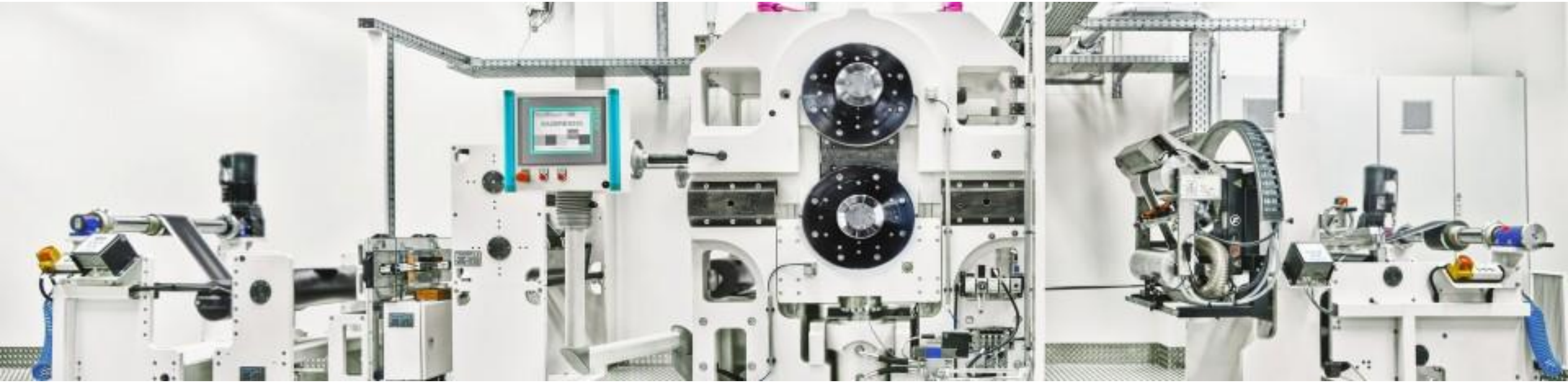
SPECIAL ELECTRICAL MACHINES & DRIVES



By: MSc Eng. ISMAEIL ALNAAB

Fourth stage, 2017 – 2018

- Research has shown that students understand more from a lecture if they write things down. Keep focus and ask if you did not understand.
- Study to Learn …… Not just to pass an exam.
- Your attendance is important to you, not for me. Make sure you sign the attendance sheet.
- Homework's are crucial, 10% of your mark depends on them.
- This course has a computer class, where simulation of inverter, converter and drive systems are carried out.
- Do not fully depend on me, go and search the YOUTUBE and GOOGLE.
- Try to understand why are you studying this heavy material, is there any relationship between this material and the real world.

Syllabus :

Chapter 1: AC Voltage Controllers:
- 1- Single phase controllers
- 2- Three phase controllers

Chapter 2: Frequency converters (Cycloconverters):
- 1- Single phase cycloconverters
- 2- Three phase controllers cycloconverters
- 3- Reduction of output harmonic

Chapter 3: Inverters:
- 1- multilevel inverters
- 2- Resonant pulse inverters

Chapter 4: Motor drives:
- 1- DC motor drives
- 2- Induction motor drives
- 3- cycloconverter motor drives
- 4- step motor drives

Syllabus :

Chapter 5: Power supllies:
1- DC power supplies
2- AC power supplies

Chapter 6: Digital control power electronics:
1- Programable logic devices (PLDS)
2- Applications

Chapter 7: Special Machines:
1- Stepper motor
2- Brushless motor
3- Switched Reluctance motor (SRM)
4- Permanent magnet motor
5- Hysteresis motor
6- Linear induction motor

Introduction:

Machines

DC Machines

- PM brushed DC machine.
- Electro Magnet:
  - A- Separately Excited.
  - B- Self Excited:
    - 1-series wound.
    - 2-shunt wound.
    - 3-compound wound:
      - i- Long shunt.
      - ii- Short shunt.

Special Machines

- Stepper motor
- Servomotor
- Brushless motor
- Switched reluctance motor

AC Machines

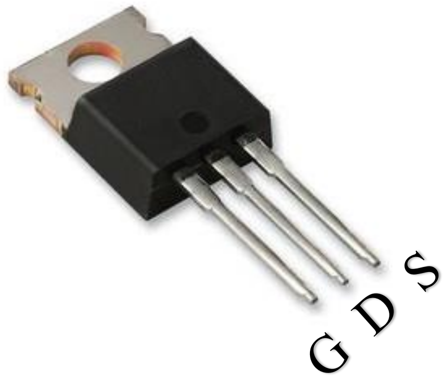
- Induction machine:
  - A- Single phase.
  - B- Three phase.
- Synchronous machine

Special Machines: They are used for special applications.
Machines whose stator coils are energized by electronically switched currents.
They are designed and built primarily for use in feedback control system.

Power semiconductor device: Is a device used as a switch or rectifier in power electronics.

Examples: Thyristor, Power MOSFET, GTO, and IGBT

Power MOSFET :



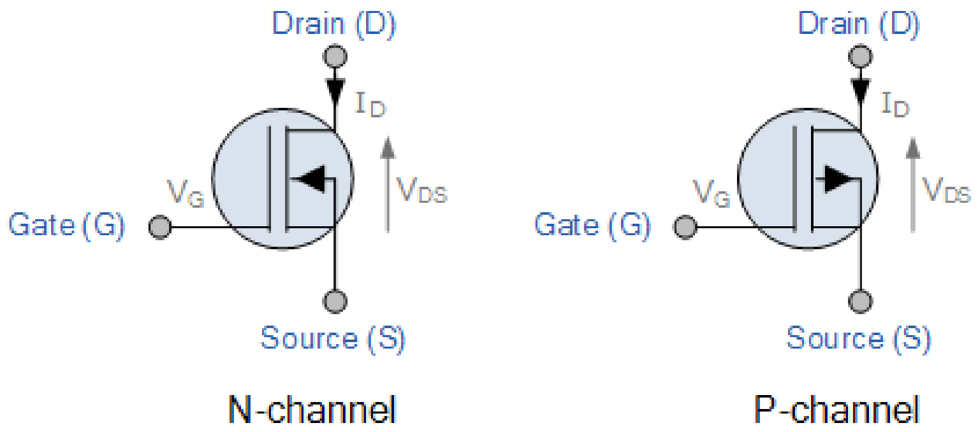


Fig (1) Power MOSFET model and types

Switching times range from tens of nanoseconds to a few hundred microseconds

Chapter 1: AC voltage controllers

If a thyristor switch is connected between ac supply and load, the power flow can be controlled by varying the rms value of ac voltage applied to the load; and this type of power circuit is known as an ac voltage controller.

AC voltage controller or AC regulator is an electronic module based on either thyristors, TRIACs, SCRs or IGBTs, which converts a fixed voltage, fixed frequency alternating current (AC) electrical input supply to obtain variable voltage in output delivered to a resistive load.

Most common applications of ac voltage controller:

- Industrial heating
- light controls
- speed control of fans
- winding machines

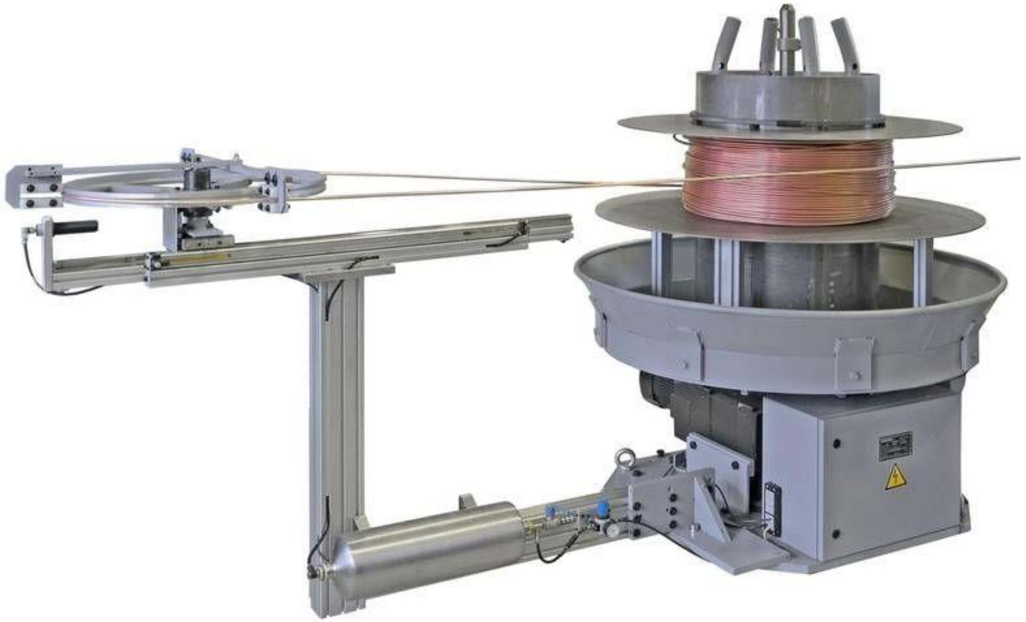


Fig (2) winding machine

For power transfer, two types of control are normally used:

1- On-OFF control

2- Phase-angle control

AC voltage controllers

- Single phase controllers
  - Unidirectional Half-Wave control
  - Bidirectional Full-Wave control
- Three phase controllers
  - Unidirectional Half-Wave control
  - Bidirectional Full-Wave control

1- On-OFF control

The On-OFF control is similar to a normal switch operation ON – OFF, but of course here we have a time period, which means the ON-OFF will happen automatically depends on the gate signal “gate signal is a voltage that is necessary to switch on the semiconductor switch, the voltage varies from one semiconductor to another”.

If the gate of the switch “thyristor” is ignited with the signal, the switch will be on for only half a cycle, means only the top or bottom of the ac current and voltage wave will pass, as shown in figure (3) below.

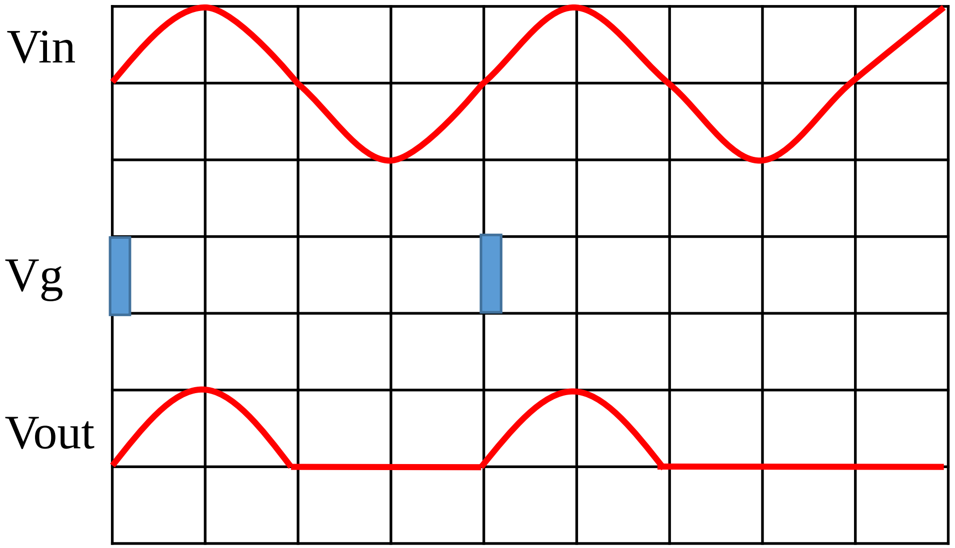


figure (3) single phase half wave “Unidirectional” control

This is exactly how the single phase half wave “Unidirectional” control works.

If a single phase full wave “Bidirectional control is needed, another thyristor has to be used for the bottom half of the cycle, as shown in figure (4).

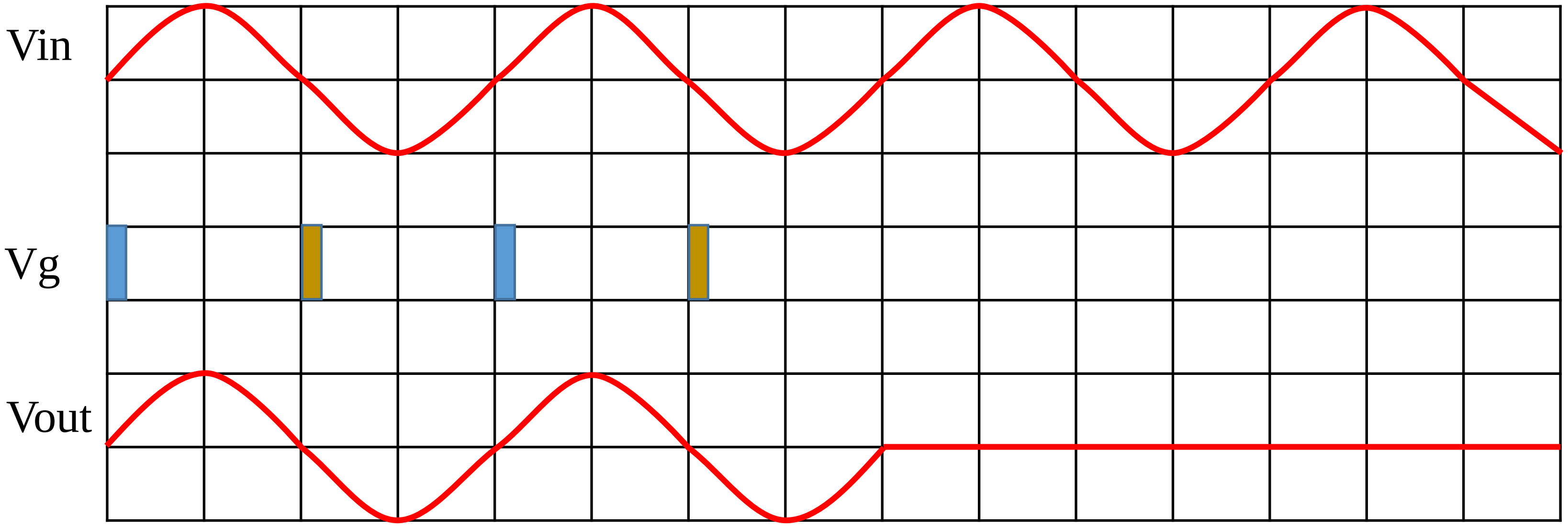


figure (4) single phase full wave “Bidirectional” control

Therefore, you are the one who decides when the next ON time will be for the thyristor, you can just keep igniting the gate ON each half a cycle and the switches will let the top and the bottom waves pass, but if you want zero voltage and current, then you have to use a delay “Delay time”. For instance, you give the first and second thyristor two gate signals, then delay time, then two gate signals, and so on.

2- Phase-angle control

In phase-angle control, the thyristor is not going to be ignited from the beginning of the cycle. There will be a delay time “an angle”, and it is expressed with the symbol (α). As a fact, the half cycle is 180 degrees, therefore if we want to ignite the thyristor and switch it ON for only ½ (half the cycle) therefore, the angle α has to be 90. Figure (5) will explain this clearly.

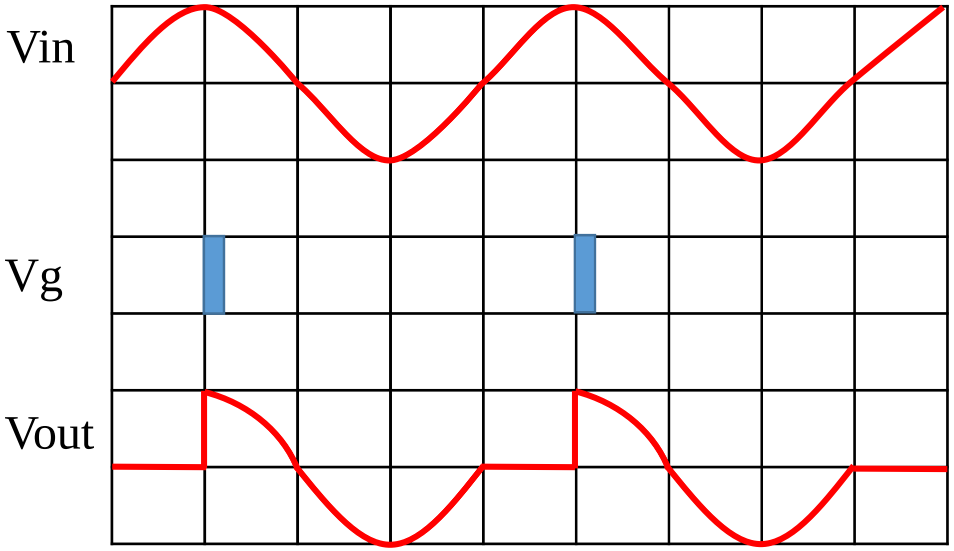


figure (5) single phase half wave “Unidirectional” control

Note: This is a unidirectional control, only the first half off the cycle is being controlled, “only one thyristor” while the second half of the cycle is let pass because of the free wheeling diode.

If two thyristors are being used for the first and second half of the cycle, and both are shifted by angle α; Guess how the wave will appear??

AC voltage controllers:

1- Single phase full wave controller “Bidirectional”, Using ON-OFF control.

T1 = Thyristor 1

T2 = Thyristor 2

Vs = source voltage, for example 220 volt.

Is = source current.

R = RL = Resistive load

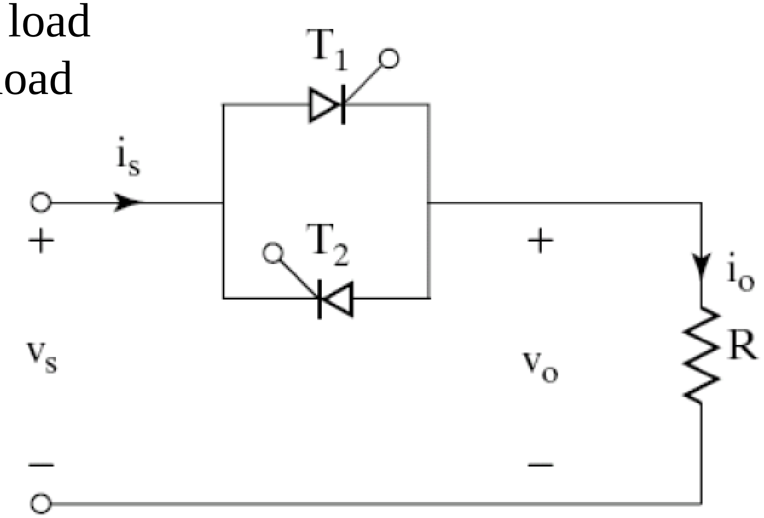
Vo = Output voltage supplied to the load

Io = Output current supplied to the load

N = number of cycles turned on

M = number of cycles turned off

Cycle = 360 degree



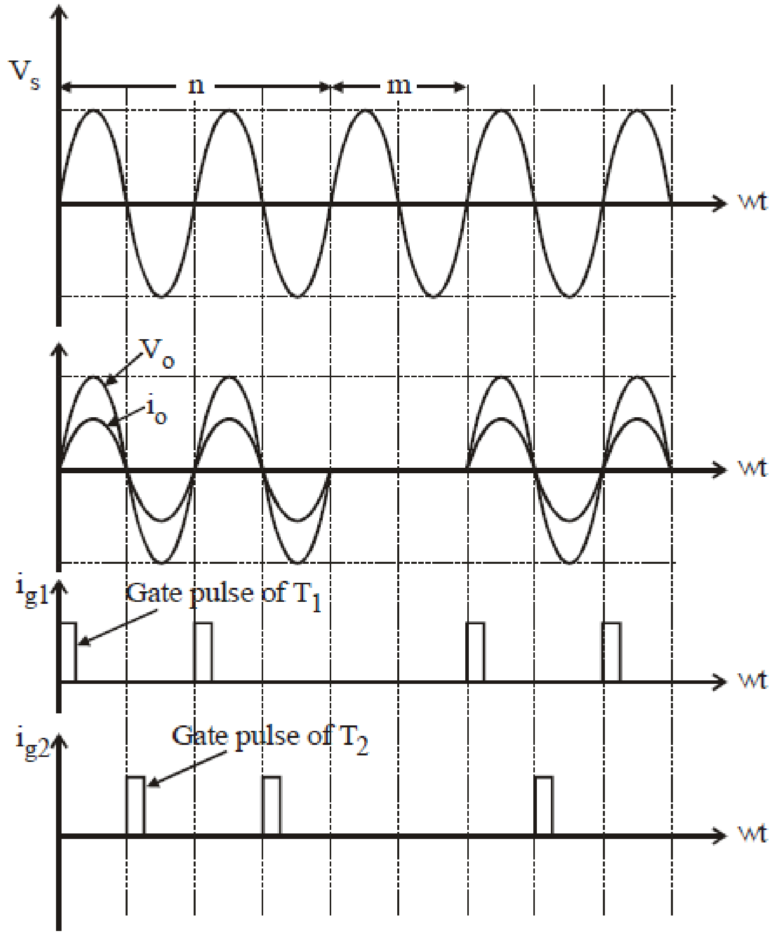


figure (6) Single phase full wave controller “Bidirectional”, Using ON-OFF control.

This type of control is used in applications which have high mechanical inertia and high thermal time constant (Industrial heating and speed control of ac motors). Due to zero voltage and zero current switching of Thyristors, the harmonics generated by switching actions are reduced.

For a sine wave input supply voltage:

$$vs = Vm \sin wt = \sqrt{2} Vs \sin wt$$

Vs= RMS value of input ac supply = $\frac{Vm}{\sqrt{2}}$ = RMS phase supply voltage.

If the input ac supply is connected to load for 'n' number of input cycles and disconnected for 'm' number of input cycles, and T is the input cycle time (time period), then

$$T_{on} = T * n$$
$$T_{off} = T * m$$
$$T = \frac{1}{f} \quad , where\ f\ is\ the\ input\ supply\ frequency.$$
$$T_{out} = T_{on} + T_{off}$$

$$Vout = \sqrt{\frac{n}{2\pi\,(n+m)}\int_0^{2\pi} 2Vs^2\,\sin^2 wt\; d(wt)}$$

$$Vout = Vs * \sqrt{\frac{T_{on}}{T_{out}}} = Vs\ * \sqrt{\frac{T\ * n}{T(n+m)}} = Vs\sqrt{k}$$

$where\ k = \dfrac{n}{n+m}\ , and\ it\ is\ called\ the\ duty\ cycle$

$Vout = the\ rms\ output\ voltage\ "root\ mean\ square"$

Derivation is necessary, Homework, you may need this: $sin^2\theta = \frac{1-\cos 2\theta}{2}$

Example 1.1

2- Single phase half wave controller “Unidirectional”, Using phase angle control

T1 = Thyristor 1
D1 = Free wheeling diode.
Vp = Primary voltage of transformer, for example 220 volt
Vs = Secondary voltage of transformer, for example 110 volt.
Is = source current.
R = RL = Resistive load
Vo = Output voltage supplied to the load
Io = Output current supplied to the load

The circuit showing in figure (7) is suitable only for low-power resistive loads, such s heating and lighting.

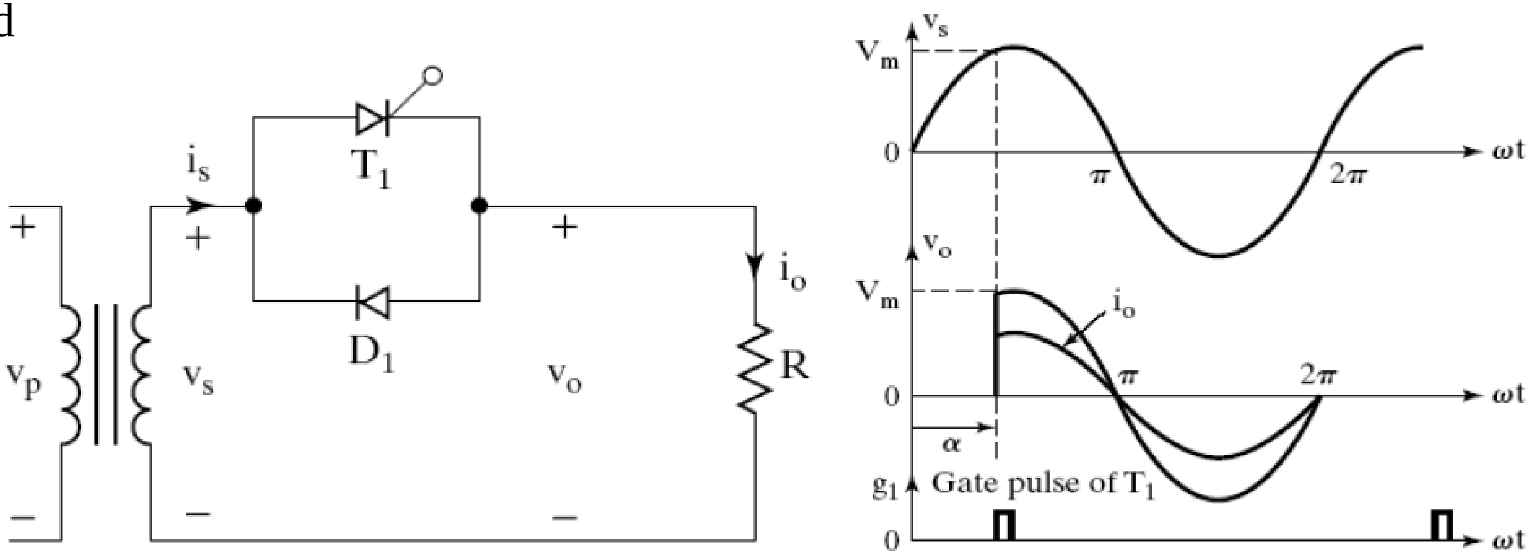


figure (7) Single phase half wave controller “Unidirectional”, Using phase angle control

For a sine wave input supply voltage:

$$vs = Vm \sin wt = \sqrt{2}Vs \sin wt$$

Vs= RMS value of secondary supply voltage = $\frac{Vm}{\sqrt{2}}$

$The\ delay\ angle\ "phase\ angle"\ of\ T1\ is\ wt = \alpha$

Before the thyristor is being switched on, from $wt = 0$ to $< \alpha$

$Vout\ and\ I\ out\ will\ be\ zero$

After the thyristor is being switched on, from $wt = \alpha\ to\ 2\pi$

$V_{out} = Vm \sin wt$

$I_{out} = \frac{Vout}{R} = \frac{Vm \sin wt}{R}$ “Not for use, it is just to explain that the wave will follow the exact path of the input voltage”

The rms output voltage is found from the following formula

$$V_{out} = \sqrt{\frac{1}{2\pi}\left[\int_{\alpha}^{\pi} 2Vs^2 sin^2\ wt\ d(wt) + \int_{\pi}^{2\pi} 2Vs^2 sin^2\ wt\ d(wt)\right]} \Longrightarrow V_{out} = Vs\sqrt{\frac{1}{2\pi}\left(2\pi - \alpha + \frac{\sin 2\alpha}{2}\right)}$$

Derivation is necessary, Homework, you may need this: $sin^2\theta = \frac{1-\cos 2\theta}{2}$

Be aware !! you can use the following formula as well, to find the exact answer, try it.

$$V_{out} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{2\pi} 2Vs^2 sin^2\, wt\; d(wt)} \Longrightarrow V_{out} = Vs\sqrt{\frac{1}{2\pi}\left(2\pi - \alpha + \frac{\sin 2\alpha}{2}\right)}$$

The $avarage$ output voltage is found from the following formula

$$V_{av} = V_{dc} = \frac{1}{2\pi}\int_{\alpha}^{2\pi} \sqrt{2}\, Vs\; \sin wt\;\; d(wt)$$

$$V_{dc} = \frac{\sqrt{2}Vs}{2\pi}(\cos\alpha\; - 1)$$

Example 1.2

By using the expression for $Vout\ rms$ we can obtain the control characteristics, which is the plot of RMS output voltage $Vout\ rms$ versus the trigger angle α . A typical control characteristic of single phase half-wave phase controlled ac voltage controller is as shown below

Trigger angle α in degrees	Trigger angle α in radians	$V\ out\ rms$
0°	0	$Vs = \frac{Vm}{\sqrt{2}}$
30°	$\frac{\pi}{6}$	0.992765 Vs
60°	$\frac{\pi}{3}$	0.949868 Vs
90°	$\frac{\pi}{2}$	0.866025 Vs
120°	$\frac{2\pi}{3}$	0.77314 Vs
150°	$\frac{5\pi}{6}$	0.717228 Vs
180°	π	0.707106 Vs

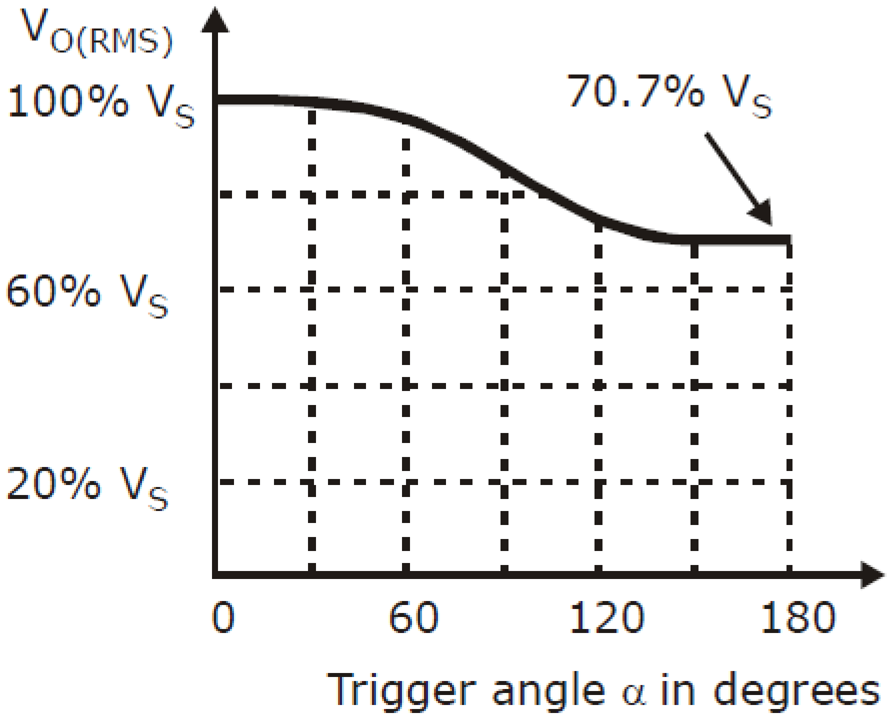


Fig (8) Control characteristics of single phase half-wave phase controlled ac voltage controller

3- Single phase full wave controller "Bidirectional", Using phase angle control

T1 = Thyristor 1
T2 = Thyristor 2
Vs = source voltage, for example 220 volt.
Is = source current.
R = RL = Resistive load
Vo = Output voltage supplied to the load
Io = Output current supplied to the load

The firing pulses of T1 and T2
Are kept 180° apart.

Therefore the firing angle of
The second Thyristor is:

$$\alpha 2 = \alpha 1 + \pi$$

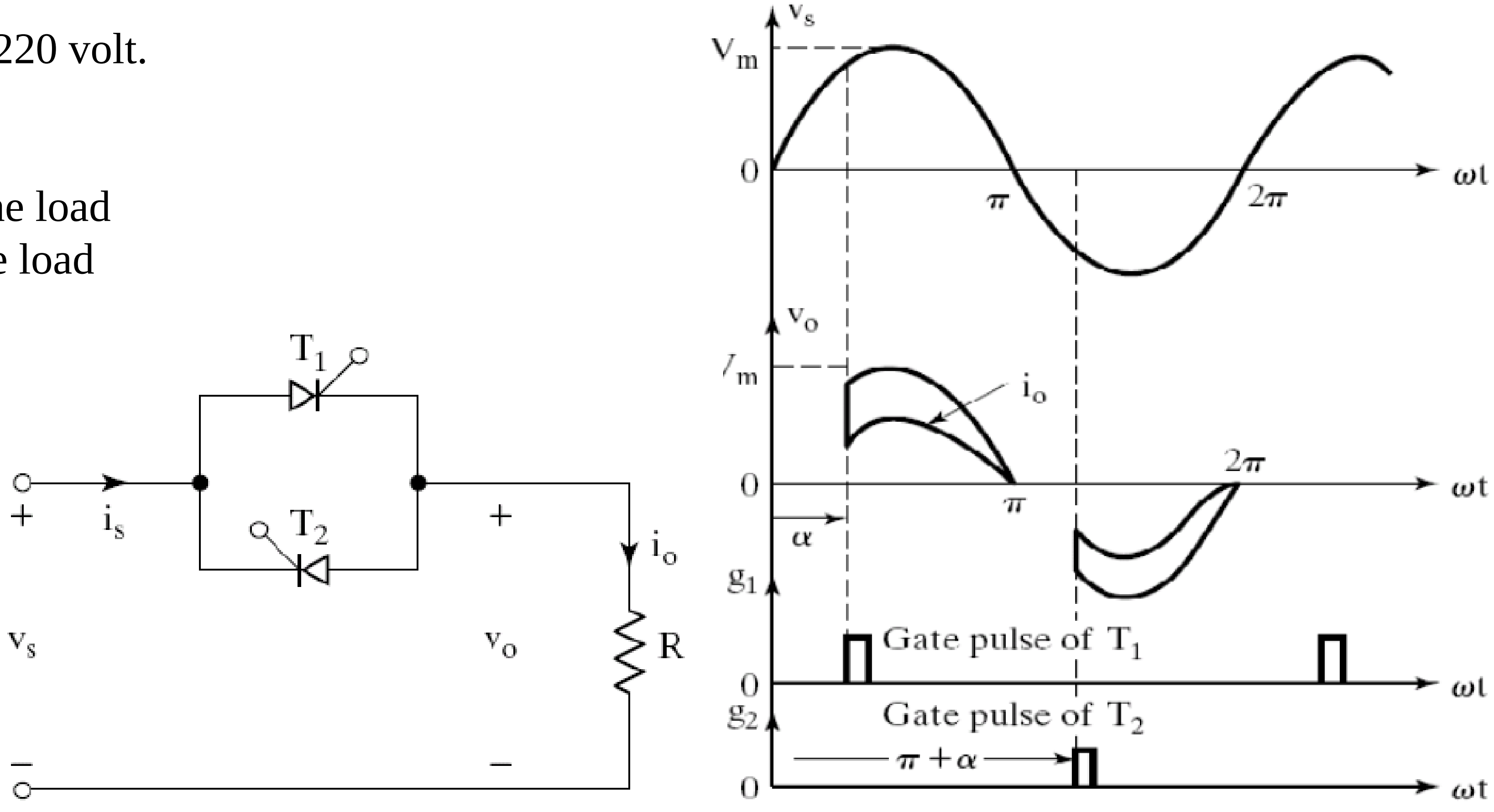


Fig (9) Single phase full wave controller "Bidirectional", Using phase angle control

The rms output voltage can be found from the following formula

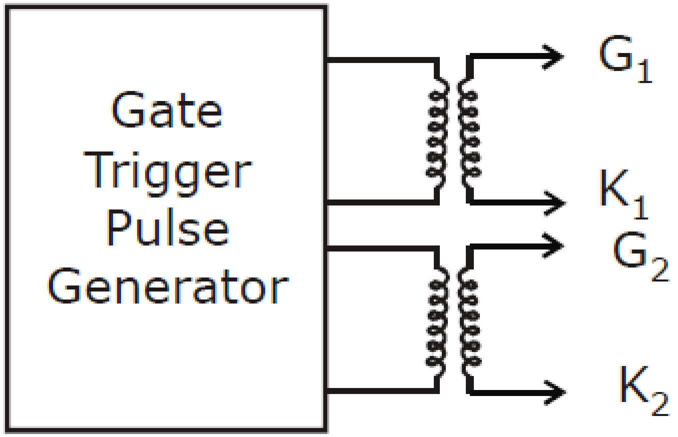
$$V_{out} = \sqrt{\frac{2}{2\pi}\int_{\alpha}^{\pi} 2Vs^2\, sin^2wt\; d(wt)} \implies V_{out} = Vs\sqrt{\frac{1}{\pi}\left(\pi - \alpha + \frac{\sin 2\alpha}{2}\right)}$$

By varying α from 0 to π, V_{out} can be varied from Vs to 0

Need For Isolation

In the single phase full wave ac voltage controller circuit using two SCRs or Thyristors T1 and T2 in parallel, the gating circuits (gate trigger pulse generating circuits) of Thyristors T1 and T2 must be isolated. Figure (10) shows a pulse transformer with two separate windings to provide isolation between the gating signals of T1 and T2 .

Single phase full wave ac voltage controller circuit using two SCRs or a single triac is generally used in most of the ac control applications.



A typical control characteristic of single phase full-wave phase controlled ac voltage controller is as shown below

Trigger angle α in degrees	Trigger angle α in radians	$V\ out\ rms$
0°	0	Vs
30°	$\frac{\pi}{6}$	0.985477 Vs
60°	$\frac{\pi}{3}$	0.896938 Vs
90°	$\frac{\pi}{2}$	0.7071 Vs
120°	$\frac{2\pi}{3}$	0.44215 Vs
150°	$\frac{5\pi}{6}$	0.1698 Vs
180°	π	0 Vs

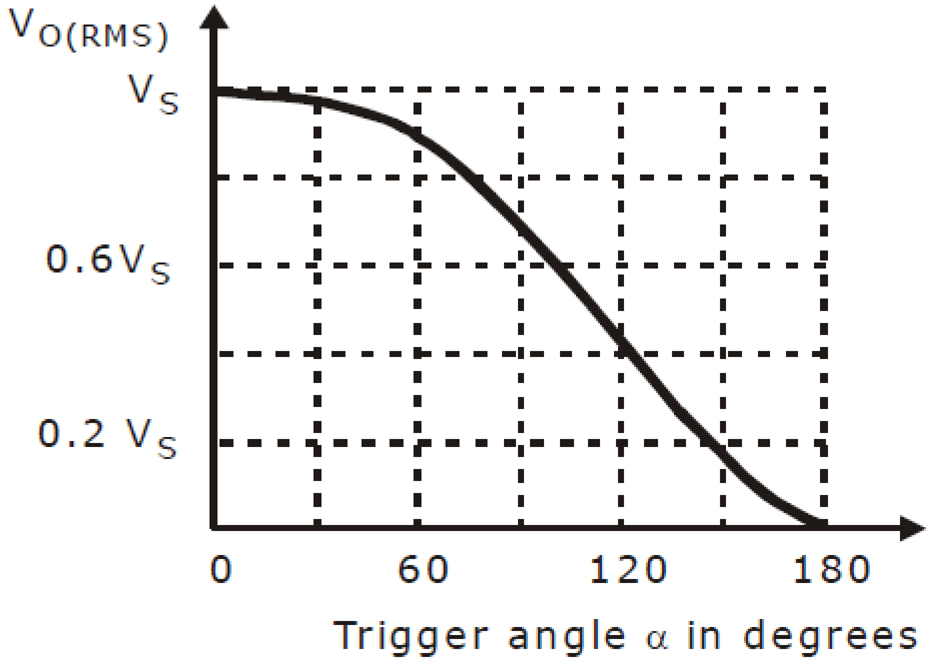


Fig (11) Control characteristics of single phase full-wave phase controlled ac voltage controller

Other types of single phase full wave ac voltage controller circuits:

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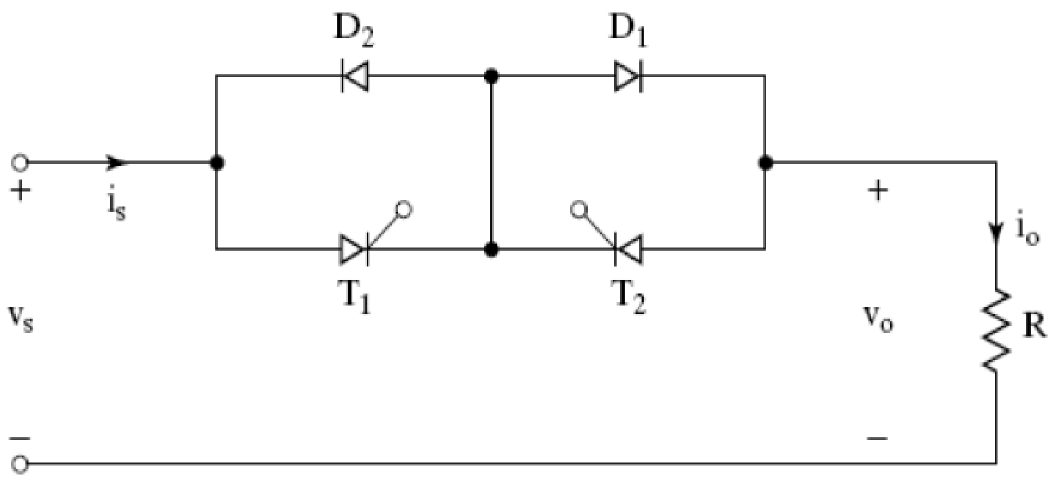
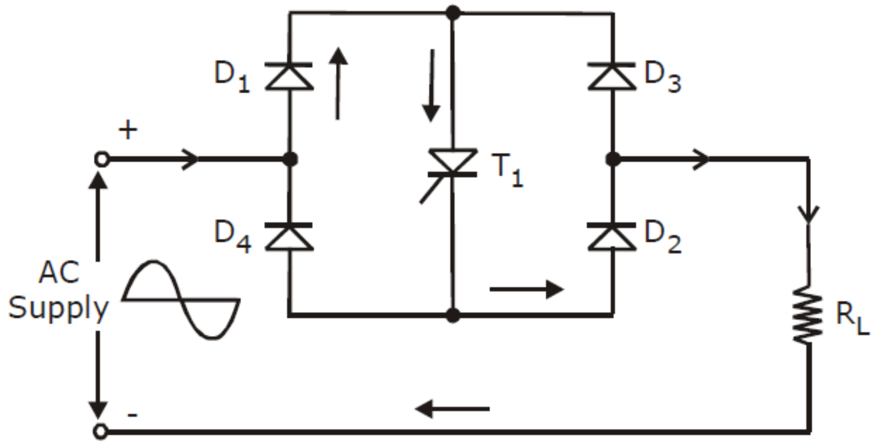
<tr><th>Single phase full wave ac controller with common cathode.</th><th>Single phase full wave ac voltage controller using a single thyristor.</th></tr>
<tr><td>
</td><td>
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Fig (12) 2 types of single phase full wave ac voltage controller

Example 1.3

4- Three phase full wave controller "Bidirectional" with Y connected resistive load, Using phase angle control

The three phase half wave controller "unidirectional" is not normally used in ac motor drives, due to the dc input current and higher harmonic content. There are many types of circuits used for the three-phase ac regulators (ac to ac voltage converters), unlike single-phase ones.
The three-phase loads (balanced) are connected in star or delta. Two thyristors connected back to back, or a Triac, is used for each phase in most of the circuits as described.

Figure (13) below shows the circuit diagram of three-phase full-wave controller with a Y connected resistive load.
The firing sequence of Thyristors is T1 – T2 – T3 – T4 – T5 – T6

Phase voltages	Line voltages $(wt + 30)$
$E_{AN} = \sqrt{2}\,Vs \sin wt$	$E_{AB} = \sqrt{6}\,Vs \sin\left(wt + \frac{\pi}{6}\right)$
$E_{BN} = \sqrt{2}\,Vs \sin\left(wt - \frac{2\pi}{3}\right)$	$E_{BC} = \sqrt{6}\,Vs \sin\left(wt - \frac{\pi}{2}\right)$
$E_{CN} = \sqrt{2}\,Vs \sin\left(wt - \frac{4\pi}{3}\right)$	$E_{CA} = \sqrt{6}\,Vs \sin\left(wt - \frac{7\pi}{6}\right)$

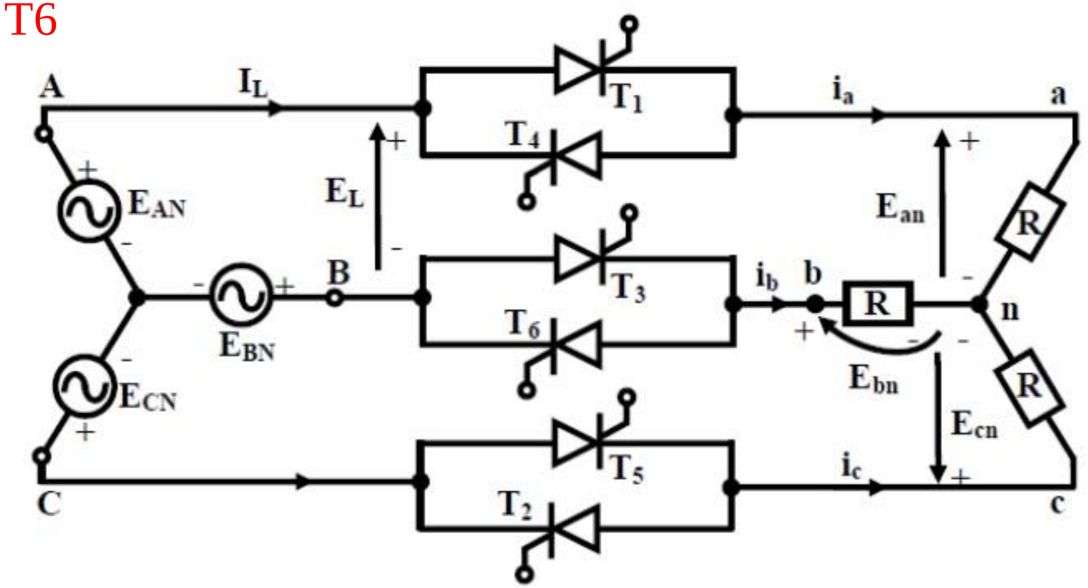


Fig (13) Three-phase, three-wire ac regulator

For a time instant, there are 2 possible conduction states:

– Each phase has a thyristor conducting. Load voltages are the same as the source voltages. (Ean wave follow EAN wave).

– There are only 2 thyristors conducting, each from a phase. The load voltages of the two conducting phases are half of the corresponding line to line voltage, while the load voltage of the other phase is 0.

Figure (14) shows how the output voltage (Load voltage) of phase (a) Ean can be calculated

The firing angle α is 60°
Three phase → 120° between each phase
The angle of each square equals to 30°

The supply phase voltages:
Phase EAN
Phase EBN
Phase ECN

The load phase voltages:
Phase Ean
Phase Ebn
Phase Ecn

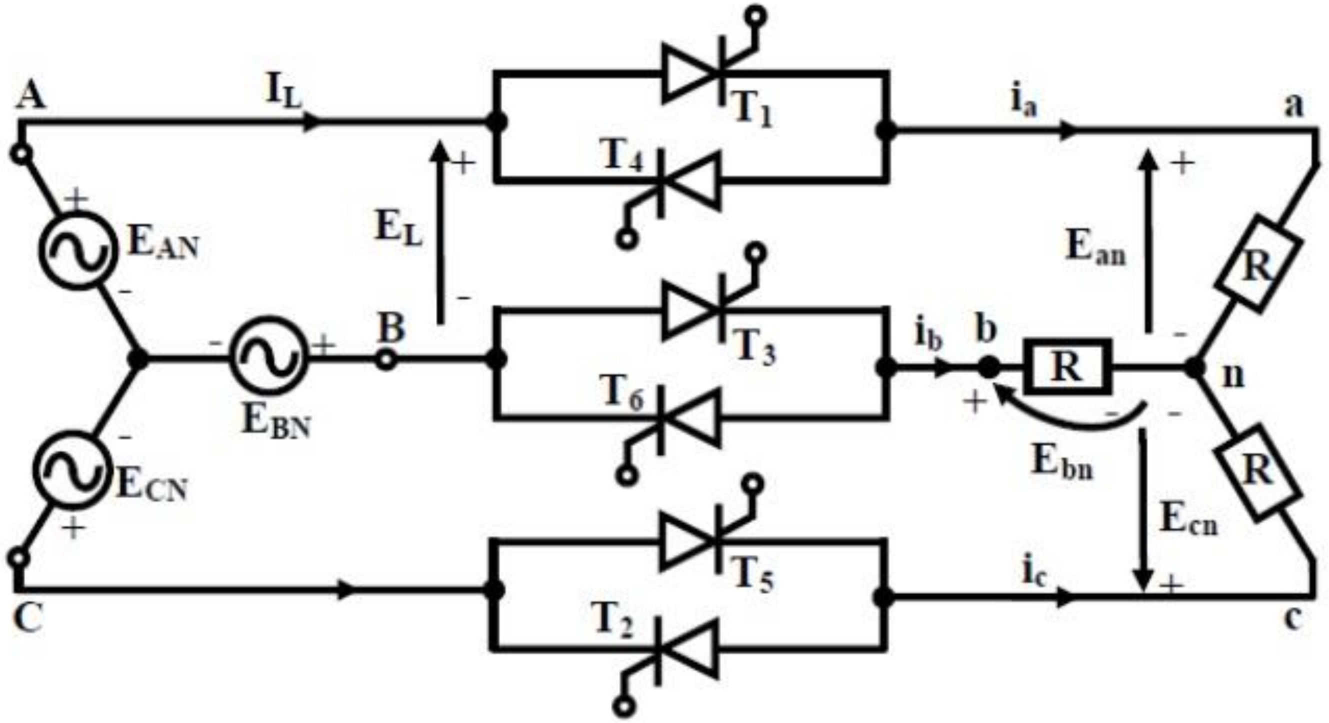


Fig (13) Three-phase, three-wire ac regulator

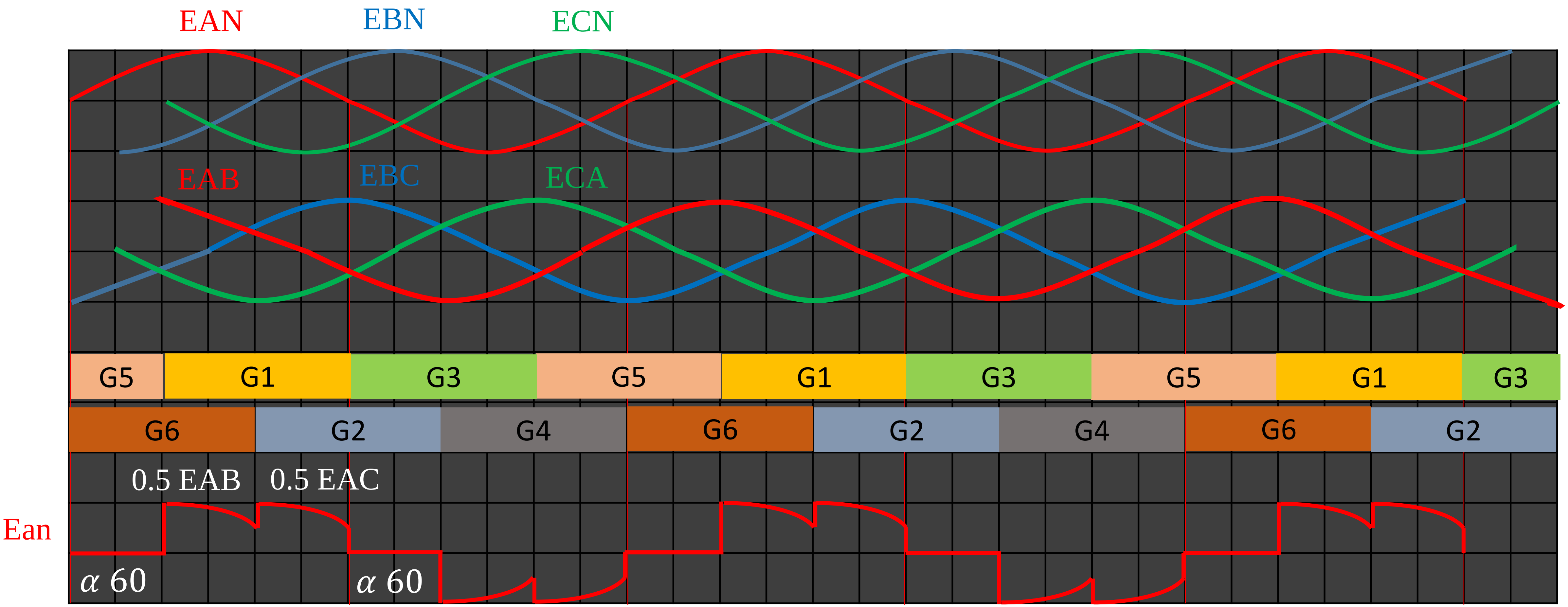


Figure (14) Three phase full wave controller Ean Waveform when α = 60°

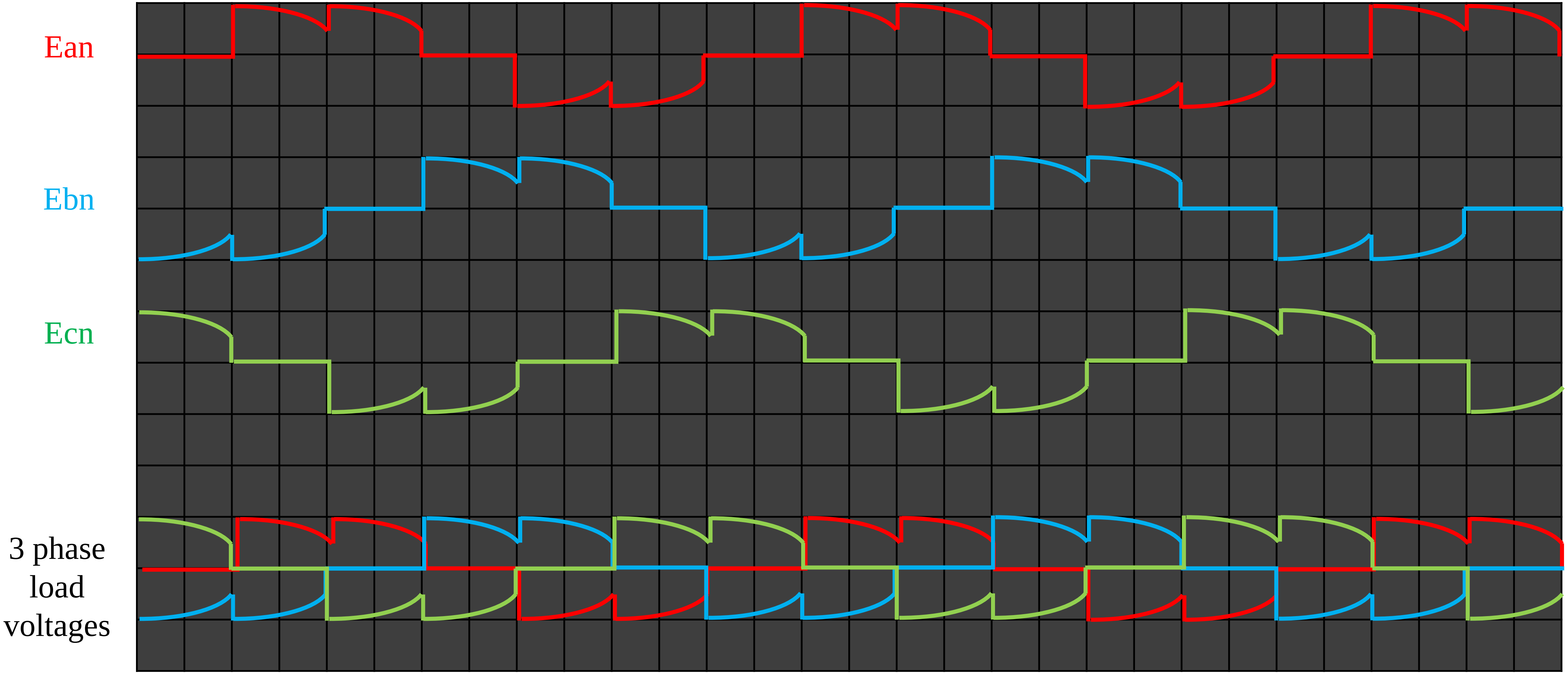


Figure (15) Three phase full wave controller, load phase voltage waveforms when α = 60°

Note: α cannot exceed 150.

The RMS output voltages for Y connected load can be found as follows:

- For 0° <= α < 60°

$$V_{out} = \sqrt{6}Vs\sqrt{\frac{1}{\pi}\left(\frac{\pi}{6}-\frac{\alpha}{4}+\frac{\sin 2\alpha}{8}\right)}$$

- For 60° <= α < 90°

$$V_{out} = \sqrt{6}Vs\sqrt{\frac{1}{\pi}\left(\frac{\pi}{12}+\frac{3\sin 2\alpha}{16}+\frac{\sqrt{3}\cos 2\alpha}{16}\right)}$$

- For 90° <= α <= 150°

$$V_{out} = \sqrt{6}Vs\sqrt{\frac{1}{\pi}\left(\frac{5\pi}{24}-\frac{\alpha}{4}+\frac{\sin 2\alpha}{16}+\frac{\sqrt{3}\cos 2\alpha}{16}\right)}$$

Figure (16) Single phase controller Three phase controller

Example 1.4

Chapter 2: Frequency converters (Cycloconverters):

Variable output voltage at variable frequency can be obtained from two-stage conversion: fixed ac to variable dc (controlled rectifier) and variable dc to variable ac at variable frequency (inverter). However, Cycloconverters can eliminate the need of one or more intermediate converters.

Cycloconverter: is a direct-frequency changer that converts ac power at one frequency to ac power at another frequency. The maximum output frequency is limited and it is only a fraction of the source frequency.

Major applications of cycloconverters are low-speed, ac motor drives ranging up to 15,000 kW with frequencies from 0 to 20 HZ.

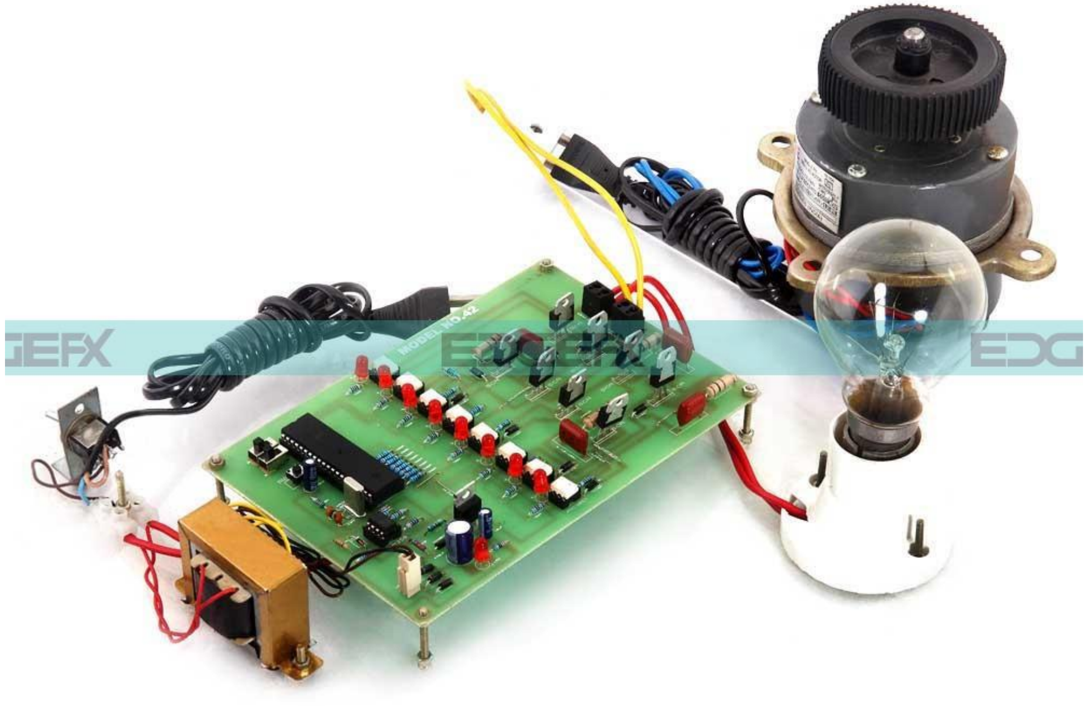


Figure (17) Cycloconverter

Types of Cycloconverters:

1- Single-Phase / Single-Phase Cycloconverters
2- Single-Phase semi-converter Cycloconverters
3- Three-Phase / Single-Phase Cycloconverters
4- Three-Phase / Three-Phase Cycloconverters

1- Single-Phase / Single-Phase Cycloconverters

The principle of operation of single phase / single phase cycloconverters can be explained with the help of figure (18) below. The two single phase full wave controlled converters are operated as bridge rectifiers (back-to-back connection of two full-wave rectifier circuits). However, their delay angles are such that the output voltage of one converter is equal and opposite to that of the other converter

The input voltage, vs is an ac voltage at a frequency, Fin. For easy understanding assume that all the thyristors are fired at $\alpha = 0°$ firing angle, i.e. thyristors act like diodes. Note that the firing angles are named as αp for the positive converter and αn for the negative converter.

Operation of the circuit:

1- During the first half period of the output frequency $T - posetive$, converter (P) operates as a normal controlled rectifier. The firing angles of P converter are:
(T1) and (T2) at (α) and gating (T3) and (T4) at (Π+α).

2- During the second half period of the output frequency $T - negative$ converter (N) operates as a normal controlled rectifier. The firing angles of N converter are:
(T1') and (T2') at (Π - α) and gating (T3') and (T4') at (2Π - α).

Figure 19 shows the operating waveforms for this converter with a resistive load.

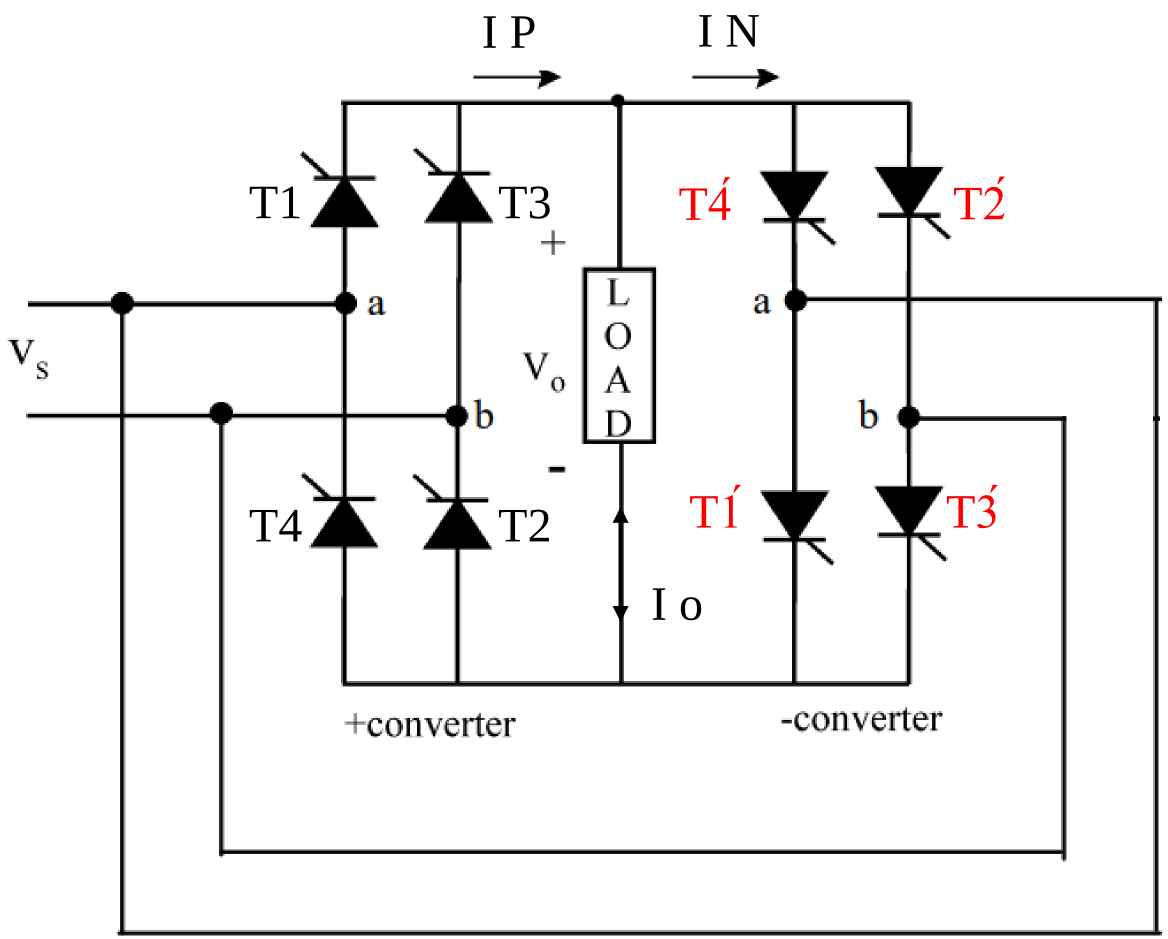


Figure (18) Single-Phase Cycloconverter

The output frequency can be found from:

If there are four input cycles as shown in figure (19-a) and one output cycle as shown in figure (19-b), then if the input frequency equals to 60 the output frequency $Fout = \frac{Fin}{4} = \frac{60}{4} = 15\ HZ$

$$Fout\ = \frac{Fin}{No.integrated\ cycles}$$

Each converter (rectifier) works for half the full time output time (Tout). $Tout\ = \frac{1}{Fout}$

$Tout = Tp + Tn$

If there are 4 cycles then there have to be 4 tops and 4 bottoms.

$Vdc\ 2\ = -Vdc\ 1$

$\alpha n\ = \pi - \ \alpha p$

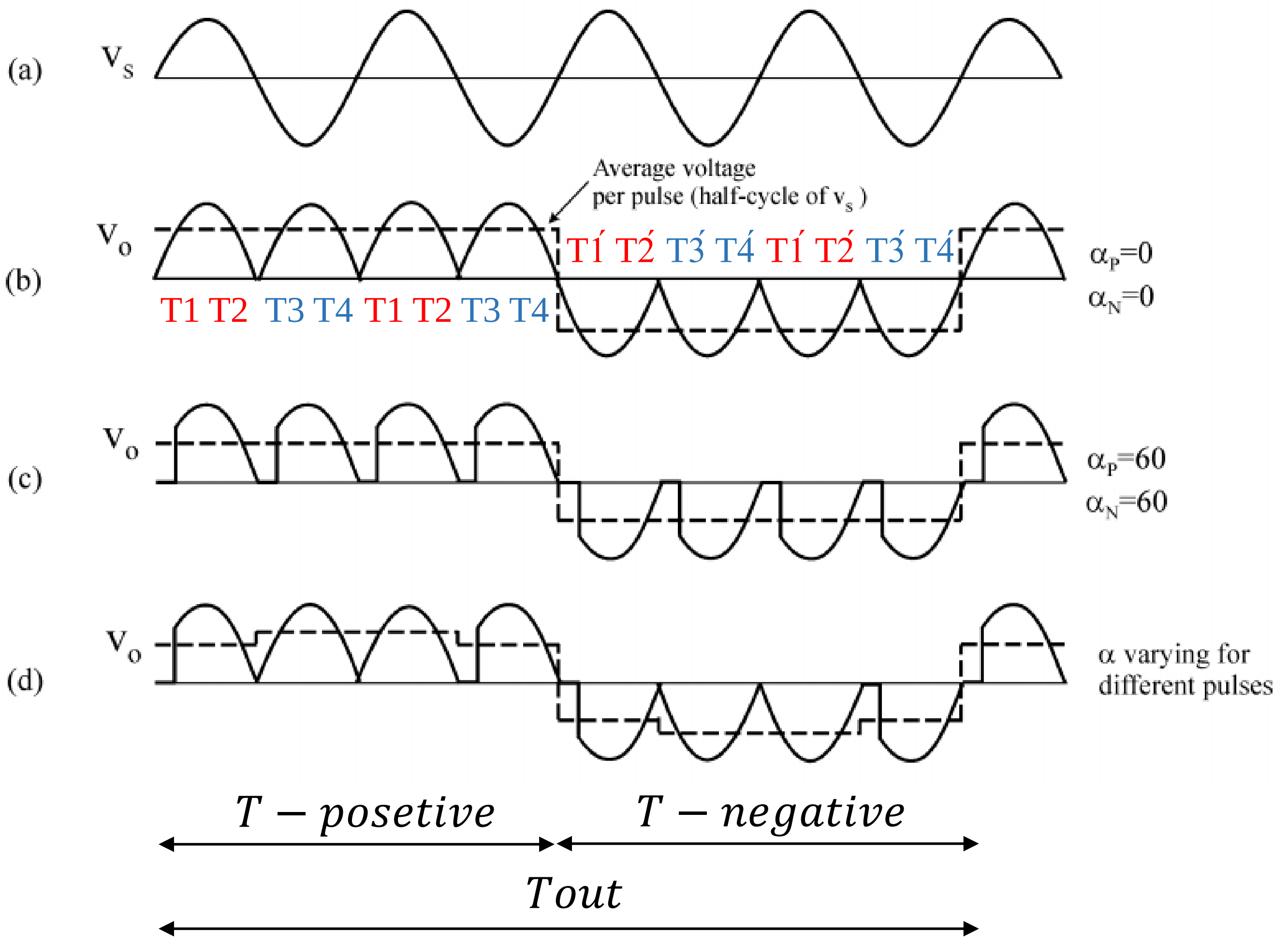


Figure (19) The operating waveforms of single phase cycloconverter with a resistive load

2- Single phase semi-converter cycloconverter

Figure (20) shows the single phase semi-converter cycloconverter. The only different is having diodes in the lower legs instead of thyristors. It's operation is similar to the single phase cycloconverter.

1- During the first half period of the output frequency $T-posetive$ convert P operates as a normal controlled rectifier with a delay angle (αp = α) that is by gating (T1) at (α) and gating (T3) at (Π+α).

2- During the second half period of the output frequency $T-negative$ convert N operates as a normal controlled rectifier with a delay angle (αN = Π - α) that is by gating (T1') at (Π - α) and gating (T3') at (2Π - α).

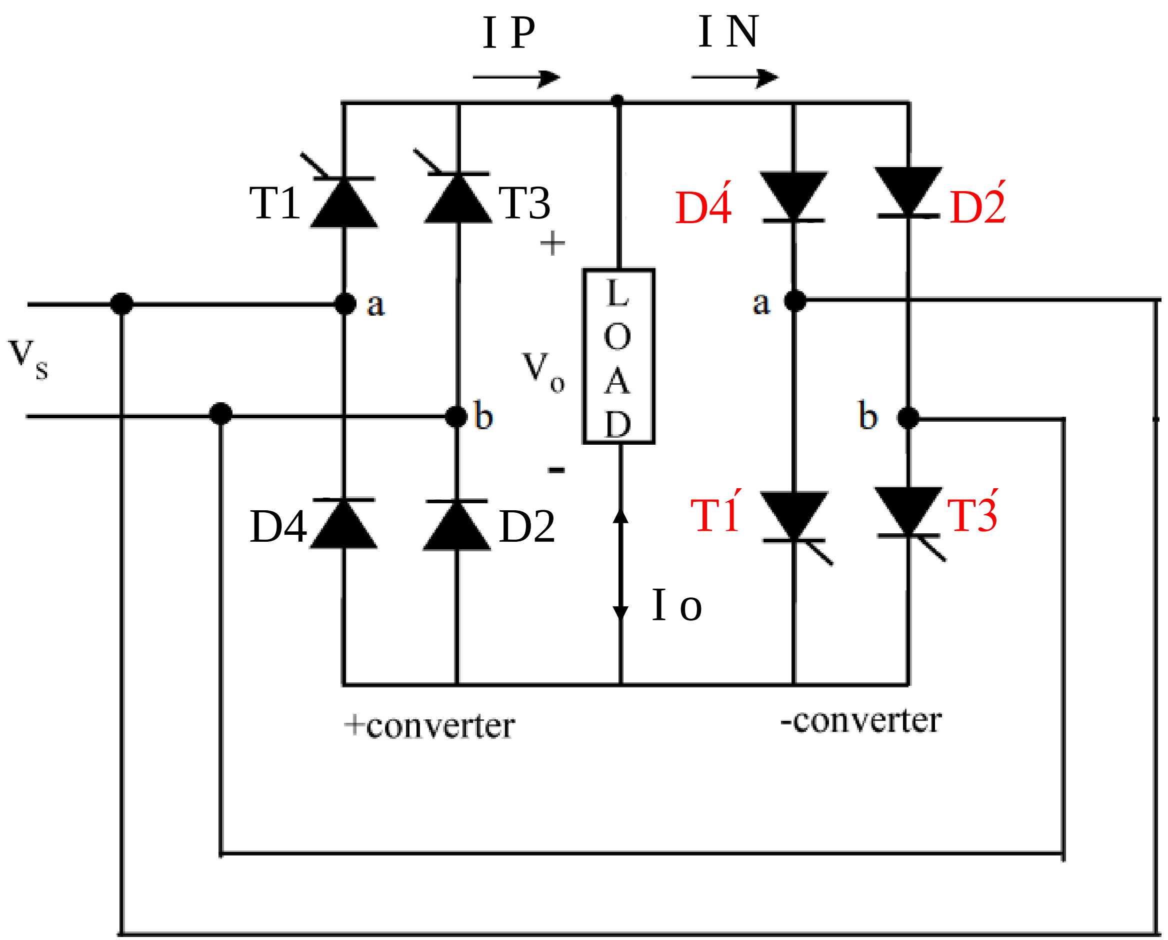


Figure (20) Single-Phase semi-converter Cycloconverter

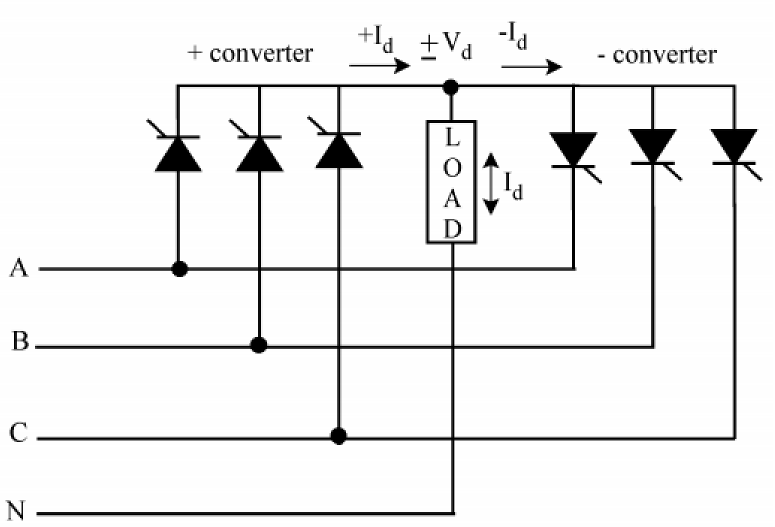
Example 2.1

3- Three-Phase / Single-Phase Cycloconverters

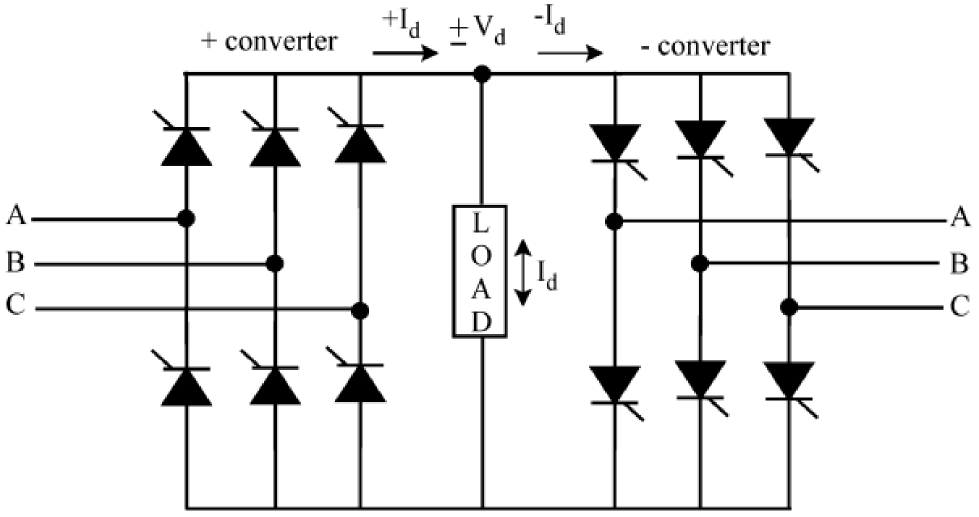
There are two types of Three-Phase / Single-Phase Cycloconverters:

- Half-wave Cycloconverter shown in figure (21 – a)
- Bridge Cycloconverter shown in figure (21 – b)

Like the 1Φ-1Φ case, the 3Φ-1Φ Cycloconverter applies rectified voltage to the load. Both positive and negative converters can generate voltages at either polarity, but the positive converter can only supply positive current and the negative converter can only supply negative current. The circuit of a three-phase to single-phase bridge cyclo-converter is shown in Figure (21-b). The synthesis of output waveform for an output frequency of 12 HZ is shown in figure (22). The positive converter operates for half the period of output frequency and the negative converter operates for the other half period. The analysis of this cycloconverter is similar to that of single phase / single phase cycloconverters.



(21 – a) Half-wave Cycloconverter



(21 – b) Bridge Cycloconverter

Gating sequence:

1- During the first half period of the output frequency $To/2\ (T - positive)$, operate converter P as a normal three phase controller rectifier with a delay angle of $(\alpha P = \alpha)$.

2- During the second half period $To/2\ (T - negative)$, operate converter N as a normal controlled three phase rectifier with a delay angle of $(\alpha N = \pi - \alpha)$.

The two half cycles are combined to form one complete cycle of the output voltage, the frequency being decided by the number of half cycles of input voltage waveform used for each half cycle of the output.

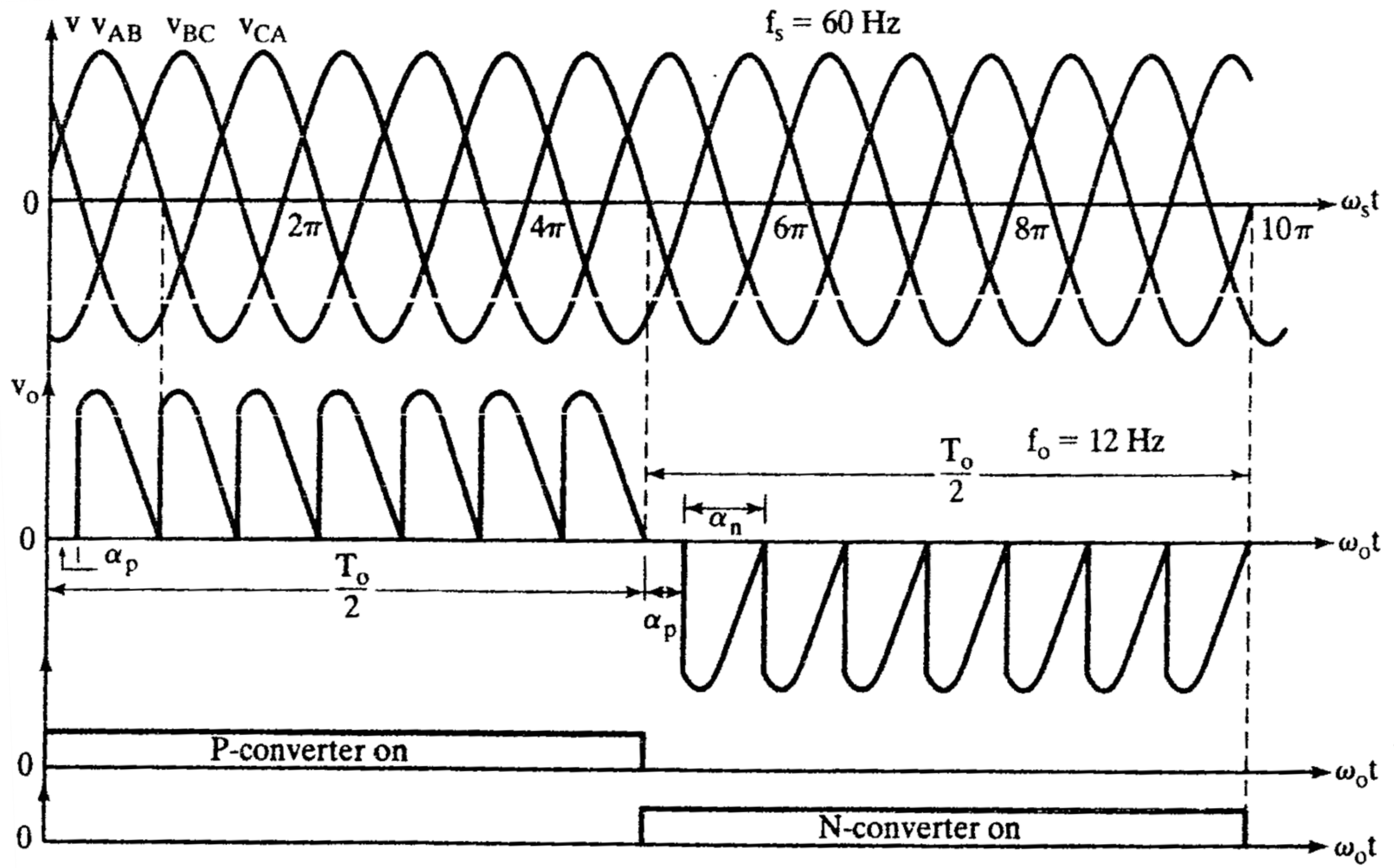


Figure (22) Waveform for resistive load,
Three-Phase / Single Phase Bridge Cycloconverter

4- Three-Phase / Three-Phase Cycloconverters

The control of 3-phase ac motors requires a three phase voltage at a variable frequency. The cycloconverter in figure (21) can be extended to provide three phase output by having 3 three phases converters, as shown in figure (23) Each phase consists of 6 thyristors, and total of 18 thyristors are required.
An 18-thyristor cycloconverter it is also called half-wave cycloconverter.

The three-phase cycloconverters are mainly used in ac machine drive systems running three phase synchronous and induction machines. They are more advantageous when used with a synchronous machine due to their output power factor characteristics. A cycloconverter can supply lagging, leading, or unity power factor loads while its input is always lagging. A synchronous machine can draw any power factor current from the converter. This characteristic operation matches the cycloconverter to the synchronous machine. On the other hand, induction machines can only draw lagging current, so the cycloconverter does not have an edge compared to the other converters in this aspect for running an induction machine. However, cycloconverters are used in Scherbius drives for speed control purposes driving wound rotor induction motors.

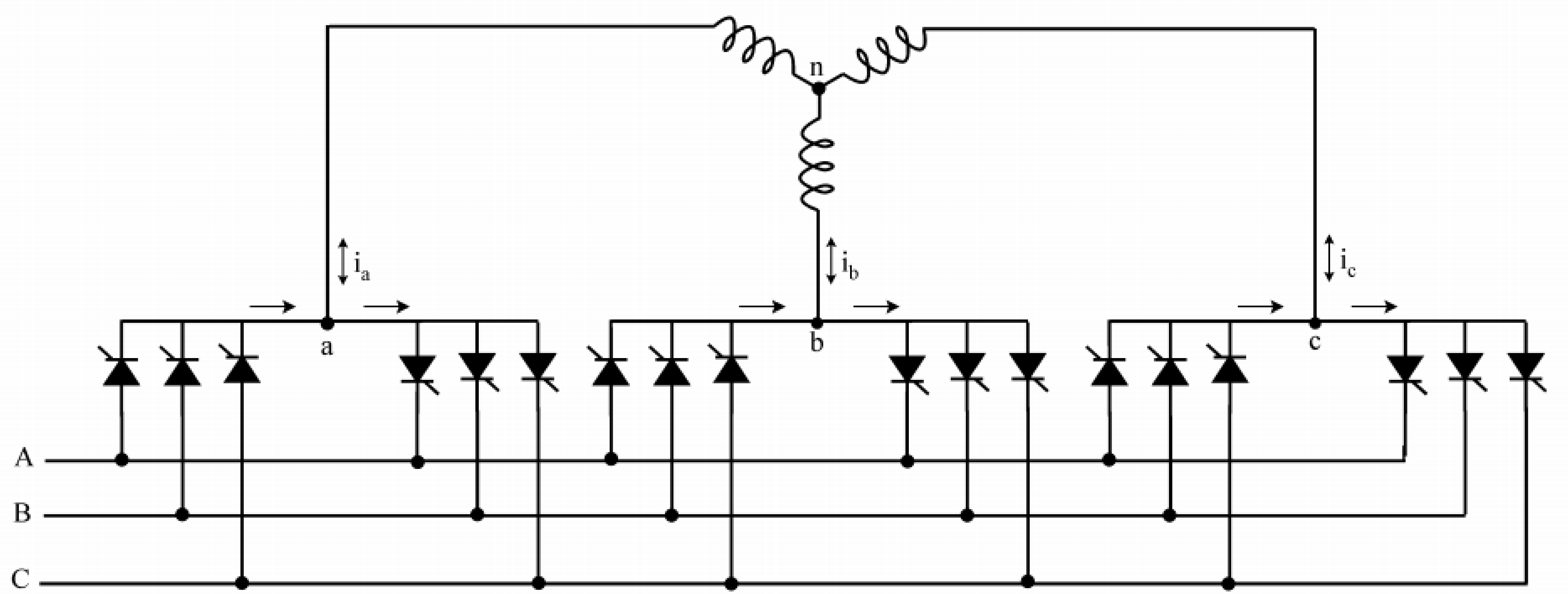


Figure (23) An 18-thyristor cycloconverter it is also called half-wave cycloconverter

If six full wave three-phase converters are used, 36 thyristors would be required, as showin in figure (24), bridge cycloconverter.

5- Reduction of Output Harmonics

We can notice from figure (19) and (22) that the output voltage is not purely sinusoidal, and as a result the output voltage contains harmonics. The following equation:

$$PF = \frac{Po}{Vs\ Is} = \frac{Vo \cos\theta}{Vs} = \cos\theta \sqrt{\frac{1}{\pi}\left(\pi - \alpha + \frac{\sin 2\alpha}{2}\right)}$$

Shows that the input PF depends on the delay angle of thyristors and is poor, esprcially at the low output voltage range. The output voltage of cycloconverters is basiclly made up of segments of input voltages and the avarage value of a segment depends on the delay angle for that segment.

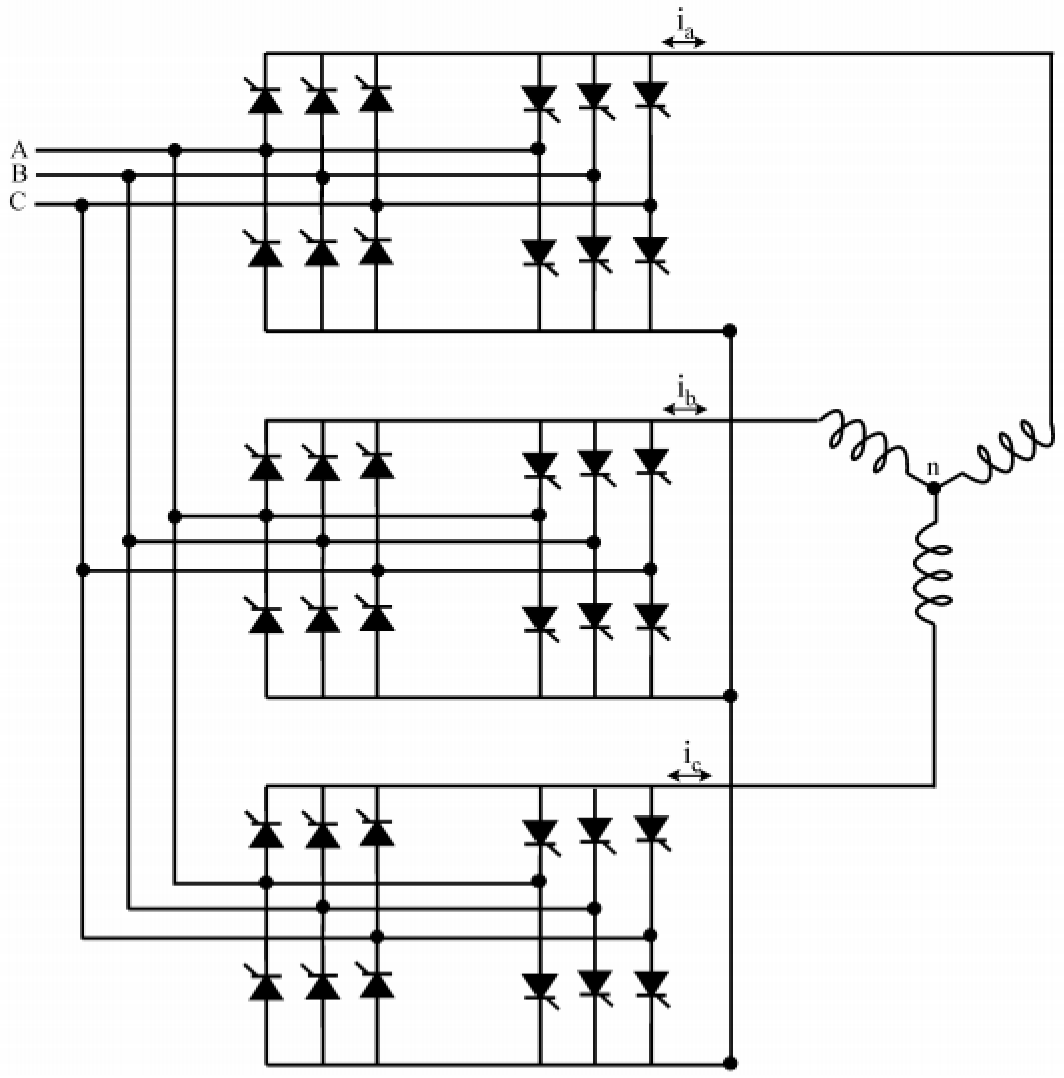


Figure (24) bridge cycloconverter, 36 thyristors.

If the delay angles of segments were varied in such a way that the avargae values of segments correspond as closely as possible to the variation of desired sinusoidal output voltage, the harmonics on the output voltage can be minimized [2,3]. The following equation

$Vdc = \frac{\sqrt{2}Vs}{2\pi}(\cos\alpha - 1)$ indicates that the avarage output voltage of a segment is a cosine function of delay angle. The delay angles for segments can be generated by comparing a cosine signal at source frequency

$\left(vc = \sqrt{2}Vs\cos wst\right)$

with an ideal sinusoidal reference voltage at the output frequency $\left(vr = \sqrt{2}Vr\sin wot\right)$.

Figure (25) shows the generation of gating signals for the thyristors of the cycloconverters in figure (21-b).

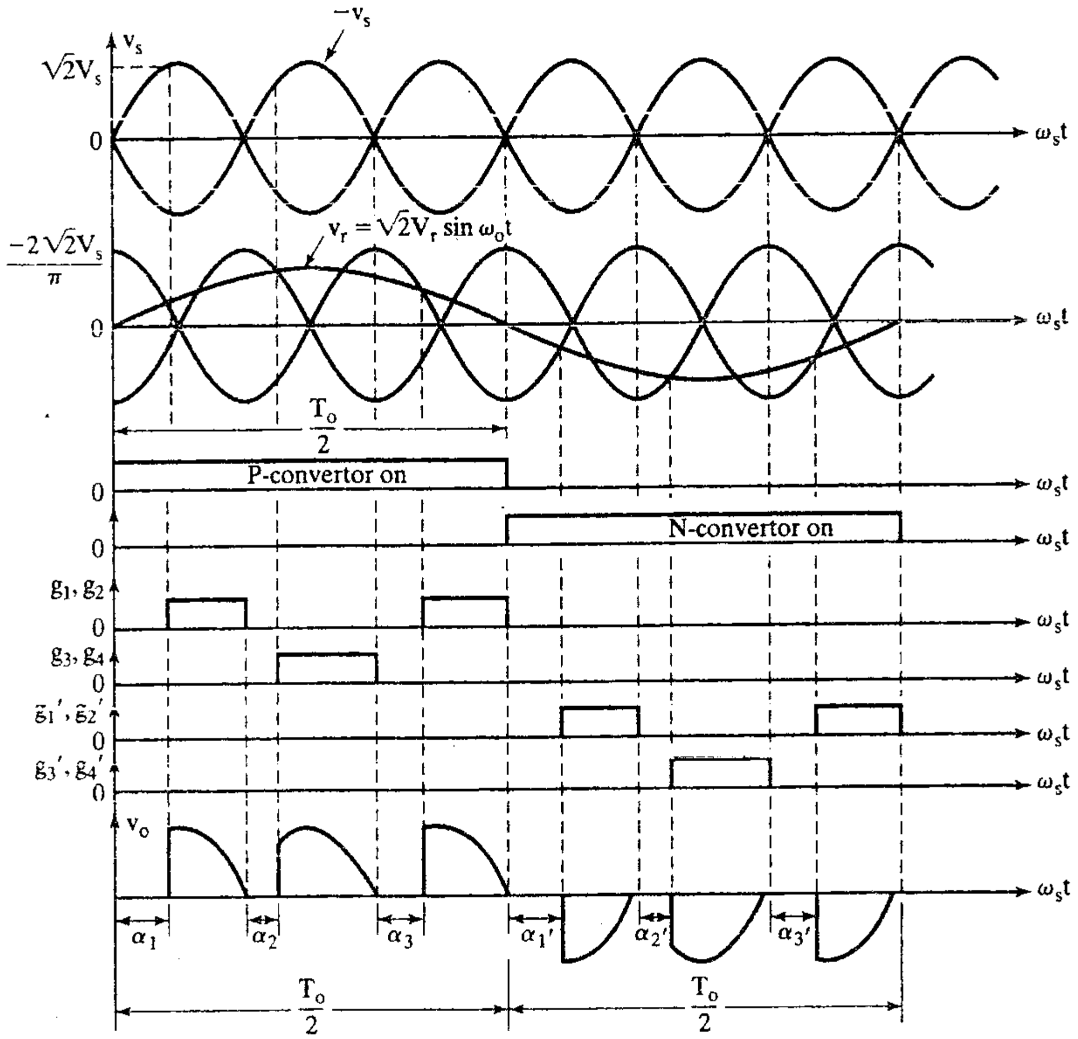


Figure (25) Generation of thyristor gating signals.

The maximum average voltage of a segment (which occurs for $\alpha P = 0$) should be equal to the peak value of output voltage; for example:

$$VP = \frac{2\sqrt{2}Vs}{\pi} = \sqrt{2}Vo$$

which gives the rms value of output voltage as

$$Vo = \frac{2Vs}{\pi} = \frac{2Vp}{\pi}$$

Example 2.2

Homework

Chapter 3: Inverters

Introduction:

Inverters are used to create single or polyphase AC voltages from a DC supply. In the class of polyphase inverters, three-phase inverters are by far the largest group. A very large number of inverters are used for adjustable speed motor drives. The typical inverter for this application is a "hard-switched" voltage source inverter producing pulse-width modulated (PWM) signals with a sinusoidal fundamental [Holtz, 1992]. Recently research has shown detrimental effects on the windings and the bearings resulting from unfiltered PWM waveforms and recommend the use of filters [Cash and Habetler, 1998; Von Jouanne et al., 1996]. A very common application for single-phase inverters are so-called "uninterruptable power supplies" (UPS) for computers and other critical loads. Here, the output waveforms range from square wave to almost ideal sinusoids. In addition to the very common hard-switched inverters, active research is being conducted on soft switching techniques. Hard-switched inverters use controllable power semiconductors to connect an output terminal to a stable DC bus. On the other hand, soft switching inverters have an oscillating intermediate circuit and attempt to open and close the power switches under zero-voltage and or zero-current conditions.

Modern inverters use insulated gate bipolar transistors (IGBTs) as the main power control devices [Mohan et al., 1995]. Besides IGBTs, power MOSFETs are also used especially {for lower voltages, power ratings, and applications that require high efficiency and high switching frequency}. In recent years, IGBTs, MOSFETs, and their control and protection circuitry have made remarkable progress. IGBTs are now available with voltage ratings of up to 3300 V and current ratings up to 1200 A. MOSFETs have achieved on-state resistances approaching a few milliohms. In addition to the devices, manufacturers today offer customized control circuitry that provides for electrical isolation, proper operation of the devices under normal operating conditions and protection from a variety of fault conditions [Mohan et al., 1995]. In addition, the industry provides good support for specialized passive devices such as capacitors and mechanical components such as low inductance bus-bar assemblies to facilitate the design of reliable inverters. In addition to the aforementioned inverters, a large number of special topologies are used. A good overview is given by Gottlieb [1984].

Fundamental Issues:

Inverters fall in the class of power electronics circuits. The most widely accepted definition of a power electronics circuit is that the circuit is actually processing electric energy rather than information. The actual power level is not very important for the classification of a circuit as a power electronics circuit. One of the most important performance considerations of power electronics circuits, like inverters, is their energy conversion efficiency. The most important reason for demanding high efficiency is the problem of removing large amounts of heat from the power devices. Heat produced from on-state losses and switching losses.

Inverters

- Multilevel inverters
- PWM inverters
- Resonant pulse inverters

MULTILEVEL INVERTERS:

Before we start with the multilevel inverters let us discuss the two-level inverter. (The voltage source inverters produce an output voltage or a current with levels either 0 or ±Vdc). Figure (26) shows the ac voltage waveform produced using two-level inverter. It is obvious that the amount of ripple is quite high, to minimize the ripple they require high switching frequency along with various pulse width modulation strategies.

In high power and high voltage applications, these two-level inverters however, have some limitations in operating at high frequency mainly due to switching losses and constraints of device ratings. Moreover, the semiconductor switching devices should be used in such a manner as to avoid problems associated with their series-parallel combinations that are necessary to obtain capability of handling high voltages and currents.

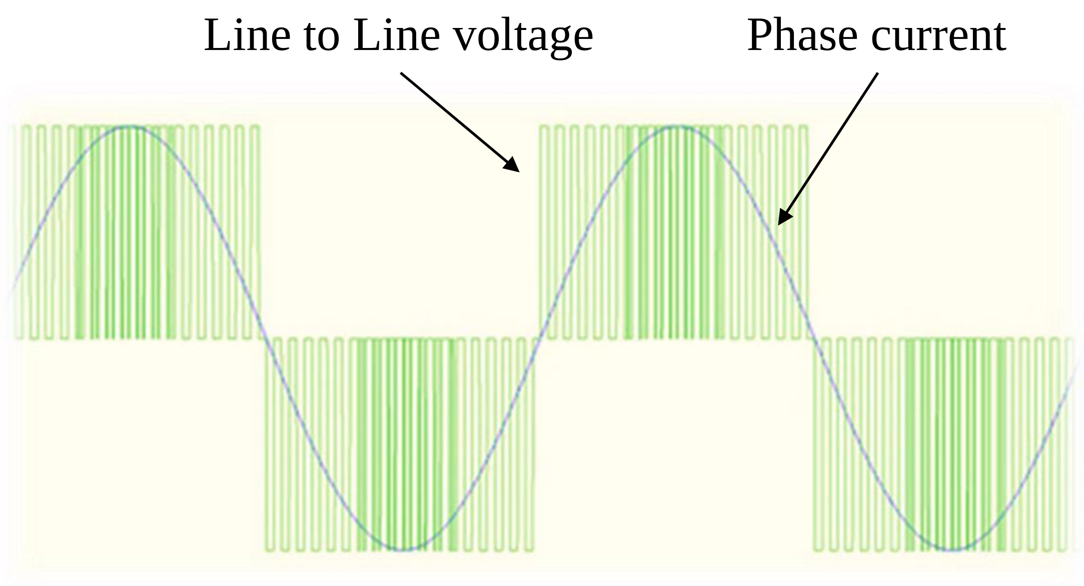


Figure (26) ac voltage and current waveforms produced using two-level inverter.

It may be easier to produce a high-power, high-voltage inverter with the multilevel structure because of the way in which device voltage stresses are controlled in the structure. Increasing the number of voltage levels in the inverter without requiring higher rating on individual devices can increase the power rating. The unique structure of multilevel voltage source inverters allows them to reach high voltages with low harmonics without the use of transformers or series-connected synchronized-switching devices. As the number of voltage levels increases, the harmonic content of the output voltage waveform decreases significantly.

Let us consider a three-phase inverter system as shown in figure (27), with a dc voltage Vdc. Series-connected capacitors constitute the energy tank for the inverter providing some nodes to which the multilevel inverter can be connected. Each capacitor has the same voltage Em which is given by $Em = \frac{Vdc}{m-1}$

Where m denotes the number of levels. The team level is referred to as the number of nodes to which the inverter can be accessible. An m-level inverter needs (m – 1) capacitors.

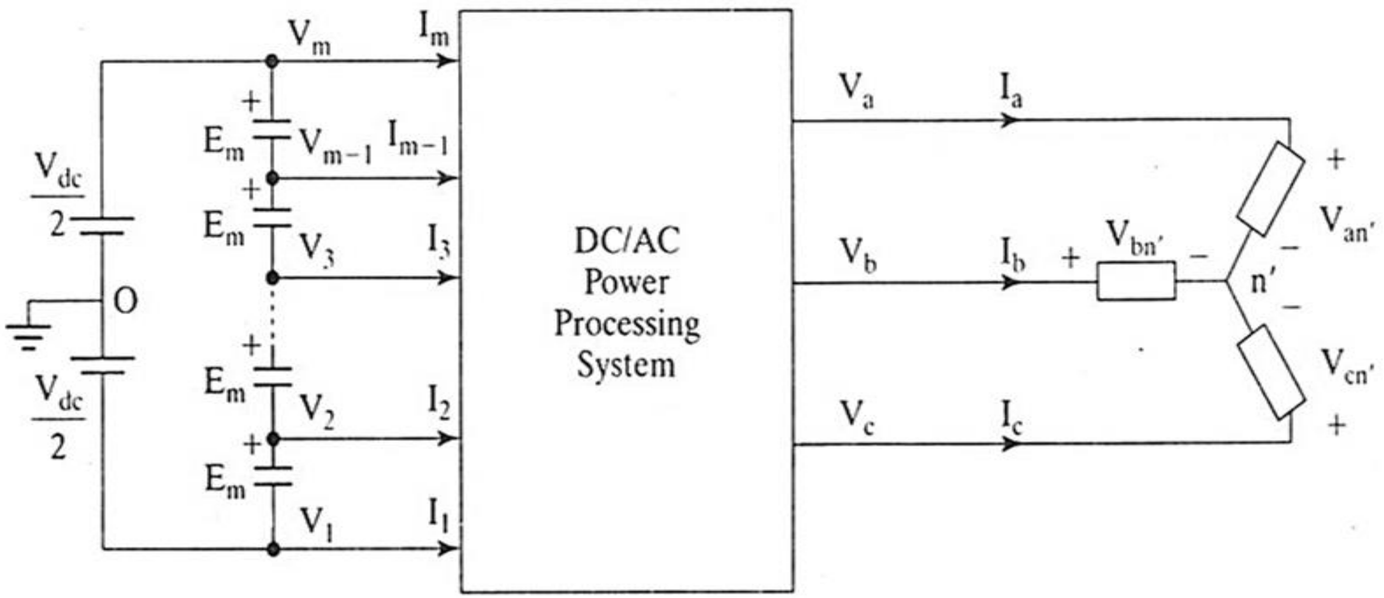


Figure (27) Three phase multilevel power processing system
5 level inverter

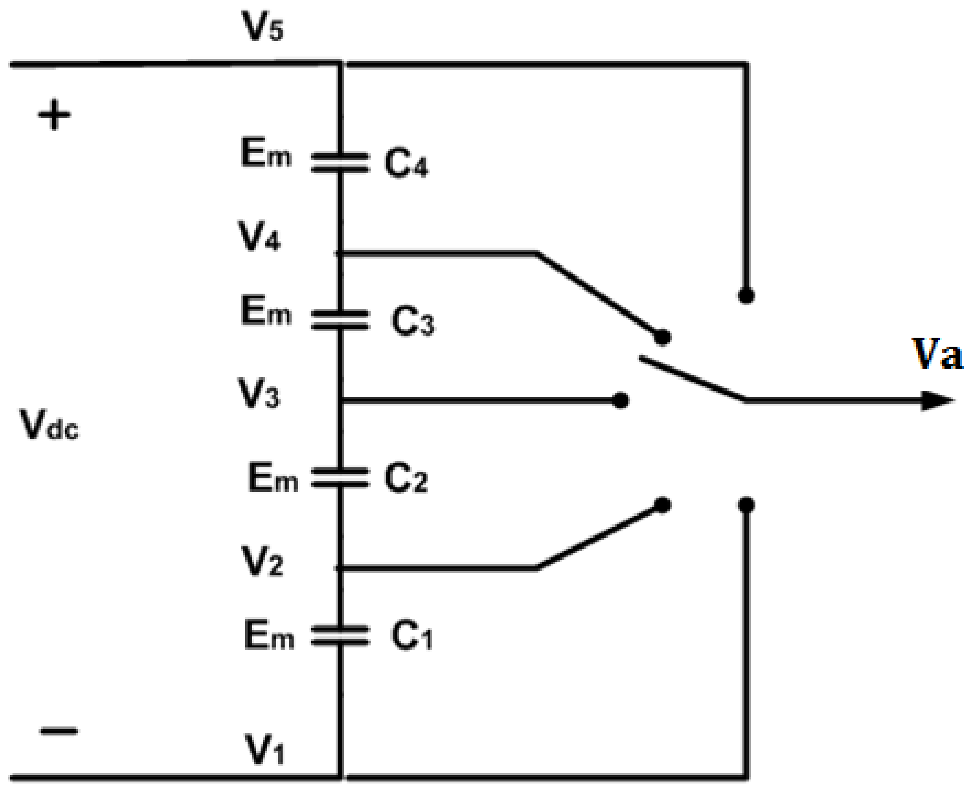


Figure (28) schematic of single pole of multilevel inverter by a switch

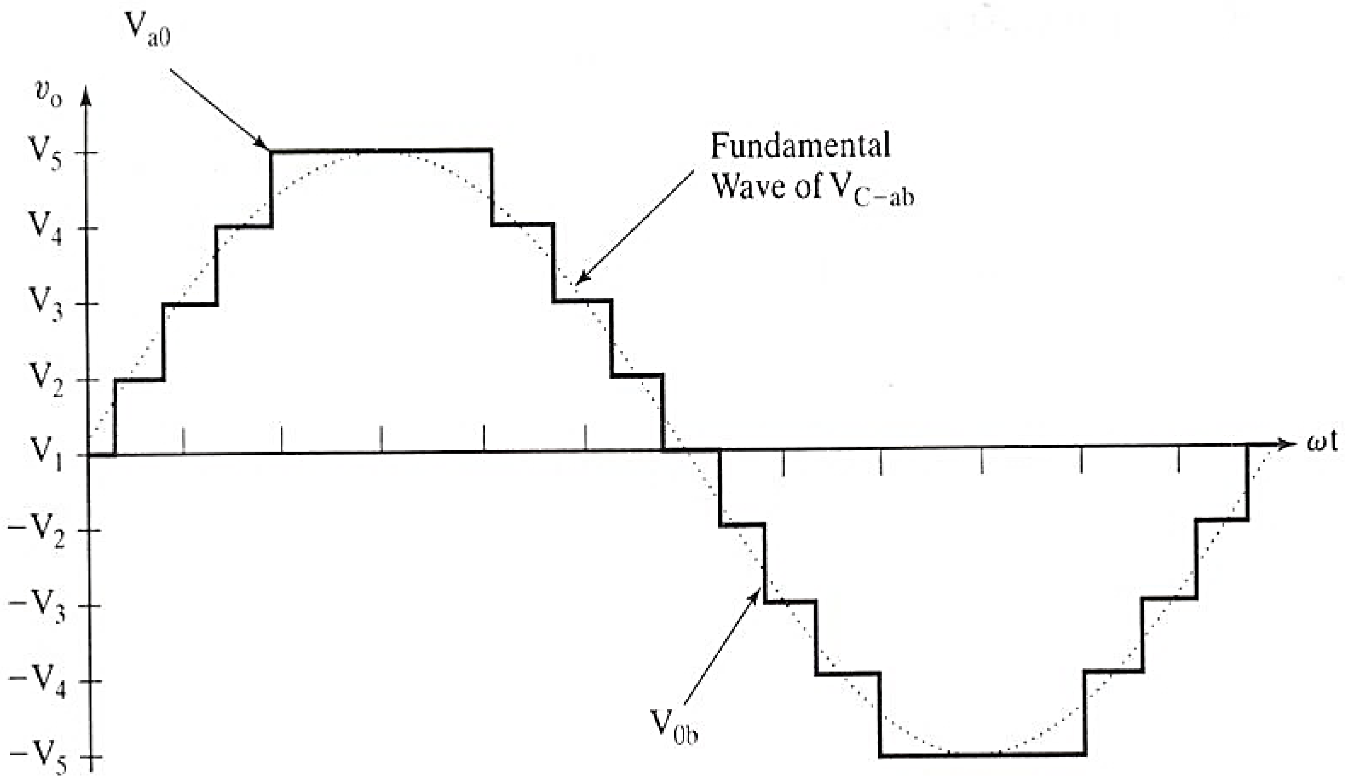


Figure (29) typical output voltage of a five level multilevel inverter

To generate an output voltage with both positive and negative values, the circuit topology has another switch to produce the negative part. $vab = vao + vob = vao - vbo$

The actual realization of the switch requires bidirectional switching devices for each node. The topological structure of multilevel inverter must:

1- Have less switching devices as far as possible.

2- Be capable of withstanding very high input voltage for high power applications.

3- Have lower switching frequency for each switching device.

Advantages of using multilevel inverters:

1- Reduced harmonic distortion.

2- Multilevel converters produce smaller CM (Common-mode) voltage. (the stress in the bearings of a motor connected to a multilevel motor drive can be reduced).

3- Input current: Multilevel converters can draw input current with low distortion.

4- Switching frequency: Multilevel converters can operate at both fundamental switching frequency and high switching frequency PWM. It should be noted that lower switching frequency usually means lower switching loss and higher efficiency.

Multilevel inverters are three types:

1- Diode clamped or Neutral-Point Clamped type

2- Flying capacitors type

3- Cascaded or H-bridge type

1- Diode-Clamped multilevel inverter

A diode clamped multilevel (m – level) inverter (DCMLI) typically consists of (m – 1) capacitors on the dc bus and produces m level on the phase voltage. This inverter uses diodes and provides the multiple voltage levels through the different phases to the capacitor banks which are in series. A diode transfers a limited amount of voltage, thereby reducing the stress on other electrical devices. The maximum output voltage is half of the input DC voltage.

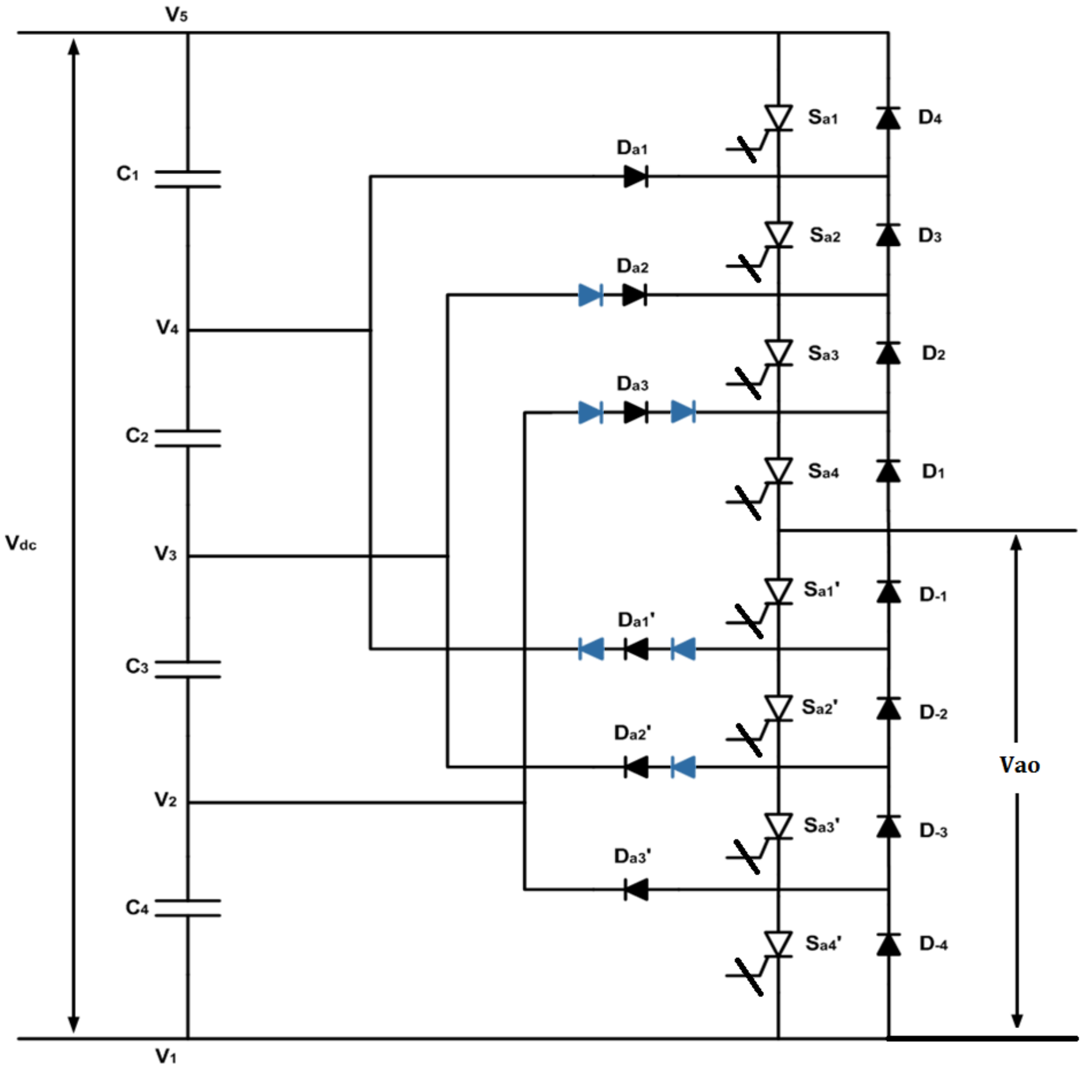
Figure (30 – a) shows one leg and figure (30 – b) shows a full bridge five level diode clamped converter. The dc bus consists of four capacitors, C1, C2, C3 and C4. For a dc bus voltage Vdc the voltage across each capacitor is Vdc/4, and each device voltage stress is limited to one capacitor voltage level Vdc/4 through clamping diodes. An m-level inverter leg requires:

(m – 1) capacitors, 2(m – 1) switching devices and (m – 1)(m – 2) clamping dioses.

Each phase leg voltage tracks one-half of the sinusoidal wave. The resulting line voltage is a nine-level staircase wave. This implies that an m-level converter has an m-level output phase-leg voltage and a (2m – 1) level output line voltage.

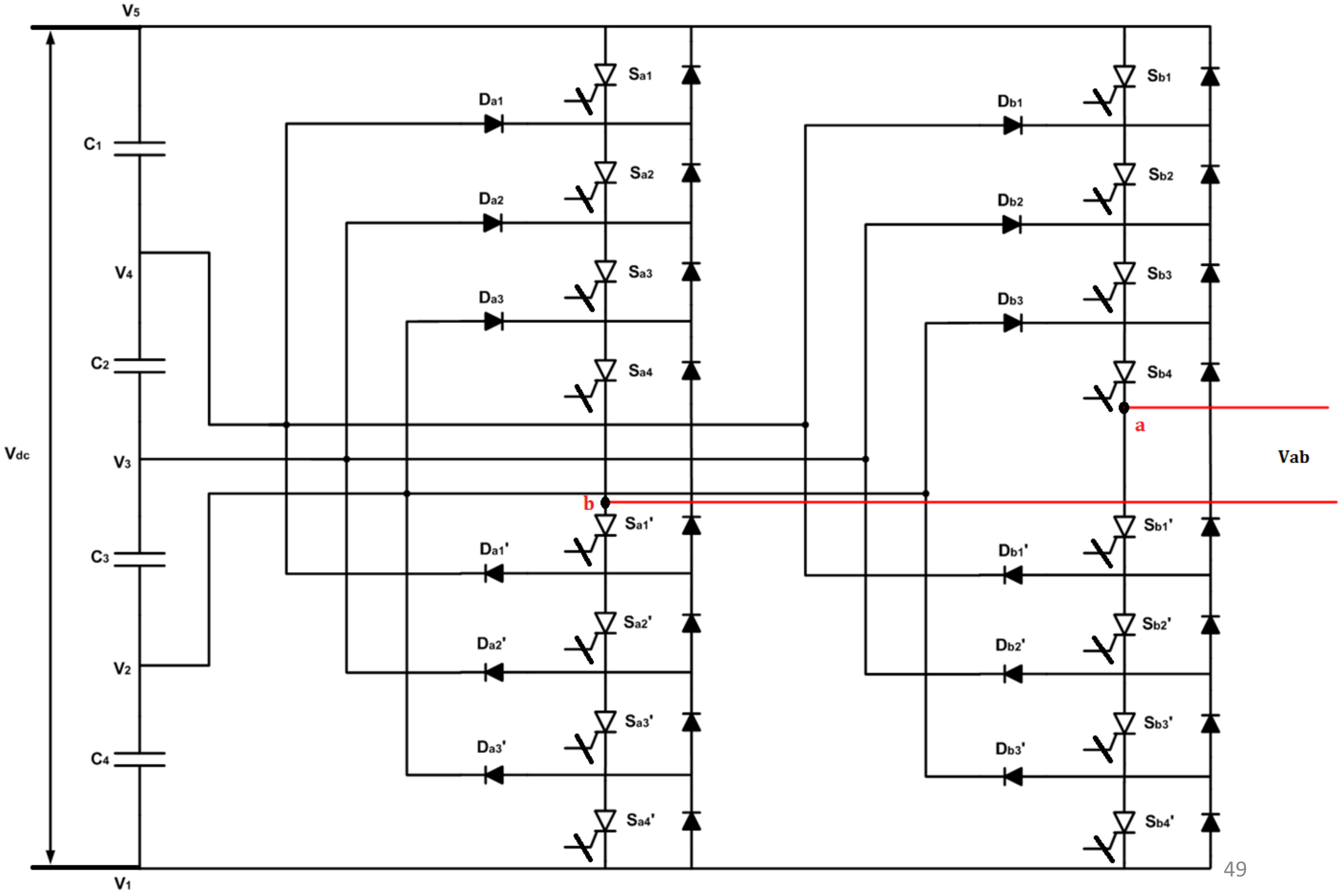
Principle of Operation:
To produce a staircase output voltage let us consider only one leg of the 5 – level inverter. The D.C. rail 0 is the reference point of output phase voltage. The steps to synthesize 5 – level voltages as follow

1. For output voltage level $Vao = Vdc$: Turn on all upper half switches Sa1 through Sa4.
2. For output voltage level $Vao = 3Vdc/4$: Turn on upper three switches *Sa2* through *Sa4* & one lower switch *Sa1′*.
3. For output voltage level $Vao = Vdc/2$: Turn on two upper switches *Sa3, Sa4* & lower two switches *Sa1′, Sa2′*.
4. For output voltage level $Vao = Vdc/4$: Turn on one upper switch *Sa4* & lower three switches *Sa1′* through *Sa3′*.
5. For output voltage level $Vao = 0$: Turn on all lower half switches *Sa1′* through *Sa4′*.



(30 – a) One leg of a bridge (5 level diode clamped inverter)

Homework: design a (4 – level) diode clamped multilevel inverter with the help of figure (30 – a) and (30 – b) and list the diode clamped voltage levels and their switch states in a table.



(30 – b) Single phase full bridge (5 level diode clamped multilevel inverter)

Advantages of diode-clamped inverter:

1- When the number of levels is high enough, the harmonic content is low enough to avoid the need for filters.

2- Inverter efficiency is high because all devices are switched at the fundamental frequency.

3- The control method is simple.

Disadvantages of diode-clamped inverter:

1- Excessive clamping diodes are required when the number of levels is high.

2- It is difficult to control the real power flow of the individual converter in multi-converter systems.

There is an improved diode-clamped inverter, represented by connecting an appropriate number of diodes in series.

2- Flying-Capacitors multilevel inverter

Figure (31) shows a three-phase 3-level Flying-Capacitors multilevel inverter (FCMLI). Each phase leg has an identical structure. The main concept of this inverter is to use capacitors. It is of series connection of capacitor clamped switching cells. In this inverter switching states are like in the diode clamped inverter. Clamping diodes are not required in this type of multilevel inverters.

Number of levels = m

Number of main capacitors = (m-1)

Number of flying capacitors = (m-1)(m-2)/2

Number of switches = 2(m-1)

Line staircase voltage = (2m-1)

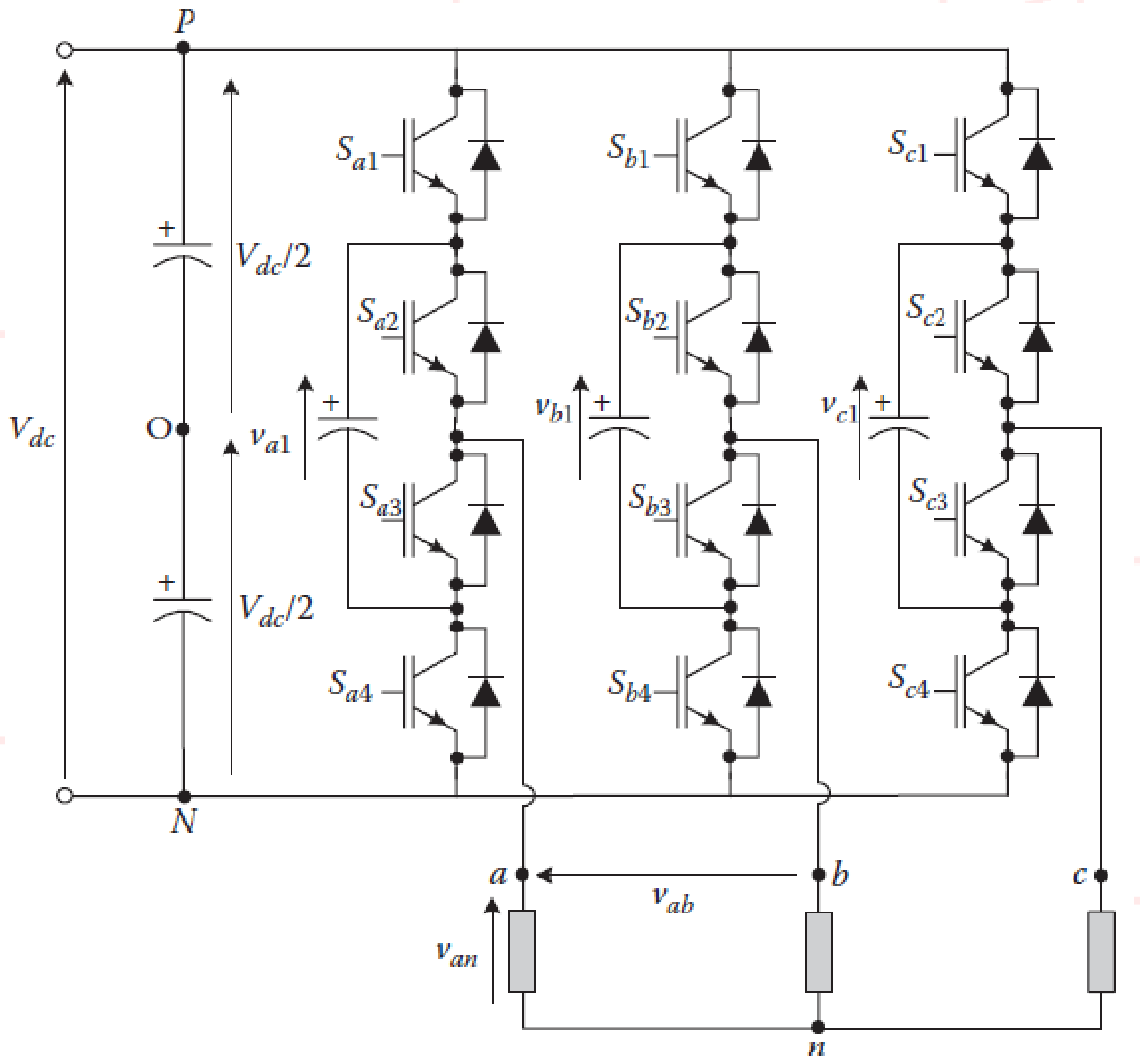


Figure (31) three-phase 3-level Flying-Capacitors multilevel inverter

Principle of operation:

To produce a staircase-output voltage, let us consider a single phase 5-level inverter shown in figure (32) as an example. The dc rail 0 is the reference point of the output phase voltage. There are many possible switch combinations to generate the five-level output voltage. The table below lists a possible combination of the voltage levels and their corresponding switch states.

Homework, try to find another possible switch combination of the flying capacitor inverter.

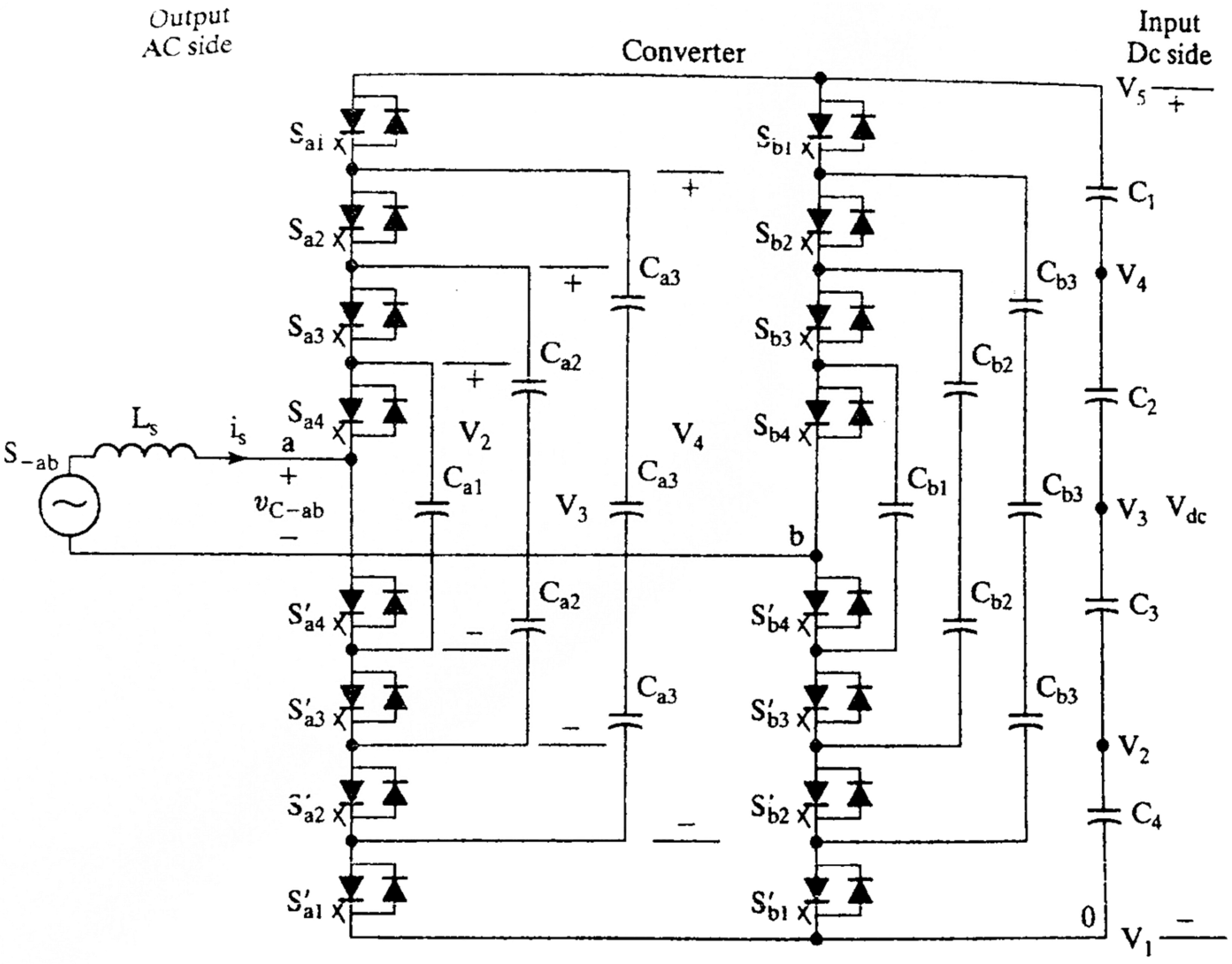


Figure (32) single phase 5-level Flying-Capacitors multilevel inverter

$Output\ Va0$	$Sa1$	$Sa2$	$Sa3$	$Sa4$	$Sa4'$	$Sa3'$	$Sa2'$	$Sa1'$
$V5 = Vdc$	1	1	1	1	0	0	0	0
$V4 = 3Vdc/4$	1	1	1	0	1	0	0	0
$V3 = Vdc/2$	1	1	0	0	1	1	0	0
$V2 = Vdc/4$	1	0	0	0	1	1	1	0
$V1 = 0$	0	0	0	0	1	1	1	1
$Output\ Va0$	$Sa1$	$Sa2$	$Sa3$	$Sa4$	$Sa4'$	$Sa3'$	$Sa2'$	$Sa1'$
$V5 = Vdc$								
$V4 = 3Vdc/4$								
$V3 = Vdc/2$								
$V2 = Vdc/4$								
$V1 = 0$								

Table (3-1) Two possible combination of the voltage levels and their corresponding switch states

Advantages of flying capacitors inverter:

1- Large amount of storage capacitors can provide capabilities during power outages.

2- These inverters provide switch combination redundancy for balancing different voltage levels.

3- Like the diode clamp inverter with more levels, the harmonic content is low enough to avoid the need for filters.

4- Both real and reactive power flow can be controlled.

Disadvantages of flying capacitors inverter:

1- An excessive number of storage capacitors is required when the number of levels is high. High level inverters are more difficult to package with the bulky power capacitors and are more expensive too.

2- The inverter control can be very complicated, and the switching frequency and switching losses are high for real power transmission.

3- Cascaded multilevel inverter

A cascade multilevel inverter consists of a series of H-Bridge (single-phase, full-bridge) inverter units. The general function of this multilevel inverter is to synthesize a desired voltage from several separated dc source (SDCSs) which may be obtained from batteries, fuel cells, or solar cells. Figure (33) shows the basic structure of a single phase cascaded inverter with SDCSs (5-level). Each SDCSs is connected to an H-bridge inverter. The ac terminal voltages of different level inverters are connected in series. Unlike the diode clamp or flying capacitors inverter, the cascaded inverter does not require any voltage clamping diodes or voltage balancing capacitors.

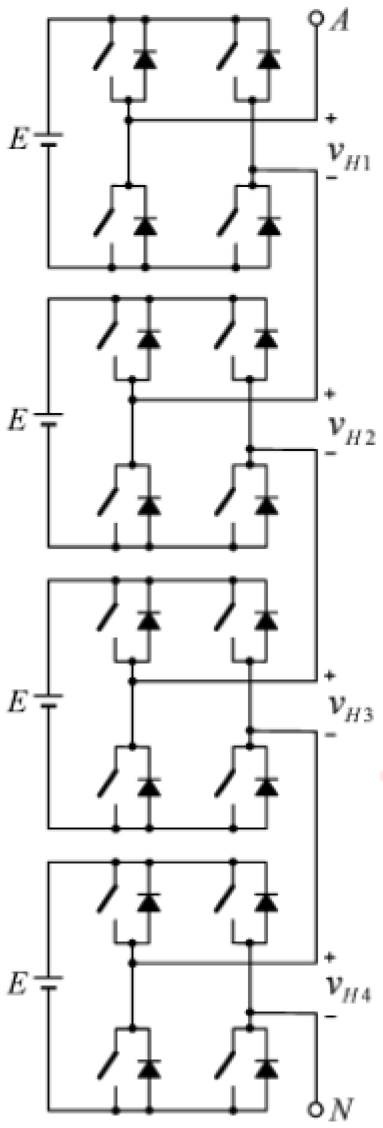


Figure (33) Circuit diagram of single phase 5-level cascaded multilevel inverter

Principle of operation:
Figure (34) shows the synthesized phase voltage waveform of a five-level cascaded inverter with four SDCSs. The phase output voltage is synthesized by the sum of four inverter outputs:
$van = va1 + va2 + va3 + va4.$
Each inverter level can generate three different voltage outputs: $+Vdc$, 0 , $-Vdc$, by connecting the dc source to the ac output side by different combinations of the four switches, $S1, S2, S3$ and $S4$. Using the bottom level as the example ($va4 = V4$)

Turning on $S1$ and $S4$ yields $va4 = +Vdc$.
Turning on $S2$ and $S3$ yields $va4 = -Vdc$.
Turning off all $switches$ yields $va4 = 0$.

Similarly, the ac output voltage at each level can be obtained in the same manner. If Ns is the number of dc sources, the output phase voltage level is $m = Ns + 1$. Thus, a five level cascaded inverter needs four SDCSs and four full bridges.

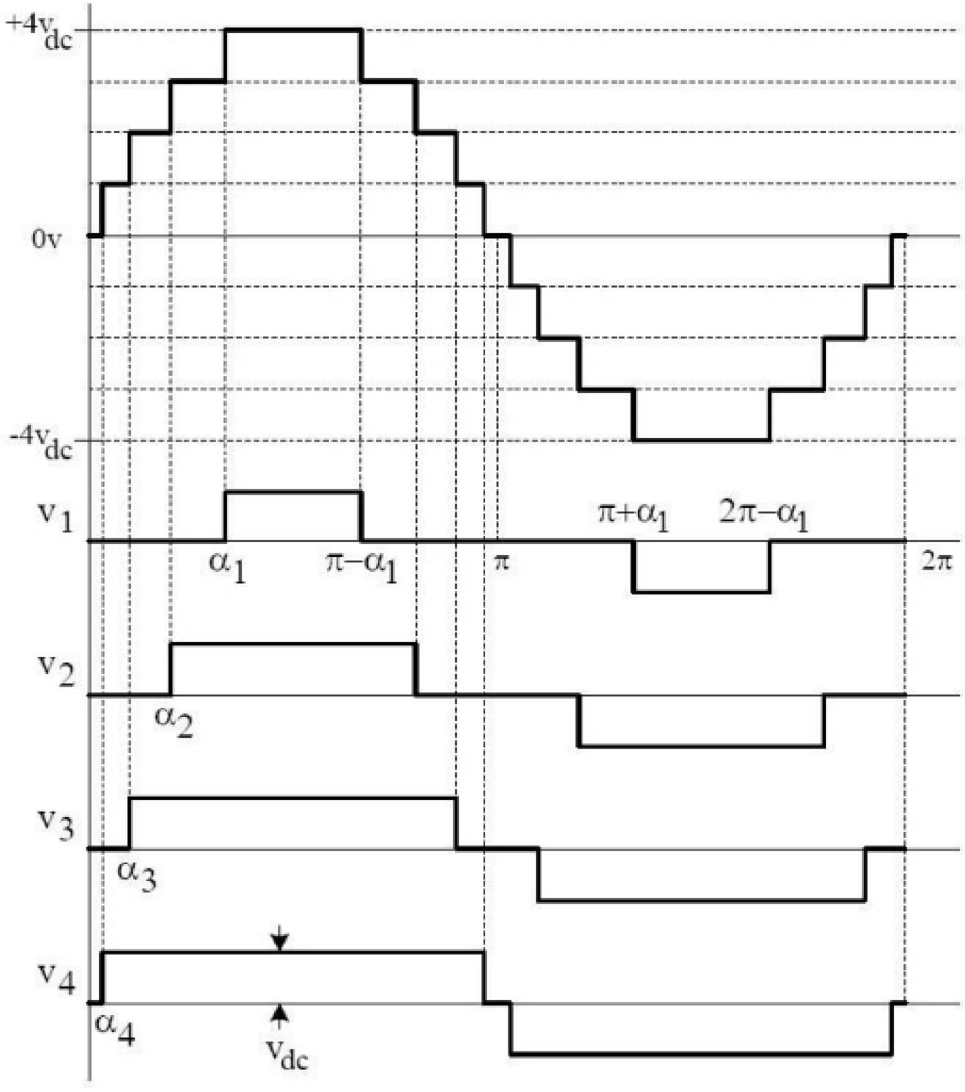


Figure (34) Output waveform of single phase 5-level cascaded multilevel inverter

Controlling the conducting angles at different inverter levels can minimize the harmonic distortion of the output voltage. Each H-bridge unit generates a quasi-square waveform by phase shifting its positive and negative phase leg switching timings.

Advantages of cascaded inverter:
1- Compared with the diode-clamped and flying-capacitors inverters, it requires the least number of components to achieve the same number of voltage levels.
2- Optimized circuit layout and packaging are possible because each level has the same structure and there are no extra clamping diodes or voltage-balancing capacitors.
3- Soft-switching techniques can be used to reduce switching losses and device stresses.

Disadvantages of flying capacitors inverter:
1- It needs separate dc sources for real power conversions, thereby limiting its applications.

Homework, Try to make a single phase 5-level cascaded multilevel inverter using MATLAB simulation.

RESONANT PULSE INVERTERS:

Resonant inverters are electrical inverter based on resonant current oscillation. It is known as DC to DC Converter or Dc to Ac PWM inverter. If the switching devices are turned on and off when the voltage across a device or its current becomes zero. i.e. The voltage and current are forced to pass through zero crossing by creating an LC-resonant circuit is called as resonant pulse inverter.

Main function is to reduce switching losses of the devices (MOSFET & IGBT).

Classifications of resonant pulse inverter:

1- Series-resonant inverter
2- Parallel-resonant inverter
3- Class E resonant converter
4- Class E resonant rectifier
5- Zero voltage switching (ZVS) resonant converters
6- Zero current switching (ZCS) resonant converters
7- Two-quadrant (ZVS) resonant converters
8- Resonant DC-link inverters

1- Series resonant inverter:

- The resonating components and switching device are placed in series with the load to form an under-damped circuit.
- The current through the switching devices falls to zero due to the natural characteristics of the circuit.
- This type of inverter produces an approximately sinusoidal wave form at a high Frequency, ranging from 200Hz to 100KHz.
- Applications: Induction Heating, Sonar transmitter, Fluorescent Lighting, Ultrasonic generators.

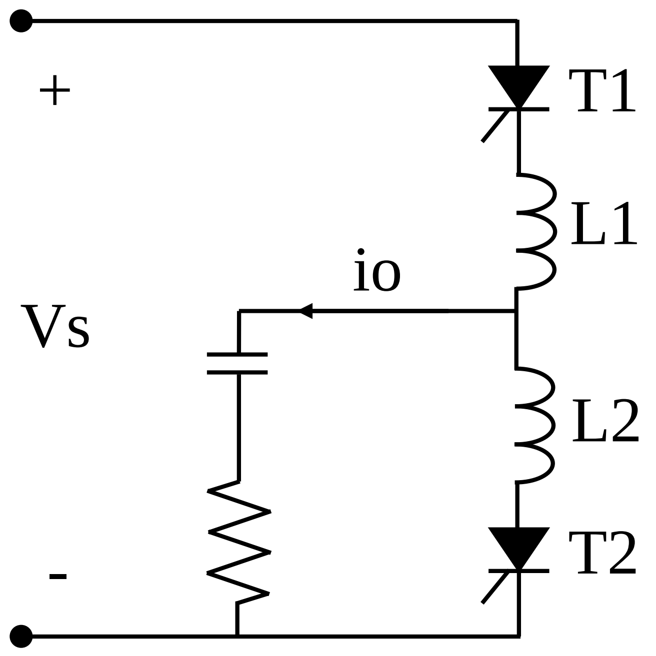


Figure (35) Circuit diagram of series resonant inverter

2- Parallel Resonant inverter:

- Parallel Resonant inverter is dual of series resonant inverter.
- It is supplied from a current source so that the circuit offers high impedance to the switching current.
- Current is continuously controlled , that gives better short circuit protection under fault condition.

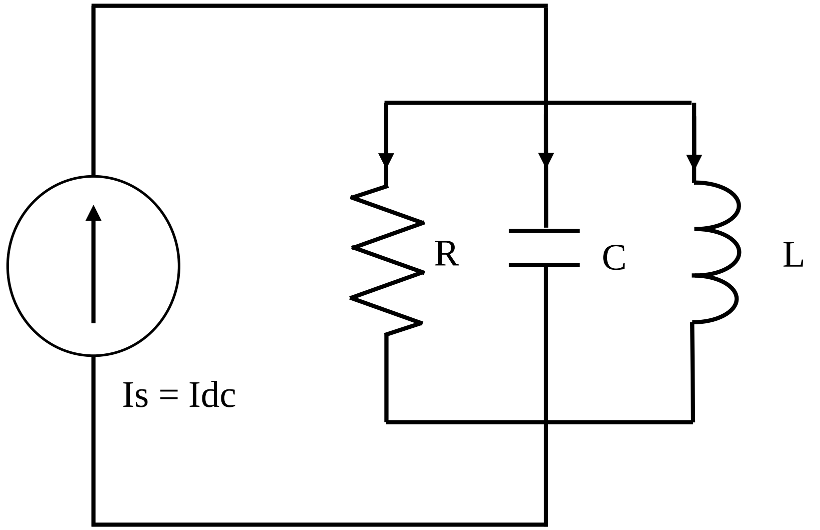


Figure (36) Circuit diagram of parallel resonant inverter

3- Class E resonant converter:

- It has low switching losses , yielding a high efficiency of more than 95%.
- A class E resonant inverter uses only one transistor.
- Used in low power application requiring less than 100 W & high frequency electric lamp.

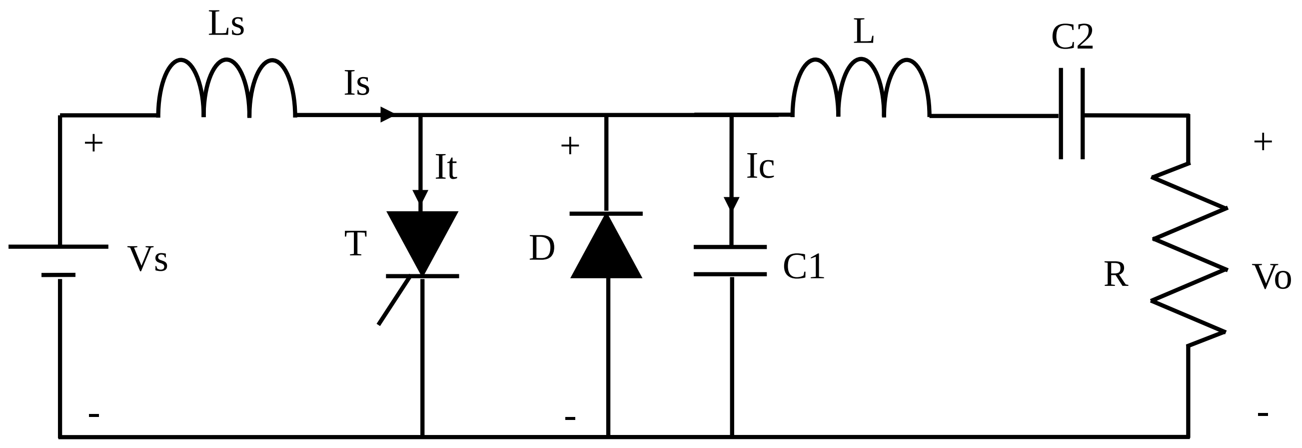


Figure (37) Circuit diagram of E resonant converter

4- Class E Resonant Rectifier:

- Class E Resonant Rectifier is based on the principle of Zero Voltage Switching(ZVS) .
- The diode turn off at zero voltage.
- A high frequency diode rectifier suffers from disadvantage that is switching losses , harmonic content.

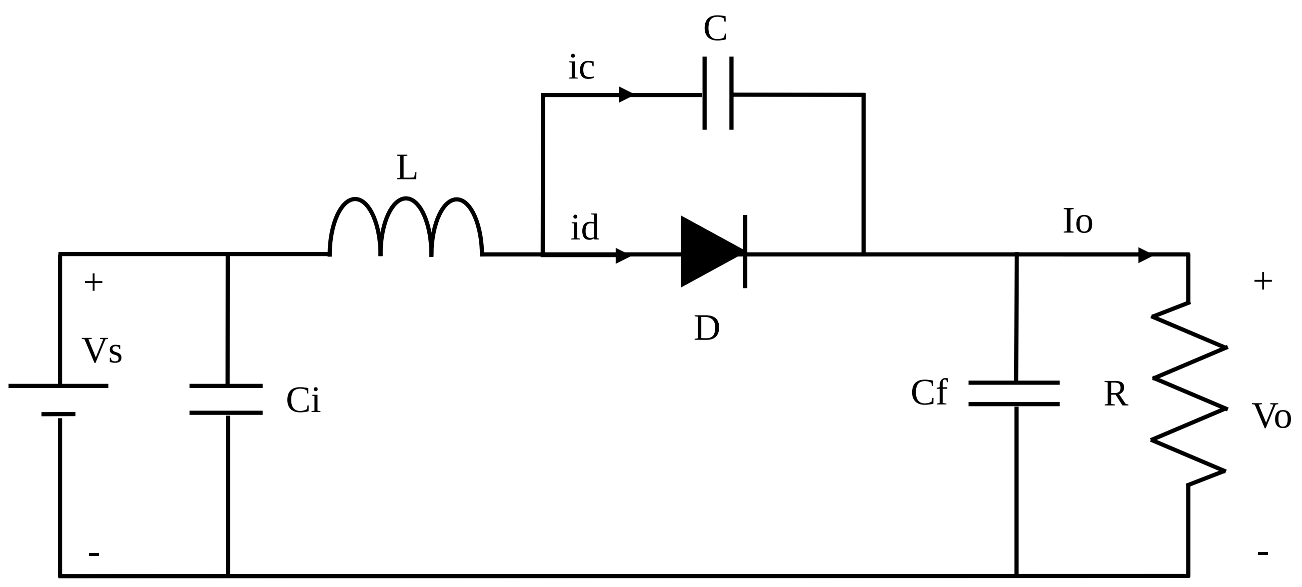


Figure (38) Circuit diagram of E resonant rectifier

5- Zero Voltage Switching (ZVS) Resonant Converter:

- The ZVS Resonant Converter turn on & turn off at zero voltage.
- Output voltage control can be achieved by varying the frequency & operates with constant off time control.
- The capacitor C is connected in parallel with the switch S1 to achieve ZVS.

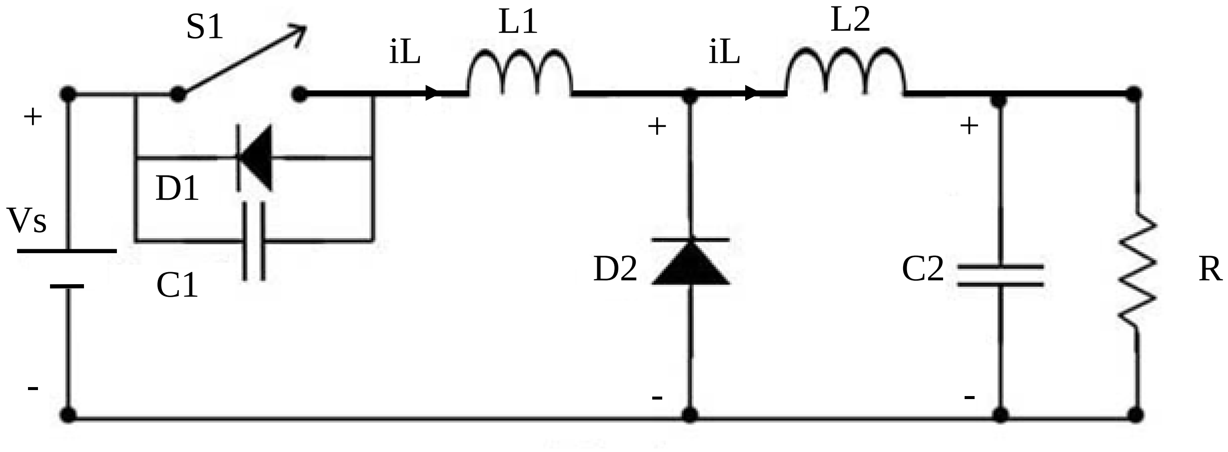


Figure (39) Circuit diagram of Zero Voltage Switching (ZVS) resonant inverter

6- Zero Current Switching (ZCS) Resonant Converter:

- Zero Current Switching (ZCS) Resonant Converter turn On & turn off at zero current.
- This converter can operate at higher range frequency that is 1MHz to 2Mhz.
- The inductor L is connected in series with a power switch S1 to achieve ZCS.

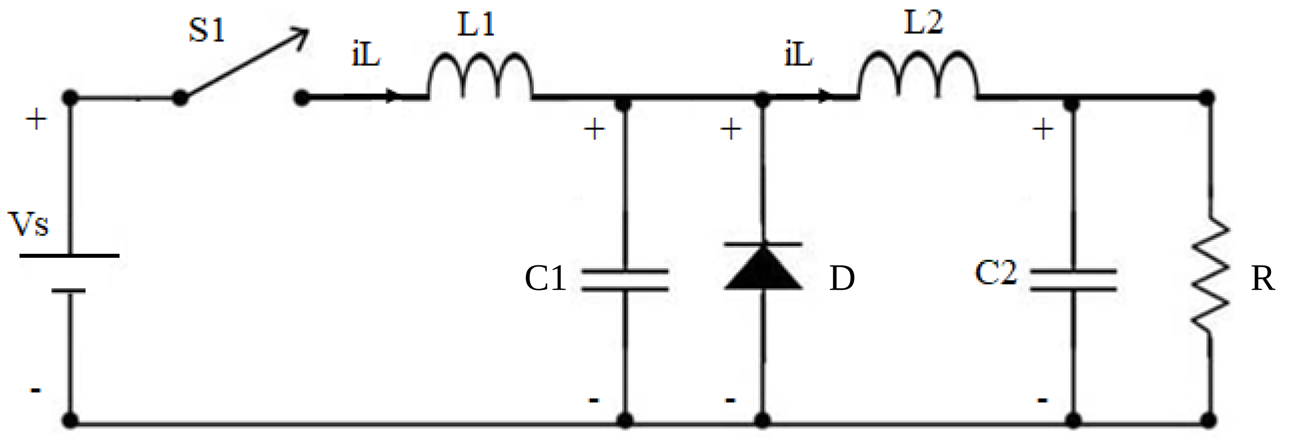


Figure (40) Circuit diagram of
Zero Current Switching (ZCS) resonant inverter

7- Two Quadrant ZVS Resonant Converter :

- In this converter the ZVS concept is extended
- $Here\ Fout\ >\ Fsupply$
- $Fo = 1/(2\pi\sqrt{LC})$

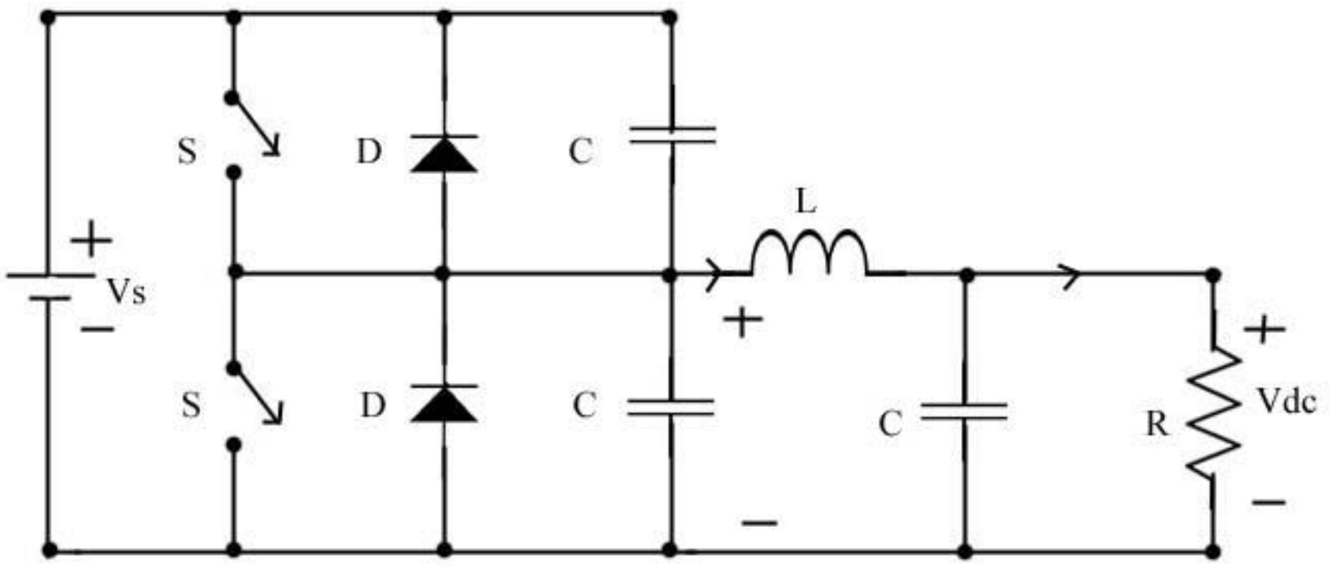


Figure (41) Circuit diagram of
Two Quadrant ZVS resonant inverter

8- Resonant dc-link inverter:

- The DC link inverter is similar to the PWM inverter.
- In dc-link inverters , a resonant circuit is connected between the inverter & DC supply. So that the input voltage to the inverter oscillates between zero and a value slightly greater than twice the DC input voltage.

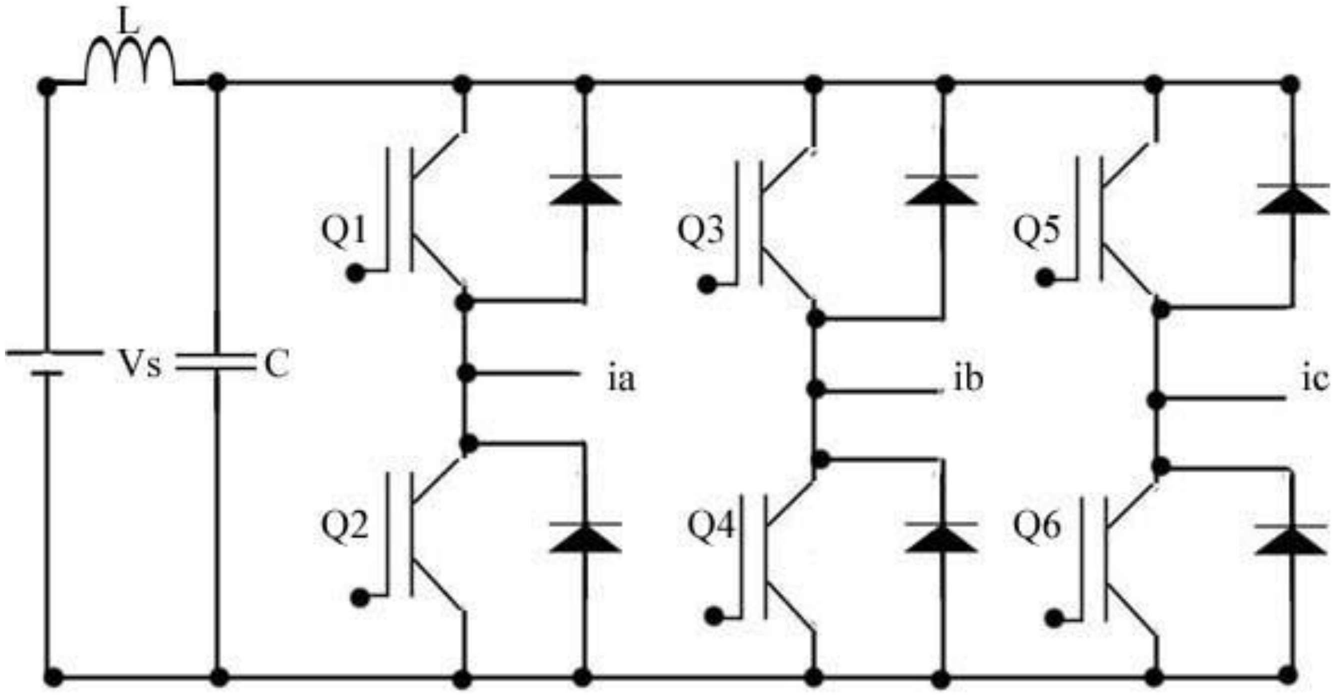
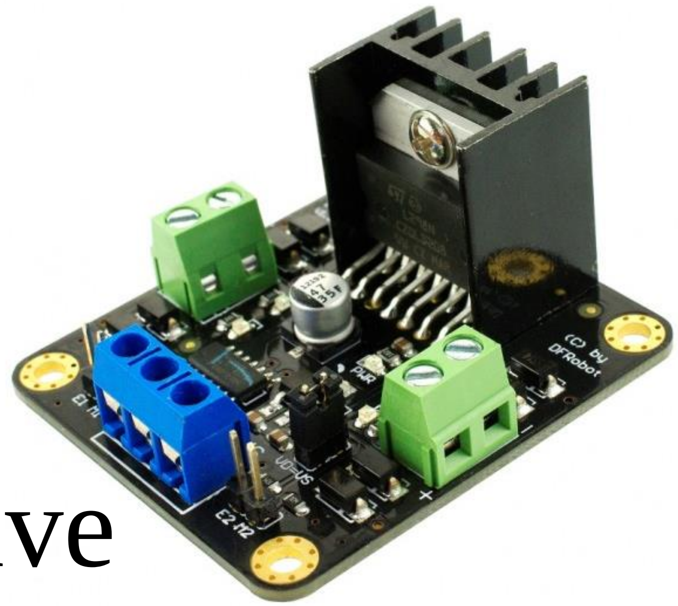


Figure (42) Circuit diagram of Resonant dc-link inverter

Chapter 4: Motor Drive

Electric drives for motors are used to draw electrical energy from the mains and supply the electrical energy to the motor at whatever voltage, current and frequency necessary to achieve the desired mechanical output.

DC Drive



AC Drive

4.1- DC DRIVES:

Dc motors play a significant role in modern industrial drives. They can provide a high starting torque and it is also possible to obtain speed control over a wide range. The method of speed control are normally simpler and less expensive than those of ac drives. It might be a few decades before the dc drives are completely replaced by ac drives.

Controlled rectifiers provide a variable dc output voltage from a fixed ac voltage, whereas a dc-dc converter can provide a variable dc voltage from a fixed dc voltage. Due to their ability to supply a continuously variable dc voltage, controlled rectifiers and dc-dc converters made a revolution in modern industrial control equipment and variable-speed drives, with power levels ranging from fractional horsepower to several megawatts. Controlled rectifiers are generally used for speed control of dc motors, the alternative form would be a diode rectifier followed by dc-dc converter.

DC drives can be classified, in general, into three types:

1- Single-phase drives
2- Three-phase drives
3- DC-DC converter drives

Before we start with the DC drives we have to study the chrematistics of dc motors

4.1.1- DC Motor modelling revision

The equivalent circuit for a separately excited dc motor is shown in figure (43). When a separately excited motor is excited by a field current if and an armature current ia flows in the armature circuit, the motor develops a back electromotive force emf and a torque to balance the load torque at a particular speed. The field current if of a separately excited motor is independent of the armature current ia and any change in the armature current has no effect on the field current. The field current is normally much less than the armature current.

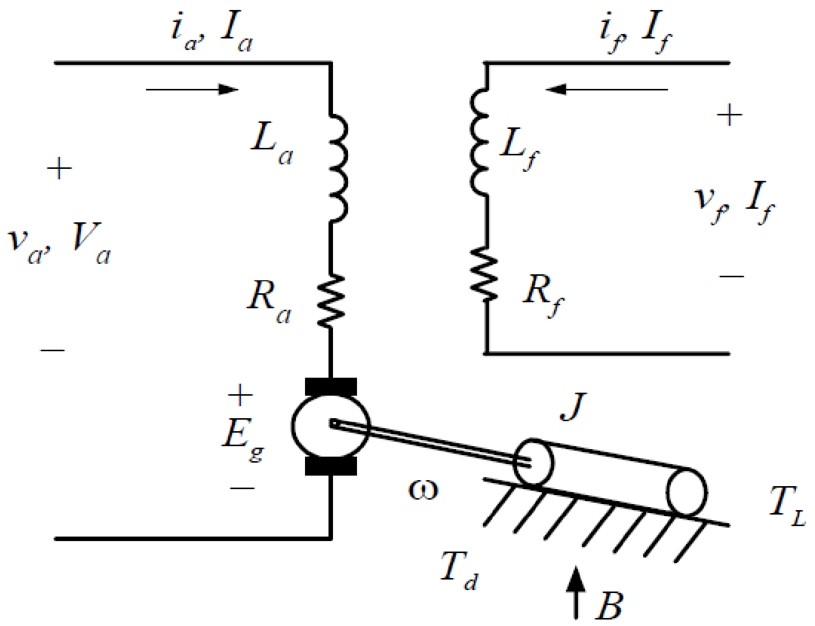


Figure (43) Equivalent circuit for a separately excited dc motor

The instantaneous field current (if) is described as $v_f = R_f i_f + L_f \frac{dif}{dt}$

The instantaneous armature current (ia) can be found from $v_a = R_a i_a + L_f \frac{dia}{dt} + e_g$

The motor back (emf), "Speed Voltage" is expressed as $E_g = K_v w i_f$

The torque developed (Td) by the motor is $T_d = K_t i_f i_a$

The developed torque must be equal to the load torque (TL) $T_d = J\frac{dw}{dt} + Bw + T_L$

Where:-

$w = motor\ angular\ speed, or\ rotor\ angular\ frequency, rad/\sec$
$B = viscus\ friction\ constant, N.m/rad/\sec$
$Kv = voltage\ constant, V/A - rad/\sec$
$Kt = torque\ constant, which\ equals\ voltage\ constant, Kv$
$La = armature\ circuit\ inductance, H$
$Lf = filed\ circuit\ inductance, H$
$Lf = field\ circuit\ resistance, \Omega$
$Rf = field\ circuit\ resistance, \Omega$
$TL = load\ torque, N.m$

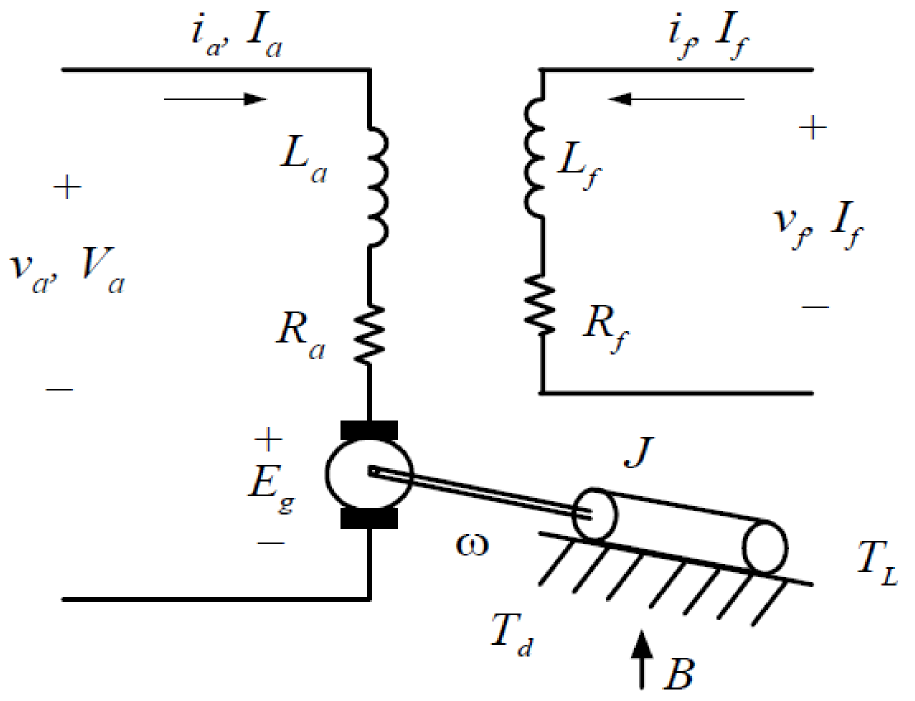


Figure (43) Equivalent circuit for a separately excited dc motor

Under steady-state conditions, the time derivatives $\left(\frac{d}{dt}\right)$ in these equations are zero and the steady-state average quantities are:

$$v_f = R_f I_f$$
$$E_g = K_v w I_f$$
$$V_a = R_a I_a + E_g$$
$$V_a = R_a I_a + K_v w I_f$$
$$T_d = K_t I_f I_a = Bw + TL$$

The developed power Pd = Tdw

The speed of a separately excited dc motor can be found from

$$w = \frac{V_a - R_a I_a}{K_v I_f} = \frac{V_a - R_a I_a}{K_v \frac{V_f}{R_f}}$$

We can notice from the above equation that the motor speed can be varied by:

(1) Controlling the armature voltage Va, known as voltage control

(2) Controlling the field current If, known as field control

(3) Torque demand, which corresponds to an armature current Ia, for a fixed field current If

The speed, which corresponds to the rated armature voltage, rated field current and rated armature current, is known as the rated speed “base speed”.

In practice, for a speed less than the base speed, the armature current and field currents are maintained constant to meet the torque demand, and the armature voltage Va is varied to control the speed. For speed higher than the base speed, the armature voltage is maintained at the rated value and the field current is varied to control the speed. However, the power developed by the motor (= Torque * Speed) remains constant.

Figure (44) shows the characteristics of torque, power, armature current and field current against speed.

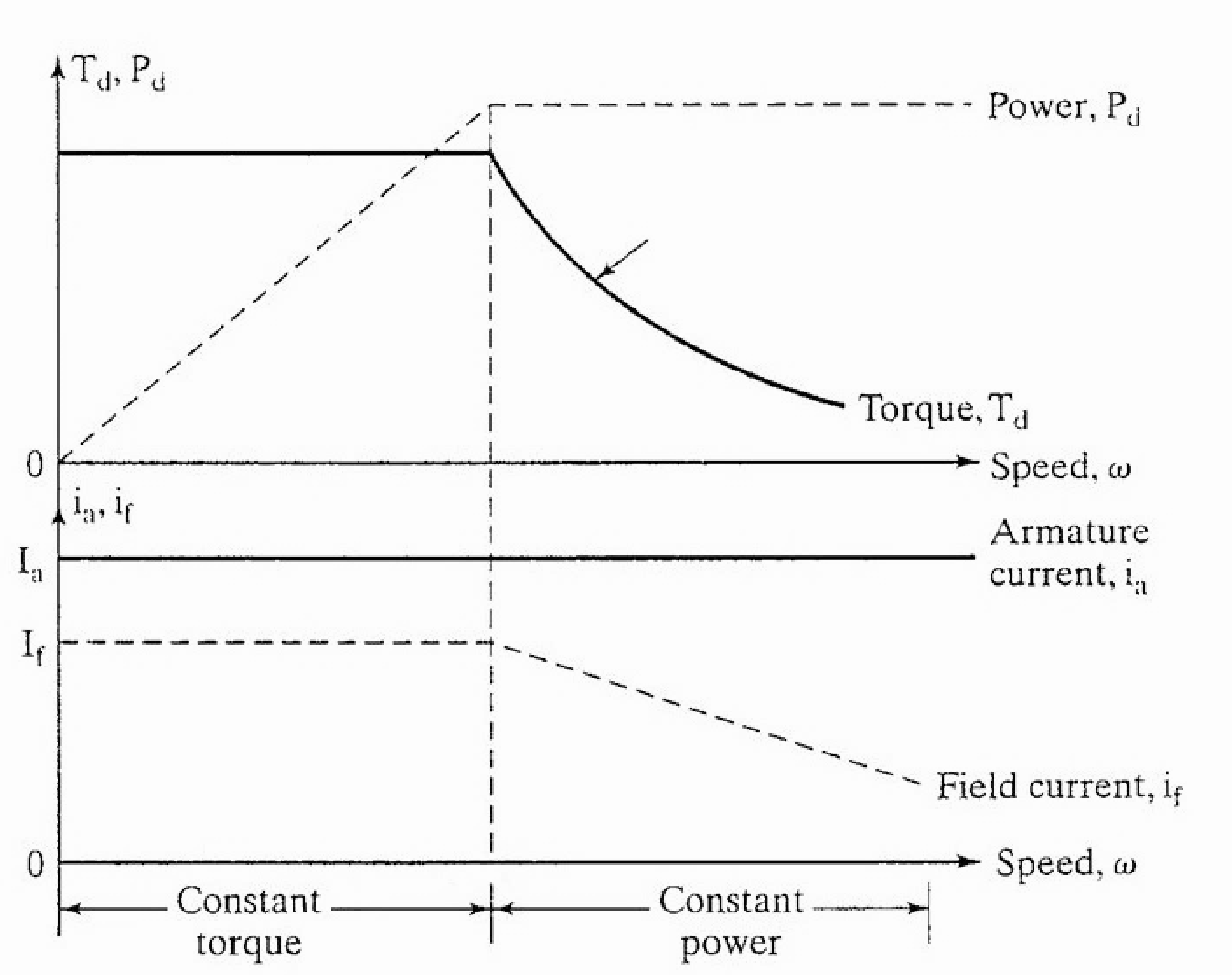


Figure (44) characteristics of separately excited dc motor

Homework, The field of a dc motor can be connected in series with the armature circuit;

1- What is the name of this motor?

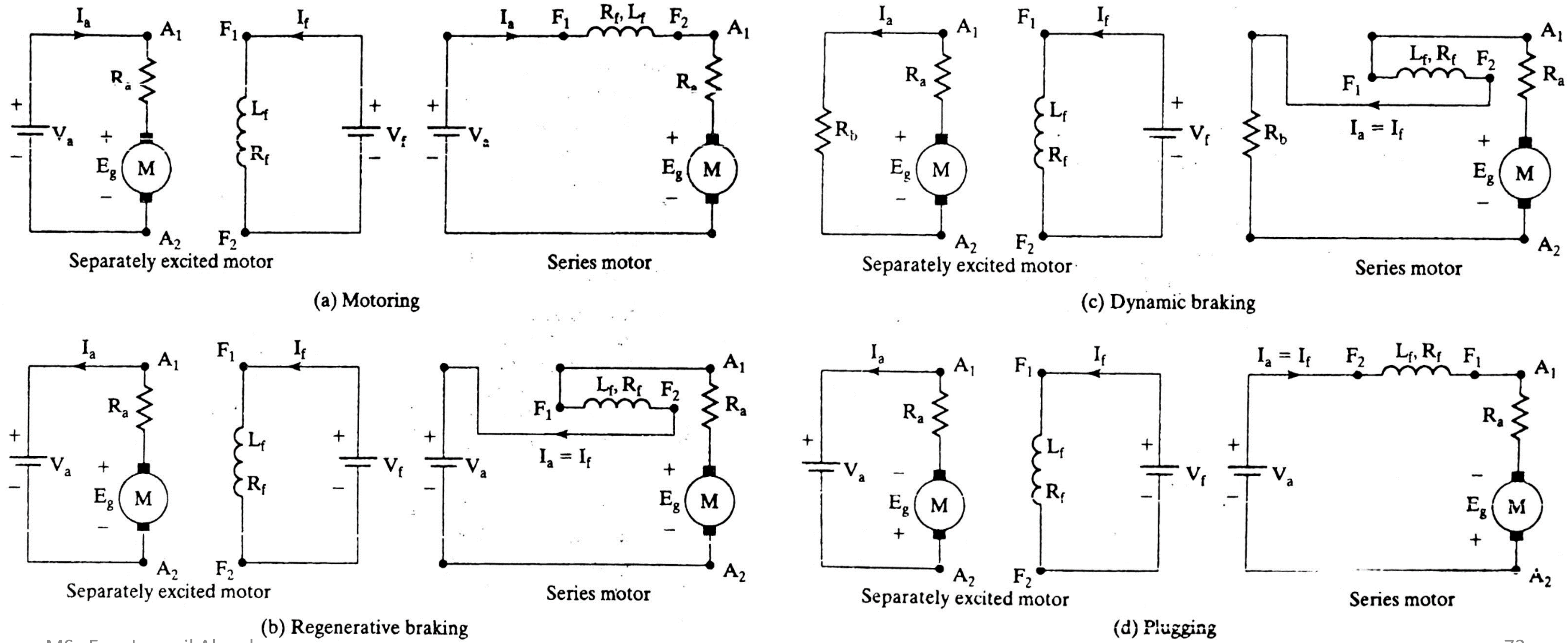
2- Draw the equivalent circuit of the motor?

3- Drive the motor equations to find the speed of the motor in terms of armature current and voltage?

4- Draw a graph showing the characteristics of torque, power, armature current and field current against speed of the motor?

4.1.2- Operation Modes:

In variable speed applications, a dc motor may be operating in one or more modes. The motor has four operating modes, which are: Motoring, Regenerative breaking, Dynamic breaking, Plugging. Figure (45) shows the details of the circuit of each mode.



Four quadrant operation of dc motor:

Figure (46) shows the polarities of the supply voltage Va, back emf Eg, and armature current Ia for a separately excited motor. In forward motoring (quadrant I), Va, Eg, and Ia are all positive. The torque and speed are also positive in this quadrant. During forward braking (quadrant II) the motor runs in the forward direction and the induced emf Eg continues to be positive. For the torque to be negative and the direction of energy flow to reverse, the armature current must be negative. They supply voltage Va should be kept less than Eg. In reverse motoring (quadrant III), Va, Eg, and Ia are all negative. The torque and speed are also negative in this quadrant. To keep the torque negative and the energy flow from the source to the motor, the black emf Eg must satisfy the condition |Va| > |Eg|. The polarity of Eg can be reversed by changing the direction of field current or by reversing the armature terminals. During the reverse braking (quadrant IV), the motor runs in the reverse direction. Va and Eg continue to be negative. For the torque to be positive and the energy to flow from the motor to the source the armature current must be positive. The induced emf Eg must satisfy the condition |Va| < |Eg|.

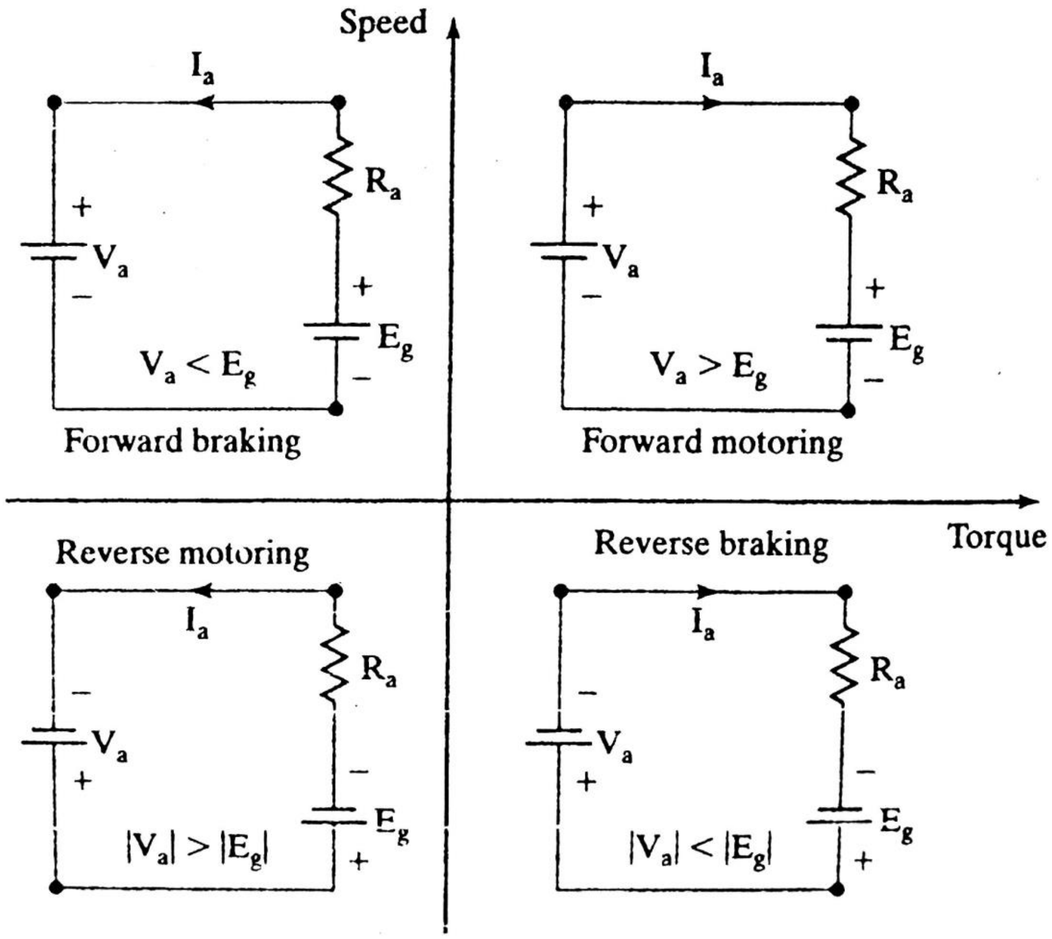


Figure (46) Four quadrant operation of dc motor

4.1.3- DC drives can be classified, in general, into three types:

1- Single-phase drives
2- Three-phase drives
3- DC-DC converter drives

1- Single-Phase Drives (ac to dc conversion)

The armature voltage of the motor can be varied by varying the delay angle of the converter αa.
The forced commutated ac-dc converter can also be used to improve the power factor PF and to reduce the harmonics.

There are four types of single-phase drives which are:

A- Single-phase half-wave converter drives	1 Thyristor
B- Single-phase semi-converter drives	2 Thyristors + 2 Diodes
C- Single-phase full-converter drives	4 Thyristors
D- Single-phase dual-converter drives	4 Thyristors + 4 Thyristors

A- Single-phase half-wave converter drives

A single phase half wave converter feeds a dc motor is shown in figure (47). The armature current is normally discontinuous unless a very large inductor is connected in the armature circuit. A freewheeling diode is always required for a dc motor load an it is a one-quadrant drive. The applications of this drive are limited to the ½ kW power level. Figure (48) shows the current waveforms for a highly inductive load. The converter in the field circuit can be semi-converter. A half-wave converter in the field circuit would increase the magnetic losses of the motor due to a high ripple content on the field excitation current.

With a single-phase half-wave converter in the armature circuit, Equation below gives the average armature voltage as:

$$Va = \frac{Vm}{2\pi}(1 + \cos \alpha a) \qquad for \quad 0 \leq \alpha a \leq \pi$$

With a semi-converter in the field circuit, Equation below gives the average field voltage as:

$$Vf = \frac{Vm}{\pi}(1 + \cos \alpha f) \qquad for \quad 0 \leq \alpha f \leq \pi$$

$Where\ Vm\ is\ the\ peak\ voltage\ (\max voltage)\ of\ the\ ac\ supply.$

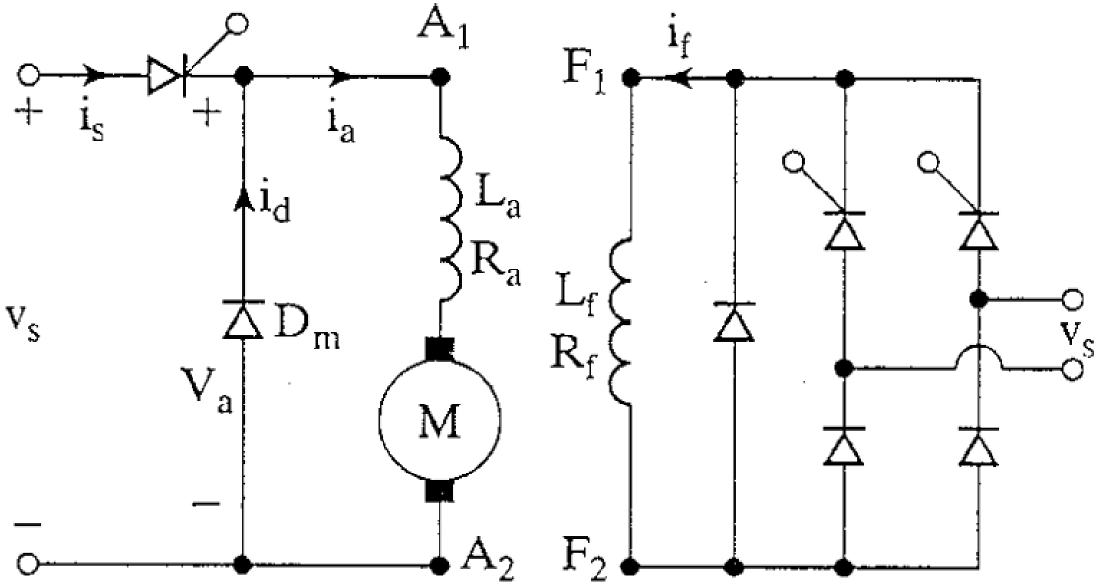


Figure (47) Circuit of single phase half wave converter connected with separately excited dc motor

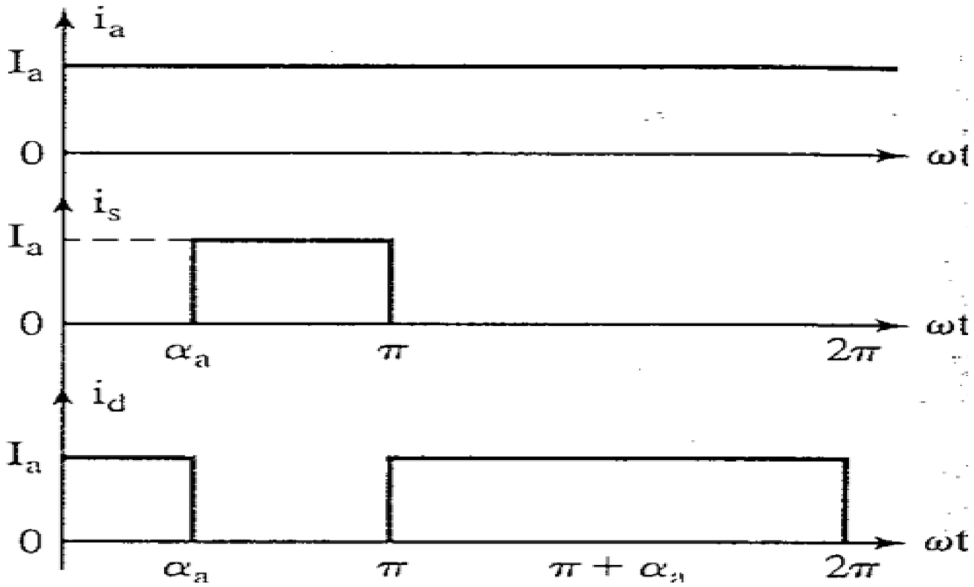


Figure (48) Current waveforms of single phase half wave converter connected with separately excited dc motor

B- Single-phase semi-converter drives

A single phase Semi-converter feeds a dc motor is shown in figure (49). It is a one-quadrant drive. The applications of this drive are limited to the 15 kW power level. The converter in the field circuit can be semi-converter. Figure (50) shows the current waveforms for a highly inductive load.

With a single-phase semi-converter in the armature circuit, Equation below gives the average armature voltage as:

$$Va = \frac{Vm}{\pi}(1 + \cos \alpha a) \qquad for \quad 0 \leq \alpha a \leq \pi$$

With a semi-converter in the field circuit, Equation below gives the average field voltage as:

$$Vf = \frac{Vm}{\pi}(1 + \cos \alpha f) \qquad for \quad 0 \leq \alpha f \leq \pi$$

$Where\ Vm\ is\ the\ peak\ voltage\ (\max voltage)\ of\ the\ ac\ supply.$

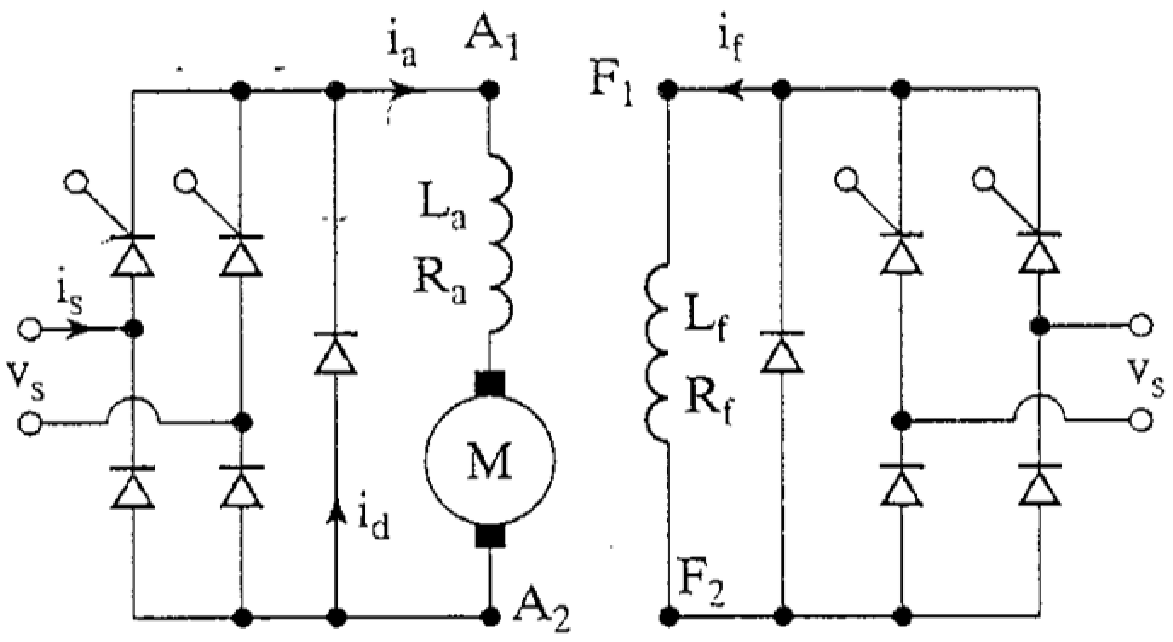


Figure (49) Circuit of single phase semi-converter connected with separately excited dc motor

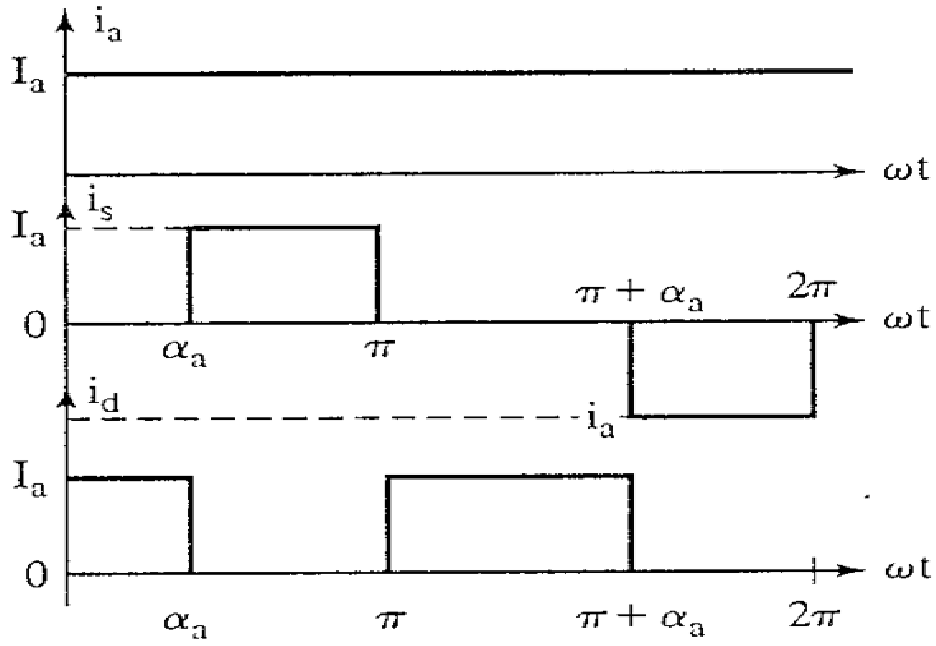


Figure (50) Current waveforms of single phase semi-converter connected with separately excited dc motor

C- Single-phase full-converter drives

A single phase full-converter feeds a dc motor is shown in figure (51). It is a two-quadrant drive. The armature converter gives $+Va\ or -Va$ and allows operation in the first and fourth quadrant. During regeneration for reversing the direction of power flow, the back emf of the motor can be reversed by reversing the field excitation. The reversal of the armature or field allows operation in the second and third quadrants. The applications of this drive are limited to the 15 kW power level. The converter in the field circuit could be semi-converter, full-converter or even dual-converter drive. Figure (52) shows the current waveforms for a highly inductive load.

With a single-phase full-converter in the armature circuit, Equation below gives the average armature voltage as:

$$Va = \frac{2Vm}{\pi}(\cos \alpha a) \qquad for \quad 0 \leq \alpha a \leq \pi$$

With a single-phase full-converter in the field circuit, Equation below gives the average field voltage as:

$$Vf = \frac{2Vm}{\pi}(\cos \alpha f) \qquad for \quad 0 \leq \alpha f \leq \pi$$

$Where\ Vm\ is\ the\ peak\ voltage\ (\max voltage)\ of\ the\ ac\ supply.$

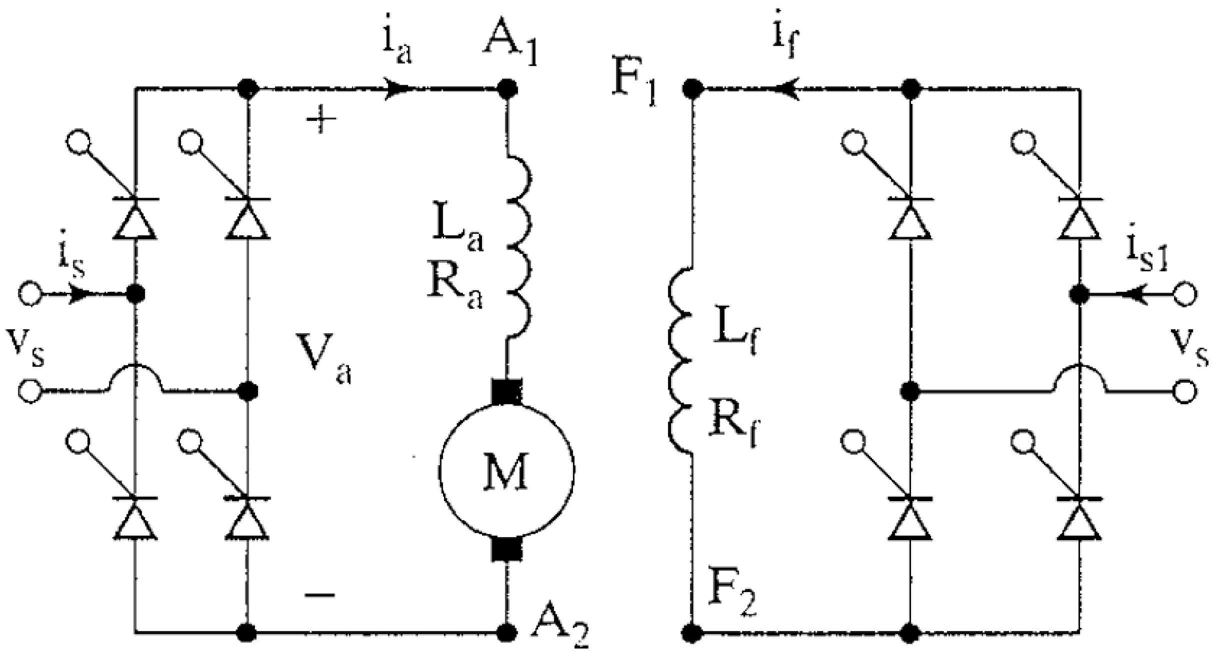


Figure (51) Circuit of single phase full-converter connected with separately excited dc motor

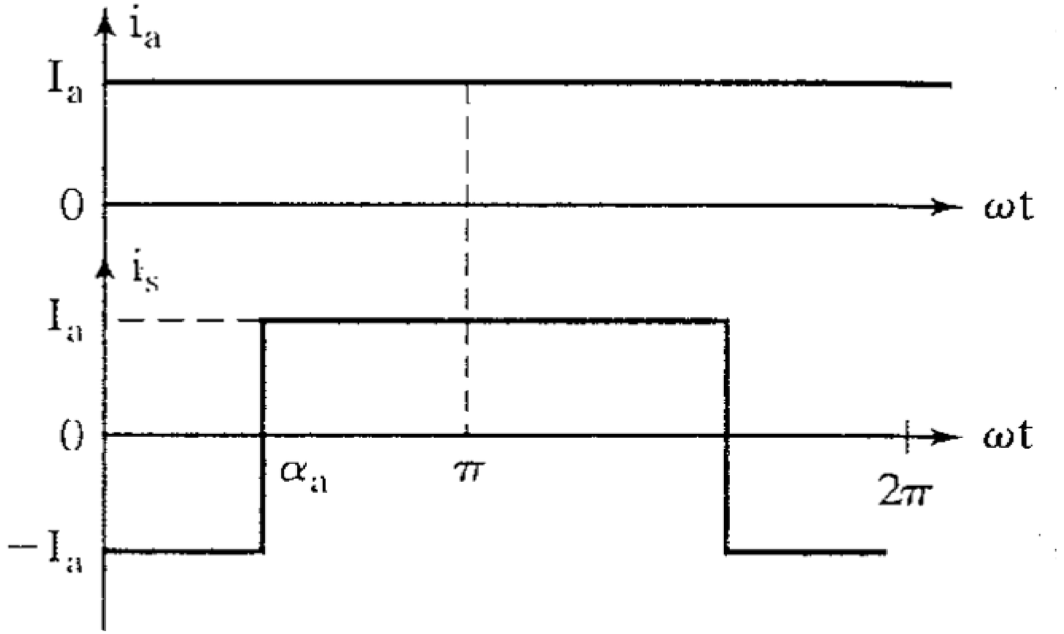


Figure (52) Current waveforms of single phase full-converter connected with separately excited dc motor

D- Single-phase dual-converter drives

A single phase dual-converter feeds a dc motor is shown in figure (53). Either converter 1 operates to supply a positive armature voltage, $+Va$ or converter 2 operates to supply a negative armature voltage, $-Va.$ Converter 1 provides operation in the first and fourth quadrants, and converter 2, in the second and third quadrants. It is a four-quadrant drive and permits four modes of operation. The applications of this drive are limited to the 15 kW power level. The converter in the field circuit could be semi-converter, full-converter or even dual-converter drive.

If converter 1 operates with a delay angle of $\alpha a1$, Equation below gives the average armature voltage as:

$$Va = \frac{2Vm}{\pi}(\cos \alpha a1) \qquad for \quad 0 \le \alpha a1 \le \pi$$

If converter 2 operates with a delay angle of $\alpha a2$, Equation below gives the average armature voltage as:

$$Va = \frac{2Vm}{\pi}(\cos \alpha a2) \qquad for \quad 0 \le \alpha a2 \le \pi$$

Where $\alpha a2 = \pi - \alpha a1$

With a full converter in the field circuit, Equation below gives the average field voltage as:

$$Vf = \frac{2Vm}{\pi}(\cos \alpha f) \qquad for \quad 0 \le \alpha f \le \pi$$

Example 4.1

Example 4.2

Example 4.3

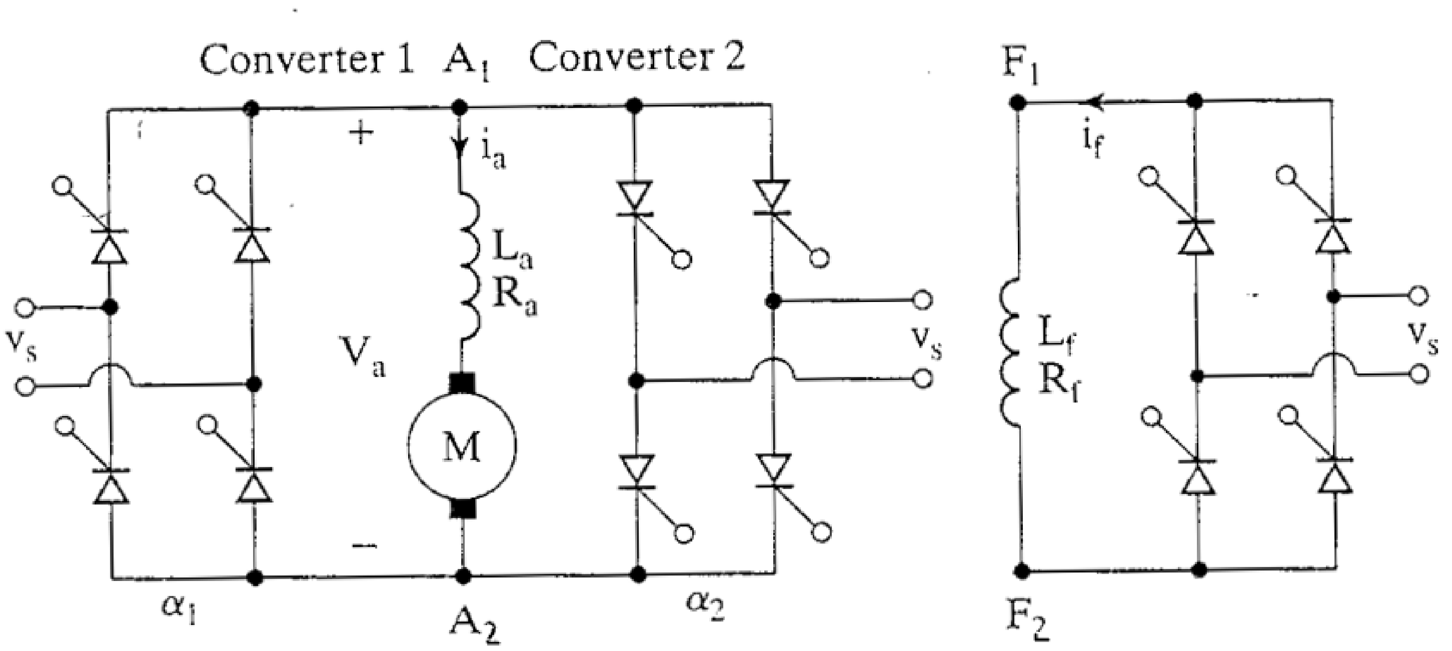


Figure (53) Circuit of single phase dual-converter connected with separately excited dc motor

2- Three-Phase Drives (ac to dc conversion)

The armature circuit of the motor is connected to the output of a three-phase controlled rectifier or a forced-commutated (regulate or reverse) three-phase ac-dc converter. Three-phase drives are used for high applications up to megawatt power levels. The ripple frequency of the armature voltage is higher than that of single-phase drives and it requires less inductance in the armature circuit to reduce the armature ripple current. The armature current is mostly continuous, and therefore the motor performance is better compared with that of single-phase drives.

Similar to the single-phase drives, three-phase drives may also be subdivided into:

A- Three-phase half-wave converter drives
B- Three-phase semi-converter drives
C- Three-phase full-converter drives
D- Three-phase dual-converter drives

A- Three-phase half-wave converter drives

A three phase half wave converter-fed dc motor drive operates in one quadrant and could be used in applications up to a 40 kW power level. The field converter could be a single-phase or three-phase semi-converter. This drive is not normally used in industrial applications because the ac supply contains dc components.

With a three-phase half-wave converter in the armature circuit, equation below gives the armature voltage as:

$$Va = \frac{3\sqrt{3}Vm}{2\pi} \cos \alpha a \qquad for\ 0 \leq \alpha a \leq \pi$$

$Where\ Vm\ is\ the\ peak\ phase\ voltage\ of\ a\ Y - connected\ three\ phase\ ac\ supply.$

With a three-phase semi-converter in the field circuit, equation below gives the field voltage as:

$$Vf = \frac{3\sqrt{3}Vm}{2\pi} (1 + \cos \alpha f) \qquad for\ 0 \leq \alpha f \leq \pi$$

B- Three-phase semi-converter drives

A three phase semi-converter-fed drive is a one quadrant drive without field reversal, and could be used in applications up to a 115 kW power level. The field converter could be a single-phase or three-phase semi-converter.

With a three-phase semi-converter in the armature circuit, equation below gives the armature voltage as:

$$Va = \frac{3\sqrt{3}Vm}{2\pi}(1 + \cos \alpha a) \qquad for\ 0 \leq \alpha a \leq \pi$$

$Where\ Vm\ is\ the\ peak\ phase\ voltage\ of\ a\ Y - connected\ three\ phase\ ac\ supply.$

With a three-phase semi-converter in the field circuit, equation below gives the field voltage as:

$$Vf = \frac{3\sqrt{3}Vm}{2\pi}(1 + \cos \alpha f) \qquad for\ 0 \leq \alpha f \leq \pi$$

C- Three-phase full-converter drives

A three phase full-converter drive is a two quadrant drive without any field reversal, and is limited to applications up to a 1500 kW. During regeneration for reversing the direction of power flow, the back emf of the motor is reversed by reversing the field excitation. The field converter should be a single-phase or three-phase full-converter.

With a three-phase full-converter in the armature circuit, equation below gives the armature voltage as:

$$Va = \frac{3\sqrt{3}Vm}{\pi}(\cos \alpha a) \qquad for\ 0 \le \alpha a \le \pi$$

Where Vm is the peak phase voltage of a $Y-$connected three phase ac supply.

With a three-phase full-converter in the field circuit, equation below gives the field voltage as:

$$Vf = \frac{3\sqrt{3}Vm}{\pi}(\cos \alpha f) \qquad for\ 0 \le \alpha f \le \pi$$

D- Three-phase dual-converter drives

Two three-phase full-wave converters are connected in an arrangement as shown in figure (54) similar to single-phase dual converter drive. Either converter 1 operates to supply a positive armature voltage +Va, or converter 2 operates to supply a negative armature voltage –Va. It is a four quadrant drive and is limited to applications up to 1500 kW. Similar to single phase drives, the field converter can be a full-wave converter or a semi-converter.

If converter 1 operates with a delay angle $\alpha a1$, equation below gives the armature voltage as:

$$Va = \frac{3\sqrt{3}Vm}{\pi}(\cos \alpha a1) \qquad for\ 0 \leq \alpha a1 \leq \pi$$

If converter 2 operates with a delay angle $\alpha a2$, equation below gives the armature voltage as:

$$Va = \frac{3\sqrt{3}Vm}{\pi}(\cos \alpha a2) \qquad for\ 0 \leq \alpha a2 \leq \pi$$

$Where\ Vm\ is\ the\ peak\ phase\ voltage\ of\ a\ Y - connected\ three\ phase\ ac\ supply.$

With a three-phase full-converter in the field circuit, equation below gives the field voltage as:

$$Vf = \frac{3\sqrt{3}Vm}{\pi}(\cos \alpha f) \qquad for\ 0 \leq \alpha f \leq \pi$$

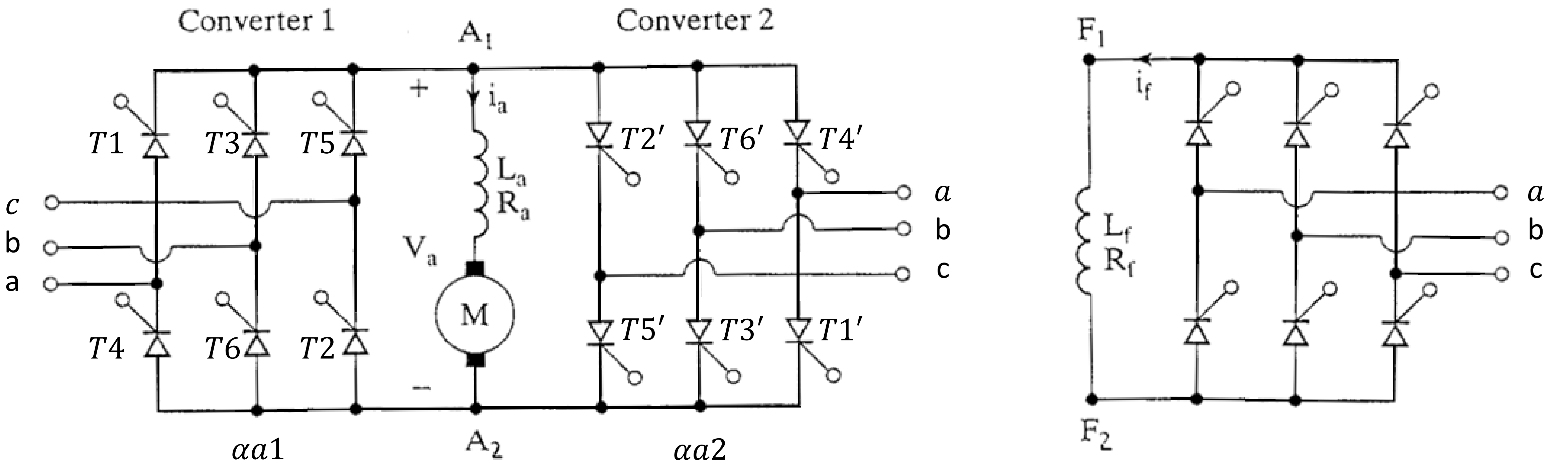


Figure (54) Circuit of three phase dual-converter connected with separately excited dc motor

Example 4.4

Example 4.5

3- DC-DC converter drives

Dc-Dc converter (or simply chopper) drives are widely used in traction applications all over the world. A dc-dc converter is connected between a fixed-voltage dc source and a dc motor to vary the armature voltage. In addition to armature voltage control, a dc-dc converter can provide regenerative braking of the motors and can return energy back to the supply. This energy saving feature is particularly attractive to transportation systems with frequent stops such as a mass rapid transit (MRT). Dc-dc converter drives are also used in battery electric vehicles (BEVs). A dc motor can be operated in one of the four quadrants by controlling the armature or field voltages (or currents). It is often required to reverse the armature or field terminals to operate the motor in the desired quadrant. If the supply is non-receptive during the regenerative braking, the line voltage would increase and regenerative braking may not be possible. In this case, an alternative form of braking is necessary, such as rheostatic braking.

The possible control models of a dc-dc converter drive are:

A- Power (or acceleration) control
B- Regenerative brake control
C- Rheostatic break control
D- Combined regenerative and rheostatic brake control
E- Four quadrant dc-dc converter drives

A- Power (or acceleration) control

The dc-dc converter is used to control the armature voltage of a dc motor. The circuit arrangement of a converter-fed dc separately excited motor is shown in figure (55). The dc-dc converter switch could be a transistor or forced-commutated thyristor dc-dc converter. The waveforms for the armature voltage, load current, and input current are shown in figure (56) assuming a highly inductive load.

The average armature voltage is $V_a = KV_s$

Where $K\ is\ the\ duty\ cycle$ of the dc-dc converter.

The power supplied to the motor is $P_o = P_{in} = V_a I_a = K\,V_s I_a$

Input power equals output power "lossless system"

Where Ia is the average armature current and it is ripple free

The average value of input current is $I_s = KI_a$

The equivalent input resistance seen by the source is $R_{eq} = \frac{V_s}{I_s} = \frac{V_s}{KI_a}$

By varying the duty-cycle k, the power flow to the motor (and speed) can be controlled. For a finite armature circuit inductance, Equation below can be applied to find the maximum peak-to-peak ripple current as:

$\Delta Imax = \frac{V_s}{R_m} tanh \frac{R_m}{4fL_m}$ Where

Rm is the total armature circuit resistance, $R_m = R_a + any\ series\ resistance$. For series motor $R_m = R_a + R_f$

Lm is the total armature circuit inductance, $L_m = L_a + any\ series\ inductance$. For series motor $Lm = L_a + L_f$

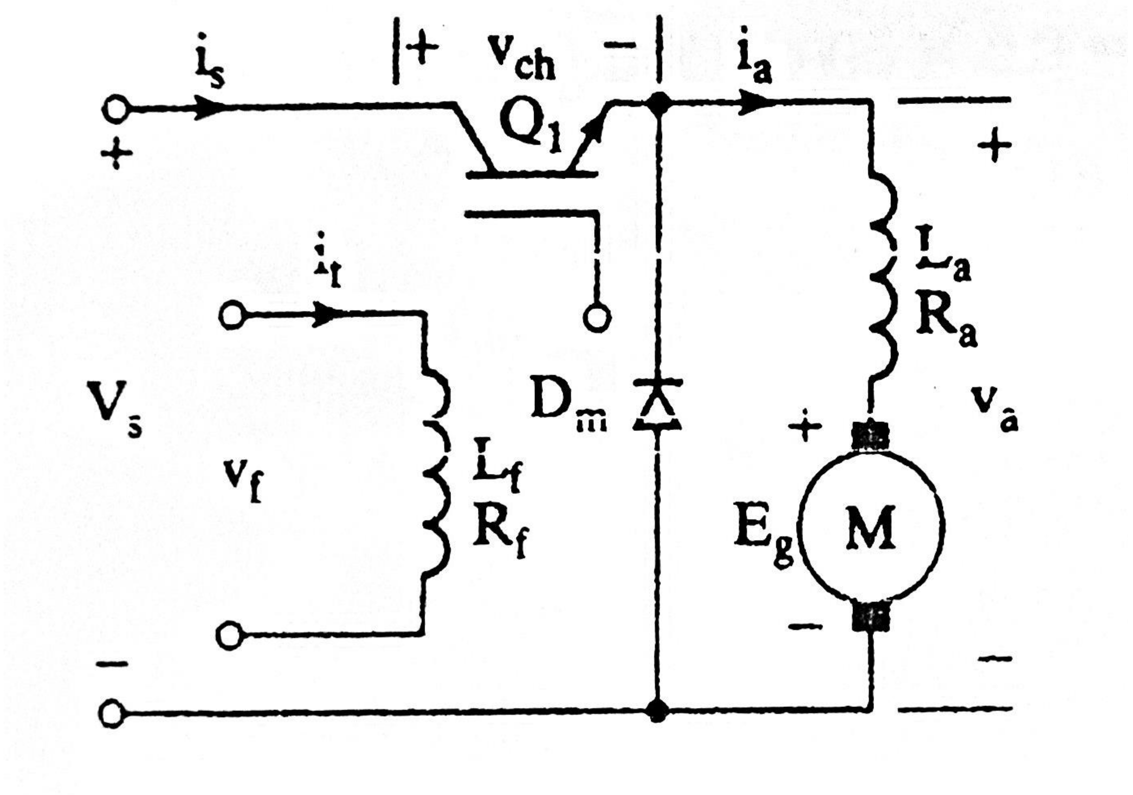


Figure (55) circuit arrangement of a converter-fed dc separately excited motor

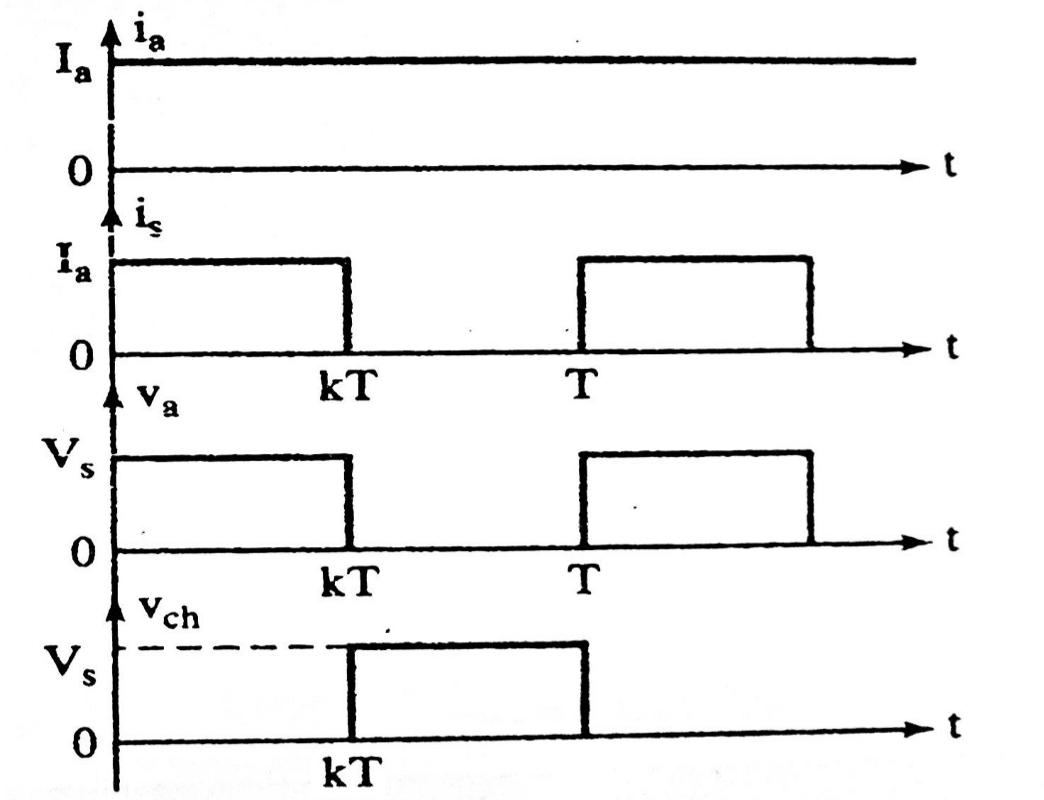


Figure (56) waveforms for the armature voltage, load current, and input current

Example 4.6

B- Regenerative brake control

In regenerative breaking, the motor acts as a generator and the kinetic energy of the motor and load is returned back to the supply. The application of dc-dc converters in regenerative braking can be explained with figure (57). It requires rearranging the switch from powering mode to regenerative breaking. Let us assume that the armature of a separately excited motor is rotating due to the inertia of the motor (and load); and in case of a transportation system, the kinetic energy of the vehicle or train would rotate the armature shaft. Then if the transistor is switched on, the armature current rises due to the short-circuiting of the motor terminals. If the dc-dc converter is turned off, diode Dm would be turned on and the energy stored in the armature circuit inductances would be transferred to the supply, provided that the supply is receptive. It is a one quadrant drive and operates in the second quadrant. Figure (58) shows the voltage and current waveforms assuming that the armature current is continuous and ripple free.

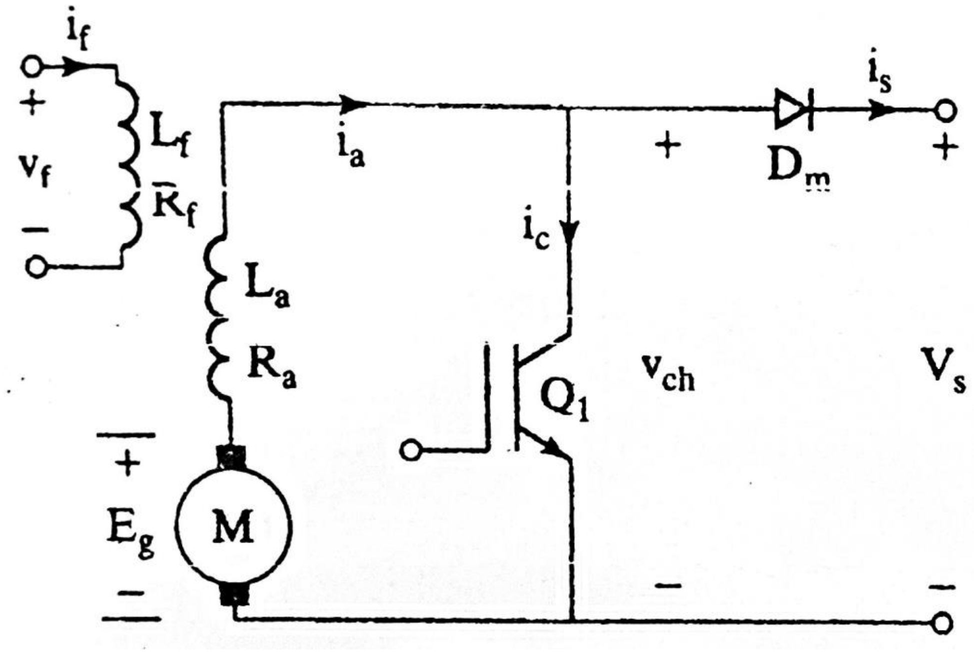


Figure (57) circuit arrangement of a converter-fed dc separately excited motor for Regenerative brake control

The average voltage across the dc-dc converter is

$V_{ch} = (1 - K)V_s$

The regenerated power can be found from

$P_g = V_s I_a (1 - K)$

The voltage generated by the motor acting as a generator is

$$E_g = K_v I_f w = V_{ch} + R_m I_a = (1 - k)V_s + R_m I_a$$

Where K_v is the machine constant and *w* is the machine speed in rad/sec

The equivalent load resistance of the motor acting as a generator is

$R_{eq} = \frac{E_g}{I_a} = \frac{V_s}{I_a}(1 - k) + R_m$

Minimum breaking speed of the motor

$E_g = K_v\, w_{min} I_f = R_m I_a \Rightarrow w_{min} = \frac{R_m I_a}{K_v I_f}$

The maximum breaking speed of a series motor can be found from

$K_v w_{max} I_f - R_m I_a = V_s \Rightarrow w_{max} = \frac{V_s + R_m I_a}{K_v I_f}$

Where $w_{min} \leq w \leq w_{max}$

The regenerative braking would be effective only if the motor speed is between these two speed limits.

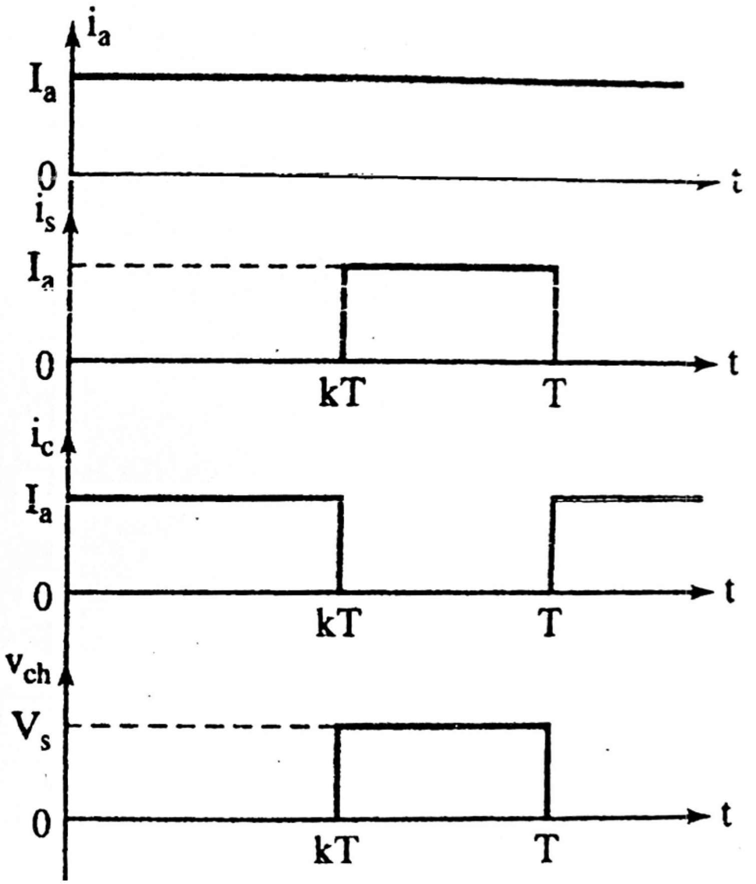


Figure (58) voltage and current waveforms assuming that the armature current is continuous and ripple free

Example 4.7

C- Rheostatic break control

In a rheostatic braking, the energy is dissipated in a rheostat and it may not be a desirable feature. In MRT systems, the energy may be used in heating the trains. The rheostatic braking is also known as dynamic braking. An arrangement for the rheostatic braking of a dc separately excited motor is shown in figure (59). This is a one quadrant drive and operates in the second quadrant. Figure (60) shows the waveforms for the current and voltage, assuming that the armature current is continuous and ripple free.

The average current of the braking resistor $I_b = I_a\,(1 - k)$

The average voltage across the braking resistor $V_b = R_b I_a (1 - k)$

The equivalent load resistance of the generator $R_{eq} = \frac{V_b}{I_a} = R_b(1 - k) + R_m$

The power dissipated in the resistor Rb is $P_b = {I_a}^2 R_b (1 - k)$

By controlling the duty cycle k, the effective load resistance can be varied from $Rm\ to\ Rm + Rb,$ and the braking power can be controlled. The braking resistance Rb determines the maximum voltage rating of the dc-dc converter.

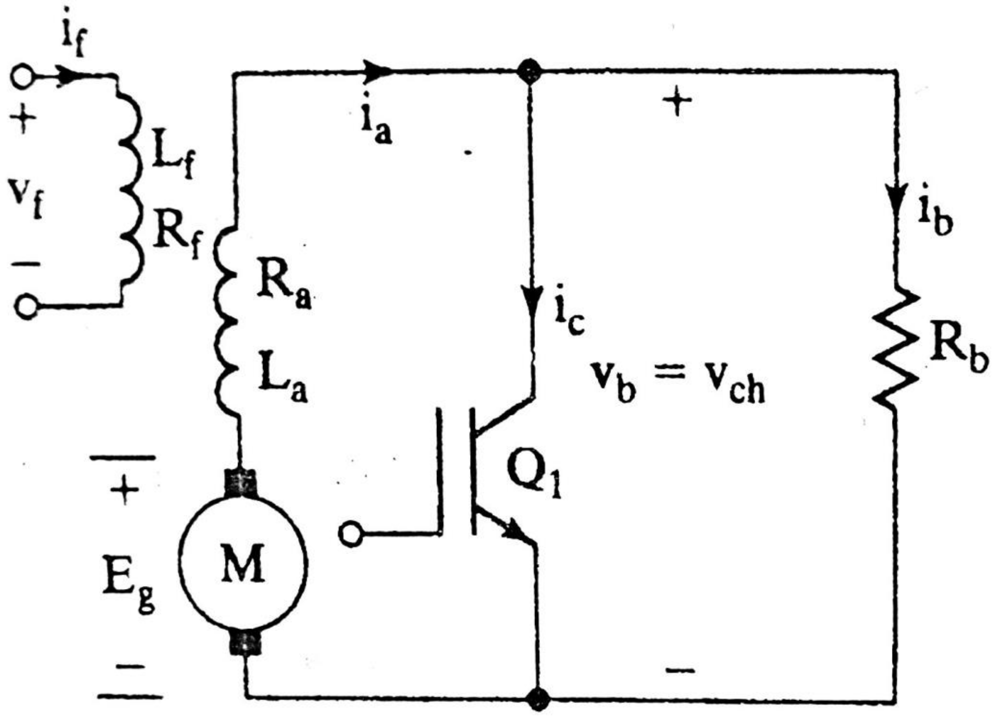


Figure (59) An arrangement for the rheostatic braking of a dc separately excited motor

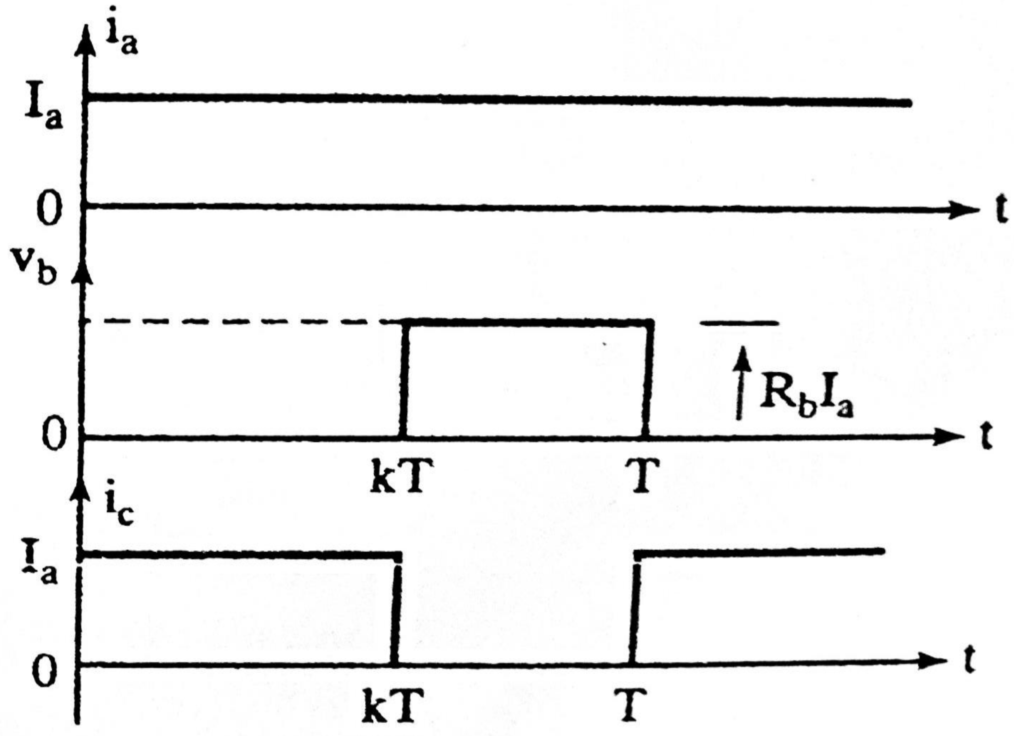


Figure (60) waveforms for the current and voltage

Example 4.8

D- Combined regenerative and rheostatic brake control

Regenerative braking is energy-efficient braking. On the other hand, the energy is dissipated as heat in rheostatic braking. If the supply is partly receptive, which is normally the case in practical traction systems, a combined regenerative and rheostatic brake control would be the most energy efficient. Figure (61) shows an arrangement in which rheostatic braking is combined with regenerative braking. During regenerative braking, the line voltage is sensed continuously. If it exceeds a certain pre-set value, normally 20% above the line voltage, the regenerative braking is removed and a rheostatic braking is applied. It allows an almost instantaneous transfer from regenerative to rheostatic braking if the line becomes nonreceptive, even momentarily. In every cycle, the logic circuit determines the receptivity of the supply. If it is nonreceptive thyristor TR is turned on to divert the motor current to the resistor Rb. Thyristor Tr is self-commutated when transistor Q1 is turned on in the next cycle.

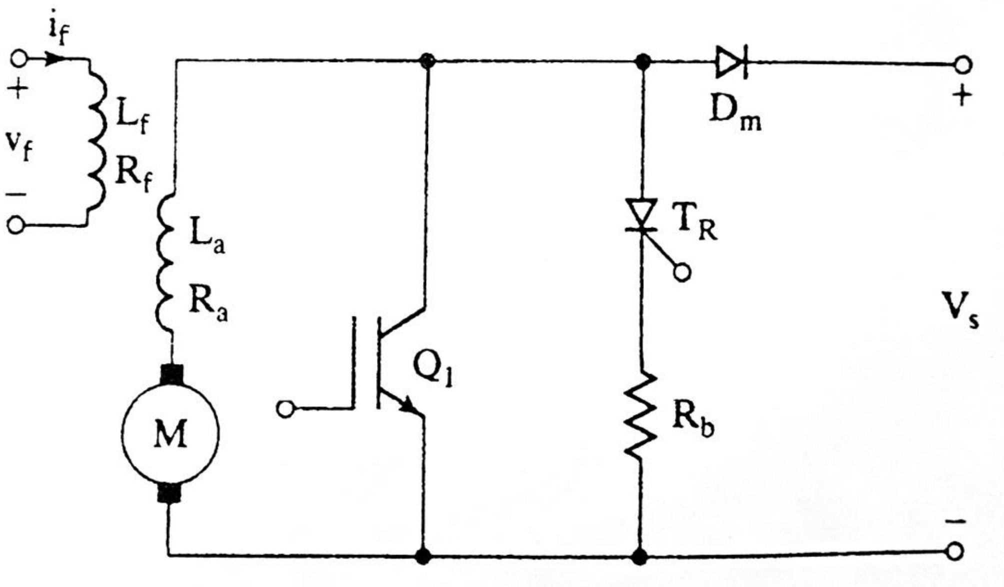


Figure (61) Circuit arrangement in which rheostatic braking is combined with regenerative braking

E- Four quadrant dc-dc converter drives

In industrial applications, four quadrant operation is required. Figure (62) shows a transistorized four-quadrant drive.

- Forward power control Q1, Q2 Q2,D3,D4
- Forward regeneration Q4-D2 D1,D2 GƆ
- Reverse power control Q3, Q4 Q4,D1,D2
- Reverse regeneration Q2-D4 D3,D4 GƆ

GƆ returns energy to the supply

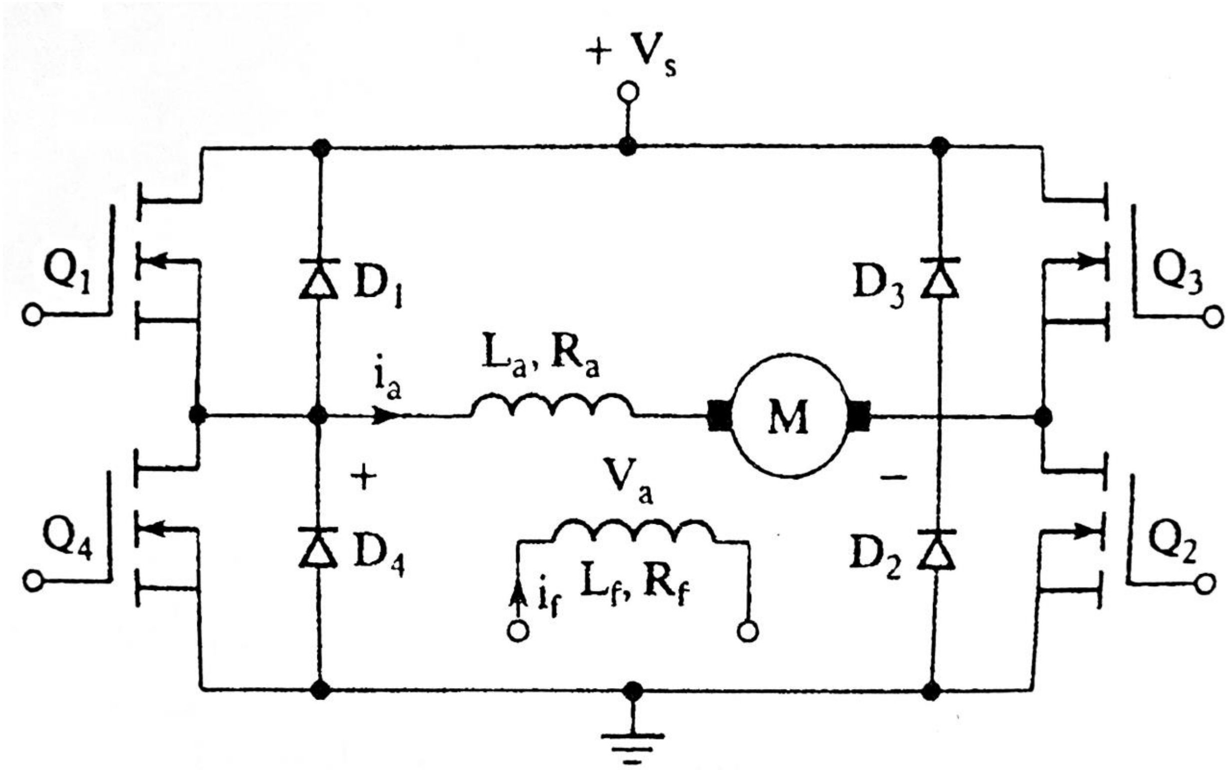


Figure (62) transistorized four-quadrant drive.

4.2- AC DRIVES:

AC motors exhibit highly coupled nonlinear, and multivariable structures as opposed to much simpler decoupled structures of separately excited dc motors. The control of ac drives generally requires complex control algorithms that can be performed by microprocessors or microcomputers along with fast-switching power converters.

The ac motors have a number of advantages:
1- They are lightweight (20 to 40% lighter than equivalent dc motors)
2- They are inexpensive
3- They have low maintenance compared with dc motors
4- They require control of frequency, voltage and current for variable speed applications “Using power electronics”

Power electronics such as Power converters, inverters and ac voltage controllers are relatively complex and more expensive, require advanced feedback control techniques such as:
1- Model reference
2- Adaptive control
3- Sliding mode control
4- field oriented control

There are two types of ac drives:
1- Induction motor drives
2- Synchronous motor drives

4.2.1- Induction motor drives:

Three phase induction motors are commonly used in adjustable-speed drives, and they have three-phase stator and rotor windings. The stator windings are supplied with balanced three-phase ac voltages, which produce induced voltages in the rotor winding due to transformer action. It is possible to arrange the distribution of stator winding so that there is an effect of multiple poles, producing several cycles of magnetomotive force (mmf) or (field) around the airgap. This field establishes a spatially distributed sinusoidal flux density in the airgap. The speed of rotation of the field is called the synchronous speed, which is defined by

$$\omega_S = \frac{2\omega}{p} \qquad \textit{where: } p \textit{ is the number of poles}$$

ω *is the supply frequency in rads per second.*

$$Slip\ (S) = \frac{\omega_S - \omega_m}{\omega_S} \Rightarrow \omega_m = \omega_S(1-S) \qquad \textit{where } \omega_m \textit{ is the speed of the motor shaft}$$

The equivalent circuit for one phase of the rotor is shown in figure (63).

Where:
R_r is the resistance per phase of the rotor winding.
X_r is the leakage reactance per phase of the rotor at the supply frequency.
R_s is the resistance per phase of the stator winding.
X_s is the leakage reactance per phase of the stator winding.
Er represents the induced rms phase voltage when the speed is zero or $s = 1$

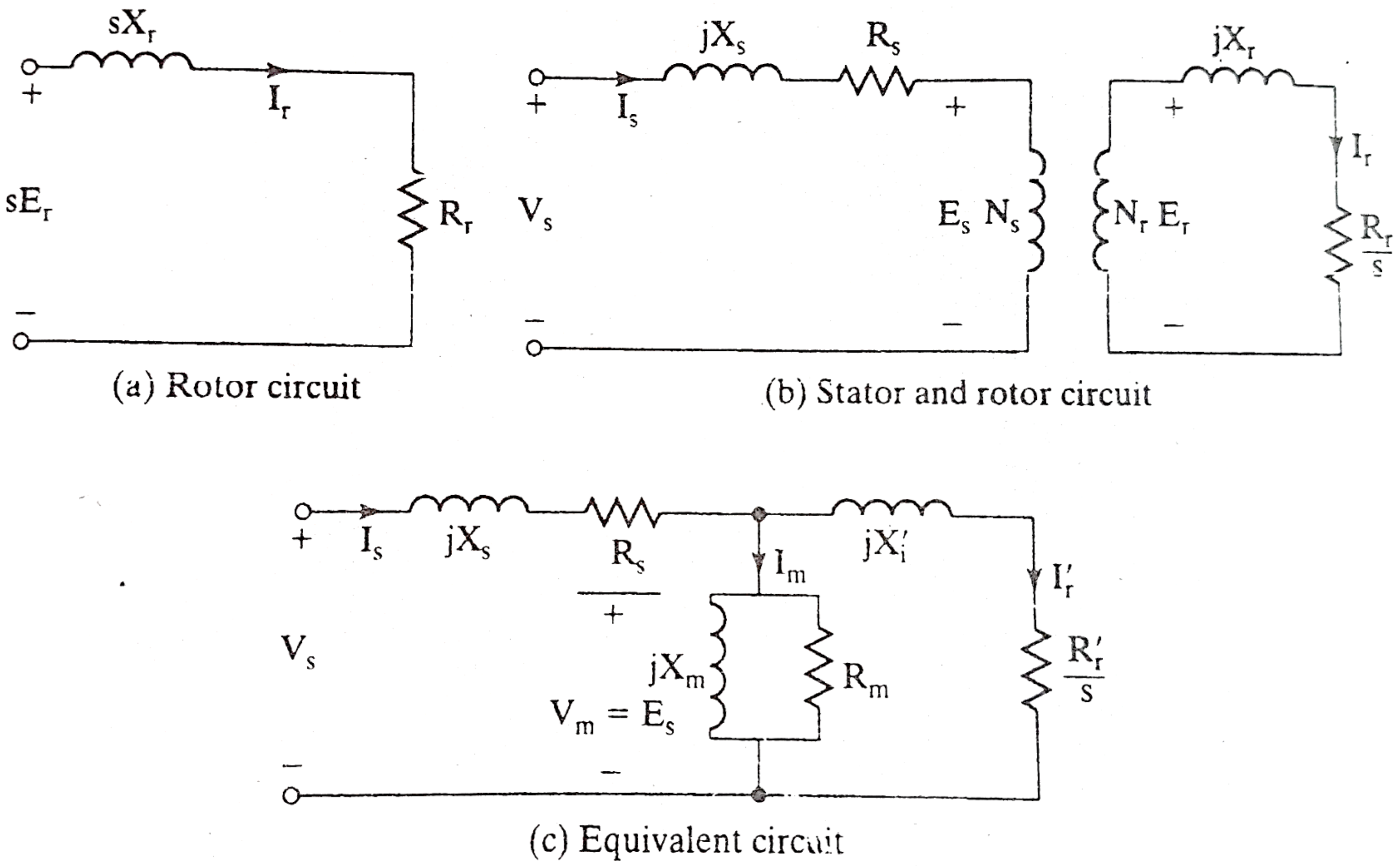


Figure (63) The equivalent circuit for one phase of the rotor

The rotor current is given by:

$$I_r = \frac{E_r}{\frac{R_r}{s} + jX_r}$$

Figure (63-c) shows the complete circuit model with all parameters referred to the stator.

R_m Represents the resistance of the core
X_m Represents the reactance of the core

There will be stator core loss, when the supply is connected and the rotor core loss depends on the slip. The friction and windage loss $(P_{no\ load})$ exists when the machine rotates.

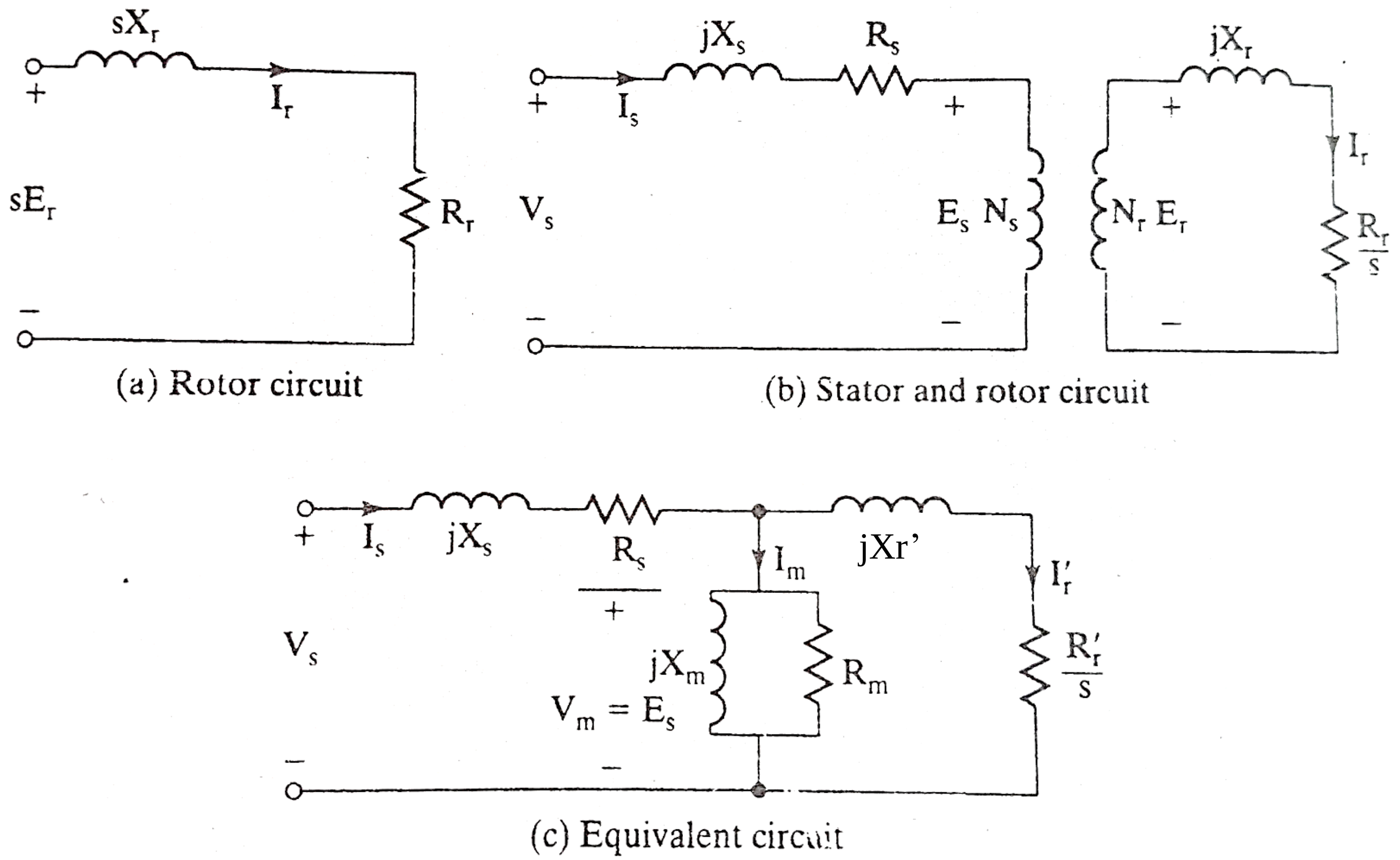


Figure (63) The equivalent circuit for one phase of the rotor

4.2.1.1- The performance parameters of a three-phase induction motor can be determined as follows:

- Stator copper loss $P_{su} = 3{I_s}^2 R_s$
- Rotor copper loss $P_{ru} = 3({I_r}')^2 {R_r}'$
- Core loss $P_c = 3{I_m}^2 R_m = \frac{3{V_m}^2}{R_m} \approx \frac{3{V_s}^2}{R_m}$
- Gap power $P_g = 3({I_r}')^2 \frac{{R_r}'}{s}$
- Developed power $P_d = P_g - P_{ru} = \left[3({I_r}')^2 \frac{{R_r}'}{s}\right] - [3({I_r}')^2 {R_r}'] = P_g(1-s)$
- Developed Torque $T_d = \frac{P_d}{\omega_m} = \frac{P_g(1-s)}{\omega_s(1-s)} = \frac{P_g}{\omega_s}$
- Input power $P_i = 3\, V_s\, I_s \cos\theta = P_c + P_{su} + P_g$
- Output power $P_o = P_d - P_{no\,load}$
- Efficiency $\eta = \frac{P_o}{P_i} = \frac{P_d - P_{no\,load}}{P_c + P_{su} + P_g} \approx \frac{P_d}{P_g} = \frac{P_g(1-s)}{P_g} = (1-s)$

Figure (64) shows the approximate per phase equivalent circuit after simplification.

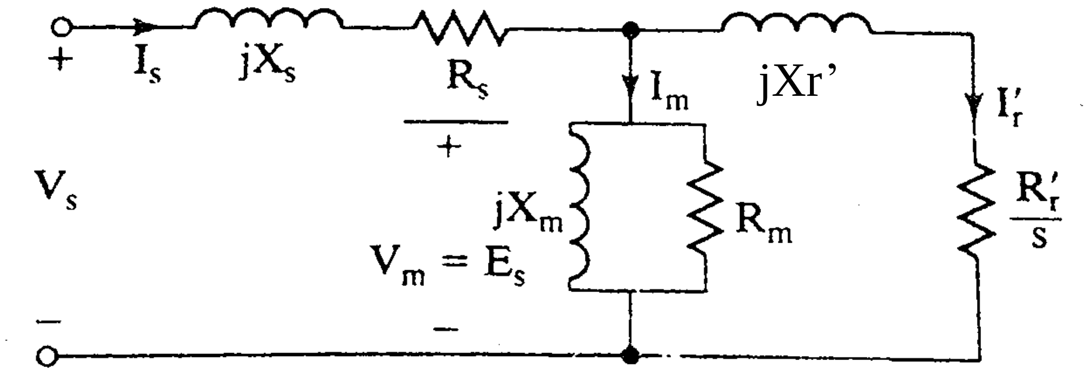
The value of X_m is normally larger and R_m is much larger than X_m, therefore R_m can be removed from the circuit model to simplify the calculation.

If ${X_m}^2 \gg \left({R_s}^2 + {X_s}^2\right)$ "Value in Ω" then $V_s \approx V_m$

And thus, the magnetizing reactance X_m may be moved to the stator winding to simplify further.

The input impedance of the motor becomes:

$$Z_i = \frac{-X_m(X_s + X_r') + jX_m\left(R_s + \frac{R_r'}{s}\right)}{R_s + \frac{R_r'}{s} + j(X_m + X_s + X_r')}$$



(c) Equivalent circuit

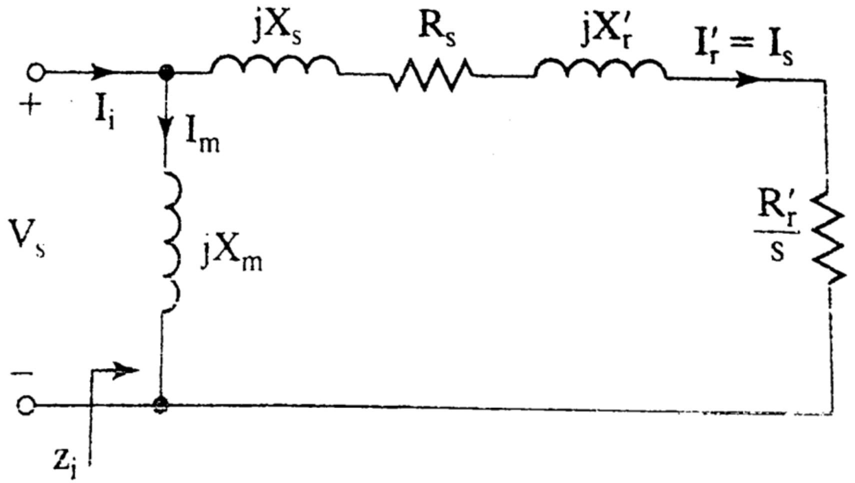


Figure (64) the approximate per phase equivalent circuit after simplification

The rms rotor current:

$$I_r{}' = \frac{V_s}{\sqrt{\left(R_s + \frac{R_r{}'}{s}\right)^2 + (X_s + X_r{}')^2}}$$

The developed torque becomes:

$$T_d = \frac{3R_r{}'V_s{}^2}{s\omega_s\left[\left(R_s + \frac{R_r{}'}{s}\right)^2 + (X_s + X_r{}')^2\right]}$$

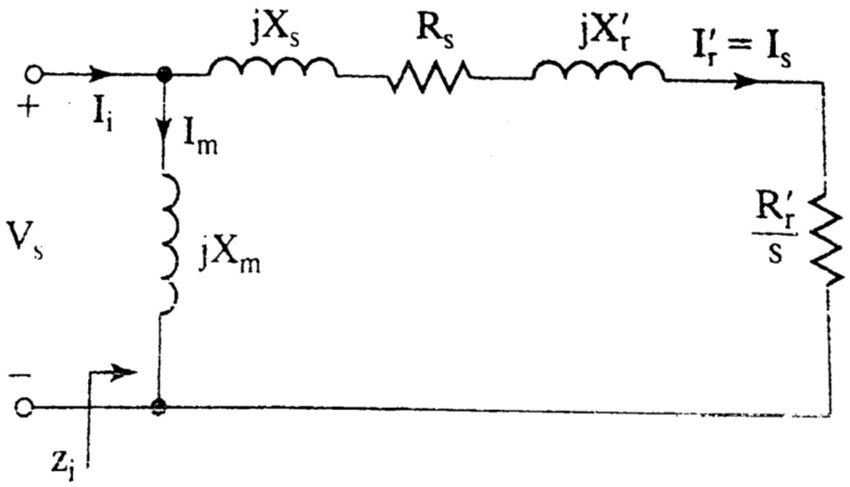


Figure (64) the approximate per phase equivalent circuit after simplification

Homework, Drive for T_d using equations from page 103 and 105.

4.2.1.2- Torque *VS* speed characteristics:

If the motor is supplied from a fixed voltage at a constant frequency, the developed torque is a function of the slip and the torque-speed characteristics can be determined from the previous equation. A typical plot of developed torque as a function of slip or speed is shown in figure (65).

There are three regions of operation:

1- Motoring or powering, $0 \leq s \leq 1$

2- Regeneration, $s < 0$

3- Plugging, $1 \leq s \leq 2$

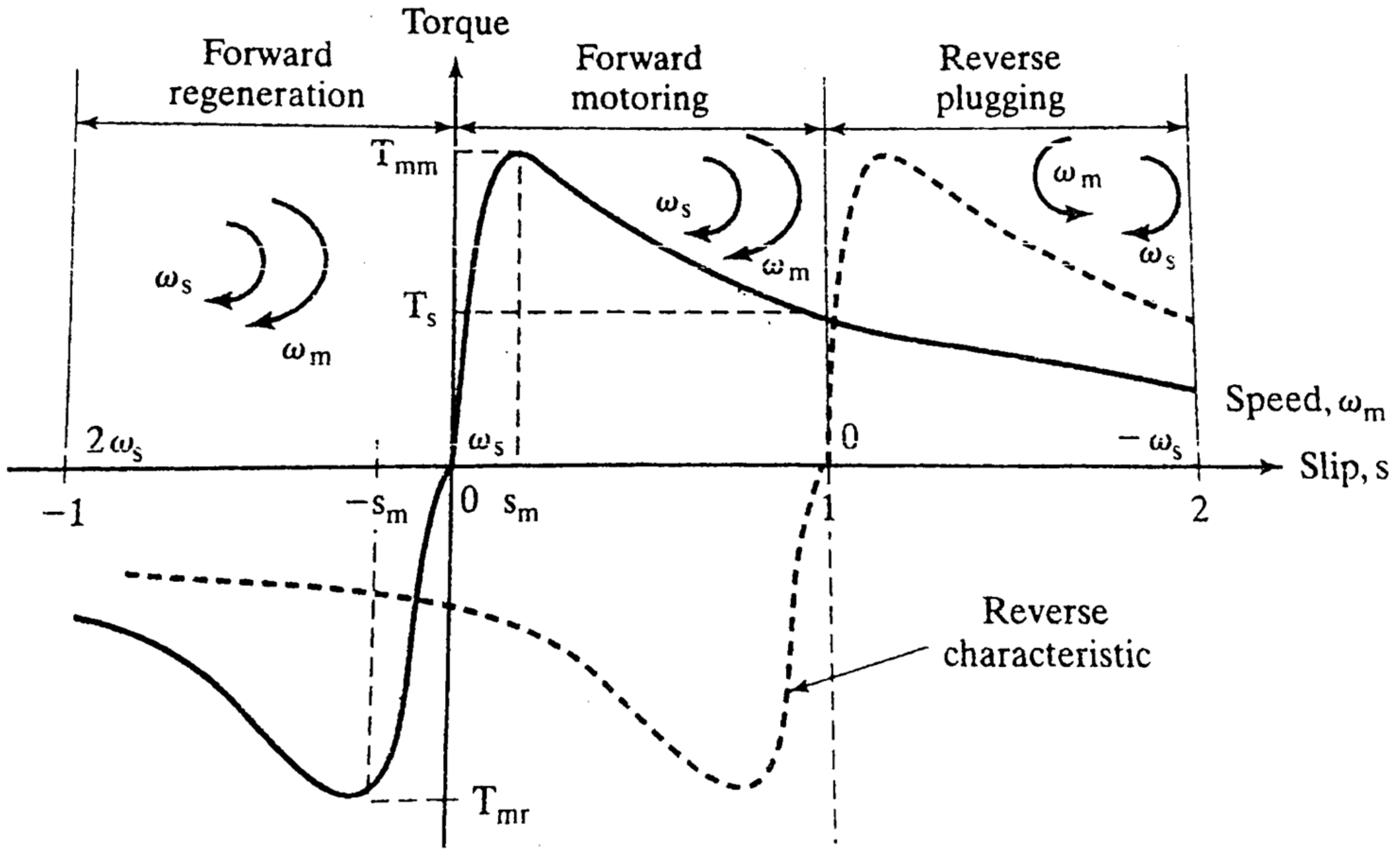


Figure (65) Torque *vs* speed characteristics

1- Motoring or powering, $\omega_s > \omega_m$ both rotates in the same direction, thus the slip is positive.
2- Regeneration, $\omega_s < \omega_m$ both rotates in the same direction, thus the slip is Negative. "the motor returns power to the supply".
3- Plugging, ω_m rotates to the opposite direction of ω_s and the slip is greater than unity. This may happen if the sequence of the supply source is reversed while forward motoring, so that the direction of the field is also reversed. The developed torque, which is in the same direction as the field, opposes the motion and acts as braking torque. The energy due to plugging brake must be dissipated within the motor and this may cause excessive heating of the motor. This type of breaking is not normally recommended.

4.2.1.2- Starting torque and maximum torque:

At starting, the machine speed $\omega_m = 0$ and $s = 1$. The starting torque can be found from the following equation by setting $s = 1$.

$$T_d = \frac{3R_r'V_s^2}{s\omega_s\left[\left(R_s+\frac{R_r'}{s}\right)^2+\left(X_s+X_r'\right)^2\right]} \quad \Longrightarrow \quad T_s = \frac{3R_r'V_s^2}{\omega_s\left[\left(R_s+R_r'\right)^2+\left(X_s+X_r'\right)^2\right]}$$

The slip for maximum torque is s_m can be determined by setting $\frac{dT_d}{d_s} = 0$ in the following equation

$$T_d = \frac{3R_r' V_s^2}{s\omega_s\left[\left(R_s + \frac{R_r'}{s}\right)^2 + (X_s + X_r')^2\right]}$$

Yields

$$s_m = \mp \frac{R_r'}{\sqrt{R_s^2 + \left(X_s + X_r'\right)^2}}$$

Substituting $s = s_m$ in the above equation of T_d gives the maximum developed torque during motoring, which is also called pull-out torque, or breakdown torque.

$$T_{mm} = \frac{3V_s^2}{2\omega_s\left[R_s + \sqrt{R_s^2 + \left(X_s + X_r'\right)^2}\right]}$$

$$T_{mr} = \frac{3V_s^2}{2\omega_s\left[-R_s + \sqrt{R_s^2 + \left(X_s + X_r'\right)^2}\right]}$$

The maximum regenerative torque by letting $s = -s_m$

Homework, If R_s is considered small compared with other circuit impedances, which is usually a valid approximation for motors of more than 1-kW rating, Drive for T_d, T_s, s_m, T_{mm} *and* T_{mr} by neglecting R_s.

The equation that gives the speed as a function of torque is:

$$\omega_m = \omega_s \left(1 - \frac{s_m}{2T_{mm}} T_d\right)$$

Example 4.9

The speed and torque of induction motors can be varied by one of the following means:

A- Stator Voltage control
B- Rotor Voltage control
C- Frequency control
D- Stator voltage and frequency control
E- Stator current control
F- Voltage, current and frequency control “Used to meet the torque-speed duty cycle of a drive”

A- Stator Voltage control

The equation of developed torque indicates that the torque is proportional to the square of the stator supply voltage and a reduction in stator voltage can produce a reduction in speed. If the terminal voltage is reduced by a factor of b. the equation will be modified as follows:

$$T_d = \frac{3R_r{}'(bV_s)^2}{s\omega_s\left[\left(R_s + \frac{R_r{}'}{s}\right)^2 + (X_s + X_r{}')^2\right]}$$

Where $b \leq 1$

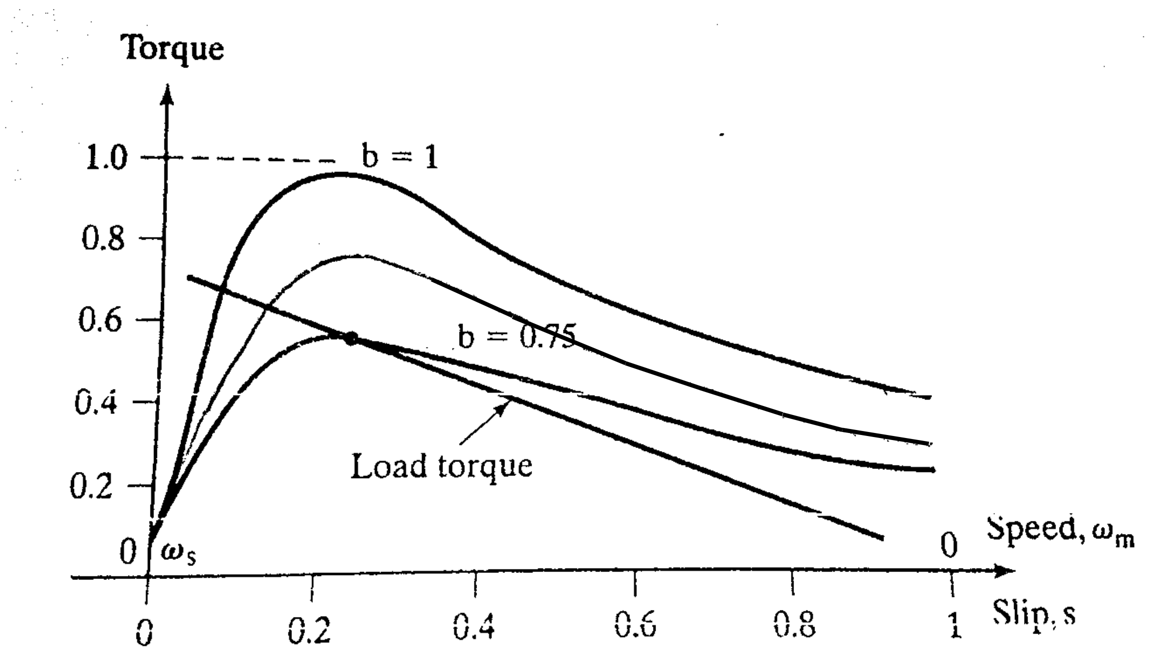


Figure (66) Torque-speed characteristics with variable stator voltage

Figure (66) shows the typical torque-speed characteristics for various values of b. The points of intersection with the load line define the stable operating points. For low slip motors, the speed range is very narrow. This type of voltage control is not suitable for a constant – torque load and is normally applied to applications requiring low-starting torque and a narrow range of speed at a relatively low slip.

In any magnetic circuit, the induce voltage is proportional to flux and frequency ,and the (rms)air-gap flux can be expressed as: $V_a = bV_s = k_m \omega \varphi$

The stator voltage can be varied using the following techniques:

1- Ac voltage controllers “normally used”
2- Voltage-fed variable dc-link inverters
3- Pulse width modulation (PWM) inverters

Example 4.10

B- Rotor Voltage control

In a wound-rotor motor, an external three-phase resistor may be connected to its slip rings, as shown in figure (67-a). The developed torque may be varied by varying the resistance Rx. If Rx is referred to the stator winding and added to Rr, the developed torque could be obtained. This method increases the starting torque, while limiting the starting current.

The typical torque-speed characteristics of this method of control is shown in figure (67-b).

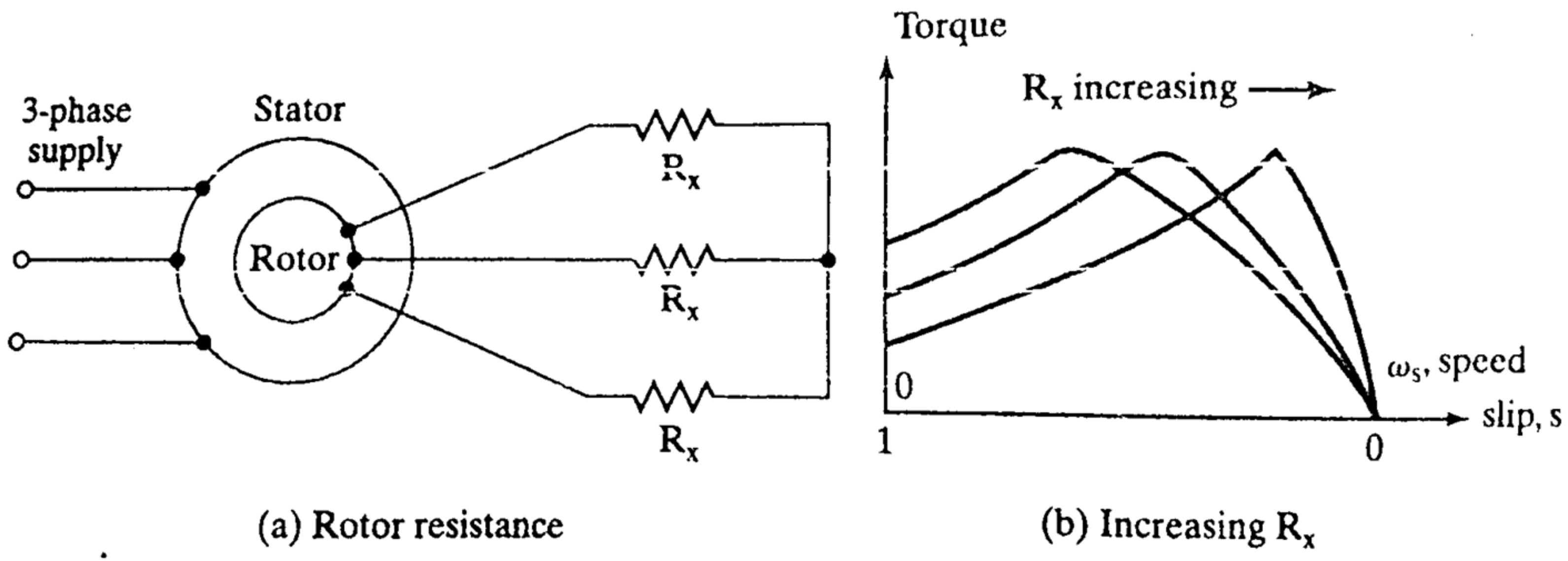


Figure (67) speed control by using rotor voltage control “motor resistance”

This is an inefficient method and there would be imbalances in voltages and currents if the resistances in the rotor circuit are not equal. A wound-rotor induction motor is designed to have a low-rotor resistance so that the running efficiency is high and the full-load slip is low.

The three phase resistors may be replaced by a three-phase diode rectifier and a dc converter, as shown in figure (68).

slip power: The portion of the air-gap power, which is not converted into mechanical power, is called slip power. The slip power is dissipated in the resistance R.

The slip power in the rotor circuit may be retuned to the supply by replacing the dc converter and resistance R with a three-phase full converter, as shown in figure (69), where the converter is operating in the inversion mode with delay range of $\frac{\pi}{2} \leq \alpha \leq \pi$, thereby returning energy to the source. The variation of delay angle permits PF and speed control. This type of drive is known as a Static Kramer Drive.

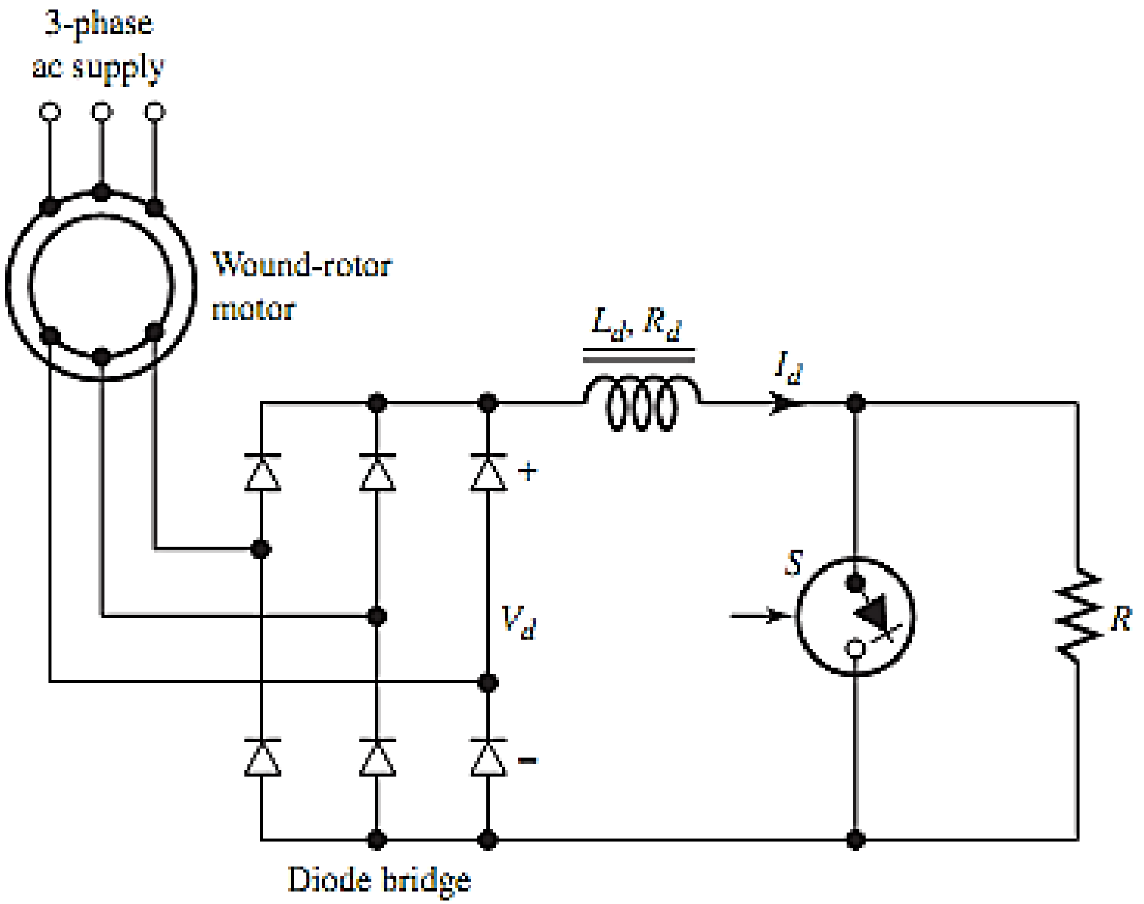


Figure (68) Slip control by dc converter

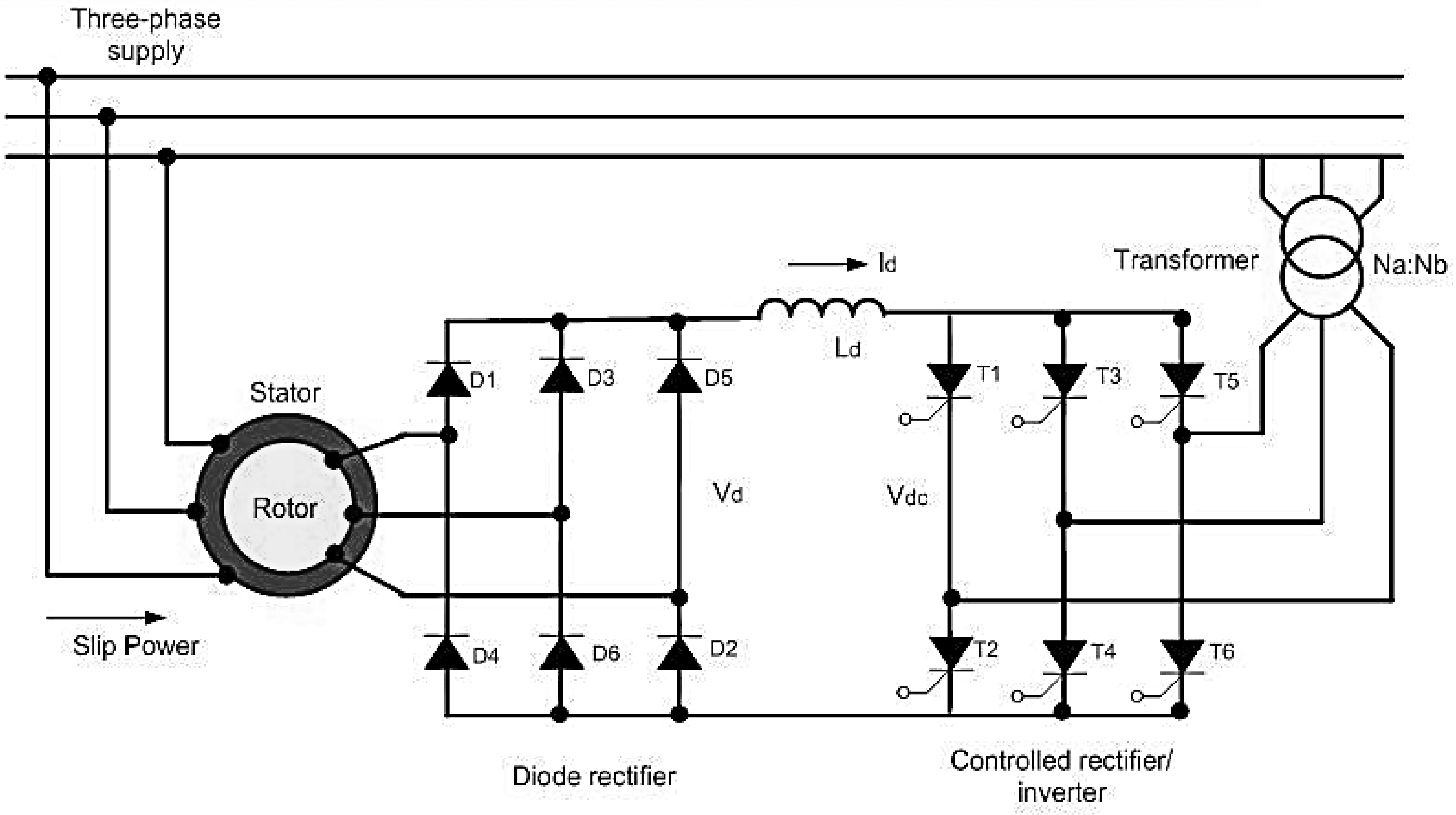


Figure (69) Static Kramer Drive

Again, by replacing the bridge rectifiers by three three-phase dual converters (or cycloconverters), as shown in figure (70). The slip PF in either direction is possible and this arrangement is called a static Scherbius drive.

The static Kramer and Scherbius drives are used in large power pumps and blower applications where limited range of speed control is required. Because the motor is connected directly to the source, the PF of these drives is generally high.

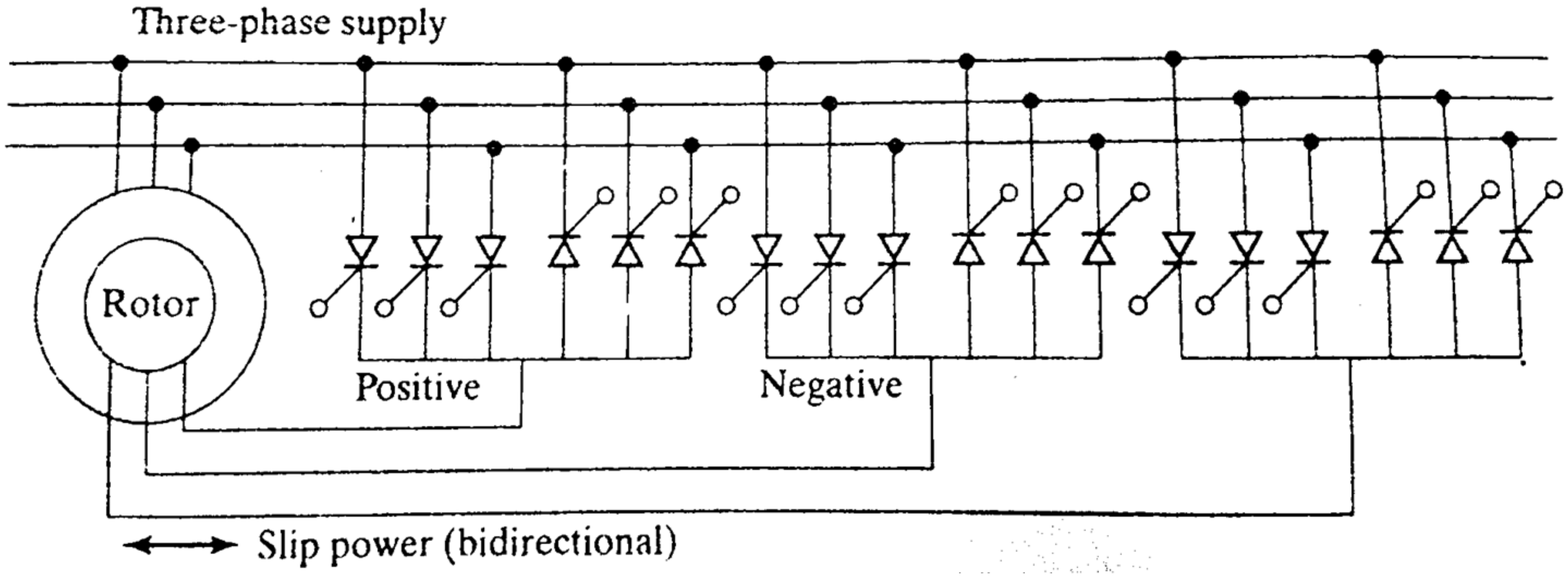


Figure (70) Scherbius Drive

C- Frequency control

The torque and speed of induction motor can be controlled by changing the supply frequency. At low frequency, the reactance's decrease and the motor current may be too high. This type of frequency control is not normally used.

If the frequency is increased above its rated value, the flux and torque would decrease.

If the synchronous speed corresponding to the rated frequency is called the base speed ω_b the synchronous speed at any other frequency becomes:

$$\omega_s = \beta\omega_b \quad \Longrightarrow \quad s = \frac{\beta\omega_b - \omega_m}{\beta\omega_b} = 1 - \frac{\omega_m}{\beta\omega_b}$$

The torque expression becomes:

$$T_d = \frac{3R_r{}'V_s{}^2}{s\beta\omega_b\left[\left(R_s + \frac{R_r{}'}{s}\right)^2 + (\beta X_s + \beta X_r{}')^2\right]}$$

The typical torque speed characteristics are shown in figure (71) for various values of β.

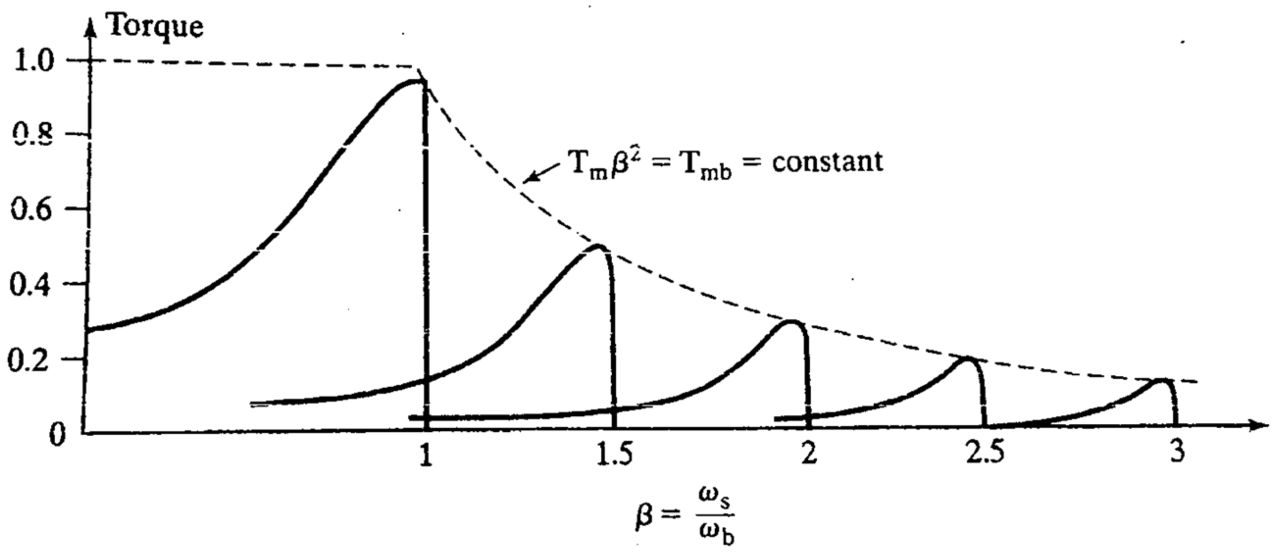


Figure (71) torque speed characteristics with frequency control

Here we need to use a three phase inverter that can vary the frequency at a fixed voltage. If Rs is negligible, the following equation gives the maximum torque at the base speed as:

$$T_{mb} = \frac{3{V_a}^2}{2\omega_b(X_s + X_r')}$$

The maximum torque at any other frequency is: $T_m = \frac{3}{2\omega_b(X_s+X_r')}\left(\frac{V_a}{\beta}\right)^2$

Thus $\frac{T_m}{T_{mb}} = \frac{1}{\beta^2}$ it can be concluded that the maximum torque is inversely proportional to frequency squared.

The corresponding slip is $S_m = \frac{R_r{'}}{\beta(X_s+X_r{'})}$

Example 4.11

D- Stator voltage and frequency control

If the ratio of voltage to frequency is kept constant, the flux remains constant. The maximum torque equation at Rs negligible indicates that the maximum torque, which is independent of frequency, can be maintained approximately constant. However at high frequency, the air-gap flux is reduced due to the drop in the stator impedance and the voltage has to be increased to maintain the torque level. This type of control is normally known as Volts/Hertz control.

If $\omega_s = \beta\omega_b$ *and the voltage to frequency ratio is constant so that* $\frac{V_a}{\omega_s} = d$

The ratio d which is determined from the rated terminal voltage Vs and the base speed ω_b is given by $d = \frac{V_s}{\omega_b}$

Therefore the maximum slip is $s_m = \frac{R_r{'}}{\sqrt{{R_s}^2+\beta^2(X_s+X_r{'})^2}}$

The typical torque-speed characteristics are shown in figure (72).

As the frequency is reduced, β decreases and the slip for maximum torque increases. For a given torque demand, the speed can be controlled according to $d = \frac{V_s}{\omega_b}$ by changing the frequency. Therefore, by varying both the voltage and frequency, the torque and speed can be controlled. The torque is normally maintained constant while the speed is varied. The voltage at variable frequency can be obtained from three-phase inverters or cycloconverters.

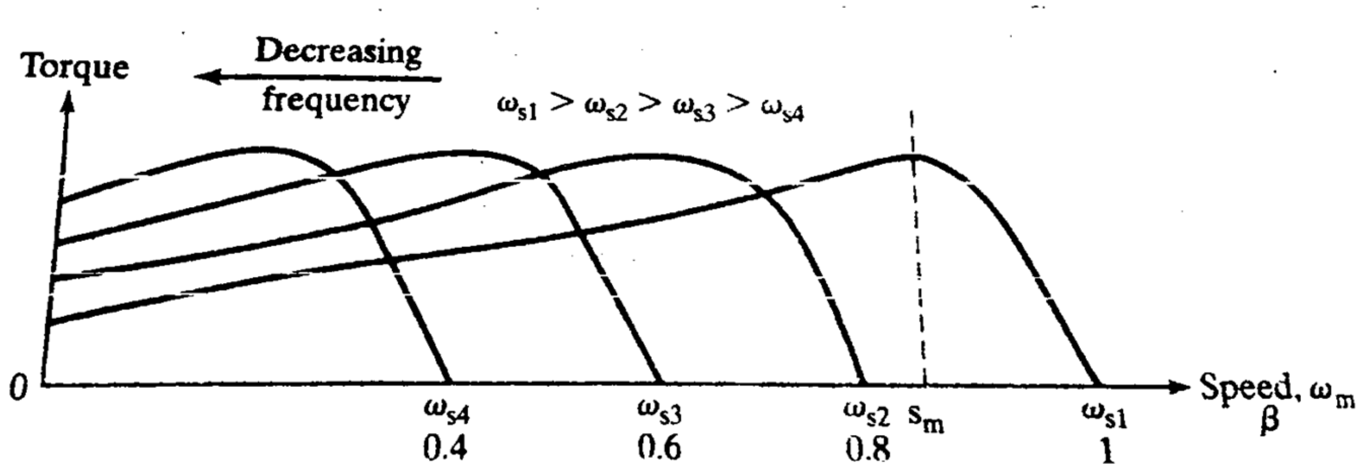


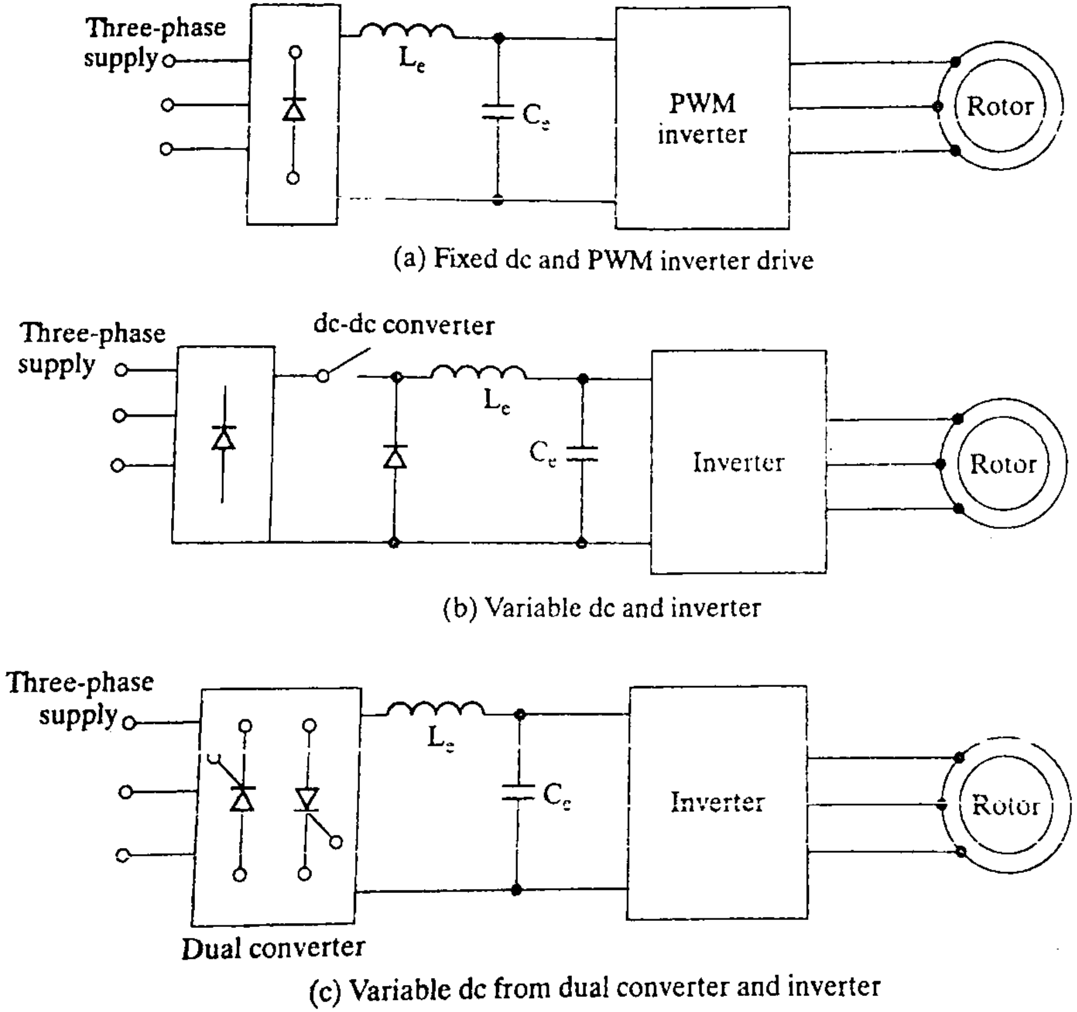
Figure (72) Torque speed characteristics with Volts/Hertz control

Three possible circuit arrangements for obtaining variable voltage and frequency are shown in figure (73) below.

A- The dc voltage remains constant and the PWM techniques are applied to vary both the voltage and frequency within the inverter.

B- The dc – dc converter varies the dc voltage to the inverter and the inverter controls the frequency.

C- The dc voltage is varied by the dual converter and frequency is controlled within the inverter.



(a) Fixed dc and PWM inverter drive
(b) Variable dc and inverter
(c) Variable dc from dual converter and inverter

Figure (73)

Chapter 5
Power Supllies

Power supplies are mainly divided into two groups: Dc power supplies and Ac power supplies.

5.1- Dc power supplies, such as: Batteries, Dc Generators, Solar Cells, Dynamo's and Electronic Power Supplies.

5.1.1- Ordinary D.C. Power Supply

An ordinary or unregulated dc power supply contains a transformer, a rectifier and a filter circuit as shown in Figure (74). The output from the rectifier is pulsating dc These pulsations are due to the presence of ac component in the rectifier output. The filter circuit removes the ac component so that steady dc voltage is obtained across the load.

The dc output voltage changes directly with input ac voltage.
The dc output voltage decreases as the load current increases. This is due to voltage drop in (a) transformer windings (b) rectifier and (c) filter circuit.
This type is mainly used in mobile phone chargers, vehicle's battery chargers and toys.

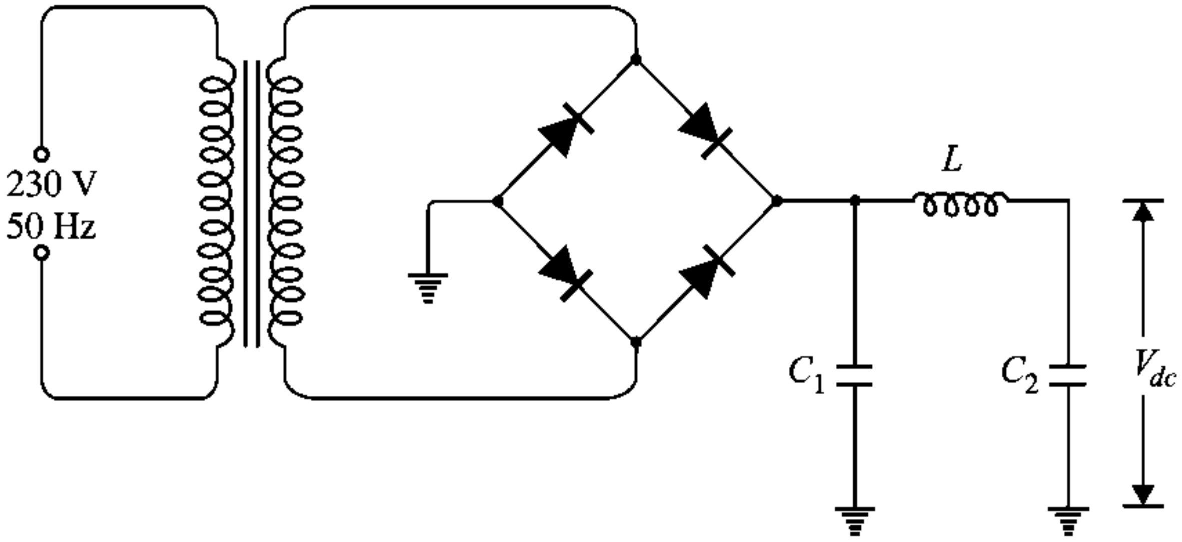


Figure (74) Ordinary D.C. Power Supply

5.1.2- Voltage regulation

The dc voltage available across the output terminals of a given power supply depends upon load current. If the load current I_{dc} is increased by decreasing R_L, Figure (75), there is greater voltage drop in the power supply and hence smaller dc output voltage will be available. Reverse will happen if the load current decreases. Therefore there has to be something called a voltage regulator.

The voltage regulation is expressed by the following relation:

$$Voltage\ regulation = \frac{V_{NL} - V_{FL}}{V_{FL}} * 100\%$$

Where:

V_{NL} = d.c. output voltage at no-load

V_{FL} = d.c. output voltage at full-load

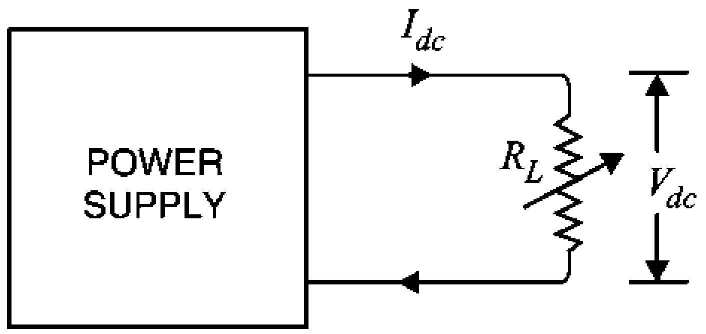


Figure (75)

In a well designed power supply, the full-load voltage is only slightly less than no-load voltage i.e. voltage regulation approaches zero. Therefore, lower the voltage regulation, the lesser the difference between full-load and no-load voltages and better is the power supply. Power supplies used in practice have a voltage regulation of 1%. Figure (76) shows the change of dc output voltage with load current. This is known as voltage regulation curve.

This type of voltage regulation is called load regulation because it indicates the change in output voltage due to the change in load current. There is another type of voltage regulation, called line regulation and indicates the change in output voltage due to the change in input voltage.

5.1.3- Minimum load resistance: The change of load connected to a power supply varies the load current and hence the dc output voltage. In order that a power supply gives the rated output voltage and current, there is minimum load resistance allowed. For instance, if a power supply is required to deliver a full-load current I_{FL} at full-load voltage V_{FL}, then,

$$R_{Lmin} = \frac{V_{FL}}{I_{FL}}$$

Thus, if a data sheet specifies that a power supply will give an output voltage of 100V at a maximum rated current of 0.4A, then minimum load resistance you can connect across supply is R_{min} = 100/0.4 = 250 Ω. If any attempt is made to decrease the value of R_L below this value, the rated dc output voltage will not be available.

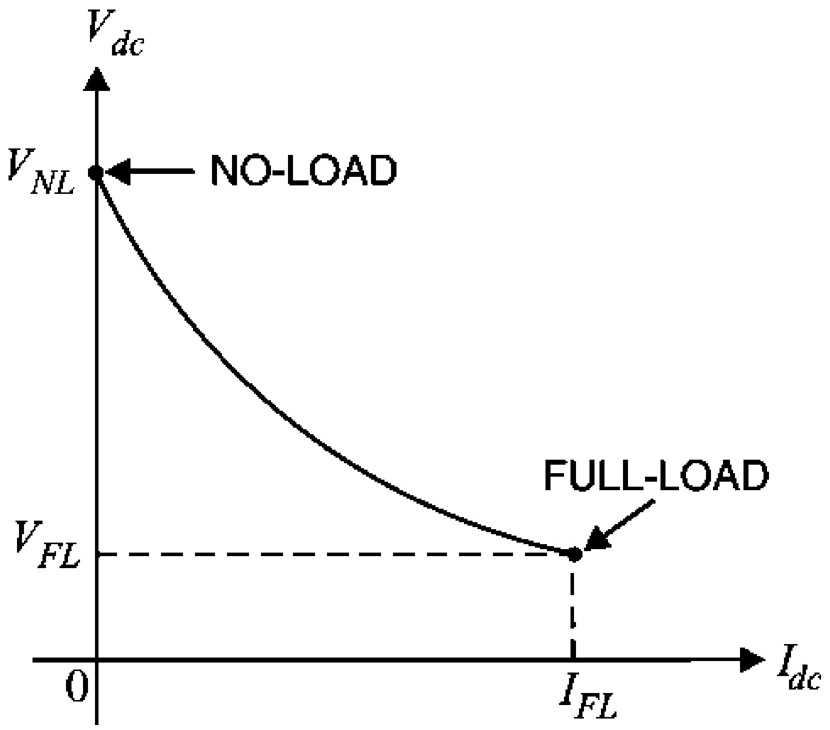


Figure (76) The change of d.c. output voltage with load current.

Examples 5.1, 5.2, 5.3

5.1.4- Regulated Power Supply:

A dc power supply which maintains the output voltage constant irrespective of a.c. mains fluctuations or load variations is known as regulated d.c. power supply. A regulated power supply consists of an ordinary power supply and voltage regulating device. Figure (77) shows the block diagram of a regulated power supply. The output of ordinary power supply is fed to the voltage regulator which produces the final output. The output voltage remains constant whether the load current changes or there are fluctuations in the input a.c. voltage.

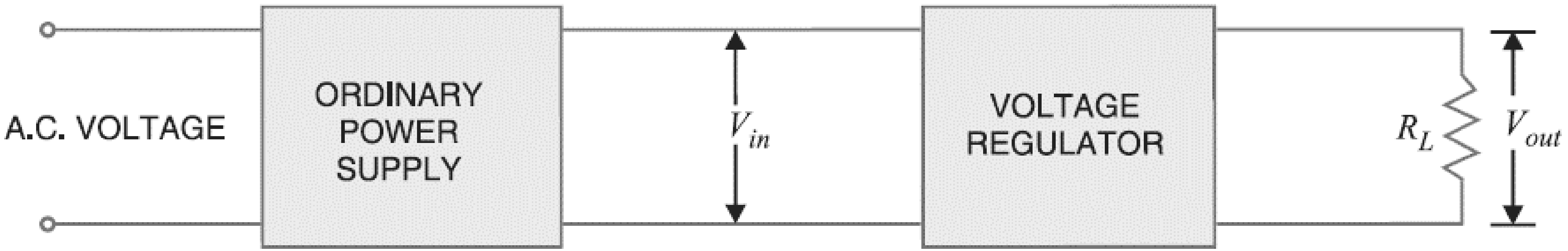


Figure (77) Block diagram of a regulated power supply

5.1.4.1- Types of voltage regulators:

There are two basic types of voltage regulators:

(A) series voltage regulator, shown in figure (78-a)

(B) shunt voltage regulator, shown in figure (78-b)

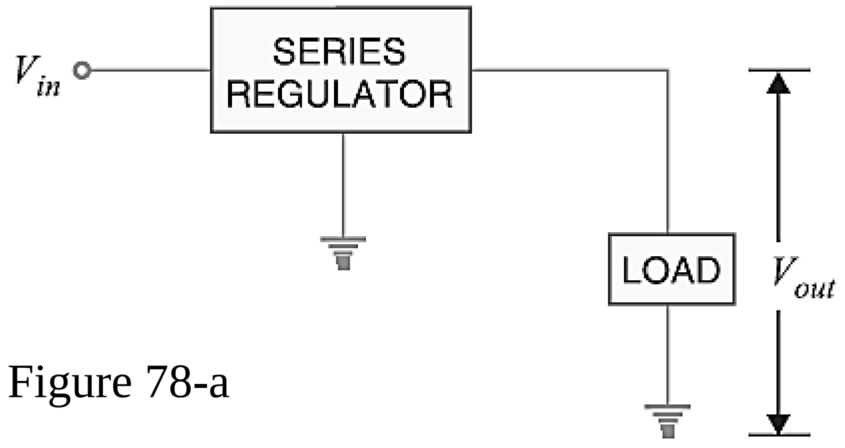


Figure 78-a

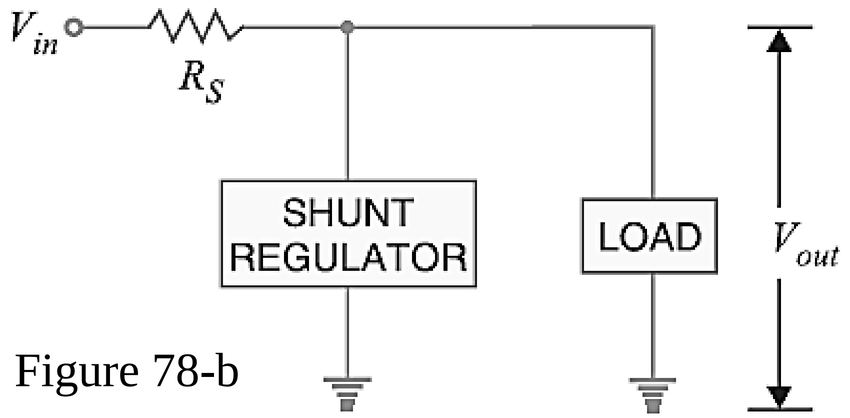


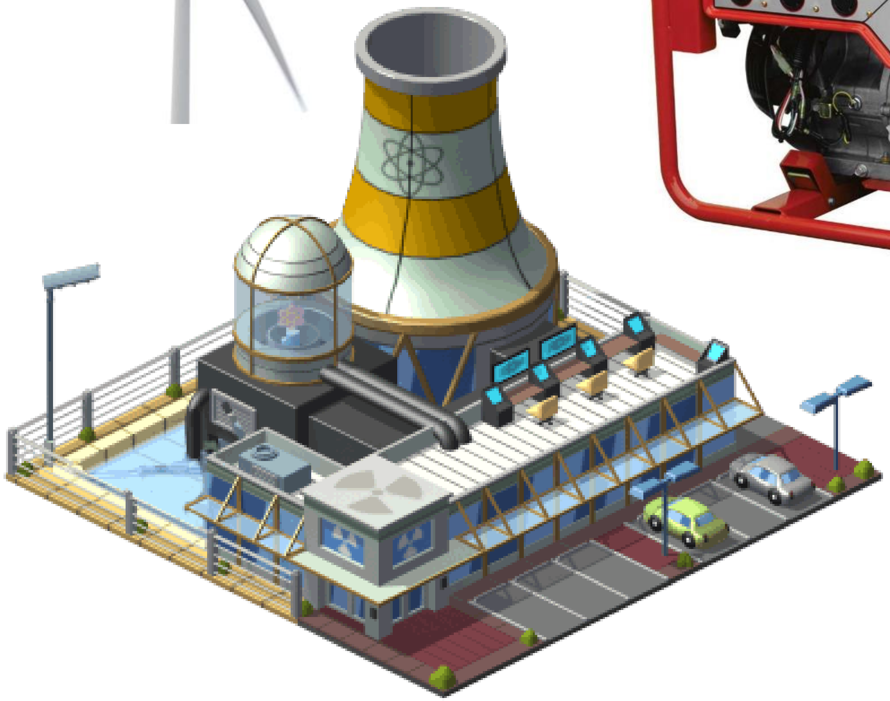
Figure 78-b

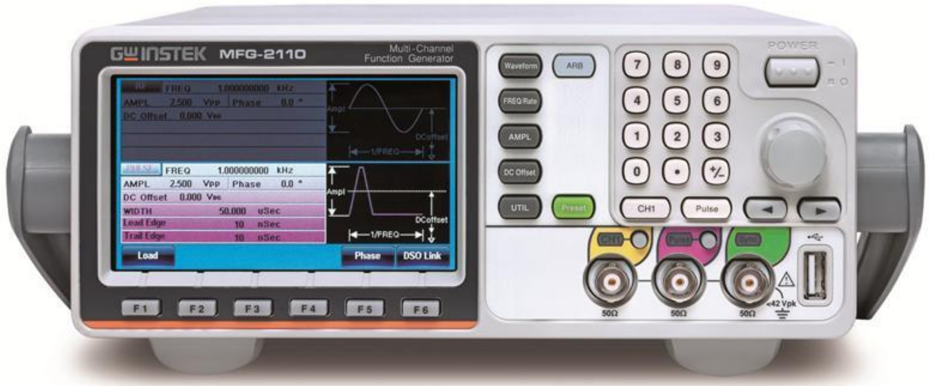
The series regulator is placed in series with the load. While, the shunt regulator is placed in parallel with the load. Each type of regulator provides an output voltage that remains constant even if the input voltage varies or the load current changes.

The subdivision types of voltage regulators are:

1- Zener Diode Voltage Regulator
2- Transistor Series or Shunt Voltage Regulator
3- Series or Shunt Feedback Voltage Regulator
4- Glow-Tube Voltage Regulator
5- Series Triode or Double Triode Voltage Regulator
6- IC Voltage Regulators
7- Fixed Positive or Negative Voltage Regulators
8- Adjustable Voltage Regulators
9- Dual-Tracking Voltage Regulators

5.2- Ac power supplies, National grid line, Generators, Wind turbines and Electronic Function Generators.





5.2.1- AC Generators used in Large Multiengine Aircrafts

Transport category aircraft typically carry hundreds of passengers and fly thousands of miles each trip. Therefore, large aircraft require extremely reliable power distribution systems that are computer controlled. These aircraft have multiple power sources (AC generators) and a variety of distribution busses. A typical airliner contains two or more main AC generators driven by the aircraft turbine engines, as well as more than one backup AC generator.

Types of Ac Generators Aircraft ac generators range in size from the tachometer instrument generator up to the 90,000 volt-ampere generators. Generators are categorized as either brush-type or brushless. Regardless of weight, shape, or rating, practically all of these generators have the following common characteristics:

• The stator (stationary armature winding) provides the ac output.
• The ac generator field (rotor) is a rotating magnetic field with fixed polarity.
• Regulating the rpm of the rotating magnetic field controls the voltage frequency.
• Controlling the strength of the magnetic field regulates the voltage.

Present military specifications require that the basic aircraft ac power system produce voltage with a value of 120 V.

5.2.2- BRUSH-TYPE Alternator

Figure (79) shows a brush-type ac generator. It consists of an ac generator and a smaller dc exciter generator as one unit. The output of the generator supplies ac to the load. The only purpose for the dc exciter generator is to supply the direct current required to maintain the ac generator field. Figure (80) is a simplified schematic of the generator

Look at figures (79) and (80) as you read this section. The exciter is a dc, shunt-wound, self-excited generator. The exciter field (2) creates an area of intense magnetic flux between its poles. When the exciter armature (3) rotates in the exciter-field flux, voltage is induced in the exciter armature windings. The output from the exciter commutator (4) flows through brushes and slip rings (5) to the generator field. Being dc, already converted by the exciter commutator, the current always flows in one direction through the generator field (6). Thus, a fixed-polarity magnetic field is maintained in the generator field windings. When the field winding rotates, its magnetic flux passes through and across the generator armature windings (7). The ac in the ac generator armature windings flows through fixed terminals to the ac load.

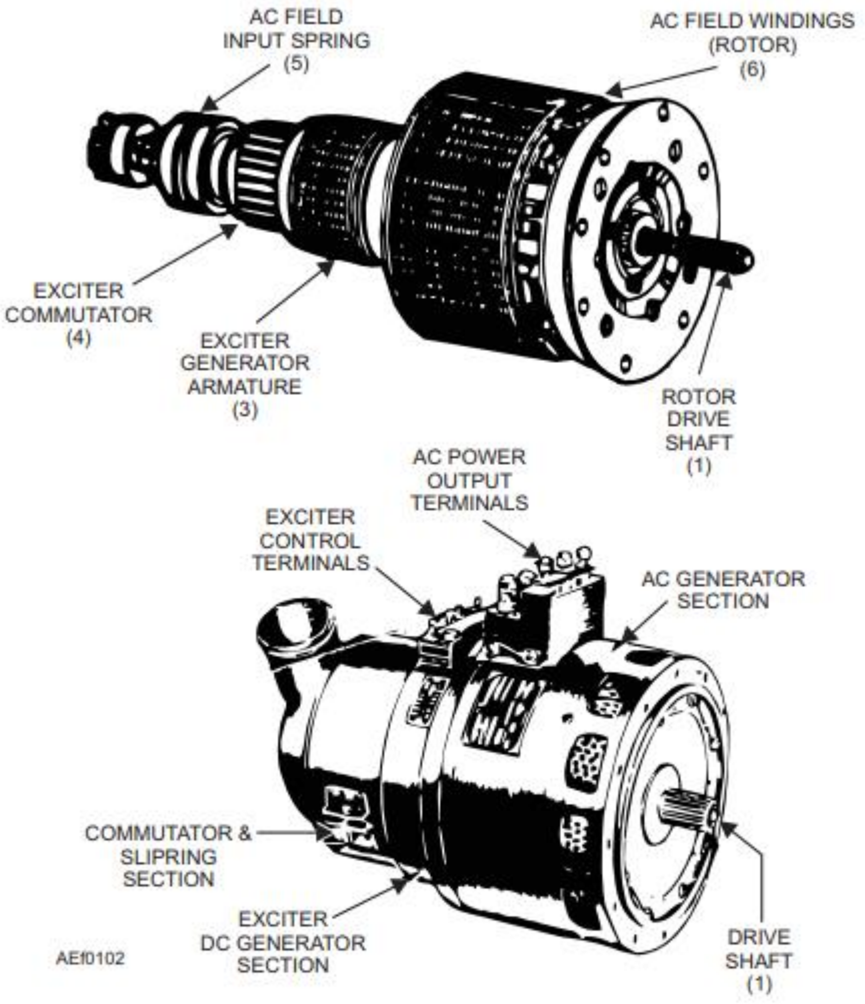


Figure (79) Brush-type, three-phase ac generator

The stationary member of the generator consists of the ac armature and the dc exciter field. Both ac and exciter terminal boards are easily accessible. All brush rigging is on the generator and has a brush cover. The slotted-hole mounting provides for ease in attaching to the engine pad. The capacitors connected between the exciter armature terminals and ground suppress radio noise.

5.2.3- BRUSHLESS-TYPE

Most naval aircraft are using brushless generators for voltage generation. The advantage of a brushless generator over a brush-type is its increased reliability and greater operating time between overhaul. Figure (81) is an expanded view of the main assembly of a brushless generator.

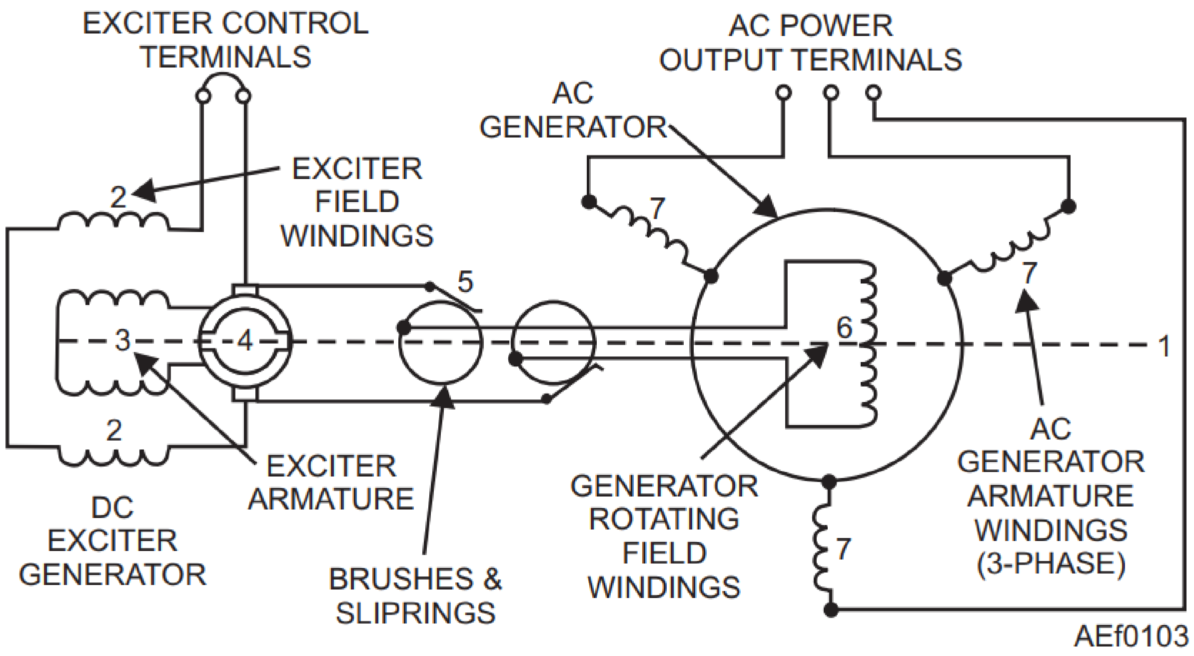
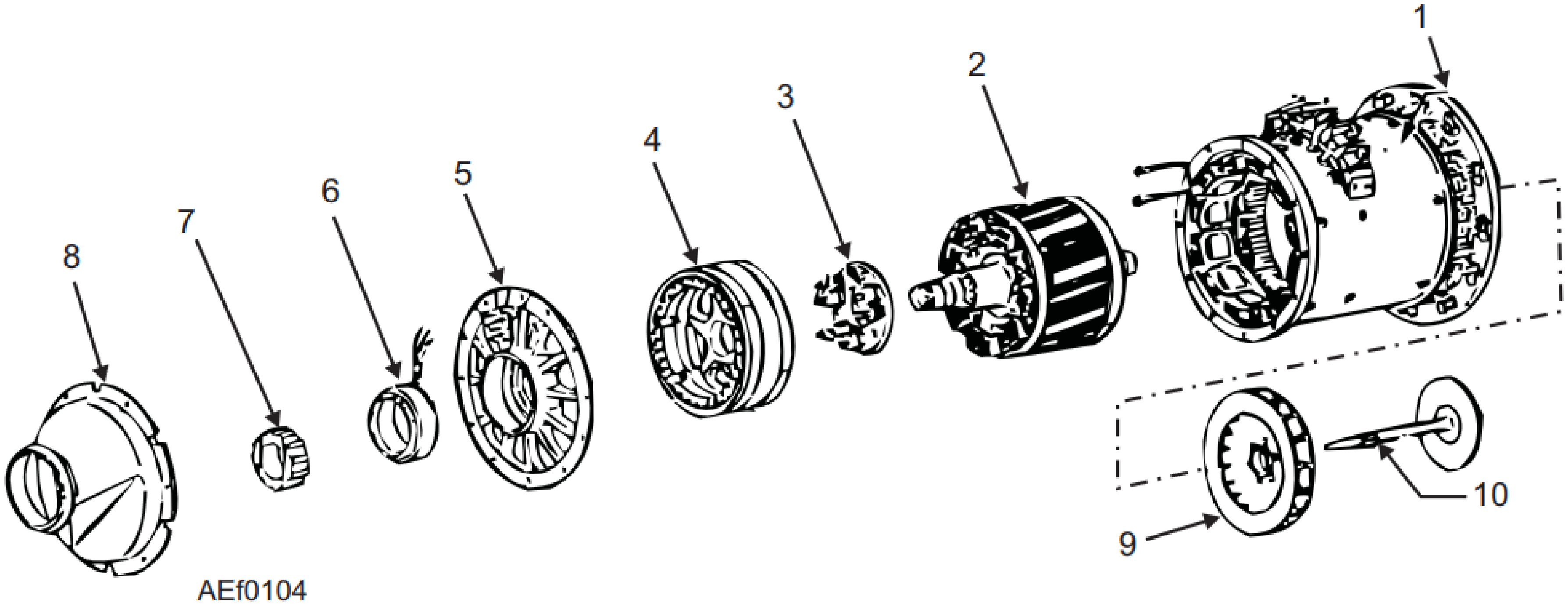


Figure (80) Brush-type, three-phase ac generator schematic



1. Stator Assembly
2. Rotor and Shaft
3. Rotating Diode Assembly
4. Exciter Rotor
5. End Bell
6. PM Generator Stator
7. Permanent Magnetic Rotor Core
8. Generator To Air Duct Adapter
9. Fan Assembly
10. Drive Shaft Assembly

Figure (81) Disassembled brushless ac generator

The brushless generator shown in figure (81) is a salient 8-pole, 6,000-rpm, ac generator. It has a 12-pole ac exciter and a three-phase, half-wave diode rectifier rotating with the exciter armature and main generator field assembly. The exciter rotor is a hollow frame assembly with the main ac field mounted on the inside and connected to a common drive shaft. A single-phase permanent magnet generator (PMG) furnishes control voltage and power for the voltage regulator. Three half-wave rectifiers are on the exciter rotor and connected to the exciter armature windings. A generator shaft shear section prevents possible damage to the engine or drive unit if the generator seizes. A fan at the drive end of the generator provides cooling airflow for the rotor and stator windings and the drive bearings. The end bell not only holds the generator together, but also houses the PMG stator and the permanent magnetic rotor core. The generator to air duct adapter allows a vent tube to be attached to the generator so that built-up air and fumes created by the spinning generator can be vented to the outside of the aircraft.

Chapter 7
Special Machines:

7.1- Stepper Motors:

7.1.1- Introduction: Stepper motors are DC motors that move in discrete steps. They have multiple coils that are organized in groups called "phases". By energizing each phase in sequence, the motor will rotate, one step at a time. With a computer controlled stepping you can achieve very precise positioning and/or speed control. For this reason, stepper motors are the motor of choice for many precision motion control applications. Stepper motors come in many different sizes, styles and electrical characteristics as shown in figure (82).

Figure (82) different types of stepper motors.

7.1.2- Features of Stepper Motors:

1- Positioning, Excellent control of precise positioning used in both 3D printers and CNC.
2- Speed Control, Excellent control of rotational speed for process automation and robotics.
3- Low Speed Torque, Stepper motor has maximum torque at low speeds.
4- Low Efficiency, They draw the most current when they are doing no work at all. Thu they tend to run hot.
5- Limited High Speed Torque, In general, stepper motors have less torque at high speeds than at low speeds.
6- No Feedback, Unlike servo motors, most steppers do not have integral feedback for position.

7.1.3- Types of Steppers:

There are three basic types of stepping motors: permanent magnet, variable reluctance and hybrid.

7.2.3.1- Rotor types:

1- variable reluctance motors have toothed soft-iron rotors. (VR)
2- Permanent magnet motors have a magnetized rotor. (PM)
3- Hybrid stepping motors combine aspects of both permanent magnet and variable reluctance technology. (HY)

7.1.3.2- Stator types:

The stator, or stationary part of the stepping motor holds multiple windings. The arrangement of these windings is the primary factor that distinguishes different types of stepping motors from an electrical point of view. From the electrical and control system perspective, variable reluctance motors are distant from the other types. Both permanent magnet and hybrid motors may be wound using either unipolar windings, bipolar windings or bifilar windings. Figure (83) shows the three types of motors.

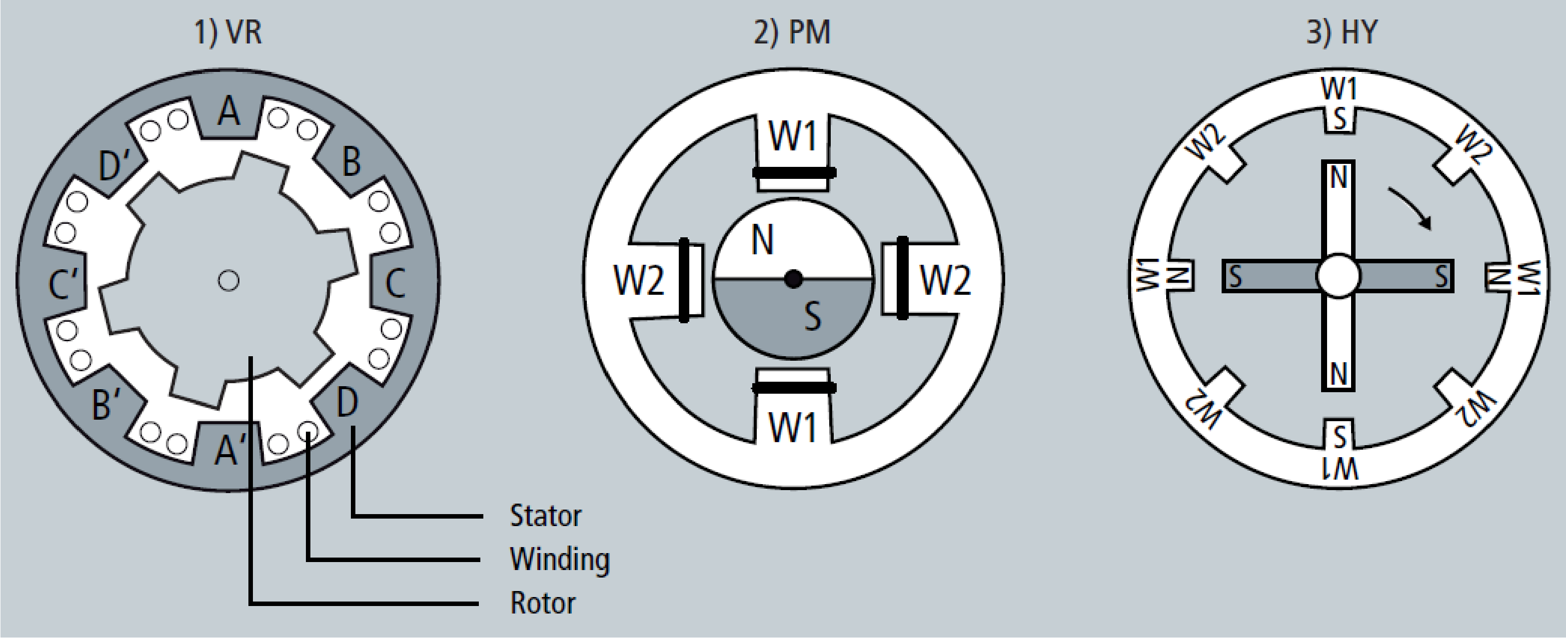


Figure (83) different types of stepper motors.

7.1.4- Motor size:

One of the first things to consider is the work that the motor has to do. As you might expect, larger motors are capable of delivering more power. Stepper motors come in sizes ranging from smaller than a peanut to big NEMA 57 monsters. Most motors have torque ratings. This is what you need to look at to decide if the motor has the strength to do what you want. NEMA 17 is a common size used in 3D printers and smaller CNC mills. Smaller motors find applications in many robotic and animatronic applications. The larger NEMA frames are common in CNC machines and industrial applications. The NEMA numbers define standard faceplate dimensions for mounting the motor. They do not define the other characteristics of a motor. Two different NEMA 17 motors may have entirely different electrical or mechanical specifications and are not necessarily interchangeable.

Figure (84) different sizes of stepper motors.

7.1.5- Step Count, Step Angle and Resolution:

The next thing to consider is the positioning resolution. The number of steps per full revolution ranges from 4 to 400. Commonly available step counts are 24, 48 and 200. Resolution is often expressed as degrees per step.

A 1.8° motor is the same as a 200 step/revolution motor = $Resolution$.

$$Step\ Angle\ (\beta) = \frac{360°}{Number\ of\ Steps\ per\ Full\ Revolution} = \frac{N_S - N_R}{N_S * N_R} * 360° = \frac{360°}{m * N_R}$$

Where: $N_R = Number\ of\ roter\ poles$ "teeth"

$N_S = Number\ of\ Stator\ poles$ "teeth"

$m = Number\ of\ stator\ phases$

Resolution can be modified using gearbox. Another way to achieve high positioning resolution is with gearing. A 32:1 gear-train applied to the output of an 16-steps/revolution motor will result in a 512 step motor.

$$\frac{Kg}{KM} = \frac{Sg}{SM}$$

A gear train will also increase the torque of the motor. Some tiny geared steppers are capable of impressive torque. But the trade off of course is speed. Geared stepper motors are generally limited to low RPM applications.

Most commercially available stepper motor drivers takes pulses as inputs. The amount of rotation of the stepping motor is proportional to the number of pulses given to the driver. The relationship of the stepping motor's rotation and input pulses is expressed as follows.

$\theta = \beta * A$ *where:* $A = Number\ of\ pulses$ $\beta = Step\ Angle$ $\theta = Rotation\ Angle$

The speed of the rotation is then proportional to the speed of the pulses. The relationship of the pulse speed (Hz) and motor speed (revolution per second) is expressed as follows:

$f = A\ /\ second$

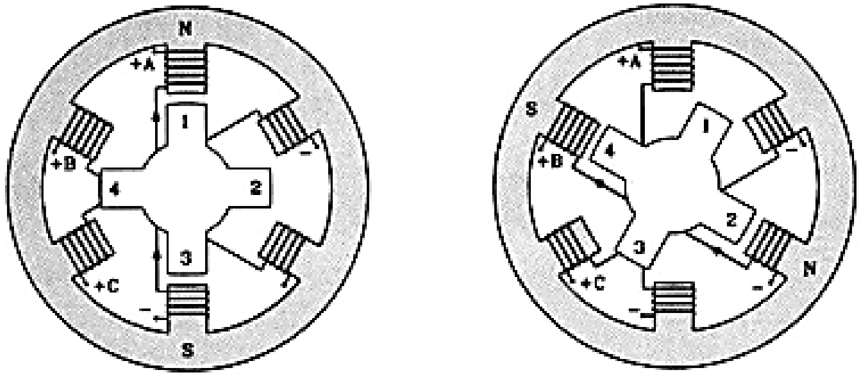
$N = \dfrac{\beta * f}{360°}$ (rps) $where$: $f = pulse\ speed\ (Hz)\ number\ of\ input\ pulses\ per\ second$

$N = Speed\ of\ the\ motor\ output\ shaft\ in\ (rps)$

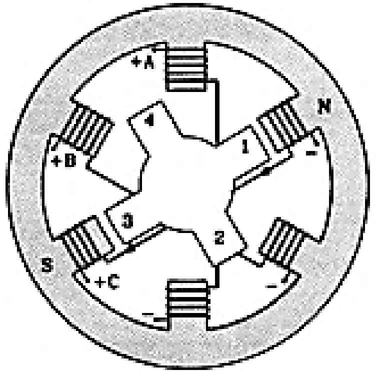
7.1.6- Basic control principles:

Since it is not sufficient to apply a constant supply voltage to the stepper motor in order to generate a rotation of the shaft, the individual coils have to be energised alternately. To this end control electronics are required for setting the speed and direction. In addition, the control electronics must support the three different step patterns that are used for influencing the indexing position of the shaft. The motor three modes of operations are:

1- Only one phase ON at a time, Figure (86-a).
2- Two phases ON at a time, Figure (86-b).
3- Mix phases operation mode "Half Step", Figure (86-c).



(a) (b)



(c)

Cycle	Phase A	Phase B	Phase C	Position
1	ON	OFF	OFF	0°
	OFF	ON	OFF	30°
	OFF	OFF	ON	60°
2	ON	OFF	OFF	90°
	OFF	ON	OFF	120°
	OFF	OFF	ON	150°
3	ON	OFF	OFF	180°
	OFF	ON	OFF	210°
	OFF	OFF	ON	240°
4	ON	OFF	OFF	270°
	OFF	ON	OFF	300°
	OFF	OFF	ON	330°
5	ON	OFF	OFF	360°

Figure (85) Only one phase ON at a time

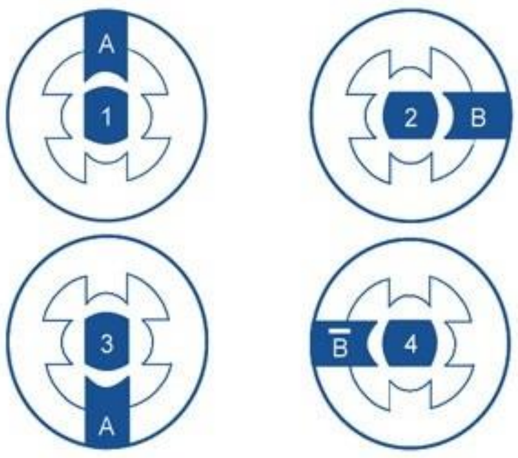


Figure (86-a) Only one phase ON at a time

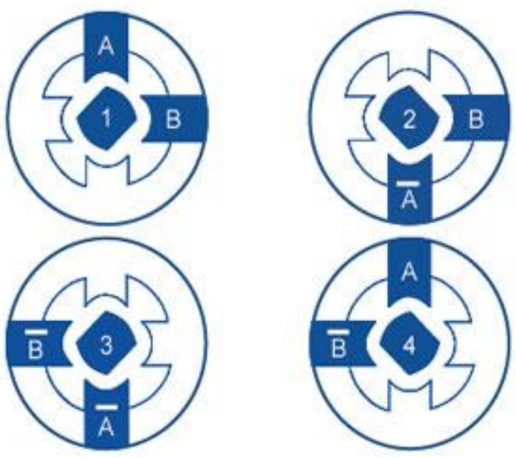


Figure (86-b) Two phases ON at a time

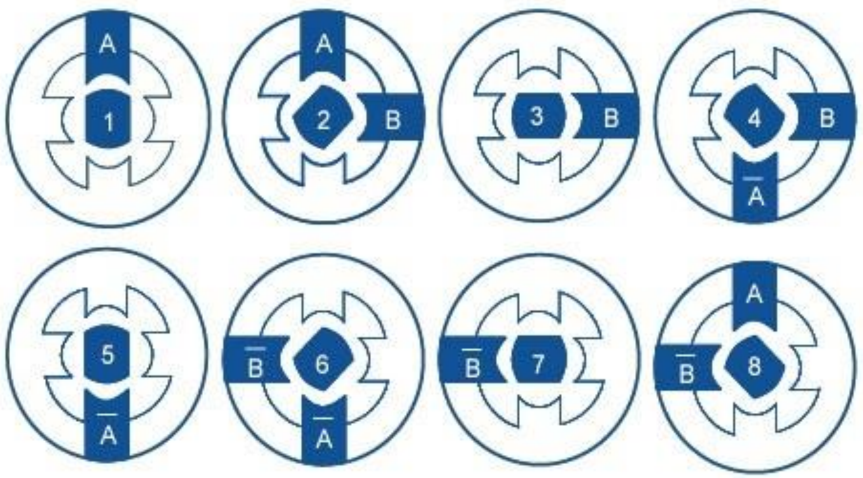


Figure (86-c) Mix phases operation mode “Half Step”

7.1.7- Coil Windings:

There are many variations in stepper motor wiring. For our purposes, we will focus on steppers that can be driven with commonly available drivers. These are Permanent Magnet or Hybrid steppers wired as 2-phase bipolar, or 4-phase unipolar. A stepper motor may have any number of coils. But these are connected in groups called "phases". All the coils in a phase are energized together.

7.1.7.1- Unipolar vs. Bipolar

Unipolar drivers, always energize the phases in the same way. One lead, the "common" lead, will always be negative. The other lead will always be positive. Unipolar drivers can be implemented with simple transistor circuitry. The disadvantage is that there is less available torque because only half of the coils can be energized at a time.

Bipolar drivers use H-bridge circuitry to actually reverse the current flow through the phases. By energizing the phases with alternating the polarity, all the coils can be put to work turning the motor.

A two phase bipolar motor has 2 groups of coils. A 4 phase unipolar motor has 4 groups of coils. A 2-phase bipolar motor will have 4 wires - 2 for each phase. Some motors come with flexible wiring that allows you to run the motor as either bipolar or unipolar.

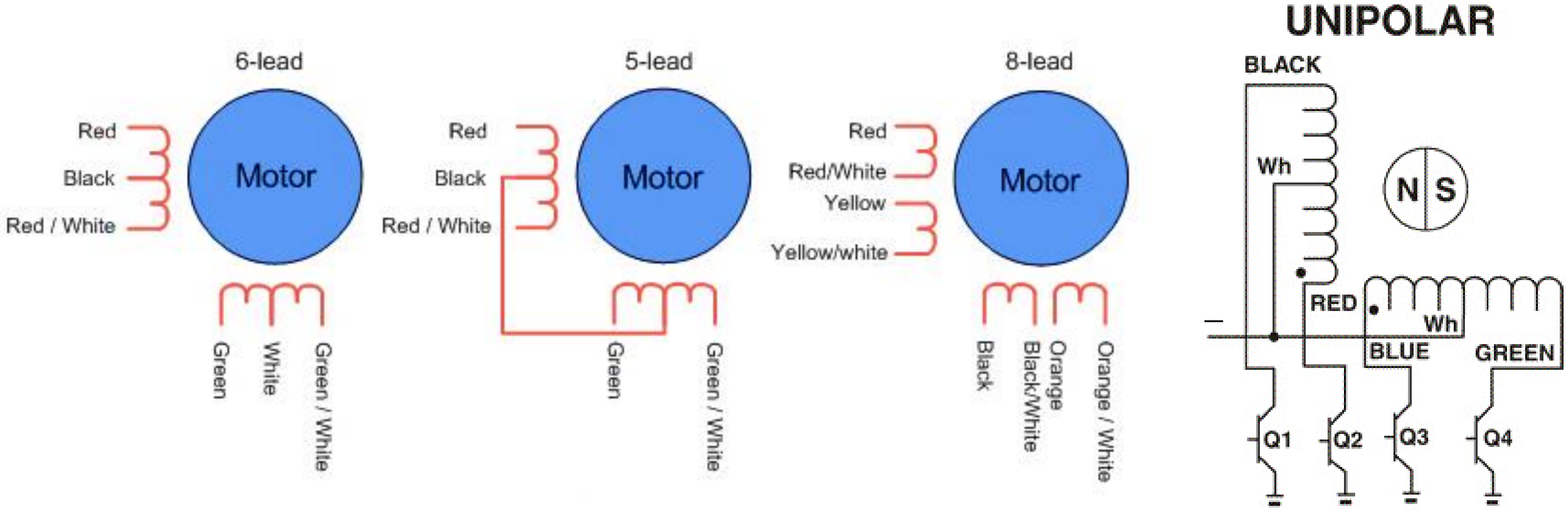


Figure (87) Unipolar vs. Bipolar

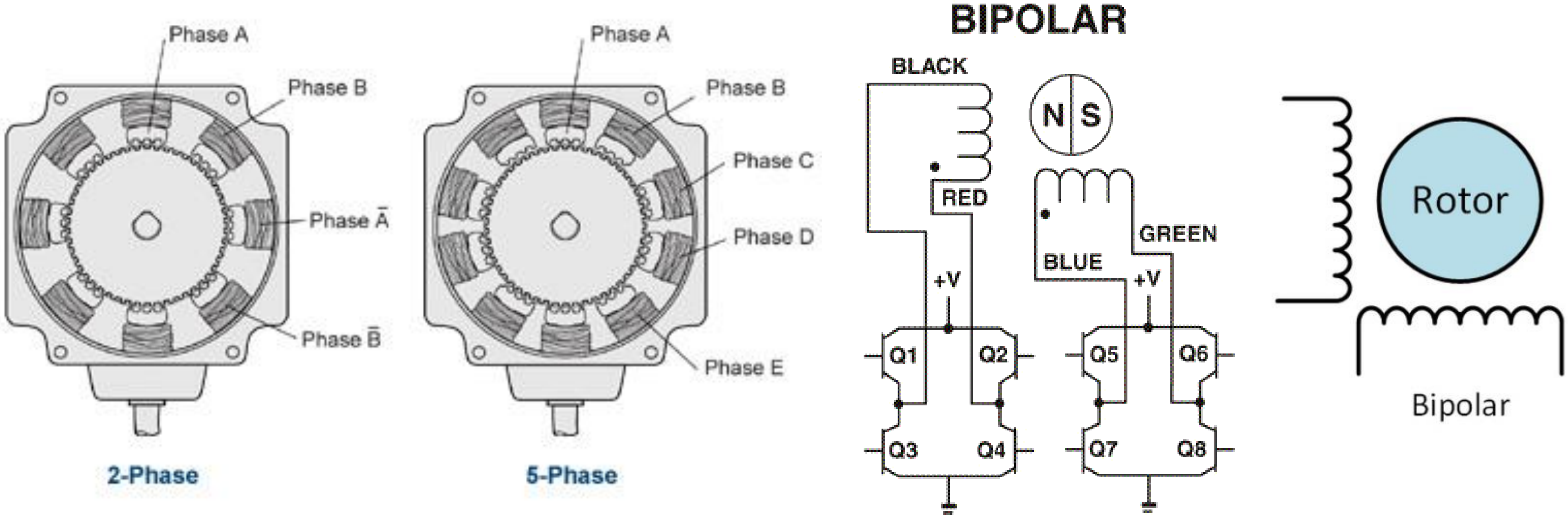
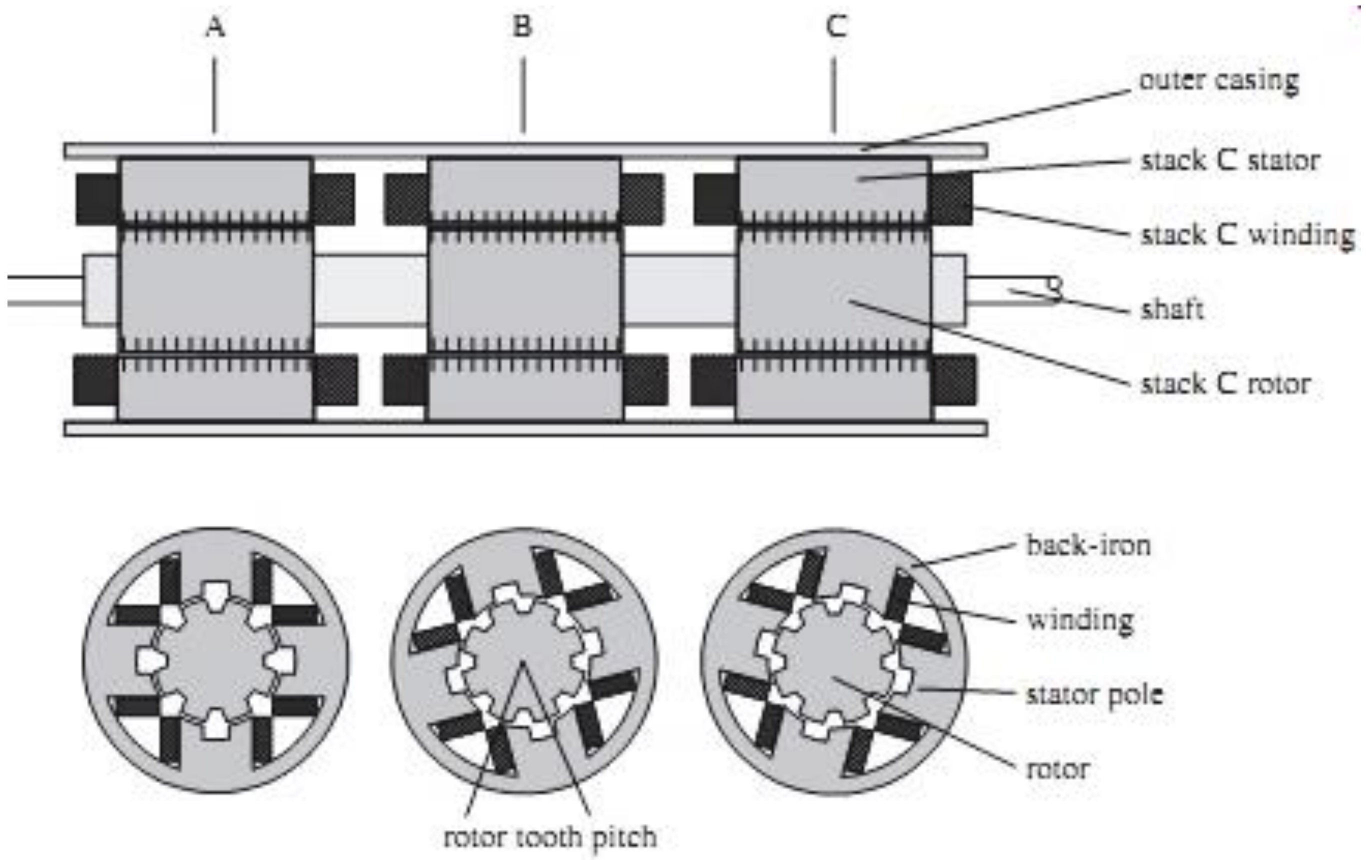


Figure (88) Unipolar vs. Bipolar

7.1.8- Multi-Stack VR Stepper Motor:



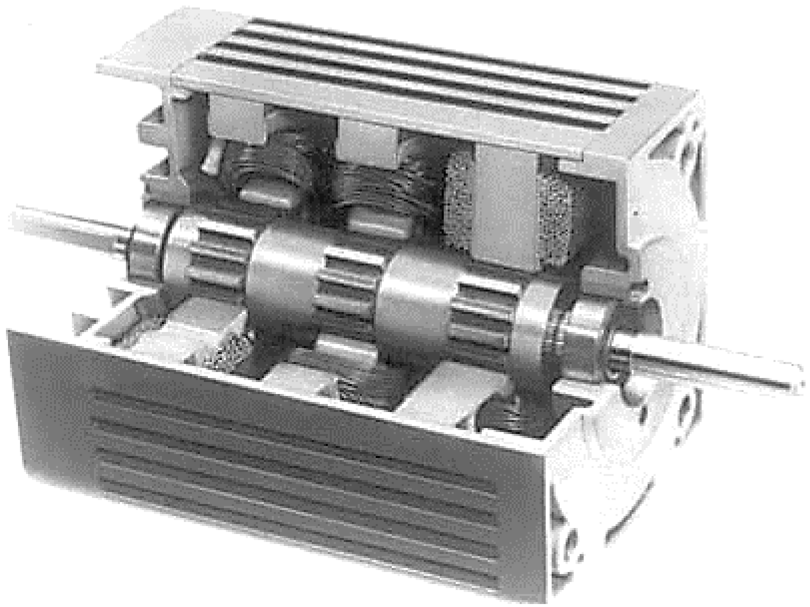


Figure (89) Multi-Stack VR Stepper Motor

7.1.9- Torque-Speed Characteristics:

Torque is a critical consideration when choosing a stepping motor. Stepper motors have different types of rated torque. These are:

- Holding torque – The torque required to rotate the motor's shaft while the windings are energized.
- Pull-in torque – The torque against which a motor can accelerate from a standing start without missing any steps, when driven at a constant stepping rate.
- Pull-out torque – The pull-out torque is measured by accelerating the motor to the desired speed and then increasing the torque loading until the motor stalls or misses steps.
- Detent torque – The torque required to rotate the motor's shaft while the windings are not energized.

Stepping motor manufacturers will specify several or all of these torques in their data sheets for their motors as shown in figure (90).
The dynamic torques, pull-in and pull-out, are a function of step rate. These torques are important for determining whether or not a stepping motor will "slip" when operating in a particular application. A "slip" refers to the motor not moving when it should or moving when it should not (overrunning a stop). In either case, the result is the controller will no longer know the position of the motor. Open loop positioning fails in this case. The motor must be adequately sized to prevent this from happening or a closed loop feedback system employed.

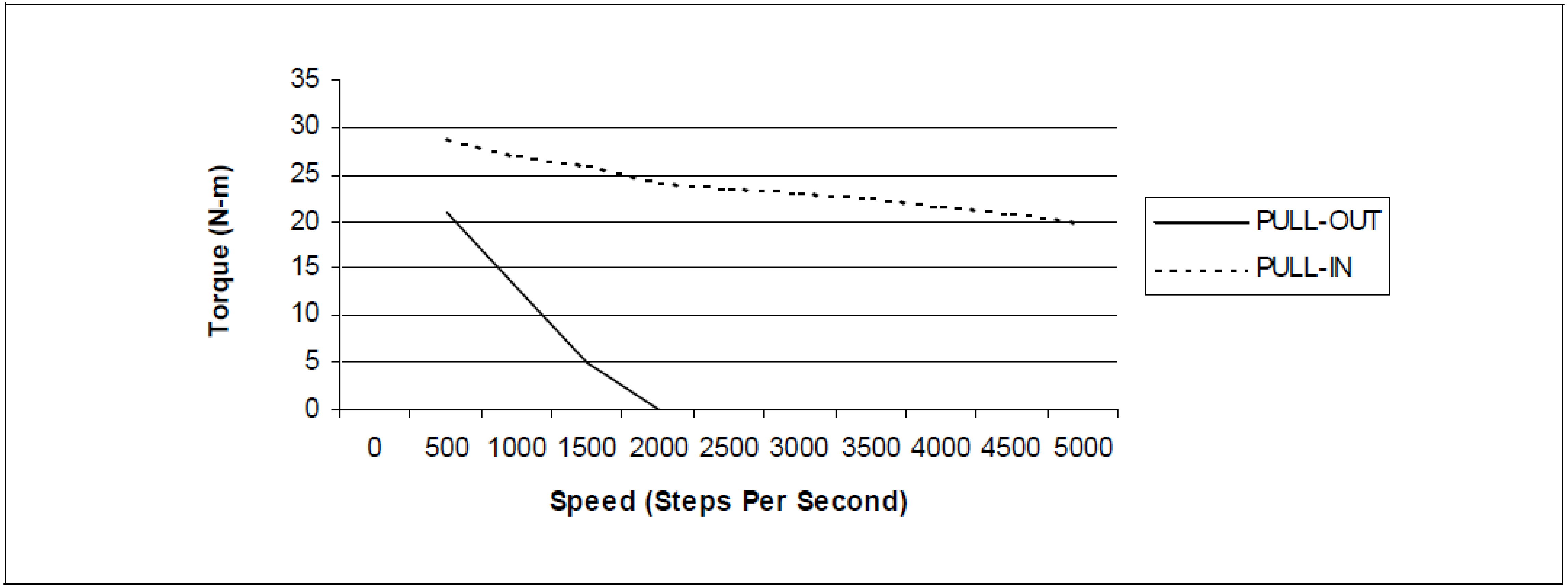


Figure (90) Torque speed characteristics

7.2- Brushless motor:

7.2.1- Introduction:

The BLDC motor is widely used in applications including appliances, automotive, aerospace, consumer, medical, automated industrial equipment and instrumentation. The BLDC motor is electrically commutated by power switches instead of brushes. Compared with a brushed DC motor or an induction motor, the BLDC motor has many advantages.

- Higher efficiency and reliability
- Lower acoustic noise
- Smaller and lighter
- Greater dynamic response
- Better speed versus torque characteristics
- Higher speed range
- Longer life

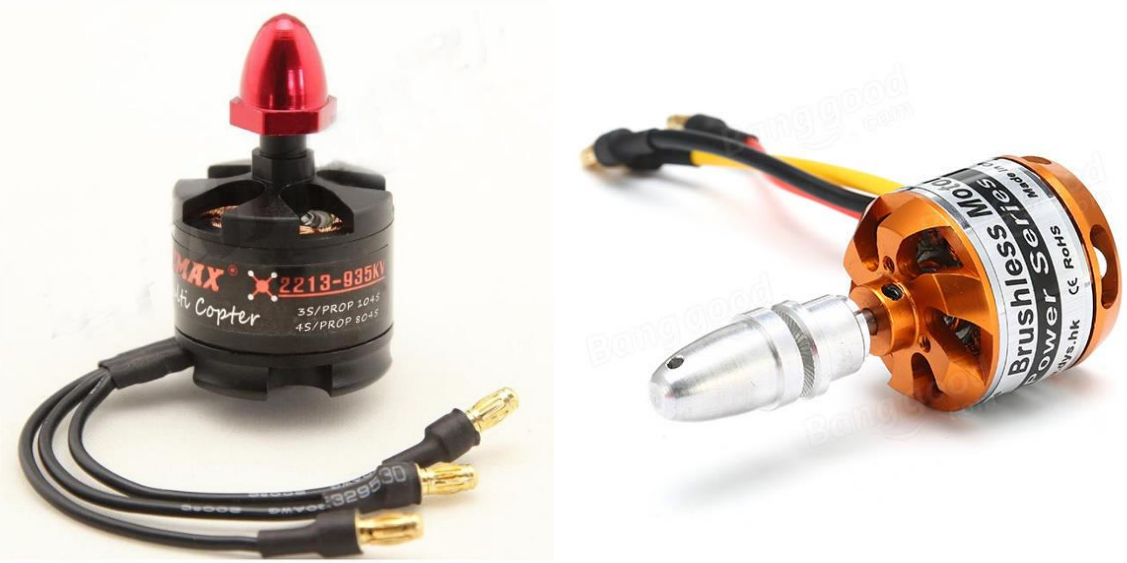
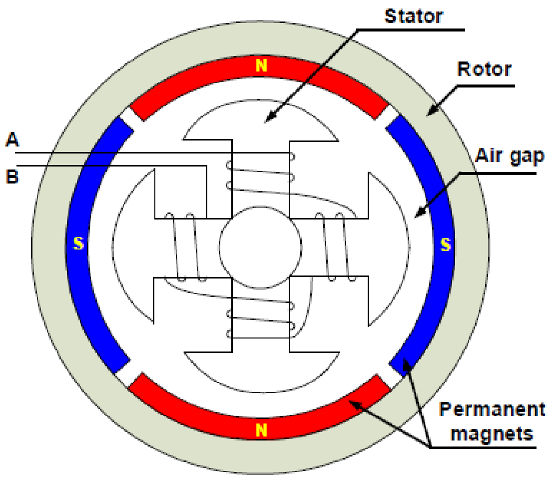


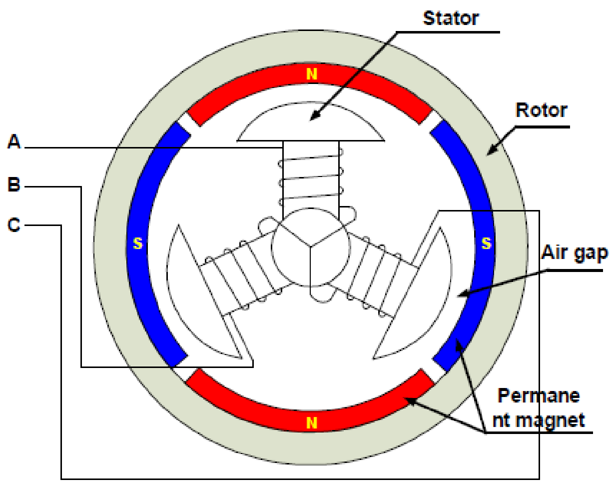
Figure (91) High speed brushless motors

7.2.2- Stator:

There are three classifications of the BLDC motor: single-phase, two-phase and three-phase. This discussion assumes that the stator for each type has the same number of windings. The single-phase and three-phase motors are the most widely used. Figure (92) shows the simplified cross section of a single-phase and a three-phase BLDC motor. The rotor has permanent magnets to form 2 magnetic pole pairs, and surrounds the stator, which has the windings.



(a) Single-phase

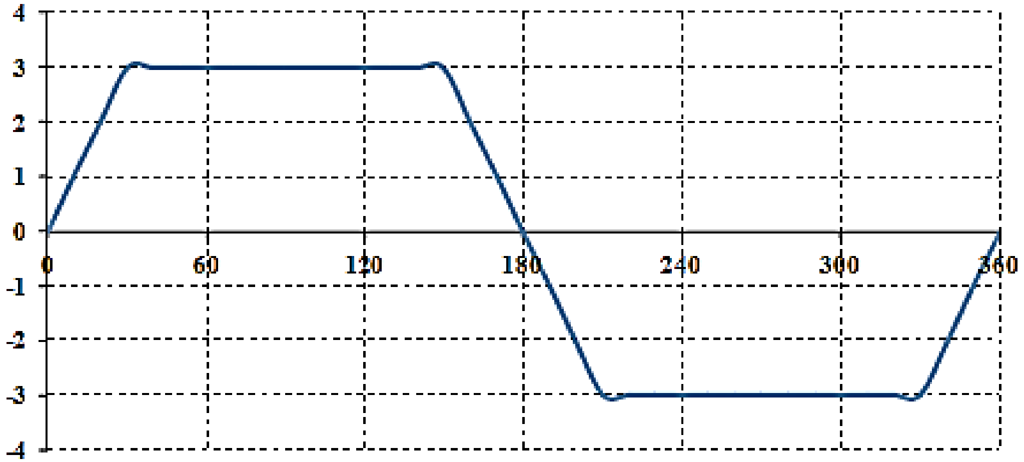


(b) Three-phase

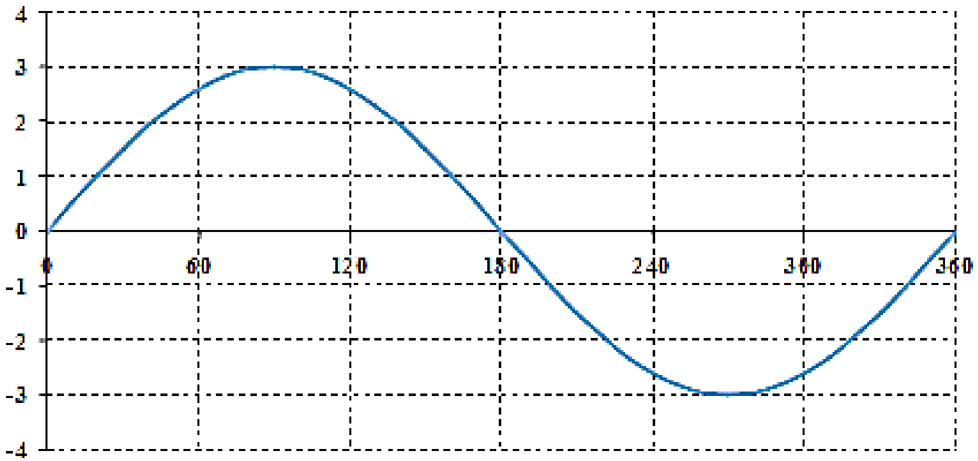
Figure (92) Simplified BLDC Motor Diagrams

A single-phase motor has one stator winding wound either clockwise or counter-clockwise along each arm of the stator to produce four magnetic poles as shown in Figure (92-a). By comparison, a three phase motor has three windings as shown in Figure (92-b). Each phase turns on sequentially to make the rotor revolve.

There are two types of stator windings: trapezoidal (93-a) and sinusoidal (93-b), which refers to the shape of the back electromotive force (BEMF) signal. The shape of the BEMF is determined by different coil interconnections and the distance of the air gap. In addition to the BEMF, the phase current also follows a trapezoidal and sinusoidal shape. A sinusoidal motor produces smoother electromagnetic torque than a trapezoidal motor, though at a higher cost due to their use of extra copper windings. A BLDC motor uses a simplified structure with trapezoidal stator windings.



(93-b) Trapezoidal back EMF waveform

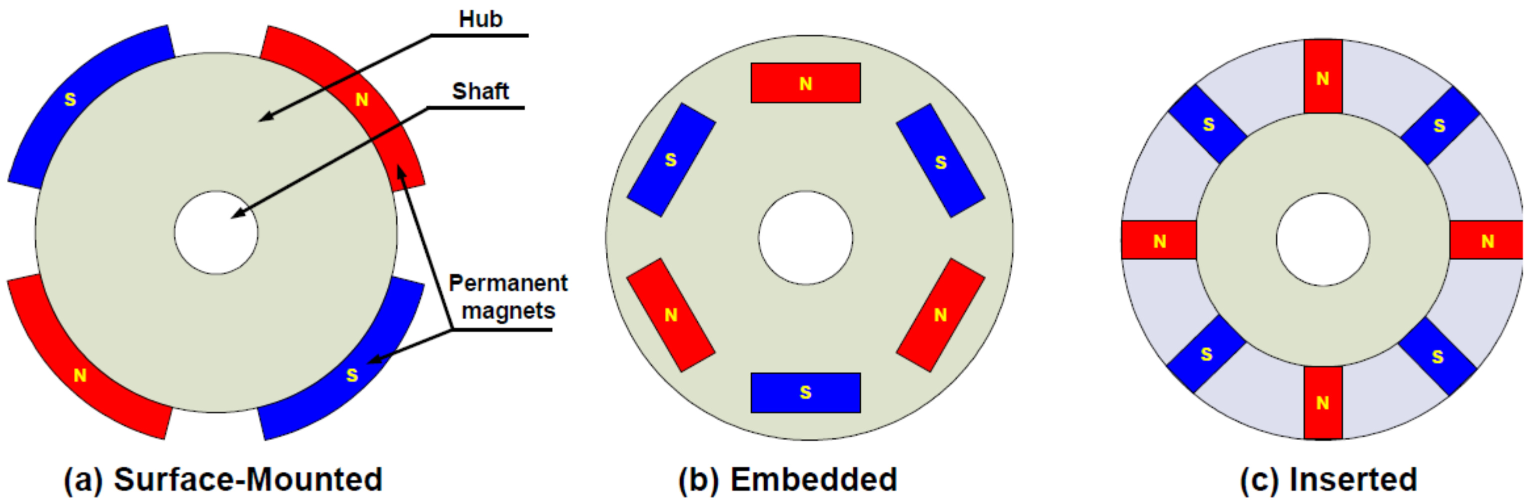


(93-a) Sinusoidal back EMF waveform

7.2.3- Rotor:

A rotor consists of a shaft and a hub with permanent magnets arranged to form between two to eight pole pairs that alternate between north and south poles. Figure (94) shows cross sections of three kinds of magnets arrangements in a rotor.

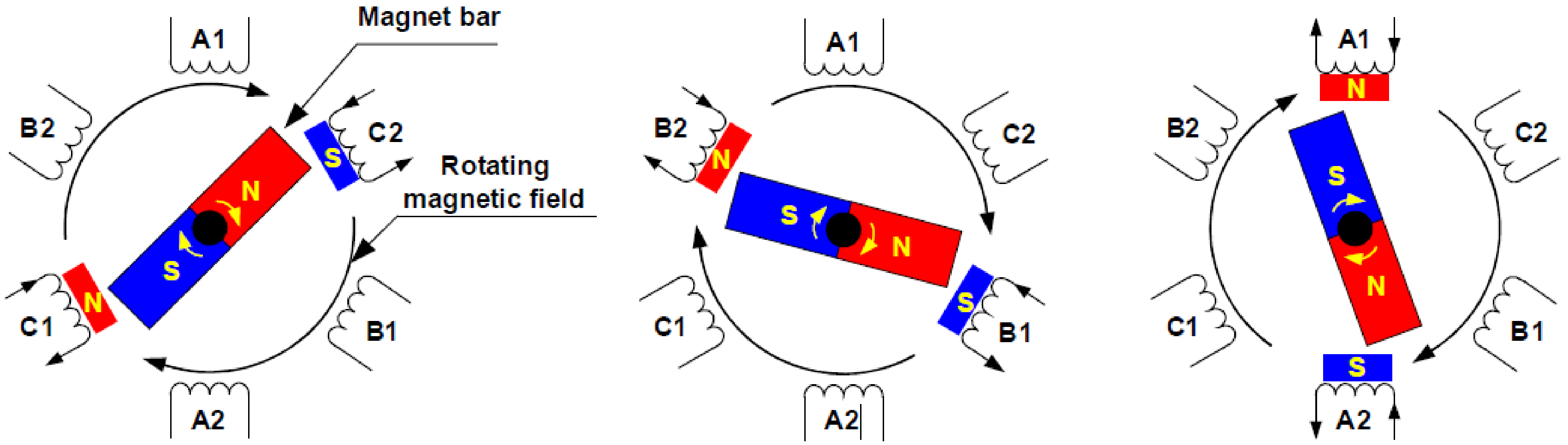
There are multiple magnet materials, such as ferrous mixtures and rare-earth alloys. Ferrite magnets are traditional and relatively inexpensive, though rare-earth alloy magnets are becoming increasingly popular because of their high magnetic density. The higher density helps to shrink rotors while maintaining high relative torque when compared to similar ferrite magnets.



(94) Rotor Magnets Cross-Sections

7.2.4- Operational Motor Theory

Motor operation is based on the attraction or repulsion between magnetic poles. Using the three-phase motor shown in Figure (95), the process starts when current flows through one of the three stator windings and generates a magnetic pole that attracts the closest permanent magnet of the opposite pole. The rotor will move if the current shifts to an adjacent winding. Sequentially charging each winding will cause the rotor to follow in a rotating field.
The torque in this example depends on the current amplitude and the number of turns on the stator windings, the strength and the size of the permanent magnets, the air gap between the rotor and the windings, and the length of the rotating arm.



(95) Motor Rotation

A BLDC motor accomplishes commutation electronically using rotor position feedback to determine when to switch the current. The structure is shown in Figure (96). Feedback usually entails an attached Hall sensor or a rotary encoder. The stator windings work in conjunction with permanent magnets on the rotor to generate a nearly uniform flux density in the air gap. This permits the stator coils to be driven by a constant DC voltage (hence the name brushless DC), which simply switches from one stator coil to the next to generate an AC voltage waveform with a trapezoidal shape.

7.2.5- Brushless dc motor control

Brushless DC motors use electric switches to realize current commutation, and thus continuously rotate the motor. These electric switches are usually connected in an H-bridge structure for a single-phase BLDC motor, and a three-phase bridge structure for a three-phase BLDC motor shown in Figure (96 and 97).

Usually the high-side switches are controlled using pulse-width modulation (PWM), which converts a DC voltage into a modulated voltage.

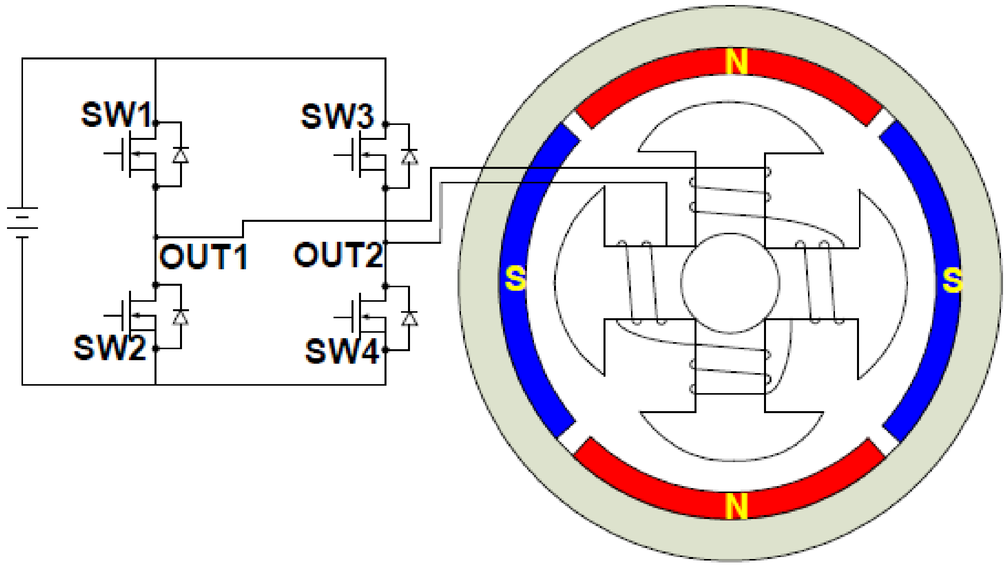


Figure (96) Single phase Brushless motor connection with H-bridge

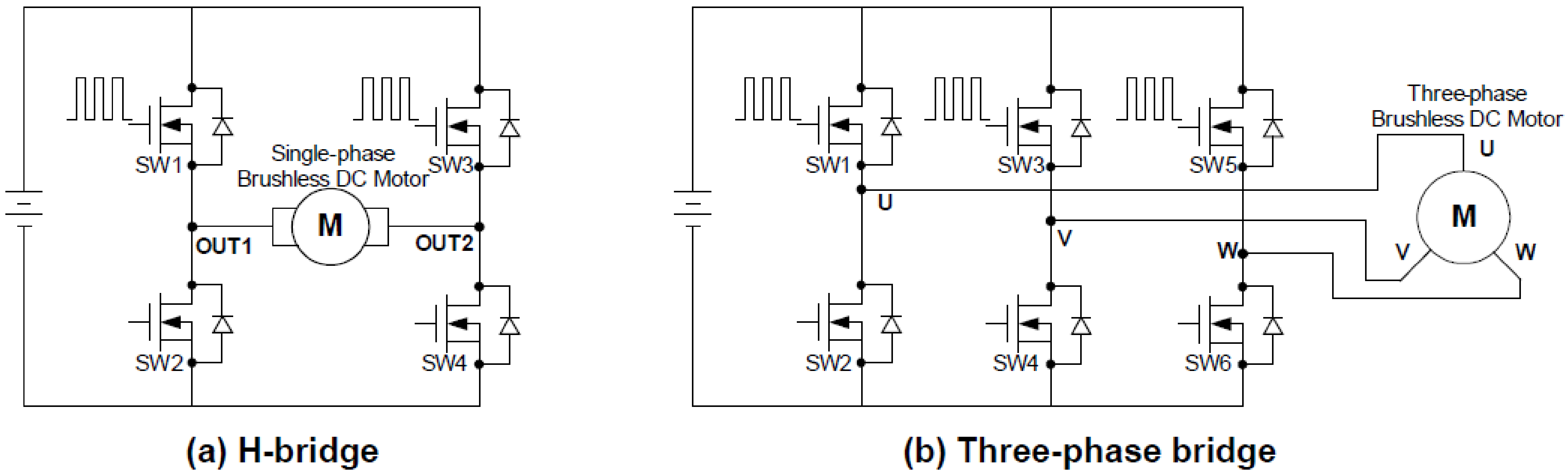
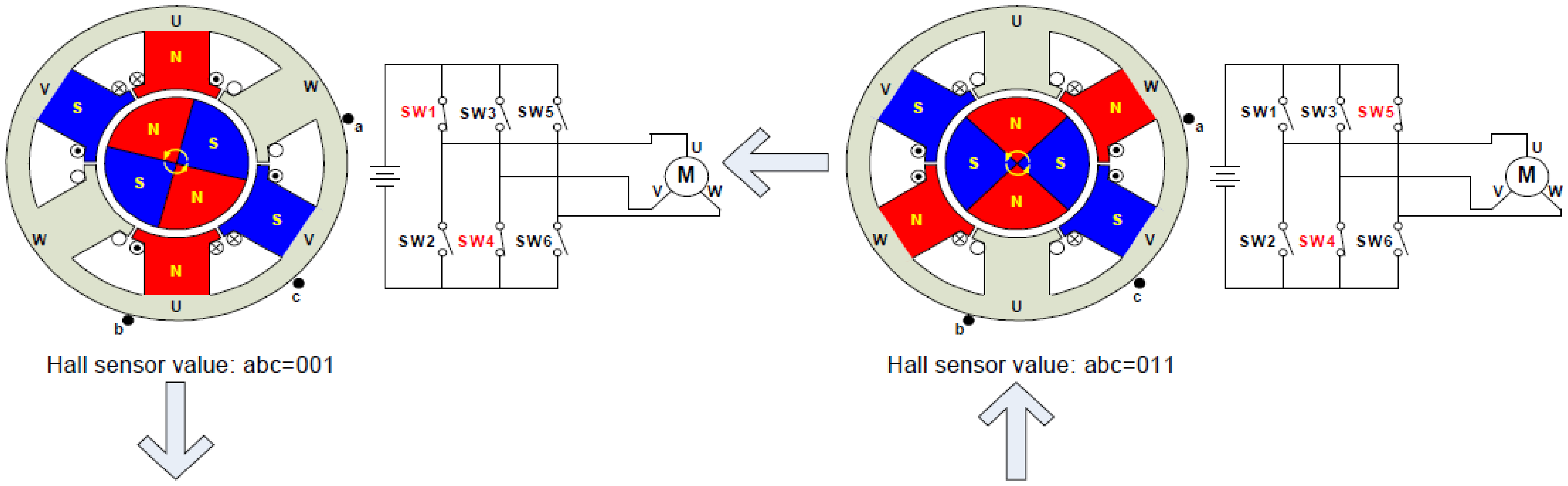


Figure (97) Electric driver circuit

7.2.6- Electronics Commutation Principle of Three-Phase BLDC Motor

A three-phase BLDC motor requires three Hall sensors to detect the rotor's position. Based on the physical position of the Hall sensors, there are two types of output: a 60° phase shift and a 120° phase shift. Combining these three Hall sensor signals can determine the exact commutation sequence.

Figure (98) shows the commutation sequence of a three-phase BLDC motor driver circuit for counter clockwise rotation. Three Hall sensors “a,” “b,” and “c” are mounted on the stator at 120° intervals, while the three phase windings are in a star formation. For every 60° rotation, one of the Hall sensors changes its state; it takes six steps to complete a whole electrical cycle. In synchronous mode, the phase current switching updates every 60°. For each step, there is one motor terminal driven high, another motor terminal driven low, with the third one left floating. Individual drive controls for the high and low drivers permit high drive, low drive, and floating drive at each motor terminal. However, one signal cycle may not correspond to a complete mechanical revolution. The number of signal cycles to complete a mechanical rotation is determined by the number of rotor pole pairs. Every rotor pole pair requires one signal cycle in one mechanical rotation. So, the number of signal cycles is equal to the rotor pole pairs.



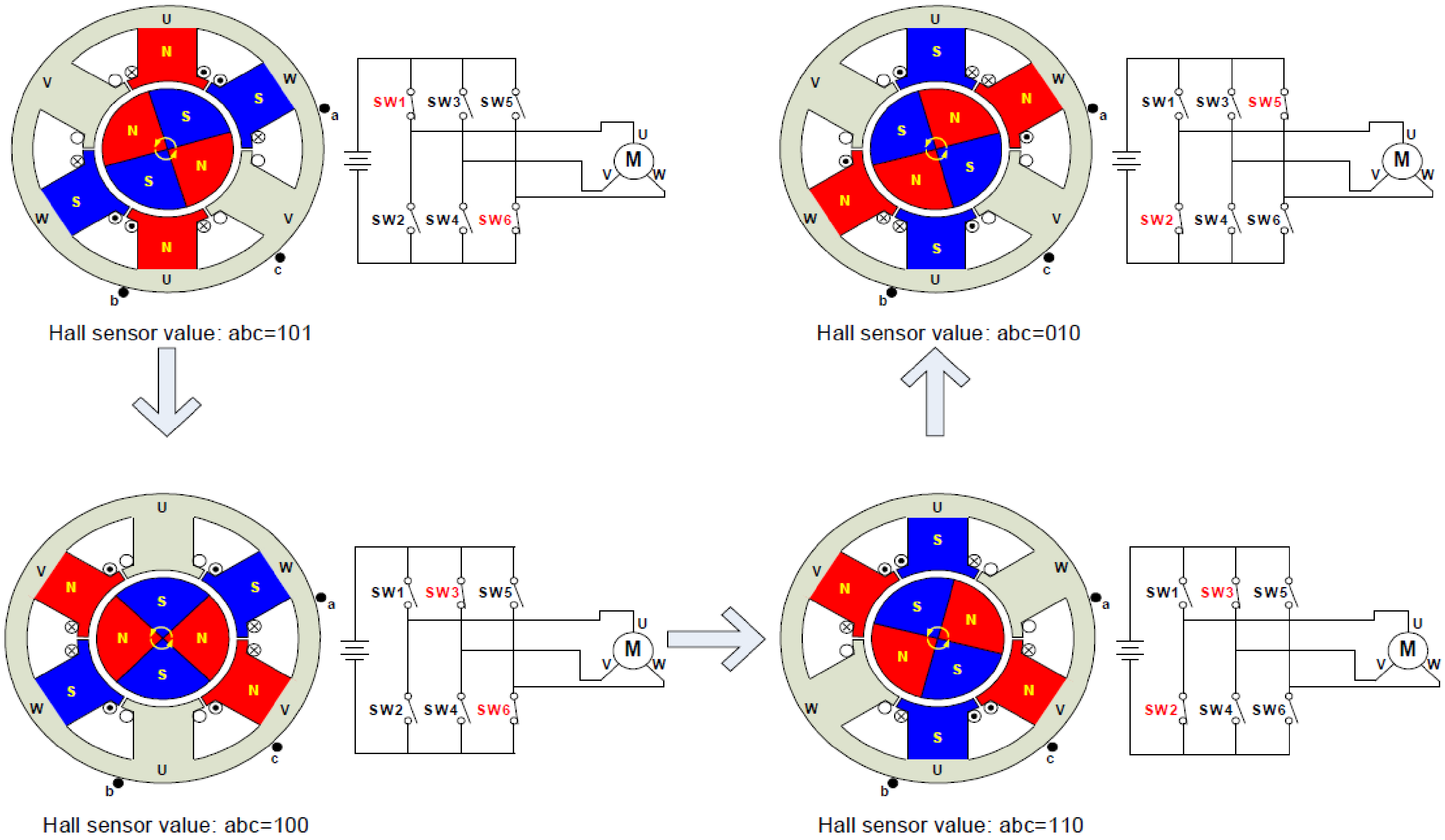


Figure (98) Three-Phase BLDC Motor Commutation Sequence

Figure (99) shows the timing diagrams where the phase windings U, V, and W are either energized or floated based on the Hall sensor signals a, b, and c. This is an example of Hall sensor signal having a 120° phase shift with respect to each other, where the motor rotates counter-clockwise. Producing a Hall signal with a 60° phase shift or rotating the motor clockwise requires a different timing sequence. To vary the rotation speed, use pulse width modulation signals on the switches at a much higher frequency than the motor rotation frequency. Generally, the PWM frequency should be at least 10 times higher than the maximum motor rotation frequency. Another advantage of PWM is that if the DC bus voltage is much higher than the motor-rated voltage, so limiting the duty cycle of PWM to meet the motor rated voltage controls the motor.

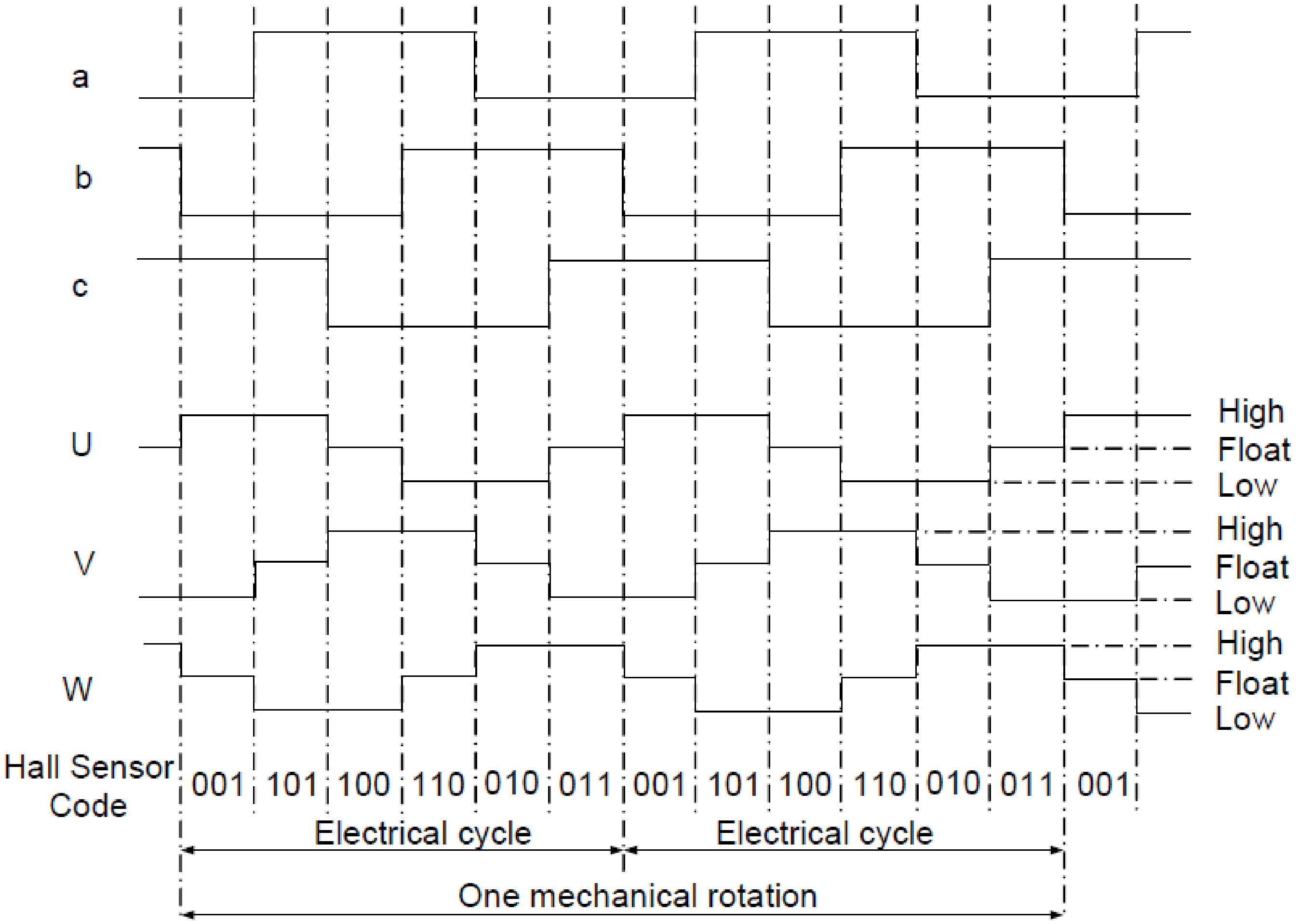


Figure (99) Three-phase BLDC motor sensor versus drive timing

7.3- SRM (Switched Reluctance Motors)

7.3.1- Introduction:

In construction, the SRM is the simplest of all electrical machines. Only the stator has windings. The rotor contains no conductors or permanent magnets. It consists simply of steel laminations stacked onto a shaft. It is because of this simple mechanical construction that SRMs carry the promise of low cost, which in turn has motivated a large amount of research on SRMs in the last decade.
The mechanical simplicity of the device, however, comes with some limitations. Like the brushless DC motor, SRMs can not run directly from a DC bus or an AC line, but must always be electronically commutated.

The basic operating principle of the SRM is quite simple; as current is passed through one of the stator windings, torque is generated by the tendency of the rotor to align with the excited stator pole.

Reluctance torque is produced by the tendency of the rotor to move to its minimum reluctance position as show in figure (100).

The direction of torque generated is a function of the rotor position with respect to the energized phase, and is independent of the direction of current flow through the phase winding. Continuous torque can be produced by intelligently synchronizing each phase's excitation with the rotor position.

The number of stator poles Ns is related to the number of phases m
$Ns = m * 2$

one pair of stator poles (and coils) per phase

And the number of rotor poles Nr is related to the number of stator poles Ns
$Nr = Ns - 2$

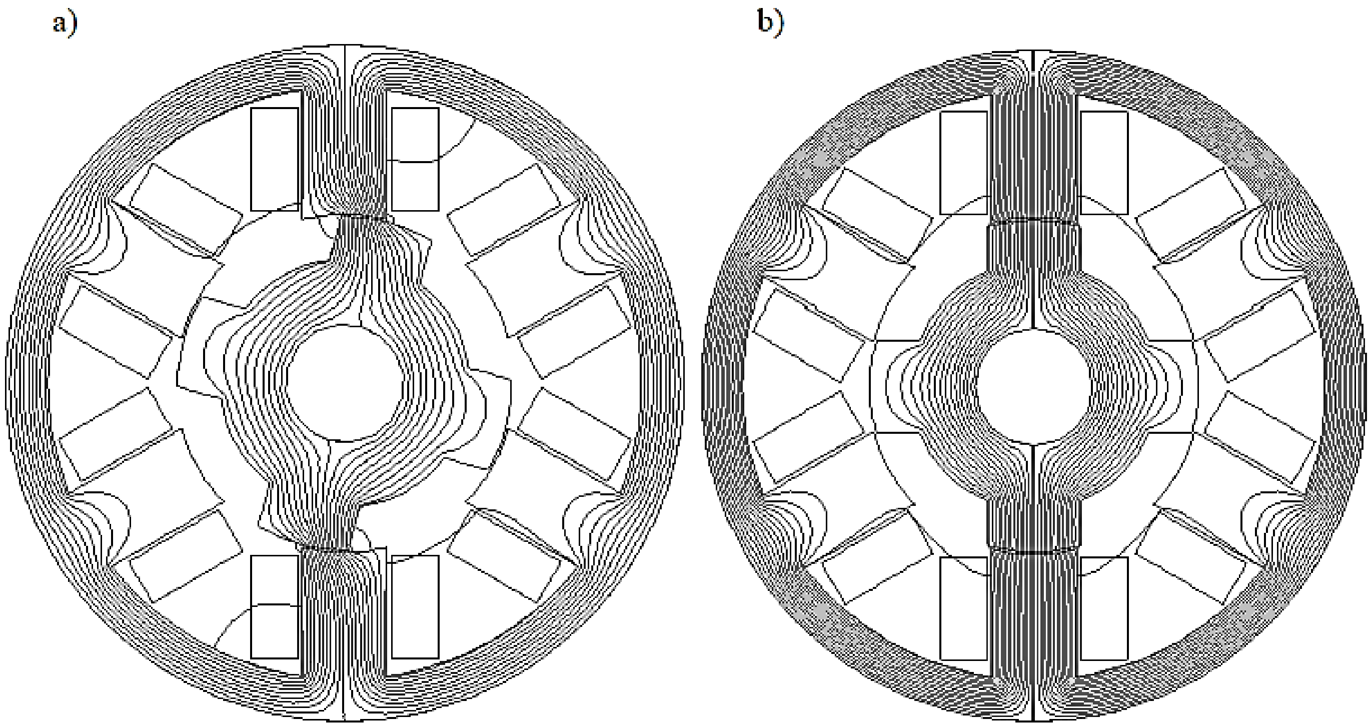
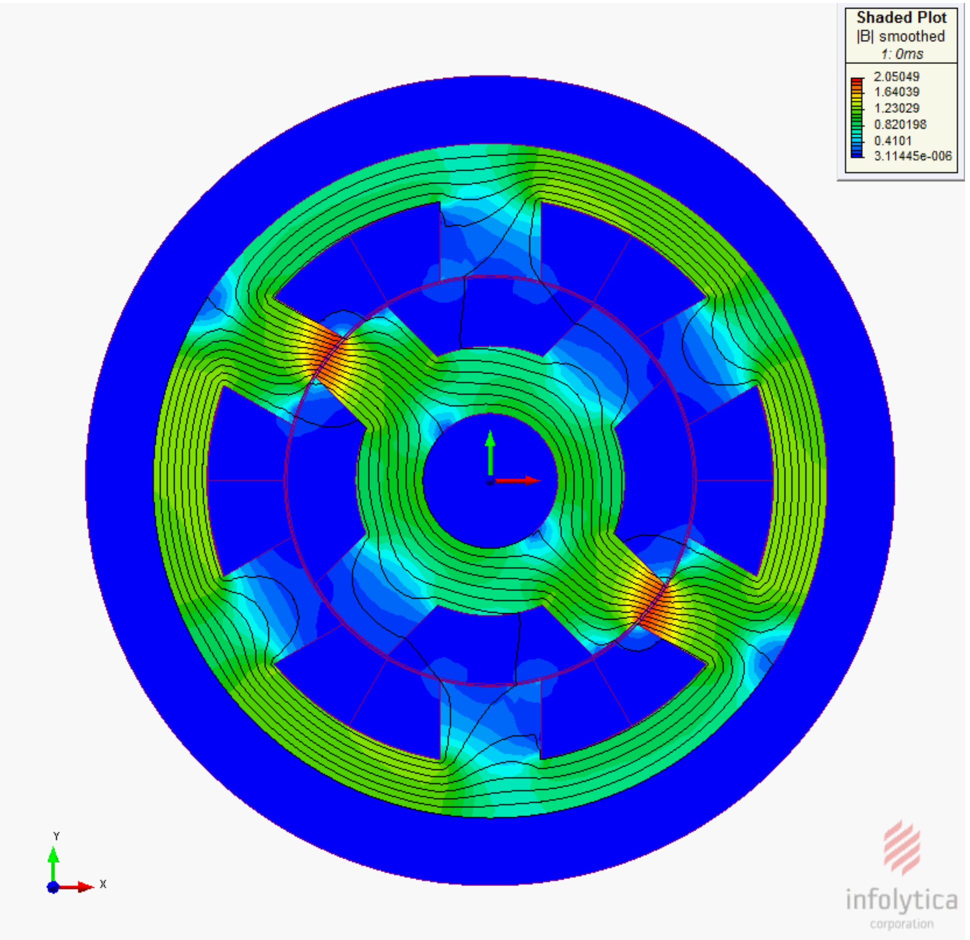
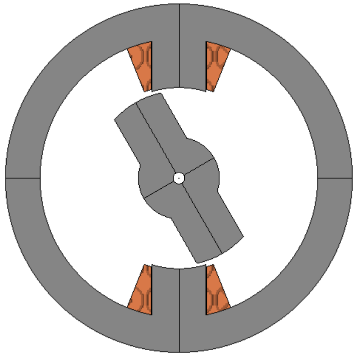
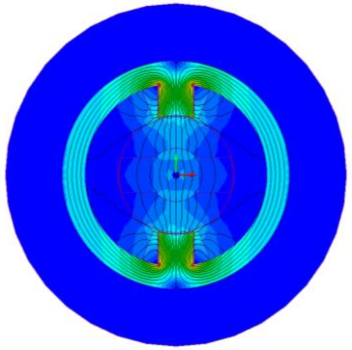


Figure (100) Magnetic field distribution in the cross-section of SRM forced by the phase constant current for:
a) non align (by 30º) rotor position, b) align rotor position.

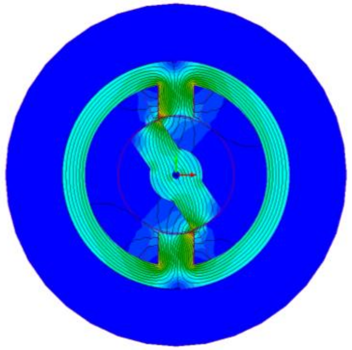
Most favoured configurations are the 6/4 three phase and the 8/6 four phase SRMs.



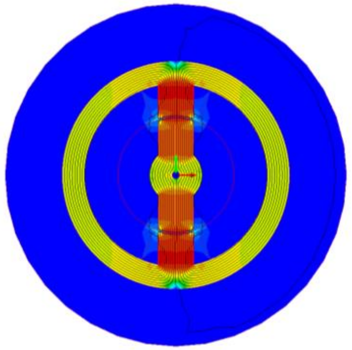




Horizontal rotor
Unaligned (zero torque)



High torque

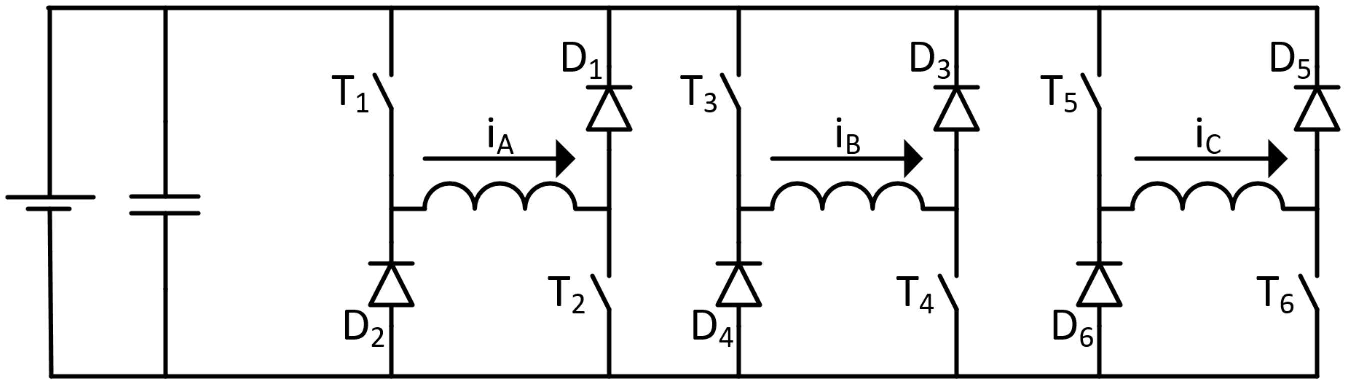


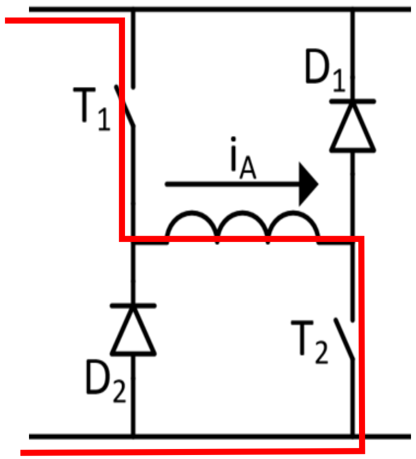
Vertical rotor
Aligned (zero torque)

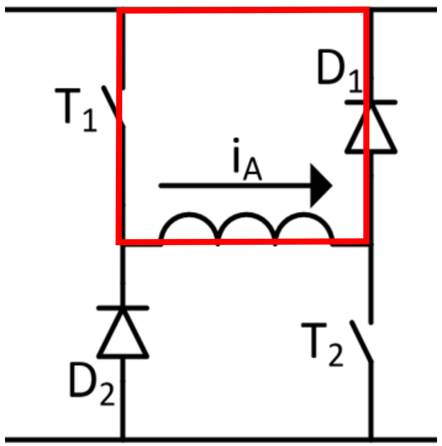
Figure (101) flux distribution in the stator and rotor

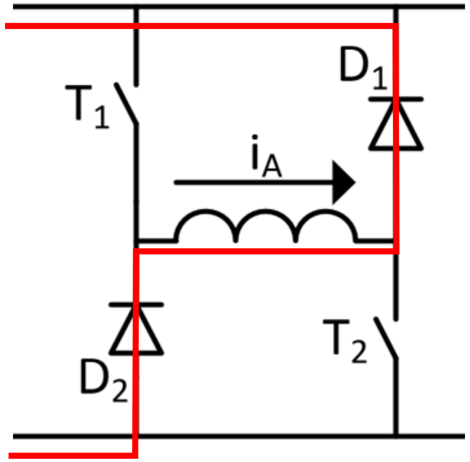
7.3.2- Drive circuit:

Asymmetric Half Bridge per phase, Consider 1 phase as shown in figure (102-b)









- Single pulse
  - T_1, T_2 on to build I_A
  - T_1, T_2 off to reduce I_A back to zero

- Soft chopping
  - T_1 “on” and T_2 rapidly switches on/off
    (alternating $+V_{DC}$ and 0V, duty cycle controls current)
  - T_1, T_2 off to reduce I_A back to zero

- Hard chopping
  - T_1 and T_2 rapidly switch on/off
    (alternating $+V_{DC}$ and $-V_{DC}$, duty cycle controls current)
  - T_1, T_2 off to reduce I_A back to zero.