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Chapter 3

POWER ELECTRONIC CONVERTERS (PECs) FOR DRIVES

Power electronic converters (PECs) for drives are now a mature technology with notable and dynamic worldwide markets. Extraordinary research and development efforts are also devoted to the subject today and are likely to continue in the future.

There is a distinct rich literature on the subject [1]. Here we only summarize the main configurations and the voltage-current waveforms while more details will be given in subsequent chapters devoted to various motor drives.

PECs may be classified in many ways. Among them we may include the type of electronic switch used, the steps in power conversion, and current (voltage) output waveforms.

Let us first review the main power electronic switches (PESs).

3.1. POWER ELECTRONIC SWITCHES (PESs)

Power electronic switches (PESs) used in PECs undergo frequent commutations from a blocked to saturated (open) condition to provide high energy conversion rates (efficiency above 85-95%) over a wide range of voltages and, when it is the case, frequencies.

The blocked state is characterized by high voltage over the power terminal of the PES when the conducting current is practically zero. The saturated (open) state is defined by the presence of the conducting current while the voltage at the power terminals is low, in the 1-2V range.

The PESs may be classified as:

a. - uncontrolled;

b. - semicontrollable;

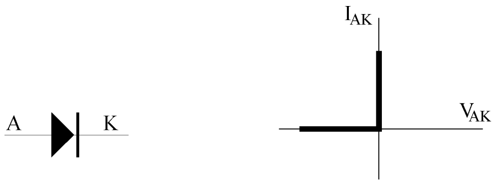
c. - fully controllable.

The diode is an uncontrolled PES (Figure 3.1a) whose state of conduction is determined solely by the direction of the current from anode (A) to cathode (K).

The ideal characteristic is shown in Figure 3.1b and shows that the diode conducts only for positive current, when the ideal voltage drop on it V_{AK} is zero. In reality V_{AK} is not zero but small (around 1-2V).

The diode is present in all PECs either as a rectifier or for protection. The diode does not have a control circuit or a driver for it.

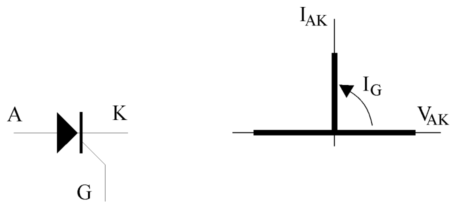
The thyristor is a semicontrollable PES. Its state of conduction may be controlled only in the sequence blocked — saturated when in the command circuit (driver) gate (G) — cathode (K) a positive current is present and if the PES is traveled by a positive current from anode (A) to cathode (K) (Figure 3.2). The saturated state is kept even after the command signal is inhibited until the current in the power circuit (A-K) becomes zero.



a.) b.)

Figure 3.1.The diode symbol a.) and its ideal characteristic b.)

The thyristor is used especially in PECs having an interface with AC power grids at high power levels and low commutation frequencies (up to 300Hz in general).



a.) b.)

Figure 3.2.The thyristor symbol a.) and its ideal characteristic b.)

The GTO (gate turn off thyristor) (Figure 3.3) is a fully controllable PES. Its saturation is obtained as for the thyristor, but its blocking is accessible when a negative current i_G is applied to the command (driver) circuit.

a.) b.)

Figure 3.3. The GTO's symbol a.) and its ideal characteristic b.)

This PES is used for high power PECs and for interfacing with AC grids. Its switching frequency is higher than that of the thyristor but still below 1 kHz in general.

The bipolar junction transistor (BJT) (Figure 3.4) is also a fully controllable PES but at high commutation frequency and low and medium (up to tens of kW) powers. Its command — saturation — is obtained through its base (B) current with respect to the emitter (E) and is maintained only in the presence of the command current. When the command current becomes zero the BJT gets blocked. The commutation time is lower than for the thyristor and the GTO. The BJT may operate only in the first quadrant (Figure 3.4) as its power circuit collector (C)-emitter (E) may not withstand negative polarization voltages.

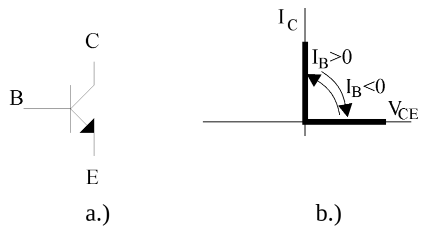


Figure 3.4. The bipolar junction transistor symbol a.) and its ideal characteristic b.)

The <u>MOS transistor</u> is also a fully controllable PES. The MOS transistor — in contrast to the other PESs — works with voltage (rather than current) signals in the command (driver) circuit gate (G) - source (S). Consequently the command power is practically zero which notably simplifies the command circuitry.

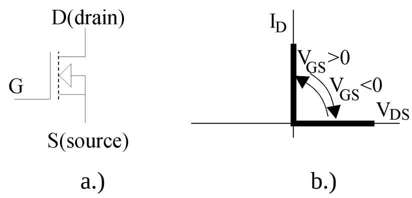


Figure 3.5. MOS Transistor symbol a.) and its ideal characteristic b.)

The MOS transistor has the lowest commutation time, allowing for very high switching frequency (tens of kHz); however, at low and moderate power and voltage levels.

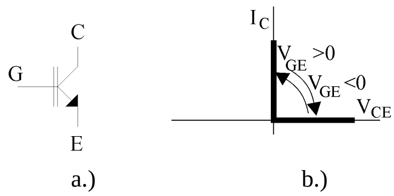


Figure 3.6. IGBT’s symbol a.) and its ideal characteristic b.)

The IGBT (insulated gate bipolar transistor) (Figure 3.6) possesses the MOS command merits (voltage command signal), the low commutation time (up to 20kHz switching frequency) and power circuit assets (low saturation voltage, larger voltage (current) ratings) of the bipolar transistor (BJT).

In the voltage/current ratings, the switching frequencies are getting higher and higher and their conduction and commutation losses are becoming lower at a high pace. As an example, PECs with IGBTs have reached in 1996 500kVA per unit and, with four units in parallel and simultaneously controlled, 2MVA.

At the same time thyristors are less expensive and in the MW (and higher) power range they are still competitive in many applications and in particular topologies. GTOs tend to win rather quickly over the power range from thyristors.

For high power, medium voltage MOS-controlled thyristors (MCTs) have been recently (1992) introduced. MCTs are turned on and off by a short voltage pulse on the MOS gate with thousands of microcells in parallel on a chip to yield high current levels.

Since 1997 the insulated gate-commutated thyristors (IGCT) are available also for high voltage, high power (4500 V, 300 A per unit). The turn off negative gate current is also 300 A but is very short.

High switching frequency characterizes both MCTs and IGCTs.

Still in the labs, SiC-based higher voltage (15 kV, 300A) medium current static power switches with a few kHz switching frequency, seem likely to revolutionize the medium and large power electronics by 2010.

The PECs may be classified many ways. In what follows we will refer to their input and output voltage/current waveforms and distinguish:

- AC-DC converters (or rectifiers);
- DC-DC converters (or choppers);
- AC-DC-AC converters (indirect AC-AC converters) - 2 stages;
- AC-AC converters (direct AC-AC converters).

We should note that AC-DC-AC converters contain an AC-DC source side converter (rectifier) and a DC-AC converter called an inverter. These converters are mostly used with AC motor drives of all power levels.

For bidirectional power flow the rectifier should be capable of working as an inverter, while the inverter is in principle capable of working as a rectifier.

Direct (one stage) AC-AC converters (cycloconverters) are applied in large power AC drives while the AC-DC-AC converters are used within the whole power range.

AC-DC converters are either part of AC-DC-AC converters or they are used independently for driving DC brush motors.

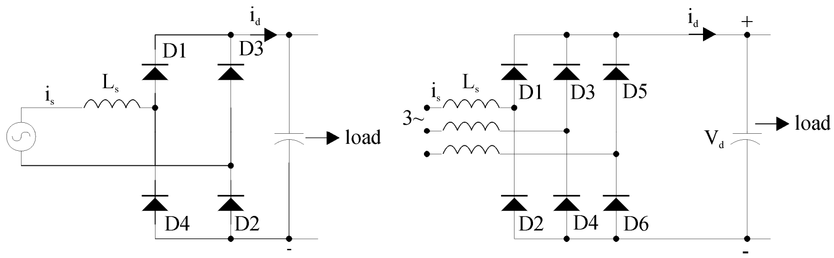
DC-DC converters are either connected directly to batteries (DC sources in general) or they are fed from uncontrolled (diode) rectifiers for driving DC brush motors, in multiphase configurations.

As the diode rectifier is used in many PECs as a line side converter, it will be presented here in some detail. All other PECs will merely be introduced here. Further details are given in subsequent chapters on various electric motor drives.

3.2. THE LINE FREQUENCY DIODE RECTIFIER FOR CONSTANT DC OUTPUT VOLTAGE V_d

In most electric drives the power is provided by the local grid at 60 (or 50) Hz in single-phase or three-phase configurations. Single phase AC is available at low power in general in various buildings, while industrial power grid is three phase. We treat them in sequence.

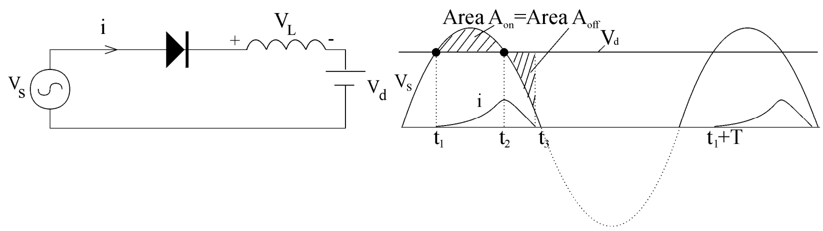
The output voltage of the diode rectifier should be as ripple free as possible and thus it requires a rather large capacitor filter (Figure 3.7).



a.) b.)

Figure 3.7. Diode rectifier with output filter capacitor: a.) single-phase, b.) three-phase

Let us consider first a basic rectifier circuit (Figure 3.8) with instantaneous commutation and a line source inductance L_s providing constant V_d on no load.



a.) b.)

Figure 3.8. a.) Basic rectifier equivalent circuit and b.) the voltage and current waveforms

The diode starts conducting when $V_s \geq V_d$ at t_1. At t_2, $V_s = V_d$ but, due to inductance L_s, the current goes into the diode until it dies out at t_3 such that $A_{on} = A_{off}$. In fact the integral of inductance voltage V_L from t_1 to t_1+T should be zero, that is, the average flux in the coil per cycle is zero

$$\int_{t_1}^{t_1+T} V_L\,dt = 0 = A_{on} - A_{off} \tag{3.1}$$

As V_d is close to the maximum value $V_s\sqrt{2}$, the current i becomes zero prior to the negative (next) cycle of V_s.

Figure 3.8 illustrates only the positive voltage, that is, diodes D_1-D_2 conducting. For the negative V_s, D_3-D_4 are open and a similar current waveform is added (Figure 3.9).

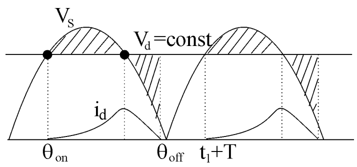


Figure 3.9. Single-phase rectifier - the waveforms

As long as the current i_d is non zero

$$V_L = L_s \cdot \frac{di_d}{dt} = \sqrt{2} \cdot V_s \cdot \sin\omega t - V_d \tag{3.2}$$

$$\omega \cdot L_s \cdot i_d = \int_{t_1}^{t_1+T} \left(\sqrt{2} \cdot V_s \cdot \sin\omega t - V_d\right) d(\omega t); \quad \theta_{on} < \omega t < \theta_{off} \tag{3.3}$$

For θ_{on}

$$V_d = \sqrt{2} \cdot V_s \cdot \sin\theta_{on} \tag{3.4}$$

For $\omega t = \theta_{off}$, id(ωt) = 0 and from (3.3) we may calculate θ_{off} as a function of θ_{on}.

Finally the average coil flux linkage L_sI_d is

$$L_s \cdot I_d = \frac{1}{\pi} \cdot \int_{\theta_{on}}^{\theta_{off}} L_s \cdot i_d(\omega t) \cdot d(\omega t) \tag{3.5}$$

For given values of L_sI_d, iteratively θ_{on}, θ_{off} and finally V_d are obtained from (3.3)-(3.5) (Figure 3.10).

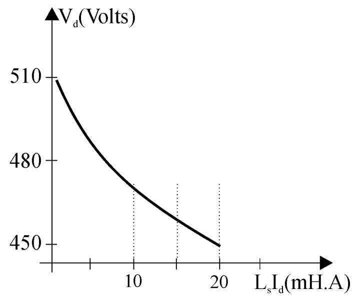


Figure 3.10. V_d versus L_sI_d

3.3. LINE CURRENT HARMONICS WITH DIODE RECTIFIERS

The line current has the same shape as i_d in Figure 3.9 but with alternate polarities (Figure 3.11). It is now evident that the line (source) current in a rectifier is rich in harmonics. This distortion from sinusoidal can be described by some distortion indexes.

Also, the current fundamental is lagging the source voltage by the displacement power factor (DPF) angle φ_1

$$DPF = \cos\varphi_1 \tag{3.6}$$

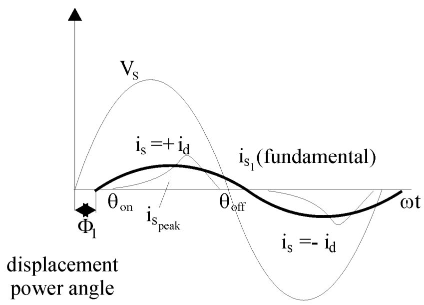


Figure 3.11. Source current shape

The source current r.m.s. value is I_s. Thus the apparent power magnitude S is

$$S = V_s \cdot I_s \tag{3.7}$$

where V_s is the r.m.s. voltage value.

The power factor
$$PF = \frac{P}{S} \tag{3.8}$$

where
$$P = V_s \cdot I_{s1} \cdot DPF \tag{3.9}$$

So
$$PF = \frac{I_{s1}}{I_s} DPF \tag{3.10}$$

A strong distortion in the line current will reduce the ratio I_{s1}/I_s, and thus a small power factor PF is obtained even if DPF is unity.

Now
$$I_s = \sqrt{I_{s1}^2 + \sum_{\upsilon=2}^{\infty} I_{s\upsilon}^2} \tag{3.11}$$

The total harmonic current distortion THD (%) is

$$THD\% = 100 \frac{I_{dis}}{I_{s1}} \tag{3.12}$$

where
$$I_{dis} = \sqrt{\sum_{\upsilon=2}^{\infty} I_{s\upsilon}^2} \tag{3.13}$$

The peak current I_{speak} is also important to be defined as a relative value constant called the crest factor (CF)

$$CF = \frac{I_{speak}}{I_s} \tag{3.14}$$

or the form factor (FF)

$$FF = \frac{I_s}{I_d} \tag{3.15}$$

It has been shown that the displacement power factor DPF is above 0.9 but the power factor PF is poor if the source inductance L_s is small.

The ratio V_d / V_s only slightly decreases with an L_sI_d / V_s ratio but both the crest factor (CF) and the form factor (FF) sharply decrease at low (below 0.03) L_sI_d / V_s values. After that, however, they only slightly decrease with L_sI_d / V_s.

The distorted waveform of the source current suggests that AC filters are required to eliminate the harmonics pollution of the local power grid. The tendency is that every PEC drive which uses a diode rectifier on the source side be provided with a source harmonics filter. More on this aspect in Chapter 13.

Example 3.1.

A single-phase diode rectifier with constant e.m.f. is fed from an AC source with the voltage $V_s(t) = V_s\sqrt{2} \cdot \sin\omega t$ (V_s = 120V, ω = 367rad/s). The discontinuous source current (Figure 3.11) initiates at $\theta_{on} = 60^0$ and becomes zero at $\theta_{off} = 150^0$. The source inductance is L_s = 5mH. Calculate the DC side voltage V_d and the waveform of the source current $i_d(\omega t)$.

According to Figure 3.9 from (3.3) we obtain

$$\int_{\theta_{on}}^{\theta_{off}} \left(\sqrt{2}\cdot V_s \cdot \sin\omega t - V_d\right)\cdot d(\omega t) = 0 \tag{3.16}$$

$$0 = \sqrt{2}\cdot V_s \cdot \left(\cos\theta_{on} - \cos\theta_{off}\right) - V_d \cdot \left(\theta_{off} - \theta_{on}\right) \tag{3.17}$$

From (3.17)

$$V_d = \frac{\sqrt{2}\cdot 120\cdot\left(\cos 60 - \cos 150\right)}{\frac{5}{6}\pi - \frac{1}{3}\pi} = 147\text{V} \tag{3.18}$$

Now from (3.3) again

$$\begin{aligned} & i_d = 0; \quad 0 < \theta < \theta_{on} \\ & i_d(\omega t) = \frac{1}{\omega L_s}\cdot\int_{\theta_{on}}^{\omega t}\left(\sqrt{2}\cdot V_s\cdot\sin\omega t - V_d\right)\cdot d(\omega t); \quad \text{for } \theta_{on} \le \theta \le \theta_{off} \\ & i_d = 0; \quad \theta_{off} < \theta < 180^0 \end{aligned} \tag{3.19}$$

Consequently

$$\begin{aligned} i_d(\omega t) &= \frac{\sqrt{2}\cdot V_s\cdot\left(\cos\theta_{on} - \cos\omega t\right) - V_d\cdot\left(\omega t - \theta_{on}\right)}{\omega L_s} \\ &= \frac{\sqrt{2}\cdot 120\cdot\left(0.5 - \cos\omega t\right) - 147\cdot\left(367t - \pi/3\right)}{367\cdot 5\cdot 10^{-3}} \\ & \text{for } 60^0 < \theta < 150^0 \end{aligned} \tag{3.20}$$

Though not convenient to use, (3.19)-(3.20) allow for the computation of I_s (rms), peak current I_{speak}, fundamental I_1, TDH% (3.12), crest factor (3.14), average DC output current Id.

3.4. CURRENT COMMUTATION WITH I_d = ct AND $L_S \neq 0$

For constant DC current I_d = ct (Figure 3.12):

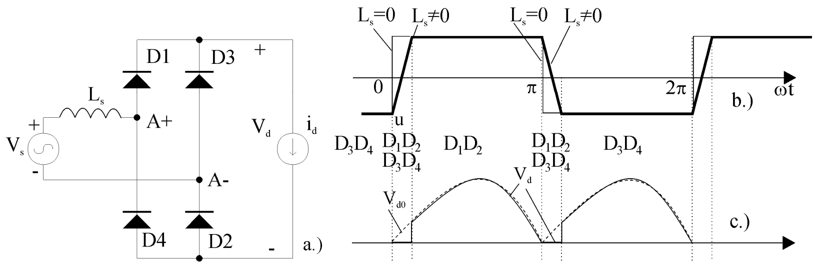


Figure 3.12. Current commutation in single-sided rectifier with I_d = ct.

a.) equivalent circuit; b.) source current; c.) rectified voltage

Ideally ($L_s = 0$), the source current will change stepwise from $-I_d$ to I_d at $\omega t = 0$ and $\omega t = \pi$ (Figure 3.12b). Due to the nonzero L_s, during commutation, all four diodes conduct and thus $V_d = 0$. For $\omega t < 0$, D_3D_4 conduct while after commutation ($\omega t > u$), only D_1D_2 are on.

As $V_d = 0$, the source voltage during commutation is dropped solely across inductance L_s

$$V_s\sqrt{2}\sin\omega t = \omega L_s \frac{di_s}{d(\omega t)} \tag{3.21}$$

Through integration for the commutation interval (0,u)

$$\int_0^u V_s\sqrt{2}\sin\omega t\cdot d(\omega t) = \omega L_s \cdot \int_{-I_d}^{I_d} di_s = 2\omega L_s \cdot I_d \tag{3.22}$$

We find

$$\cos u = 1 - \frac{2\omega L_s}{V_s\sqrt{2}}\cdot I_d \tag{3.23}$$

Now the average DC voltage V_d is

$$V_d = V_{d0} - \frac{2\omega L_s}{\pi}\cdot I_d \tag{3.24}$$

where
$$V_{d0} = \frac{2}{2\pi}\cdot\int_0^{\pi} V_s\sqrt{2}\sin\omega t\cdot d(\omega t) = \frac{2\sqrt{2}}{\pi}V_s = 0.9V_s \tag{3.25}$$

is the ideal ($L_s = 0$) average DC voltage (Figure 3.12c).

So the source inductance L_s produces a reduction in the DC output voltage for constant DC output current. The current commutation is not instantaneous and during the overlapping period angle u all four diodes are conducting.

3.5. THREE-PHASE DIODE RECTIFIERS

In industrial applications three phase AC sources are available, so three-phase rectifiers seem the obvious choice (Figure 3.13).

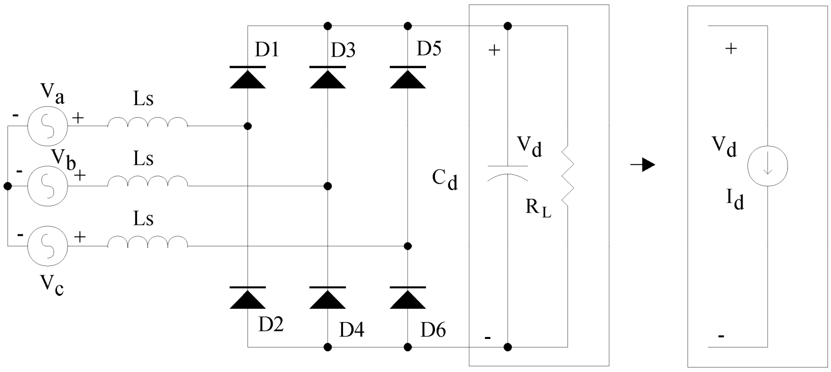


Figure 3.13. Three-phase diode rectifier

The load resistance R_L with a filtering capacitor C_d may be replaced by a constant DC current source I_d. Using the same rationale as in the previous paragraph we obtain

$$V_d = V_{d0} - \frac{3\omega L_s}{\pi} \cdot I_d \tag{3.26}$$

$$\cos u = 1 - \frac{2\omega L_s}{V_{LL}\sqrt{2}} \cdot I_d \tag{3.27}$$

with $V_{d0} = \frac{3\sqrt{2}}{\pi} V_{LL}$ where V_{LL} is the line voltage (rms).

The corresponding waveforms for $L_s = 0$ are shown in Figure 3.14 and for $Ls \neq 0$ in Figure 3.15.

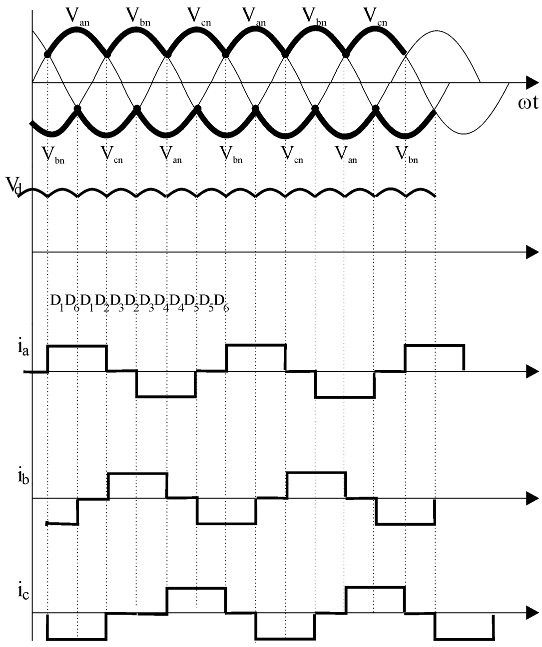


Figure 3.14. Three-phase ideal waveforms for $L_s = 0$

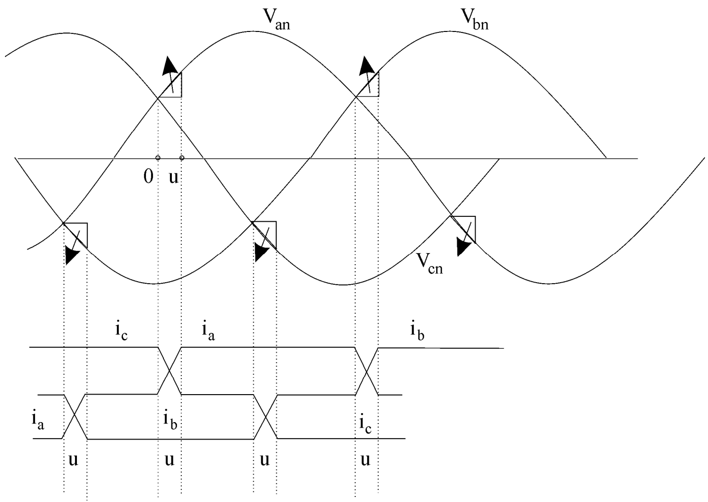


Figure 3.15. Three-phase current commutation with $L_s \neq 0$

For nonzero L_s a reduction of output DC voltage (3.26) is accompanied by all three phases conducting during the commutation angle u (Figure 3.15).

On the other hand, for constant DC voltage (infinite capacitance C_d), as for the single-phase rectifier, the source current waveform is as in Figure 3.16.

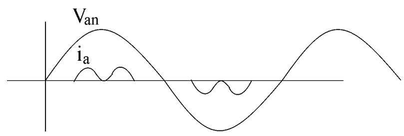


Figure 3.16. Three-phase rectifier with finite L_s and infinite C_d (V_d = ct.)
- the source current and voltage

We should note that in both cases the source currents are distorted and thus current harmonics are present in the power source.

Both current source and DC output voltage (current) harmonics in actual single-phase rectifiers are higher than in three-phase rectifiers.

Example 3.3. Commutation overlapping angle u.

For a single-phase or three-phase AC system (star connection) with phase voltage $V_s(t) = 120\sqrt{2}\sin 367t,$ calculate the commutation angles u, ideal no-load voltage and load voltage of a single or three-phase diode rectifier delivering a constant DC current I_d = 10A for the source inductance L_s = 5mH.

Solution:

For the single-phase diode rectifier, using (3.23)

$$\cos u = 1 - \frac{2\omega L_s}{V_s\sqrt{2}} \cdot I_d = 1 - \frac{2 \cdot 367 \cdot 5 \cdot 10^{-3}}{120\sqrt{2}} \cdot 10 = 0.783 \qquad (3.28)$$

$u = 22.727^0$.

The ideal no-load voltage V_{d0} (3.25) is

$$V_{d0} = \frac{2\sqrt{2}}{\pi} V_s = \frac{2\sqrt{2}}{\pi} 120 = 108V \qquad (3.29)$$

$$V_d = V_{d0} - \frac{2\omega L_s}{\pi} \cdot I_d = 108 - \frac{2 \cdot 367 \cdot 5 \cdot 10^{-3}}{\pi} \cdot 10 = 96.312V \qquad (3.30)$$

For the three-phase diode rectifier (3.27) u is

$$\cos u = 1 - \frac{2 \cdot 367 \cdot 5 \cdot 10^{-3}}{120\sqrt{2} \cdot \sqrt{3}} \cdot 10 = 0.8746 \tag{3.31}$$

$u = 12.22^0$.

V_{d0} and V_d (from 3.26) are

$$V_{d0} = \frac{3\sqrt{2}}{\pi} V_{LL} = \frac{3\sqrt{2}}{\pi} 120\sqrt{3} = 279.66V \tag{3.32}$$

$$V_d = V_{d0} - \frac{3\omega L_s}{\pi} \cdot I_d = 279.66 - \frac{3 \cdot 367 \cdot 5 \cdot 10^{-3}}{\pi} \cdot 10 = 262.128V \tag{3.33}$$

Thus the filtering capacitor C_d is notably smaller in three-phase than in single-phase diode rectifiers.

Note: This rather detailed introduction to diode rectifiers has been given because they are used frequently as source-side PECs in most electrical drives while they show a strong indication of line current harmonics and commutation aspects, to be met with in all other PECs.

3.6. PHASE-CONTROLLED RECTIFIERS (AC-DC CONVERTERS)

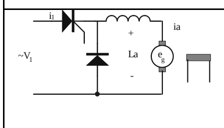
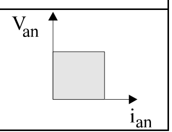
Phase-controlled rectifiers — AC-DC converters — are used to provide controlled DC output to directly supply DC brush motors or as line-source (first-stage) PECs into two stage AC-DC-AC converters for AC drives.

In principle phase-controlled rectifiers might be fully controlled or semicontrolled. A rather complete survey of various phase-controlled rectifiers is given in Table 3.1.

It is important to note the power range and quadrant operation of various configurations. We also should note that besides thyristors, GTOs or IGBTs may be used. For high powers (MW and tens of MW), and as AC side converters in AC-DC-AC converters for AC motors, special configurations are used. They will be treated in their respective chapters. Also, unity input power factor configurations are available.

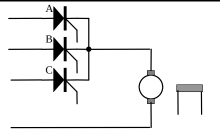
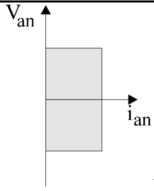
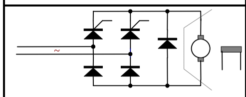
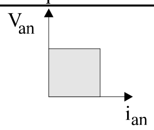
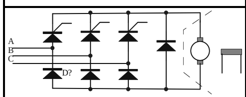
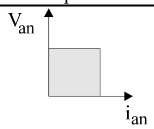
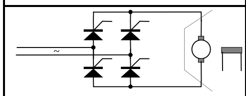
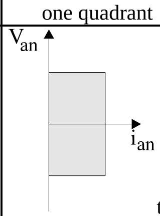
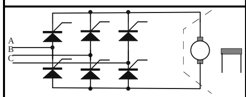
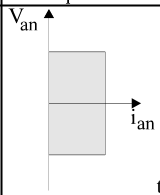
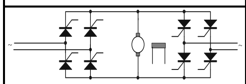
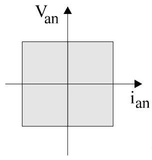
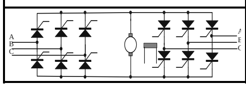
Principal details, numerical examples or digital simulation results on various rectifier configurations will occur in pertinent chapters on DC brush or large power AC motors.

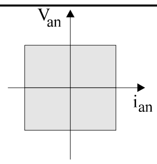
Table 3.1. Phase-controlled rectifier circuits

Circuit type		Power range	Ripple frequency	Quadrant operation
	half wave single-phase	below 0.5KW	f_s	

				one quadrant

Table 3.1. (cont´d.)

	half wave three phase	up to 50KW	$3f_s$	 two quadrant
	semi-converter single-phase	up to 75KW	$2f_s$	 one quadrant
	semi-converter three-phase	up to 100KW	$3f_s$	 one quadrant
	full converter single-phase	up to 75KW	$2f_s$	 two quadrant
	full converter three-phase	up to 150KW	$6f_s$	 two quadrant
	Dual converter single-phase	up to 15KW	$2f_s$	 fou r quadrant
	Dual converter three-phase	up to 1500KW	$6f_s$	

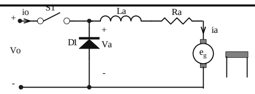
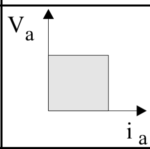
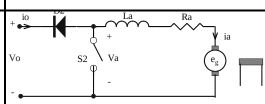
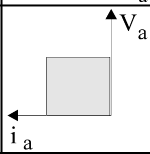
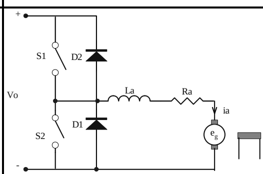
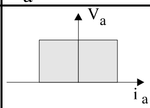
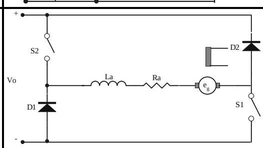
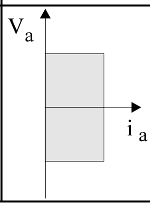
				 four quadrant

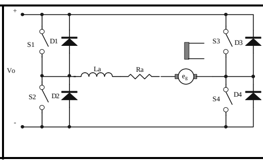
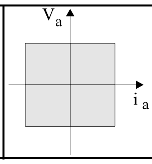
3.7. DC-DC CONVERTERS (CHOPPERS)

Choppers are DC-DC switch-mode converters with unipolar or bipolar current output capability. They are widely used in DC brush motor drives in single-phase output unipolar current configurations (Table 3.2) and for switched reluctance motors (SRM) in multiphase configurations (Figure 3.17).

Multiphase choppers for SRMs of various configurations have been proposed and they will be treated in more detail in Chapter 12 on SRM drives.

Table 3.2. Single-phase chopper configurations for DC brush motors

Type	Chopper configuration	e_a-I_a characteristics	Function
First quadrant (step-down) choppers			$V_a = V_0$ for S_1 on $V_a = 0$ for S_1 off and D_1 on
Second quadrant, regeneration (step-up) chopper			$V_a = 0$ for S_2 on $V_a = V_0$ for S_2 off and D_2 on
Two-quadrant chopper			$e_a = V_0$ for S_1 or D_2 on $e_a = V_0$ for S_2 or D_1 on $i_a>0$ for S_1 or D_1 on $i_a<0$ for S_2 or D_2 on
Two-quadrant chopper			$V_a = +V_0$ for S_1&S_2 on $V_a = -V_0$ for S_1&S_2 off and D_1&D_2 on

Four-quadrant chopper			S_4 on &S_3 off S_1&S_2 operated V_a>0 i_a - reversible S_2 on &S_1 off S_3&S_4 operated V_a<0 i_a - reversible

If an AC source is available, a diode rectifier and filter are used in front of all choppers (Figure 3.17).

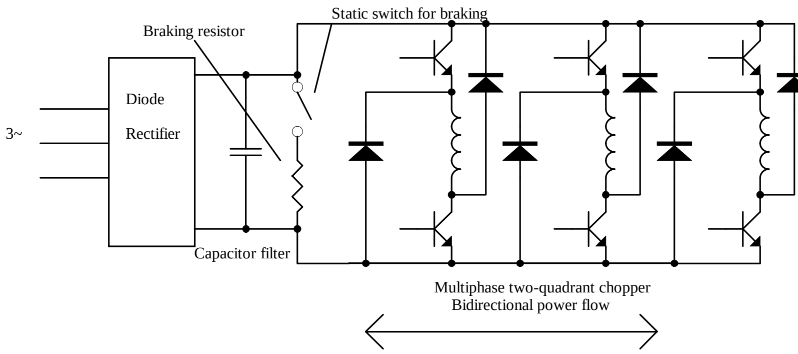


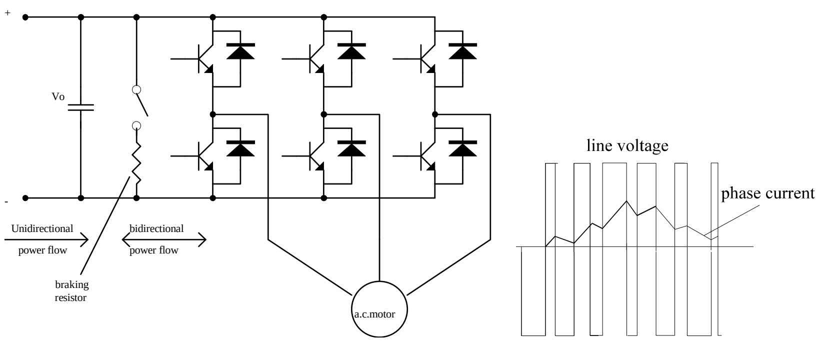
Figure 3.17. Multiphase DC-DC converters for switched reluctance motors

3.8. DC-AC CONVERTERS (INVERTERS)

DC-AC converters (inverters) are of two main types: voltage-source inverters (Figure 3.18) and current-source inverters (Figure 3.19) in the sense that the input source is of constant voltage or constant current character.

Voltage-source inverters are built in general with IGBTs or GTOs while current-source inverters are, in general, built with thyristors and GTOs and refer to high power levels (MW level and higher).

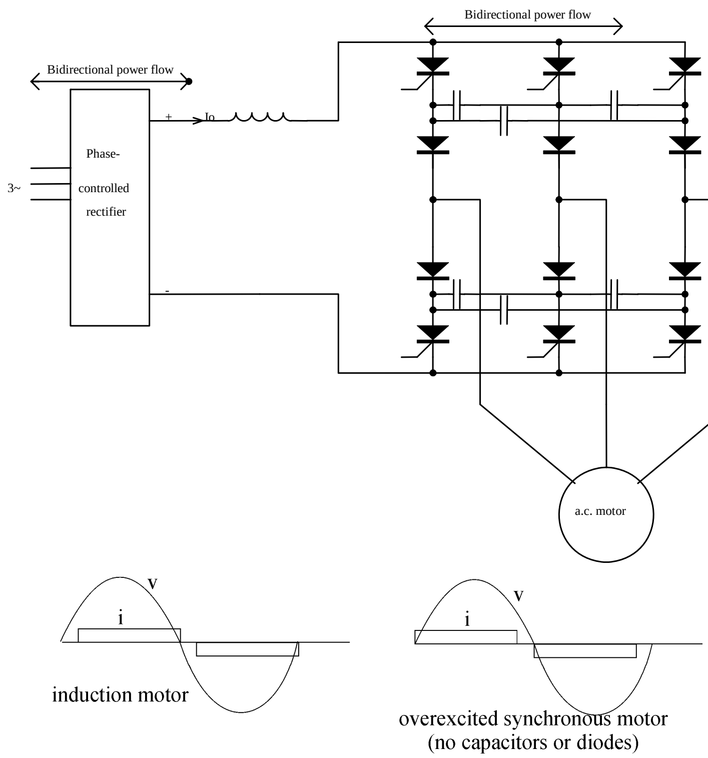
Inverters may be single phase or multiphase and they deliver bipolar current waveforms and allow for bi-directional power flow. They are used for AC motor drives.



a.) b.)

Figure 3.18. Voltage source PWM inverter:

a.) basic configuration, b.) output waveforms



a) b)

Figure 3.19. Current source inverter

a.) basic configuration; b.) ideal output waveforms (i – current, u – voltage)

When the AC motor exhibits a lagging power factor (induction motors), capacitors and diodes are required for successful commutation of thyristors in the current source inverter. In contrast, when the motor exhibits a leading power factor (overexcited synchronous motors), induced voltage (load) commutation is accomplished and thus the capacitors and the diodes are eliminated.

Though current source inverters allow for bidirectional power flow, the energy retrieved from the motor has to be either returned to the power source (Figure 3.19) or dumped into a braking resistor (Figure 3.18) when the source-side converter does not allow for bidirectional power flow.

The phase-controlled rectifier allows for bidirectional power flow that is so necessary during fast braking of high inertia loads. So, from this point of view, the configuration in Figure 3.19 is superior to that of Figure 3.18.

However, switching frequency is smaller with current source inverters and thus the motor current waveform is distorted, leading to a larger derating of the motor to avoid overheating.

On the other hand, with both AC-DC-AC converters unity input power factor and full bidirectional power flow are possible only with configurations such as those in Figure 3.20.

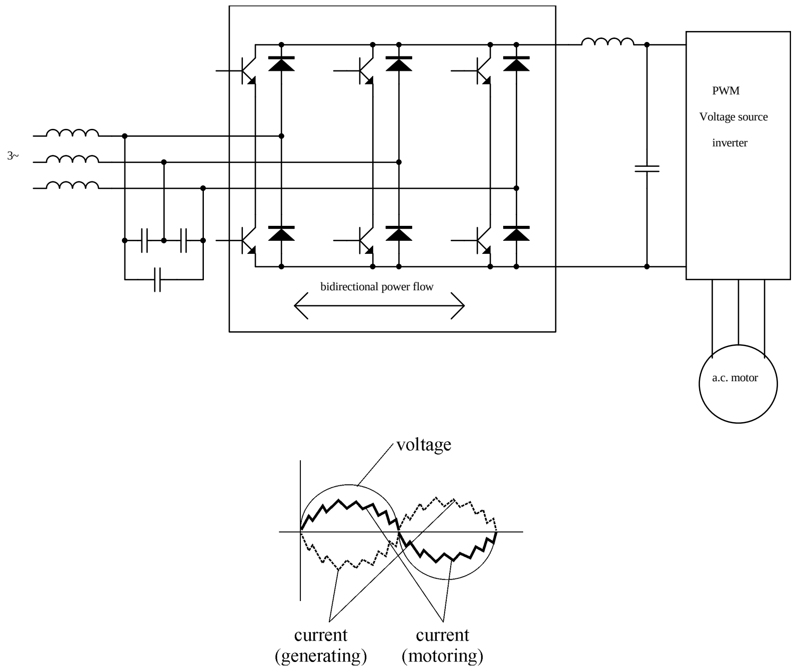


Figure 3.20. Bidirectional power flow (dual) AC-DC converter with unity power factor and sinusoidal inputs

The diode rectifier works during motoring while the IGBTs work during generating when the source-side converter will work as a PWM voltage source inverter. Unity power factor and quasisinusoidal source currents and voltages may be obtained.

Though the phase-controlled rectifier-current source inverter configuration (Figure 3.19) provides for bidirectional power flow, the input power factor decreases with rectifier DC voltage (motor speed) reduction. To provide for unity power factor and sinusoidal input and output waveforms, the structure in Figure 3.21 with GTOs has been introduced.

The capacitors on the AC source-side converter are commutated properly by an additional leg of GTOs. The same is done on the current source side. Thus the voltages and currents are ideally sinusoidal both on the source side and on the motor side through PWM. Also, the unity power factor on the source side is performed with bidirectional power flow. Note, however, that rather large capacitors and filters are required while the number of PESs is 12 in Figure 3.20 and 16 in Figure 3.21.

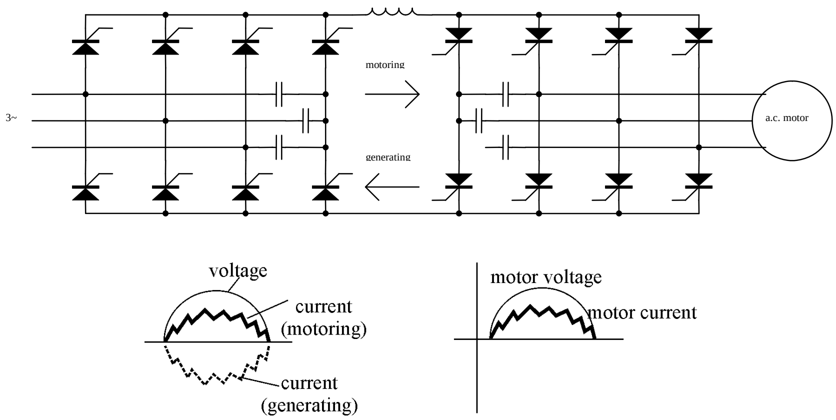


Figure 3.21. AC-DC-AC converter with bidirectional power flow and unity input power factor

All the PECs introduced so far are characterized by hard switching of PESs – at nonzero voltage or current. As in PECs both conducting and commutation losses count, when switching frequency increases so does commutation loss.

A new breed of PECs, with a very rich literature, called soft-switching (or resonant) PECs, that provide commutation at zero voltage (for IBGTs) or at zero current (for GTOs) have been proposed. They boost the switching frequency one order of magnitude [1].

As soft-switching PECs are not yet commercial for drives we do not pursue them further here. Besides AC-DC-AC converters, there are also direct AC-AC converters.

3.9. DIRECT AC-AC CONVERTERS

Direct AC-AC converters are used in industry for high power synchronous and induction motor drives (for frequencies lower than that of the power source [2]) as cycloconverters).

Cycloconverters (Figure 3.22) represent, in the six pulse configuration, a group of 2 back-to-back fully controlled rectifiers for each phase.

The source voltage and current waveforms are both ideally sinusoidal. The commutation of PESs is provided by the power source and the maximum output frequency is about one third of the input frequency. More involved configurations allow higher output frequencies [2].

A general concept of direct AC-AC converters called matrix converter has been proposed in 1980 [3-6]. Matrix converters have just reached the markets.

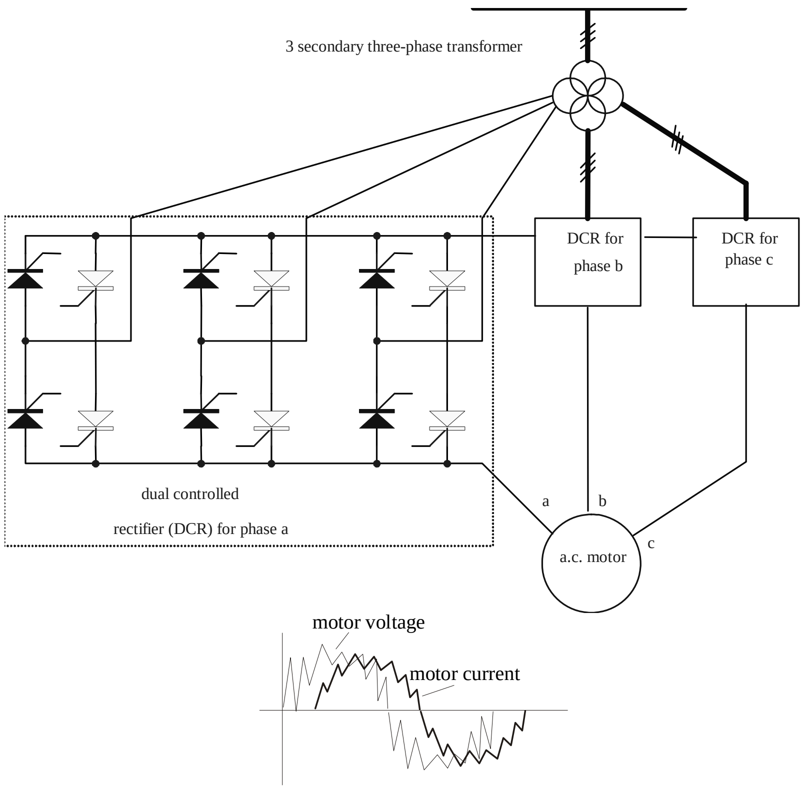


Figure 3.22. Six-pulse cycloconvertor for AC motor drives

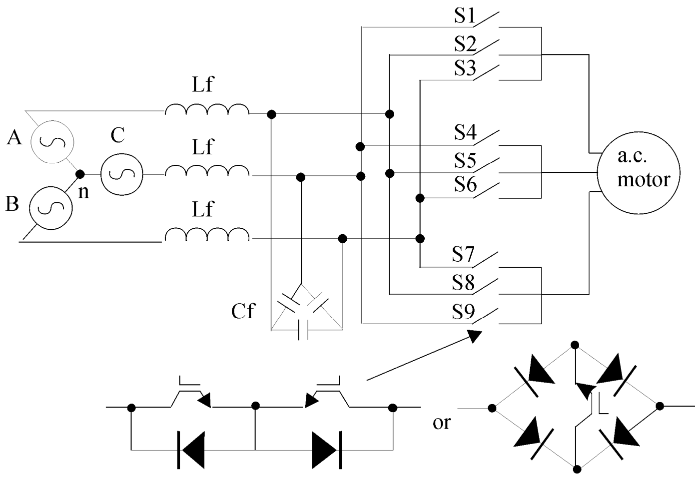


Figure 3.23. Three phase to three phase matrix converter

The matrix converter (Figure 3.23.) is a matrix of switches which allows for the connection of any input to any output phase.

The PWM techniques for matrix converters do in essence provide for a fictitious diode bridge rectifier DC link (Figure 3.24b) and then recompose the output line voltage (v_{ab}, Figure 3.24c) by pulse width modulating (PWM) this fictitious DC link voltage. One switch in each of the three banks conducts at any instant, so there are $3^3 = 27$ switching states; only lateral line switches are not closed in order to avoid line shorting.

The nine bidirectional power switches may be built either with two IGBTs and two fast switching diodes or from one IGBT and four switching diodes.

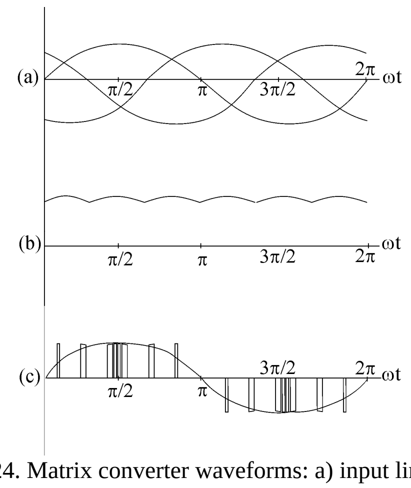


Figure 3.24. Matrix converter waveforms: a) input line voltage;
b) fictitious diode rectifier bridge like DC voltage link; c) output line voltage (v_{ab})

The L_FC_F filter is essential for the commutation of AC switches when the inductive load current has to be transfered from one line to another; it also serves to filter the line current harmonics.

The matrix converter is bidirectional in principle, with the line current almost sinusoidal.

There are no constraints on the output frequency but the maximum voltage gain is 0.86 and thus the motor has to be sized at lower voltage and higher current.

3.9.1. Low cost PWM converters

While it has been proved that the 6-leg PWM voltage source converter (Figure 3.18) is the best choice for AC sinusoidal current output in three phase loads [9], for single phase loads lower power switch count converters have been analyzed [9]. As none of them is without notable demerits we represent here just one of them (Figure 3.25), of low cost, eventually suitable for split-phase capacitor-run AC (induction and permanent magnet synchronous) small motors for home appliance (HVAC: heating, ventilating, air conditioning).

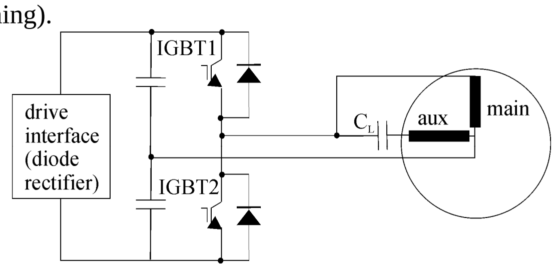


Figure 3.25. B2 inverter supplying a single phase load.

Only half of the DC link voltage is applied to the load, so the voltage rating of IGBTs is reduced, but, for the same load power, their current rating is increased. As the capacitor C_L in the load is fixed, the lowest frequency of the converter is also limited to perhaps about 6 to 10 Hz. Fortunately in HVAC applications this is acceptable.

3.10. SUMMARY

- A modern electric drive, capable of variable speeds, comprises, in general, a motor, a multistage power electronic converter, and a controller.
- Power electronic converters (PECs) process the power supplied to the motor and are classified in many ways.
- Basically the input-output waveforms are most important. PECs may be single stage or two stage. Single-stage converters are AC-DC or DC-AC or direct AC-AC
- Two-stage PECs are AC-DC-AC with an intermediate DC voltage type or current type link. Most commercial PECs are hard switched,

that is, the PESs are turned on (or off) when the voltage (current) is nonzero.

- Soft-switching (resonant) PECs make use of soft switching (under zero voltage or current) and thus are characterized by reduced commutation losses for given switching frequency. Conversely, they allow switching frequencies an order of magnitude higher than for hard switching.
- The various power electronic switches (PESs) are characterized by voltage, current, dv/dt and di/dt limitations and a certain switching frequency limit.
- The line-frequency diode rectifiers presented in some detail in this chapter show the strong influence of source inductance on DC output voltage reduction with rectified current (and highly distorted source current) though the displacement power factor (DPF) is above 0.9 in all cases.
- Filters on the source side are required to attenuate the current harmonics in the AC power source. These aspects are common to all PECs, as will be seen in subsequent chapters.

3.11. PROBLEMS

3.1. An ideal single-phase rectifier with zero source inductance L_s (Figure 3.23) produces constant DC current output I_d = 50A.

3.2. show the source current and load current waveforms;

3.3. with a sinusoidal voltage V_s = 120V (rms) at 60 Hz, calculate the DC output voltage V_d and the DC power;

3.4. for case b, calculate the source current fundamental, the displacement power factor (DPF) and the power factor (PF).

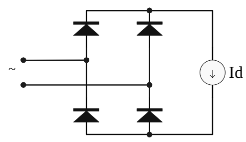


Figure 3.23. Ideal single-phase diode rectifier with zero source inductance (L_s = 0) and constant DC current I_d.

3.5. A single-phase diode rectifier with constant output voltage V_d = 120V is fed from an AC supply whose voltage is $V_s(t) = 120\sqrt{2}\cdot\sin 376t$. For the source inductance L_s = 1mH; calculate the time dependence of the DC output current.

3.6. A three-phase diode rectifier has $V_s(t) = 120\sqrt{2}\cdot\sin 376t$ and the source inductance L_s = 5mH. The maximum commutation overlapping angle is $u = 30^0$. For this situation calculate the rectifier current I_d and the ideal and actual DC output voltage V_d.

3.12. SELECTED REFERENCES

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