

CHAPTER THREE

POWER ELECTRONIC CONVERTERS FOR INDUCTION MOTOR DRIVES

3.1 Uncontrolled Operation of Induction Motors:

In a majority of induction motor drives in industrial and domestic applications, the control functions are limited to the turn-on and turn-off and, in certain cases, to assisted starting, braking, and reversing. When driving a load, an induction motor is supplied directly from a power line and operates with fixed values of stator voltage and frequency. The speed of the motor is approximately constant, motors with a stiff mechanical characteristic (i.e., with low dependence of load torque on the speed) having been usually used. As already mentioned, such a characteristic is associated with a low rotor resistance, that is, with low losses in the rotor[4][13].

Thus, high-efficiency motors, somewhat more expensive than standard motors, are particularly insensitive to load changes.

Clearly, an uncontrolled motor drive is the cheapest investment, but the lack of speed control carries another price. In many applications, a large percentage of the electric energy is wasted because of that shortcoming. The most common induction motor drives are those associated with fluid transport machinery, such as pumps, fans, blowers, or compressors.

To control the flow intensity or pressure of the fluid, valves choking the flow are used. As a result, the motor delivers full power, a significant portion of which is converted into heat in the fluid. This situation is analogous to that of a car driven with a depressed brake pedal. Energy and money savings have been the major reason for the increasing popularity of ASDs, which, typically, are characterized by short payback periods[13][7].

Sensitivity to voltage sags constitutes another weakness of uncontrolled drives. Even in highly developed industrial nations, the power quality occasionally happens to be poor. Because the torque developed in an induction motor is quadratically dependent on the stator voltage, a voltage sag can cause the motor to stall. This typically leads to intervention of protection relays that trip (disconnect) the motor. Often, the resultant process interruption is quite costly. Controlled drives can be made less sensitive to voltage changes, enhancing the "ride-through" capability of the motor[4].

3.2 Assisted Starting:

As explained in Figure 2.19, the stator current at zero slip, that is, the starting current, is typically much higher than the rated current. Using the approximate equivalent circuit in Figure 2.16, the starting current, $I_{s,st}$, can be estimated as[13]:

$$I_{s,st} = \frac{V_s}{\sqrt{(R_s + R_r)^2 + X_1^2}} \quad (3.1)$$

In this figure the motor, the starting current, at about 6.3 times higher than the rated current. For small motors this is usually not a serious issue, and they are started by connecting them directly to the power line. However, large motors, especially those driving loads with high inertia or high low-speed torque, require assisted starting. The following are the most common solutions [13]:

1. In *autotransformer starting*, illustrated in Figure 3.1, a three phase autotransformer is controlled using timed relays. The stator voltage at starting is reduced by shutting contacts 1 and 2, while contacts 3 are open. After a preset amount of time, contacts 1 and 2 are opened and contacts 3 shut.
2. In *impedance starting*, illustrated in Figure 3.2, series impedances (resistive or reactive) are inserted between the power line and the motor to limit the starting current. As the motor gains speed, the impedances are shorted out, first by contacts 1, then by contacts 2.

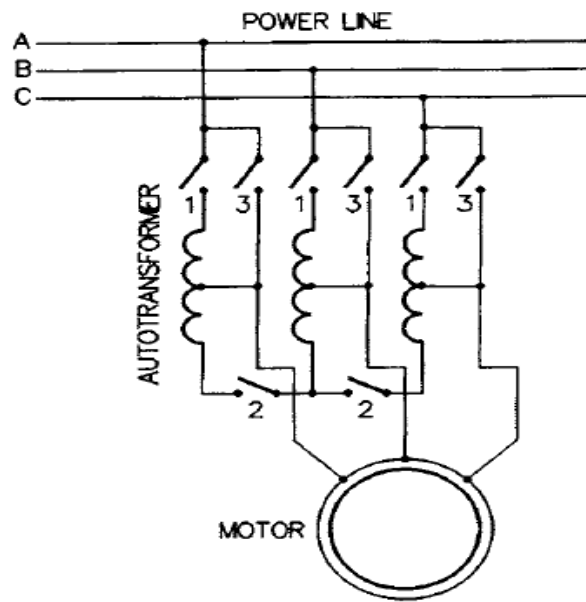


FIGURE 3.1: Autotransformer starting system.

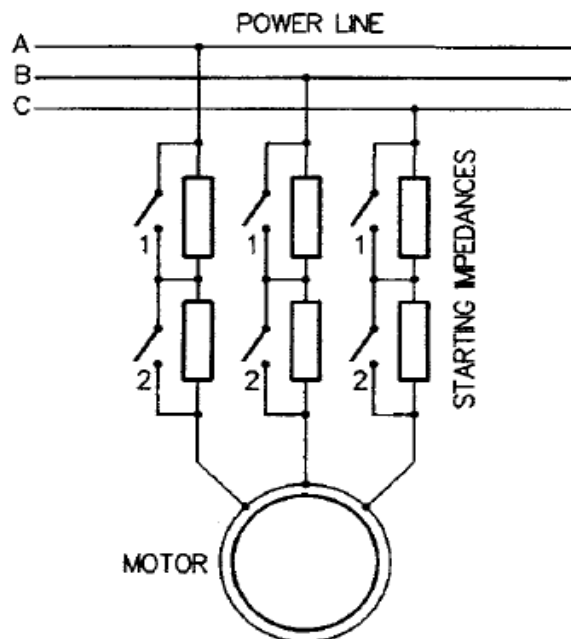


FIGURE 3.2: System with starting impedances.

3. In *wye-delta starting*, illustrated in Figure 3.3, a special switch is used to connect stator phase windings in wye (contacts "w") when the motor is started and, when the motor is up to speed, to reconnect the windings in delta (contacts "d"). With wye-connected phase windings, the per-phase stator voltage and current are reduced by in comparison with those for delta connected windings. The wye-delta switch can be controlled manually or automatically.

4. In *soft-starting*, illustrated in Figure 3.4, a three-phase soft-starter based on semiconductor power switches is employed to reduce the stator current. This is done by passing only a part of the voltage waveform and blocking the remaining part. The voltage and current waveforms are distorted, generating harmonic torques, until, when the motor has gained sufficient speed, the soft-starter connects it directly to the power line.

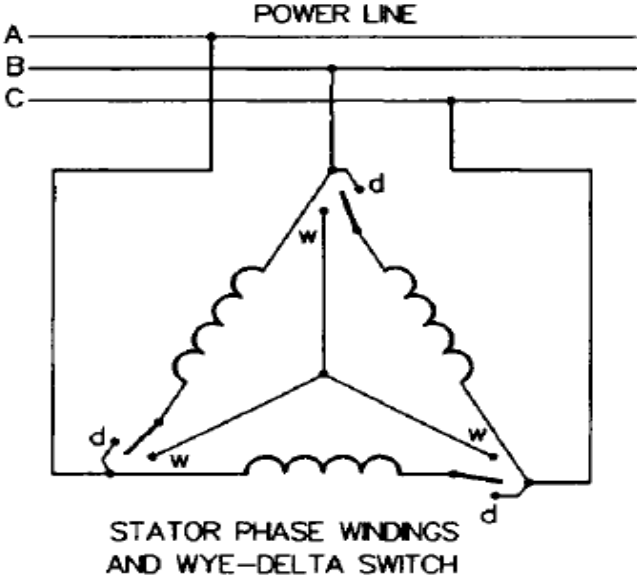


FIGURE 3.3: Starting system with the wye-delta switch.

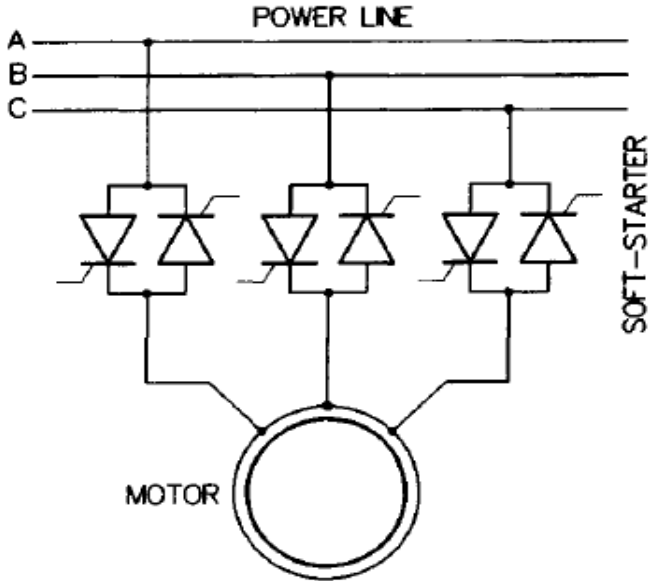


FIGURE 3.4: Soft-starting system.

3.3 Control of Stator Voltage:

As seen from Eq. (2.17), the speed of an induction motor can be controlled by changing the number of poles and the supply frequency. Changes of slip can be effected by varying the stator voltage, particularly in motors with soft mechanical characteristics. However, this method is inefficient, because rotor losses are proportional to the slip. Also, in most motors, it is ineffective because of the narrow range of controllable slip (from zero to the critical value). For wide-range speed control, adjusting the supply frequency constitutes the only practical solution. The frequency control must be accompanied by magnitude control of the stator voltage[4].

To produce adjustable-frequency, adjustable-magnitude, three-phase voltage for induction motor drives, power electronic inverters are most commonly used. Inverters are dc to ac converters, so the regular 50-Hz (60-Hz in many countries) ac voltage must first be rectified to provide the dc supply for the inverter. The soft-starters described in Section 3.2 are based on ac voltage controllers, which are ac to ac converters with adjustable rms value of the output voltage.

The frequency is not changed in ac voltage controllers; that is, the output voltage has the same frequency as the supply voltage. In the subsequent sections, rectifiers and inverters employed in ASDs with induction motors are briefly described [13][7].

3.4 Rectifiers:

Rectifiers in induction motor ASDs supply dc voltage to inverters. The three-phase full-wave (six-pulse) diode rectifier, shown in Figure 3.5, is most commonly employed. At any time, only two out of six diodes conduct the output current, i_o . These are the diodes, subjected to the highest line- to-line input voltage. For instance, if at a given instant the highest line- to-line voltage is v_{AB} , diodes DA and DB` conduct the output current, so that $i_A = i_O$ and $i_B = -i_o$. The other four diodes are then reverse biased, while the output voltage, v_o , equals v_{AB} , [13].

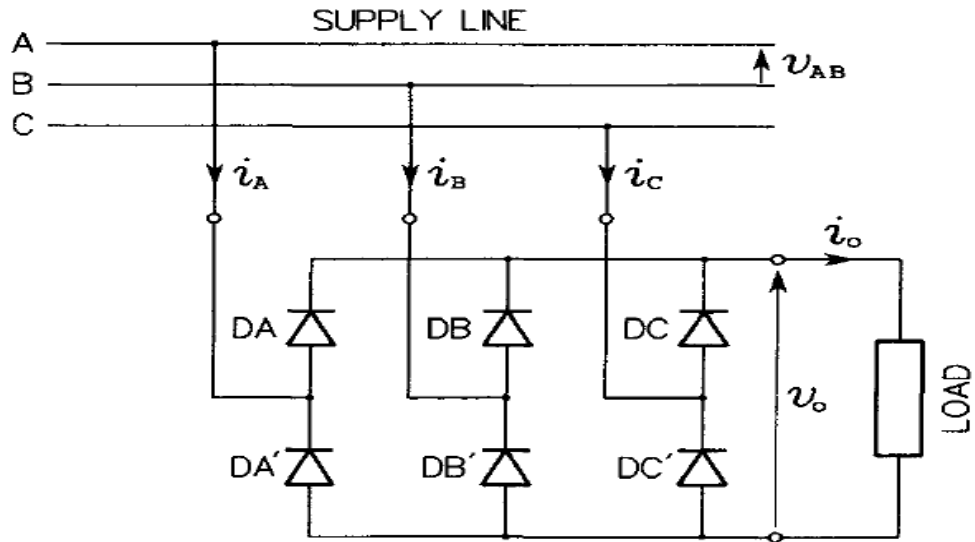


FIGURE 3.5: Six-pulse diode rectifier.

Because, thanks to the conducting diodes, the highest line-to-line input voltage appears at the output of the rectifier, the output voltage is the envelope of all six line-to-line voltages of the supply line. This is illustrated in Figure 3.6, which shows the line-to-line voltages and output voltage of the six-pulse diode rectifier. The output voltage is not ideally of the dc quality, but it has a high dc component, V_0 (average value of v_0), given by :

$$V_0 = \frac{3}{\pi} V_{LL,m} \approx 0.955 V_{LL,m} \quad (3.2)$$

where $V_{LL,m}$ denotes the peak value of line-to-line input voltage. The output current, whose example waveform is also shown in Figure 3.6, depends on the load, but its waveform has even less ripple (ac component) than does the voltage waveform.

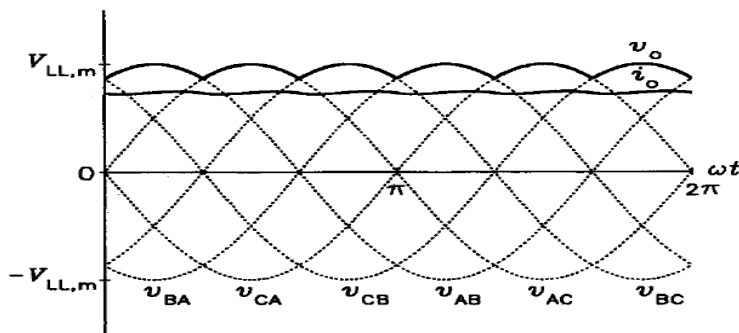


FIGURE 3.6: Waveforms of the output voltage and current in a six-pulse diode rectifier

Assuming an ideal dc output current, $i_0 = I_0$, the input line current have a rectangular waveform, as shown in Figure 3.7. This is a serious annoyance for the supplying power system, which is designed to operate with sinusoidal voltages and currents. The high harmonic content of the square-wave current drawn by the rectifier and the resultant distortion of the voltage waveforms in the power system cause interference with operation of sensitive communication equipment, and they may precipitate unwarranted intervention of system protection circuits, It should be pointed out that, thanks to the half-wave symmetry of the current waveform, no even (2nd, 4th, etc.) harmonics are present, while the three-phase balance of currents in individual supply wires causes the absence of triple harmonics (3rd, 9th, etc.) as well. As a result, the low-order harmonics in the input current of a diode rectifier are the 5th, 7th, 11th, 13th, etc. When the diodes are replaced with SCRs (silicon controlled rectifiers, also known as thyristors), TA through TC', as in Figure 3.8, a phase-controlled six-pulse rectifier is obtained, The adjustable dc output voltage, V_0 , of the rectifier is given by

$$V_0 = \frac{3}{\pi} V_{LL,m} \cos(\alpha_f) \quad (3.3)$$

where α_f denotes the firing angle, which determines instants of turning on (firing) the SCRs. Specifically, $\alpha_f = 0$ represents the situation when an SCR is fired at the same instant at which the respective diode in an uncontrolled rectifier in Figure 3.5 would begin conducting. If, in the ωt domain, the firing is delayed with respect to that instant by α_f radians, the average output voltage is reduced in proportion to $\cos(\alpha_f)$.

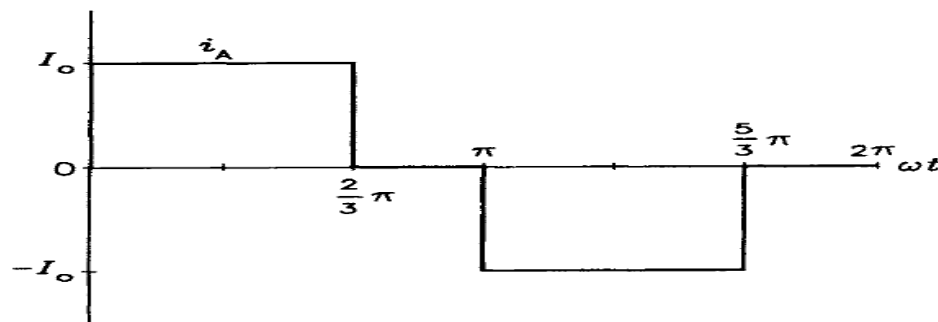


FIGURE 3.7 Waveform of the input current in a six-pulse diode rectifier.

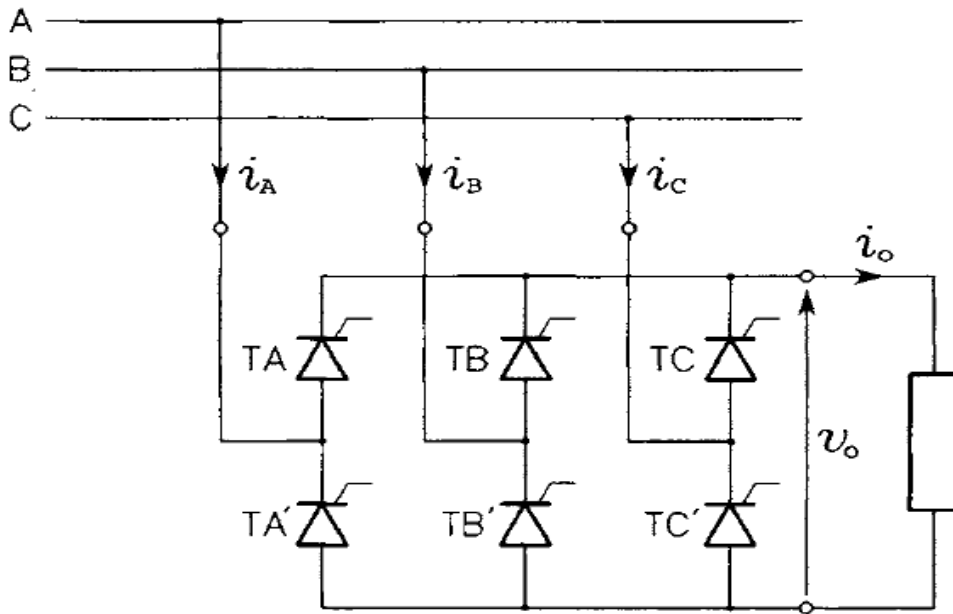


FIGURE 3.8: Six-pulse phase-controlled rectifier.

Waveforms of the output voltage, v_o , and current, i_o , with the firing angle of 45° are illustrated in Figure 3.9. Eq.(3.3) implies a possibility of negative dc output voltage when the firing angle exceeds 90° . Because the output current cannot be negative (it would have to flow from the cathode to anode of the SCRs), the negative value of V_o indicates transfer of power from the load to supply system. Clearly, that requires an active load, such as an electric machine, capable of delivering electrical energy. A controlled rectifier transferring power from the load to the supply is said to operate in the inverter mode. This mode is illustrated in Figure 3.10, which shows the output voltage and current waveforms for the firing angle of 135° . Input current waveforms in the controlled rectifier are similar to those in the diode rectifier.

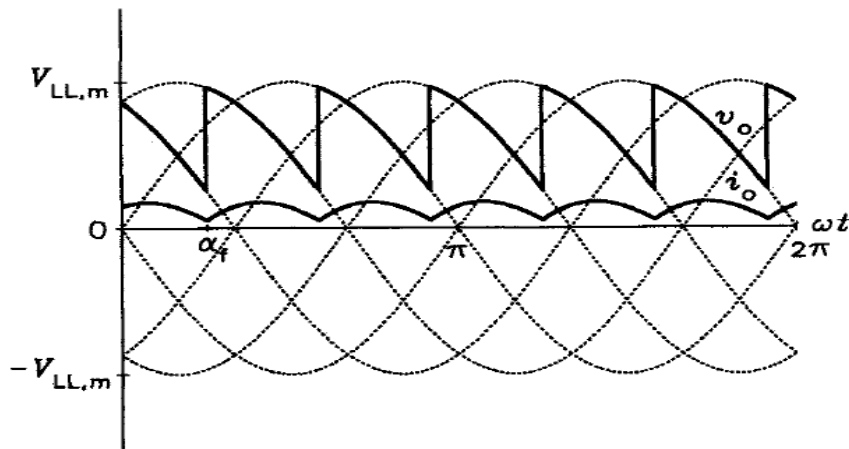


FIGURE 3.9: Waveforms of the output voltage and current in a six-pulse phase controlled rectifier ($\alpha_f = 45^\circ$).

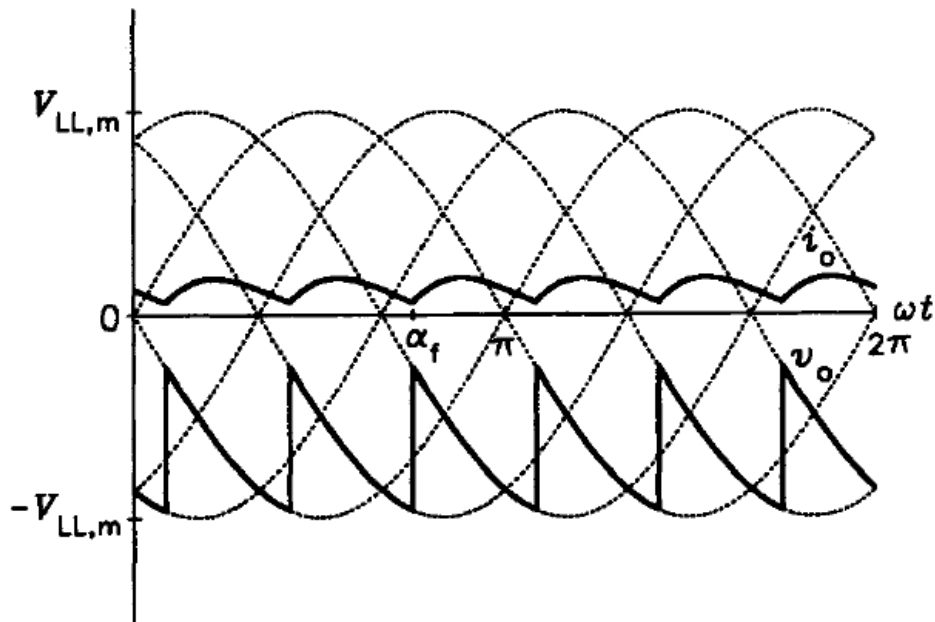


FIGURE 3.10 Waveforms of the output voltage and current in a six-pulse phase controlled rectifier in the inverter mode ($\alpha_f = 135^\circ$).

In addition to the rectangular waveform of these currents, shown in Figure 3.11, the input power factor of the controlled rectifier is lower than that of the diode rectifier. The power factor, which similarly to the dc output voltage is proportional to the cosine of the firing angle, decreases with the increase of this angle. The poor quality of currents drawn from the power system is a major disadvantage of uncontrolled and phase-controlled rectifiers.

The problem of harmonic pollution of the power system caused by power electronic converters, often called nonlinear loads is very serious and significant efforts to combat the system harmonics are being made. The most common solution is to install appropriate filters, either between the power system and the offending converter (series filters) or in parallel with the converter (parallel filters) Filters can be Passive or active.

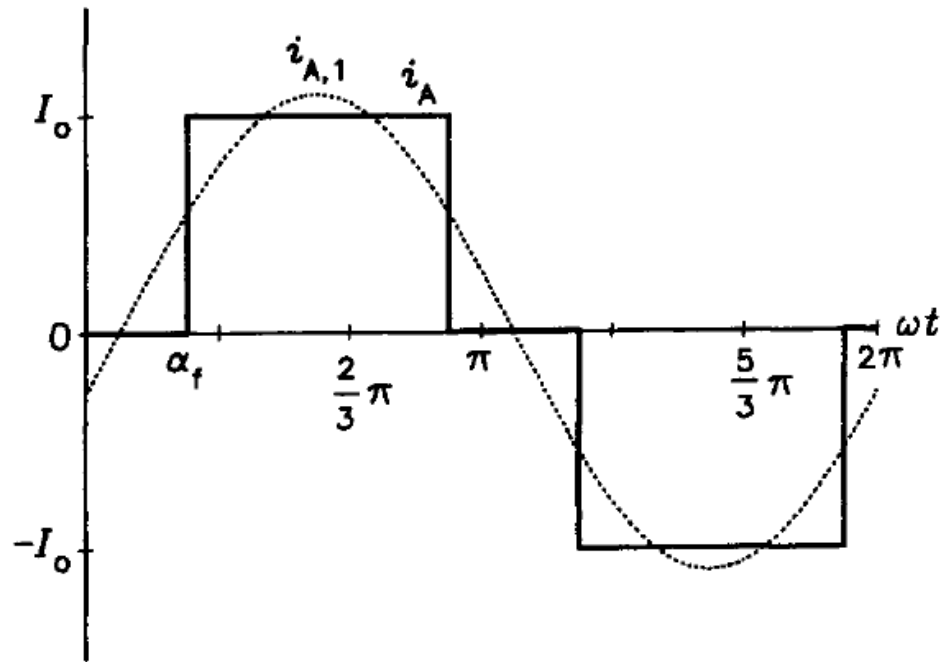


FIGURE 3.11 Waveform of the input current in a six-pulse phase-controlled rectifier.

Passive filters are Simple LC (inductive-capacitive) circuits designed to block and shunt current harmonics so that they are drawn from filter capacitors rather than from the power system. With respect to diode rectifiers, the so-called harmonic traps are often used. They are series-resonant LC circuits, tuned to frequencies of the lowest harmonics of the input current, for instance the 5th, 7th, 11th, and 13th. The harmonic traps shunt the respective harmonic currents from the power system. The remaining, unfiltered harmonics usually have such low amplitudes that waveforms of currents drawn from the system are close to ideal sinusoids.

The resonant frequencies of harmonic traps are relatively low, because even the 13th harmonic has a frequency well below 1 kHz. Therefore, the inductors and

capacitors used in the traps are large and expensive. To significantly reduce the size of passive filters, pulse width modulated (PWM) rectifiers must be used. There are two types of these converters, the voltage source and current source PWM rectifiers.

The voltage source PWM rectifier based on IGBTs, the most popular semiconductor power switch nowadays (the so-called non-punch-through IGBTs must be used because of the ac input voltages), is shown in Figure 3.12. The three-phase line with input filters based on inductors L_i and capacitors C_i constitutes the voltage source for the rectifier. The input inductors do not have to be physical components, because the supplying power system itself may possess sufficient inductance, but the capacitors are necessary.

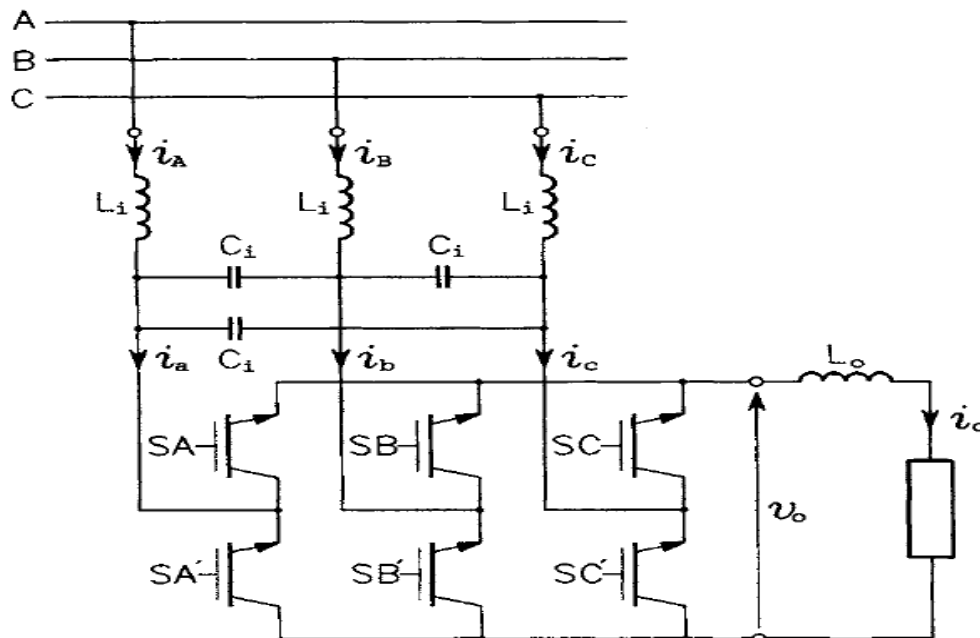


FIGURE 3.12: Voltage source PWM rectifier

The output inductance, L_o , which can be provided by the load, smooths the output current. Switches, SA through SC', of the rectifier - are turned on and off many times per cycle of the input voltage in such a way that the fundamental input currents follow desired reference values. . Example waveforms of the output voltage, v_o , and current, i_o , of the rectifier are shown in Figure 3.13, and those of the input current, i_a , and its fundamental, $i_{a,1}$, in Figure 3.14. The fundamentals are supplied from the power line, while the high frequency harmonic components of the pulsed currents i_a , i_b , and

i_c , are mostly drawn from the capacitors. As a result, waveforms of currents i_A , i_B and i_C supplied by the power system and shown in Figure 3.15, are close to ideal sinusoids, with only a small amount of ripple.

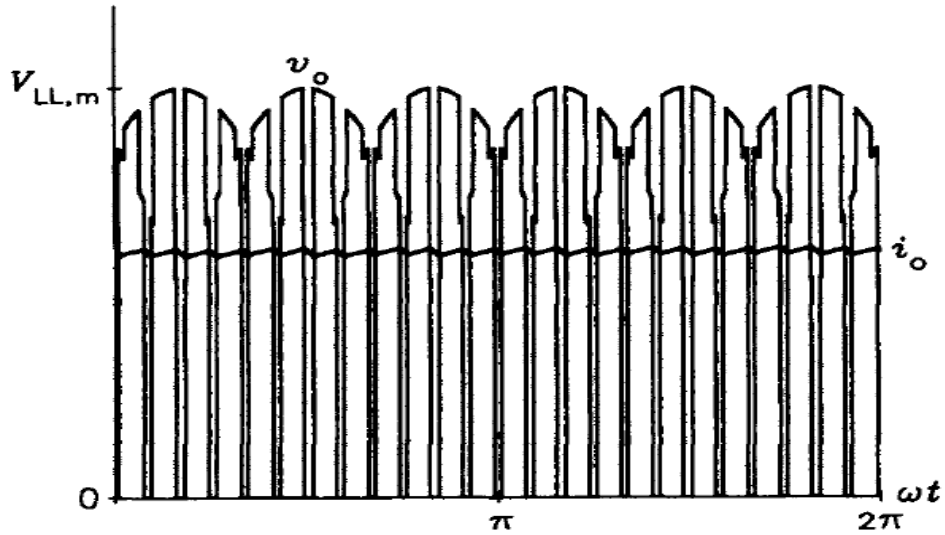


FIGURE 3.13 Waveforms of the output voltage and current in a voltage source PWM rectifier.

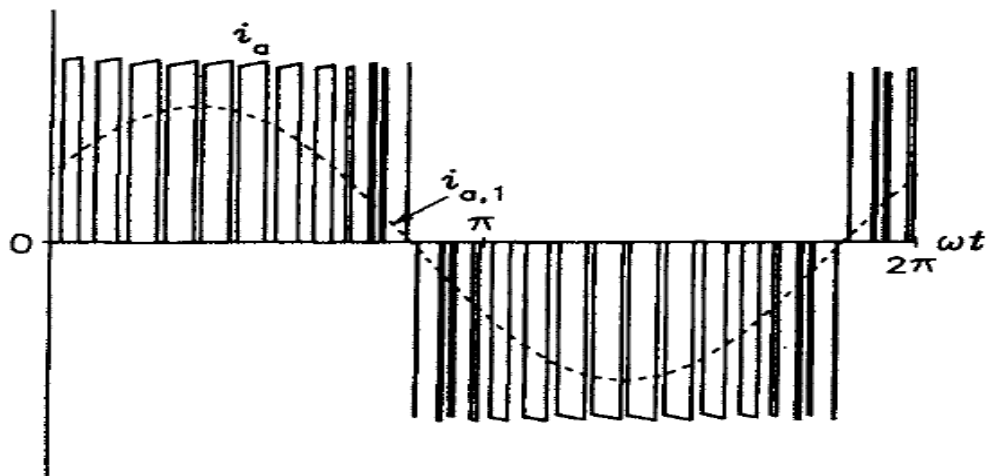


FIGURE 3.14: Waveforms of the input current and its fundamental in a voltage source PWM rectifier.

The dc output voltage of the voltage source rectifier cannot be adjusted to a value greater than the peak value of line-to-line supply voltage. In contrast, the Current source PWM rectifier shown in Figure 3.16 allows the boosting of the output voltage.

The current source properties of the rectifier result from the input inductors, L_i . Because the rectifier switches provide direct connection between the input and output of the converter, the output capacitor, C_o , is necessary to prevent connecting the input inductance, carrying certain current, with the load inductance, which may conduct a different current.

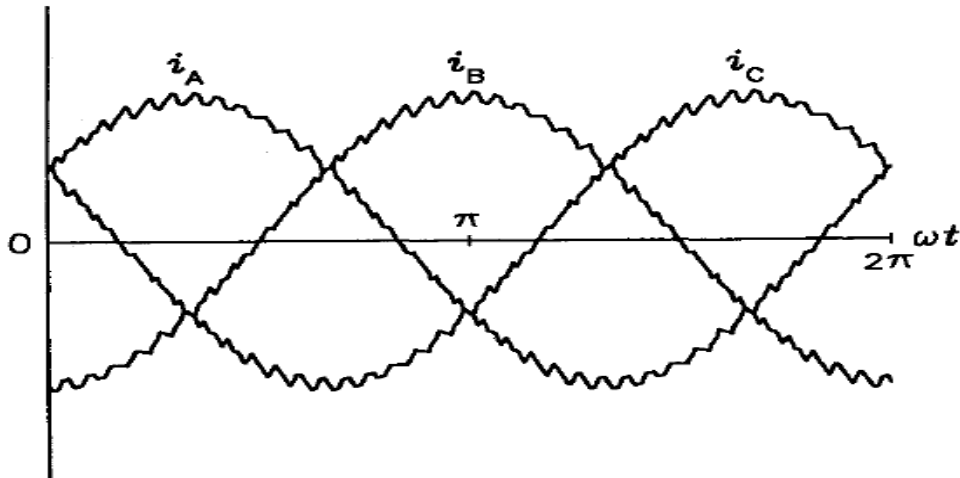


FIGURE 3.15 Waveforms of currents supplied by the power system to the voltage source PWM rectifier.

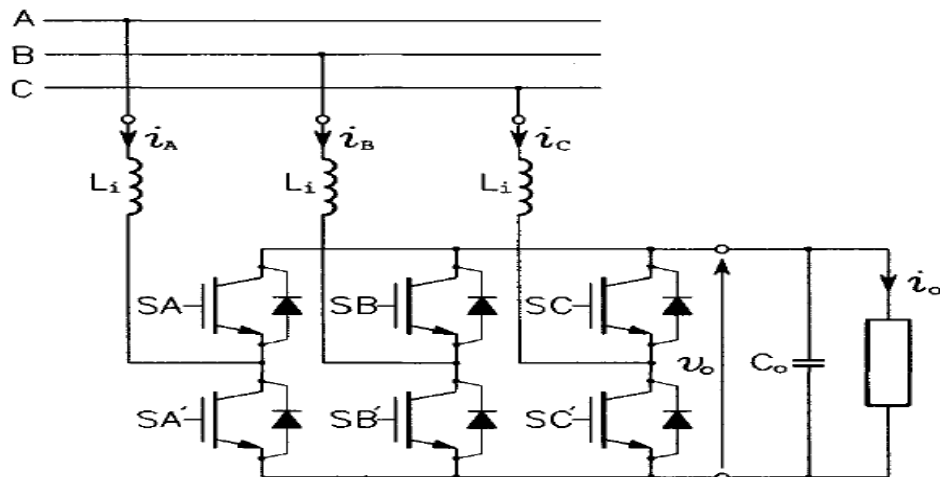


FIGURE 3.16 *PWM* rectifier.

The same capacitor smooths the output voltage, v_o . Analogously, should a smoothing capacitor be used in the voltage source PWM rectifier in Figure 3.12, a physical inductor L_i would have to be used between the rectifier output and the

capacitor to avoid connecting this capacitor, charged to a certain Voltage, across the input capacitor charged to a different voltage.

The semiconductor power switches are paired with inverse parallel freewheeling diodes, which provide alternative paths for currents that cannot flow through switches. Suppose, for example, that switch SA' is turned on and conducts current i_A , whose polarity is that shown in Figure 3.16. When the switch is turned off, the current cannot change instantly, having been maintained by the input inductor in phase A. As a result, the current will force its way through the freewheeling diode of switch SA. Thanks to the output capacitor, the output voltage and current waveforms are practically of the dc quality, with a minimal ripple. Currents drawn from the power system are similar to those in the voltage source PWM rectifier (see Figure 3.15).

The phase-controlled and PWM rectifiers have the capability of reversed power flow, necessary for efficient operation of the drive system in the second and fourth quadrants. In practice, multiquadrant drives are much less common than the single-quadrant ones, which explains the already mentioned dominance of diode rectifiers in induction motor ASDs. PWM rectifiers are mostly used in low- and medium power drive systems, with phase-controlled rectifiers employed in the higher ranges of power.

3.5 Inverter:

The three-phase voltage source inverter (VSI) is shown in Figure 3.17. The voltage Source for the inverter is made up from a rectifier and the so-called dc link, composed of a capacitor, C, and inductor, L. If the ac machine fed from the inverter operates as a motor (i.e., in the first or third quadrant), the average input current is positive. However the instantaneous input current i_i , may assume negative values, absorbed by the dc-link capacitor which, therefore, is necessary. The capacitor also serves as a source of the high frequency ac component of i_i , so that it is not drawn from the power system via the rectifier. In addition, the dc link capacitor smooths and stabilizes the voltage produced by the rectifier. The optional dc-link inductor is less

important, being introduced to provide an extra screen for the power system from the high frequency current drawn by the Inverter [13].

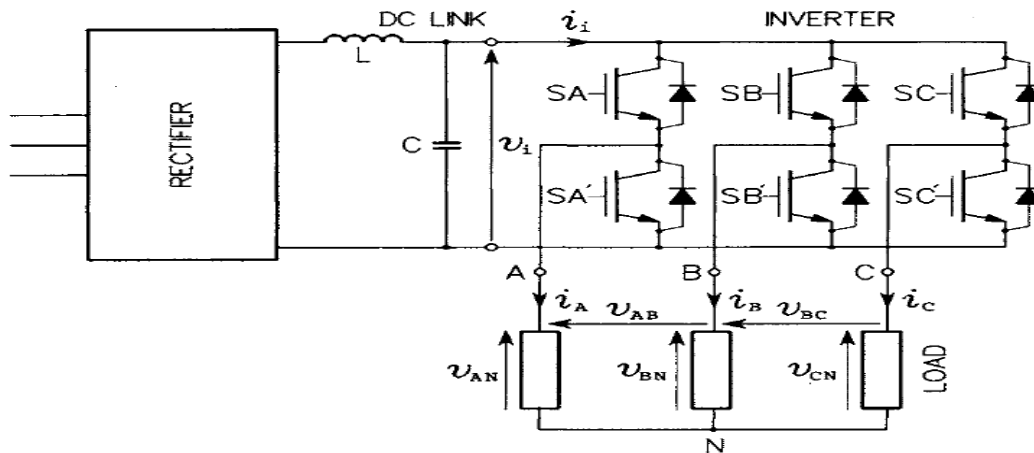


FIGURE 3.17 Voltage source inverter.

Clearly, the topology of the voltage source inverter represents an inverse of that of the current source PWM rectifier in Figure 3.16 (note, that the load of the inverter contributes the inductances corresponding to input inductances, L_i , of the rectifier). Here, the freewheeling diodes provide alternative paths for output currents. Both semiconductor power switches in a given leg (phase) of the inverter may not be on simultaneously, because they would short the input terminals. On the other hand, with both switches off, the output voltage would be indeterminable, because the potential of the respective output terminal would depend on which diode is conducting the output current in that phase. This would make the open-loop control of the output voltage impossible. Therefore, voltage source inverters are so controlled that one switch in each leg is on and the other is off. In this way, the turned-on switch connects one of the input terminals to the output terminal, and potentials of all three output terminals are always known. To avoid the so-called shot-through, that is, potentially damaging simultaneous conduction of both switches in the same leg, turn-on of a switch is delayed a little with respect to turn-off of the other switch. This delay, on the order of few microseconds, is called a dead time or blanking time.

The voltage source inverter can operate in both the PWM mode and the so-called square-wave mode, characterized by rectangular waveforms of the output

voltage. The square-wave operation yields the highest voltage gain of the inverter, but the quality of output current is poorer than that in the PWM mode.

Figure 3.18 shows the current source inverter (CSI) which, in square-wave mode, produces rectangular waveforms of the output current for consistency, IGBTs are shown here as the inverter switches, but practical current source inverters are often of such a high power that they must be based on GTOs or SCRs with commutating circuits (to turn the SCRs off). The current-source supply is provided by a controlled rectifier with closed-loop current control and the inductive dc link. The inverter differs from its voltage source counterpart by the absence of freewheeling diodes, which are unnecessary because the constant input current is never negative.

Addition of capacitors at the output allows for PWM operation of the current source inverter. These capacitors are marked in Figure 3.18 using broken lines. The switching action of inverter switches results in pulsed waveforms of currents i_a , i_b , and i_c but the capacitors shunt most of the high-frequency harmonic content of these currents. Thus, waveforms of the output currents, i_A , i_B and i_C are rippled sinusoids. This inverter is an inverse of the voltage-source rectifier in Figure 3.12.

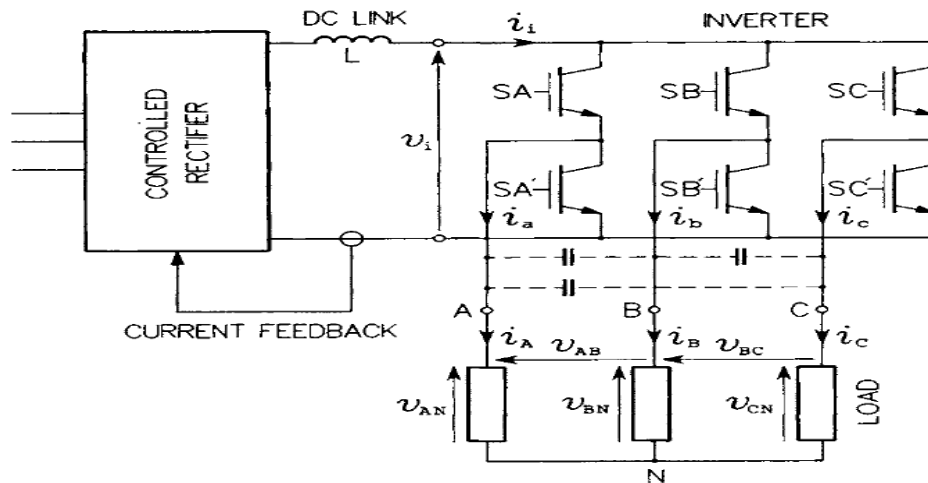


FIGURE 3.18 Current source inverter.

3.6 Frequency Changers:

A cascade of a rectifier, dc link, and inverter can be thought of as a frequency changer, in which the fixed-frequency input voltage and current are converted into adjustable-frequency output variables. Frequency changers with a reversible power flow are of particular interest in the drive technology. The rectifier in such a scheme may be of the phase-controlled or PWM type. The voltage source and current source PWM frequency changers are shown in Figures 3.19 and 3.20, respectively.

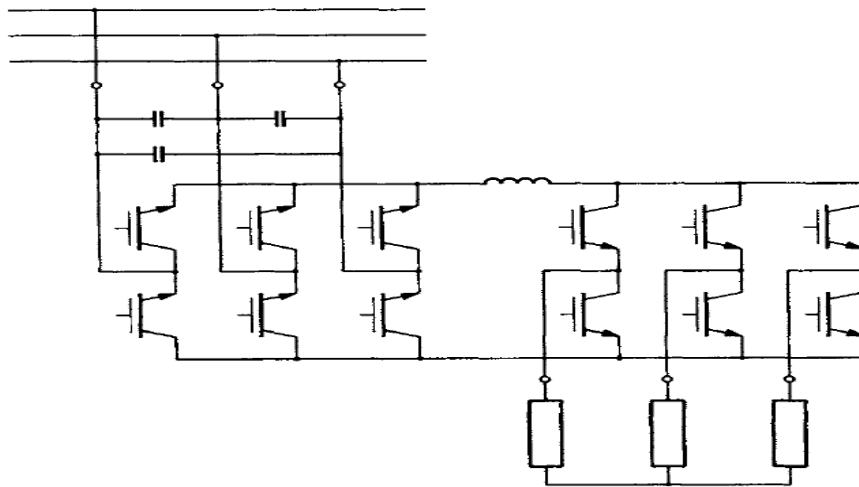


FIGURE 3.19: Voltage source PWM frequency changer.

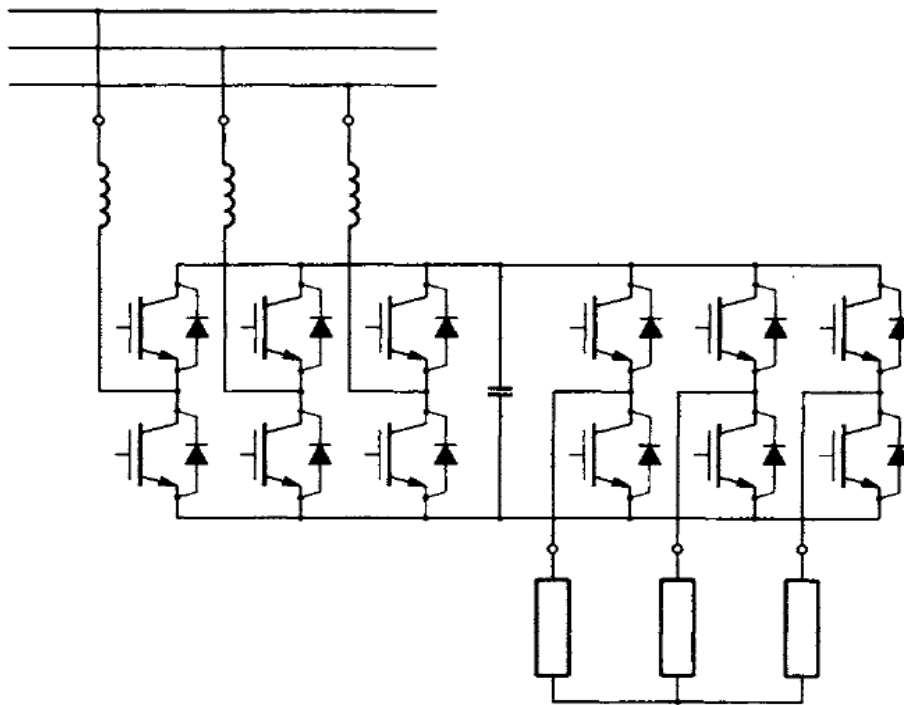


FIGURE 3.20: PWM frequency changer.

They are characterized by high-quality input currents, and they can transfer power in both directions.

3.7 Control of Voltage Source Inverters:

To explain the principles of control of inverters, it is convenient to introduce the so-called switching variables, variously defined depending on the type of inverter. For the most common, two-level voltage source inverter depicted in Figure 3.17, three binary switching variables, a , b , and c , one per phase of the inverter, are sufficient. As already mentioned, both switches in an inverter leg cannot be on simultaneously, because they would short the dc supply source (i.e., the dc-link capacitor). The situation when both switches are off is not dangerous, but the voltage at the corresponding output terminal is undetermined. This is so because, depending on the polarity of the load current, the terminal would be connected, via one of the freewheeling diodes, to either the positive or negative dc bus. Therefore, in practice, except for the very short blanking time intervals, one switch in each phase is on, and

the other is off. Consequently, each inverter leg can assume two states only, and the number of states of the whole inverter is eight (2^3).

Taking as an example phase A, the switching variable a is defined to assume the value of 1 if switch SA is on and switch SA' is off. If, conversely, SA is off and SA' is on, a assumes the value of 0. The other two switching variables, b and c , are defined analogously. An inverter state can be denoted as abc_2 . For example, with $a = 1$, $b = 0$, and $c = 1$, the inverter is said to be in State 5, because $101_2 = 5$.

It is easy to show that the line-to-line output voltages, v_{AB} , v_{BC} , and v_{CA} , of the voltage source inverter are given by

$$\begin{bmatrix} v_{AB} \\ v_{BC} \\ v_{CA} \end{bmatrix} = V_i \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (3.4)$$

When the same control principle is applied to all three phases of an inverter feeding a balanced wye-connected load, the individual line-to-neutral voltages, v_{AN} , v_{BN} and v_{CN} , are balanced too; that is;

$$v_{AN} + v_{BN} + v_{CN} = 0 \quad (3.5)$$

In addition (unconditionally),

$$v_{AN} - v_{BN} = v_{AB} \quad (3.6)$$

and

$$v_{BN} - v_{CN} = v_{BC} \quad (3.7)$$

Solving Eqs. (3.5) to (3.7) for v_{AN} , v_{BN} and v_{CN} , yields

$$\begin{bmatrix} v_{AN} \\ v_{BN} \\ v_{CN} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} \begin{bmatrix} v_{AB} \\ v_{BC} \\ v_{CA} \end{bmatrix} \quad (3.8)$$

Which, when combined with Eq. (3.4), gives

$$\begin{bmatrix} v_{AN} \\ v_{BN} \\ v_{CN} \end{bmatrix} = \frac{V_i}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} v_{AB} \\ v_{BC} \\ v_{CA} \end{bmatrix} \quad (3.9)$$

The simplest control strategy for the inverter consists in imposing the 5-4-6-2-3-1 state sequence, resulting in the already-mentioned square-wave, or six-step, mode of operation. Waveforms of the line-to-line and line-to-neutral output voltages of the inverter in this mode are shown in Figure 3.21. Each switch of the inverter is turned on and off once per cycle only, and the peak value of the fundamental line-to-line output voltage is $1.1V_i$. However, the load current is of poor quality, due to the high content of low-order voltage harmonics. Also, the magnitude of output voltage cannot be controlled within the inverter, which constitutes another disadvantage of the square-wave mode. Therefore, in most practical inverters, transition to the square-wave operation occurs only when the maximum possible output voltage is needed. Other than that, the inverter operates in the PWM mode.

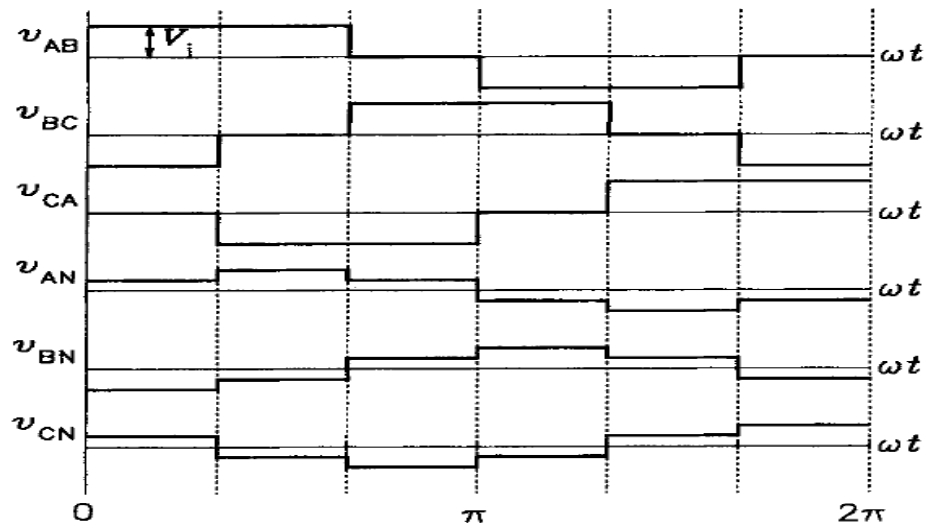


FIGURE 3.21 Output voltage waveforms in a voltage source inverter in the square wave mode.

Typical voltage waveforms in a PWM inverter are illustrated in Figure 3.22. In this example, the period of output voltage is divided into 12 so-called switching intervals. One pulse of each switching variable appears in each switching interval, and the adjustable pulse width varies from zero to the interval width. The number, N , of switching intervals per cycle of the output voltage, is given by :

$$N = \frac{f_{sw}}{f'} \quad (3.10)$$

Where f_{sw} denotes the so-called switching frequency and f' is the fundamental output frequency of inverter. The switching frequency is usually constant; thus, N depends on the output frequency only, and it is not necessarily an integer. The voltage waveforms are pulsed, not sinusoidal, and clusters of the most pronounced high harmonics coincide with multiples of the switching frequency. Thus, with typical switching frequencies on the order of several kHz, harmonic currents generated by those harmonics are weak, thanks to the low-pass action of load (motor) inductances. As a result, current waveforms in PWM inverters are close to ideal sinusoids, with only a small ripple.

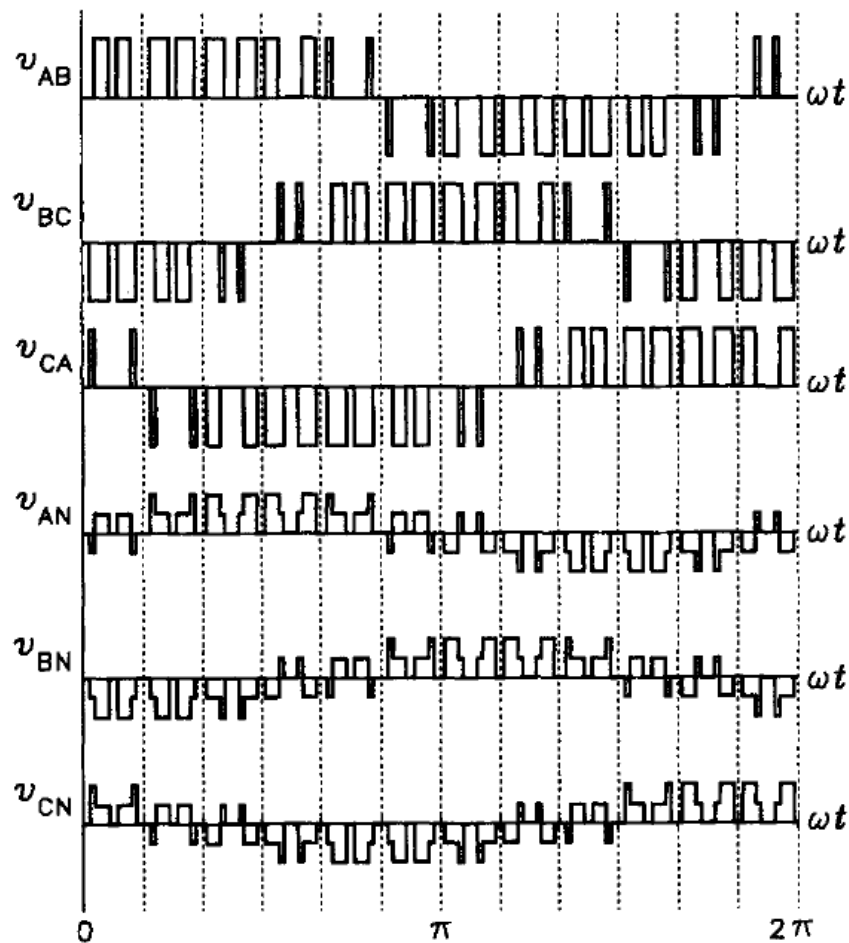


FIGURE 3.22 Output voltage waveforms in a voltage source inverter in the PWM mode.

The most Common class of PWM techniques for voltage Source inverters is based on the idea of voltage space vectors. Space vectors of electric and magnetic variables are an important tool in the analysis, modeling, and control of three-phase ac machines.

Considering three-phase voltages v_a , v_b and v_c , the corresponding voltage space vector, \mathbf{v} , is given by:

$$\mathbf{v} = v_d + jv_q \quad (3.11)$$

where :

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (3.12)$$

Voltages v_a , v_b , and v_c can denote the line-to-neutral voltages, that is, $v_a = v_{AN}$, $v_b = v_{BN}$, $v_c = v_{CN}$, or the line-to-line voltages, that is, $v_a = v_{AB}$, $v_b = v_{BC}$, $v_c = v_{CA}$. if $v_a + v_b + v_c = 0$, the abc \rightarrow dq transformation defined by Eq. (3.12) can be inverted, to yield

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & 0 \\ -\frac{1}{3} & \frac{1}{\sqrt{3}} \\ -\frac{1}{3} & -\frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} v_d \\ v_q \end{bmatrix} \quad (3.13)$$

The abc \rightarrow dq transformation transforms three actual voltages into a two-dimensional space vector in a complex plane. In particular, considering the classic two-level voltage source inverter, a voltage vector can be assigned to each of the eight states.

Space vectors of the line-to-neutral voltage associated with the eight states of the voltage source inverters are shown in Figure 3.23 in the per- unit format, with the dc input voltage, V_i , taken as the base voltage. There are six nonzero vectors, v_1 through v_6 , and two zero vectors, v_0 and v_7 ,

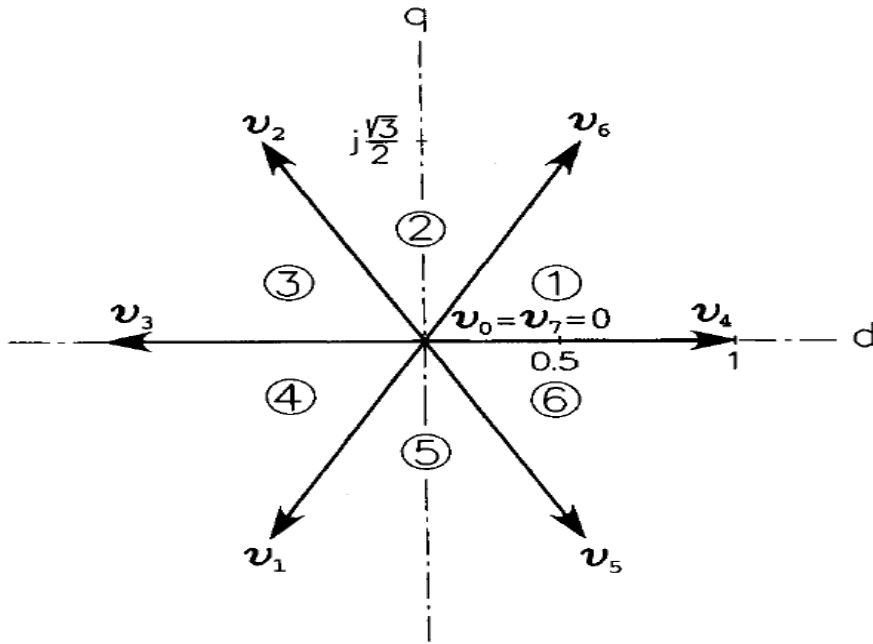


FIGURE 3.23 Space vectors of the line-to-neutral voltage (per-unit) in the two-level voltage source inverter.

resulting from clamping all the output terminals to the negative dc bus (State 0) or positive bus (State 7). The nonzero vectors divide the complex plane into six sectors (sextants), numbered from 1 to 6. Comparing Figures 3.21 and 3.23, we see that the sequence of inverter states corresponding to the consecutive nonzero voltage vectors results in the square-wave mode of operation of the inverter.

It can easily be shown that if voltages v_a , v_b , and v_c and v form a balanced set of three-phase voltages, the resultant voltage space vector, v , has the magnitude, V 1.5 times greater than the peak value of those voltages.

The phase angle, α , of the voltage vector equals that of v_a . Thus, if

$$v_a(t) = V_m \cos(\omega t), \quad (3.14)$$

where V_m , denotes a peak value, then

$$v = V e^{j\alpha} = 1.5 V_m e^{j\omega t} \quad (3.15)$$

As the time progresses, vector v revolves in the complex plane with the angular velocity ω . Consequently, the goal of inverter control can be formulated as follows:

Make the space vector of the output voltage to rotate with a desired speed, and adjust the magnitude of this vector to a desired value.

As shown in Figure 3.23, the voltage source inverter can produce only stationary voltage vectors. The popular Space Vector Pulse Width Modulation (SVPWM) technique overcomes this limitation by means of generation of the stationary vectors in such a manner that it is their time average that follows the revolving reference vector, v^* . Specifically, to synthesize the desired voltage vector in a given sextant, the two nonzero stationary vectors framing this sextant, plus a zero vector (or vectors), are used. To explain this technique, the reference vector, at a certain instant, is assumed to lie in Sextant 3, as illustrated in Figure 3.24. The local (within the sextant) angular position of v^* , β , is given by

$$\beta = \alpha - \frac{\pi}{3} \text{int} \left(\frac{3}{\pi} \alpha \right), \quad (3.16)$$

and the vector of output voltage is assembled from framing vectors, v_x and v_y (v_2 and v_3 in Sextant 3) and the zero vector (or vectors), v_z (v_0 or v_7). Specifically, inverter states producing vectors v_x , v_y , and v_z are imposed with durations $d_x T_{sw}$, $d_y T_{sw}$ and $d_z T_{sw}$ respectively, where $T_{sw} = 1/f_{sw}$ denotes the switching period, that is, the length of the switching interval. Coefficients d_x , d_y , and d_z , which can be called state duty ratios, express relative durations of individual states. Clearly,

$$d_x + d_y + d_z = 1. \quad (3.17)$$

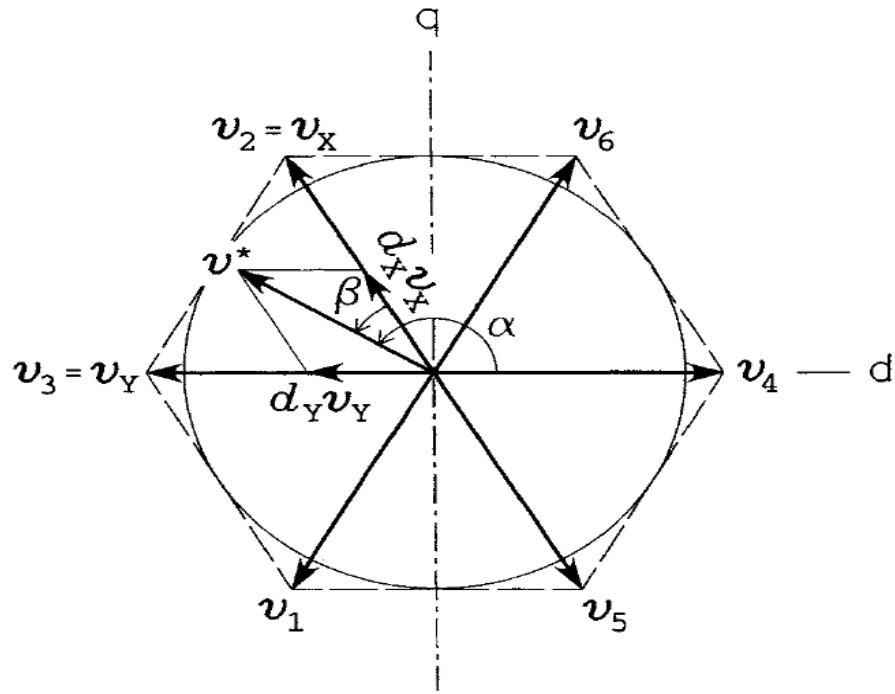


FIGURE 3.24 Illustration of the principle of the SVPWM technique

Duty ratios d_X and d_Y can be found from equation

$$v^* = d_X v_X + d_Y v_Y \quad (3.18)$$

decomposed into its real and imaginary parts to produce two real-coefficient equations. The solution is

$$d_X = m \sin \left(\frac{\pi}{3} - \beta \right) \quad (3.19)$$

And,

$$d_Y = m \sin (\beta), \quad (3.20)$$

where m denotes the so-called modulation index. The modulation index can be defined in terms of the magnitude, V , of the voltage vector and that, V_{max} , of the maximum voltage vector possible to be generated using pulse width modulation, as

$$m = \frac{V}{V_{max}} \quad (3.21)$$

The duty ratio, d_Z , of the zero state is found from Eq. (3.17) as

$$d_Z = 1 - d_X - d_Y \quad (3.22)$$

3.8 Control of Current Source Inverters:

Current source inverters are less commonly used in induction motor ASDs than voltage source inverters, mostly due to the poorer quality of output currents. Still, they have certain advantages, such as imperviousness to over currents, even with a short circuit in the inverter or the load. The absence of freewheeling diodes further increases the reliability. Also, current source inverters are characterized by inherently excellent dynamics of the phase angle control of the output current. Such control is realized by changing the state of inverter and the resultant redirecting of the source current. However, the magnitude adjustments of output currents can only be performed in the supplying rectifier. The rectifier allows bidirectional flow of power, and, because the input current is always positive, the input voltage becomes negative when the power flows from the load to the supply power system. Therefore, semiconductor power switches used in a current source inverter must have the reverse blocking capability.

In contrast with voltage source inverters, the simultaneous on-state of both switches in the same inverter leg is safe and recommended for a short period of time initiating a state change of the inverter. This is to avoid the danger of interrupting the current, which would result in an overvoltage. Consequently, switching variables are defined differently than those in the voltage source inverter. In the subsequent considerations, variables a , b , and c are assigned to switches SA, SB, and SC (e.g., $a=1$ means that SA is on), and variables a' , b' , and c' to switches SA', SB', - and SC' (see Figure 3.18). Then, the output line currents, i_A , i_B , and i_C of the current source inverter can be expressed as :

$$\begin{aligned}i_A &= (a - a')I_i \\i_B &= (b - b')I_i\end{aligned}\tag{3.23}$$

and :

$$i_C = (c - c')I_i$$

Where I_i denotes the constant input current. If the motor has a delta- Connected stator, then the currents, i_{AB} , i_{BC} and i_{CA} , in the individual phase windings are given by :

$$\begin{bmatrix} i_{AB} \\ i_{BC} \\ i_{CA} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} \quad (3.24)$$

The peak value of the fundamental line currents is approximately $1.1I_i$. Switching variables in the square-wave operation mode of the current source inverter are shown in Figure 3.25 and the resultant output current waveforms in Figure 3.26. It can be seen that at any time only two switches conduct the output currents. This conduction pattern is typical for the voltage source rectifier which, indeed, is an inverse of the current source inverter.

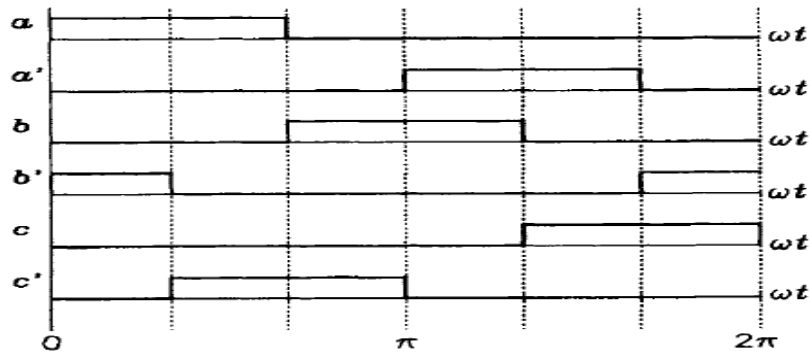


FIGURE 3.25 : Switching variables in the current source inverter in the square-wave operation mode.

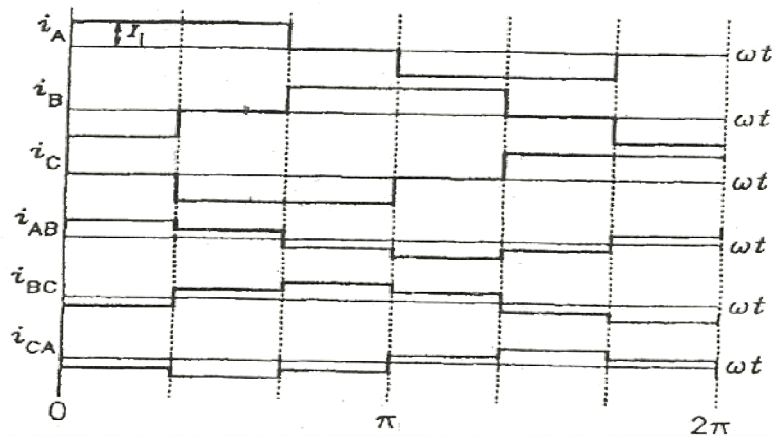


FIGURE 3.26 Output current waveforms in a current source inverter in the square-wave operation mode.

3.9 Summery of The Chapter:

Most induction motors in industrial and household use operate in an uncontrolled manner, being supplied directly from the power system. The motor speed is roughly constant, but the developed torque is sensitive to changes in the stator voltage. In many applications, significant energy savings could be realized by replacing the uncontrolled drive with an adjustable-speed one.

Motors with difficult starting conditions require means for assisted starting so that the motor does not overheat. Autotransformers, series impedances, wye-delta switches, or electronic soft-starters are commonly employed. Induction motors in ASDs are supplied from inverters, which are dc to ac power electronic converters. The dc supply voltage for inverters is provided by rectifiers. These usually have the three-phase bridge topology and are based on power diodes or, if control of the input current or inverted power flow is required, on SCRs. Poor quality of currents drawn from the power system is the major disadvantage of such rectifiers, and expensive input filters must be installed to alleviate this problem. The size of input filters can greatly be reduced when PWM rectifiers are employed. They can be of the voltage source or current source type, the latter converters being capable of boosting the output voltage above the peak value of the ac input (line-to-line) voltage.

Two-level voltage source inverters are most common in practice. Current source inverters are also used, usually in high-power drives. These inverters are more robust than voltage source inverters, and the dynamics of current phase control is excellent. The current quality in the square-wave mode of operation is poor, though. In that respect, PWM current source inverters, with output capacitors, are a better solution; but the required size of the capacitors limits the power range of these converters.

A cascade of the rectifier, dc link, and inverter constitutes a frequency changer. PWM frequency changers, characterized by high-performance operation and capable of the reversed power flow, can be of the voltage- source or current-source type. The voltage source PWM frequency changer is based on a voltage source PWM rectifier

and a current source inverter. Conversely, in the current source PWM frequency changer, a current source rectifier and a voltage source inverter are employed.

The most popular PWM technique for voltage, source inverters is based on the concept of voltage space vectors. A voltage space vector is obtained by transformation of values of actual voltages in a three-phase system into a complex number. Three-phase currents in a three-wire system can similarly be transformed.

In contrast to voltage source inverters which, in the PWM mode, allow control of both the frequency and magnitude of the output voltages, current source inverters are incapable of the magnitude control of output currents. This can only be done in the current source (controlled rectifier) supplying the inverter.