° with double-pulse technique is indicated. The phase voltages of five-phase permanent magnet generator are measured as shown in part a where the rotational speed tends to have a frequency around 18 Hz and rms value of 56 V. The delay angle is calculated from the



Figure 13. *Load voltage and supply current waveforms: (a) load voltage and (b) supply current.*





zero-crossing point determined by the pulse generator as indicated in **Figure 15b** where gate signals 1, 2, and 6 confirm that the phase shift between gates 1 and 2 is 72° and between gates 1 and 6 is 180°. The delay angle is calculated after 54° from the start of the phase voltage [3, 5]. If the delay angle is increased to 36°, the results



Figure 15. *Gating pulse generation: (a) Phase voltage for PM generator; (b) g1, g2, and g6 for firing angle zero; and (c) g1, g2, and g6 for firing angle 36°.*



Figure 16. *Gating pulses for firing angle 36° (g1–g10).*

show that the relation between g1, g2, and g6 will be the same but shifted to 90° from the starting of phase voltage as shown in **Figure 15c**.

Example 6: For the converter given in '**Example 5**', plot the gating signals Solution

Figure 16 shows the gating signals for firing angle 36°.

6. Conclusion

This chapter introduces the five-phase, 10-pulse, line commutated rectifier. The relation between phase voltage and line voltage for five-phase source is introduced where line voltage equals $1.1756V_{ph_max}$ and leads the phase voltage by 54° for adjacent phases, while it equals $1.902V_{ph_max}$ and leads the phase voltage by 18° for nonadjacent phases. The converter performance and analysis for both AC side and DC side are detailed for both uncontrolled and controlled rectifiers. The average voltage of the DC side is $1.87V_{ph_max}$ with ten pulses per one cycle, while it is 1.654

 V_{ph_max} with six pulses for three-phase counterpart. Moreover, the DC-side voltage ripple is around 5%, while it is around 14% for full-wave three-phase converter. The switch (diode or thyristor) carries only 20% of the load current during one cycle, while it carries 33.3% in three-phase counterpart, and no-phase shifting transformer is required like 12-pulse converter. Also, the implementation of gating signal generation is introduced. The gating signal generation adopts double-pulse techniques and ensures the real-time synchronization between the five-phase source and gating signals. The phase shift pulse of adjacent phases is 72°, while the phase shift between pulses applied for switches on the same phase adopts 180°.

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