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Scalar Controlled Three Phase Induction Motors using Variable Frequency Drives

Eng.Ahmad AL-Enezi
The Public Authority for Applied Education & Training Shuwaikh – Industrial Institute Department of Electrical Engineering

ABSTRACT
This report is mainly concerned with the speed control of three phase induction motors (IMs) using variable frequency drive (VFD). Detailed study of conventional two levels, three-leg voltage source inverter (VSI) is adopted using pulse width modulation (PWM). The proposed control strategy adjusts theIM speed by changing both the voltage magnitude and frequency of the VSI. This approach is so-called "constant V/F" where the ratio of voltage magnitude and frequency is kept constant in order to maintain the magnetic flux which in turns keep fixed torque under varied speed conditions.

A dedicated case study is introduced illustrating the mathematical modeling of induction motor and respective characteristics. The modeling of the proposed case study has been verified using time domain simulations via MATLAB/Simulink engineering tool. This way, the system performance of uncontrolled induction motor has been investigated during transient and steady state operation in terms of the rotor and stator currents, motor speed, and developed electro-magnetic torque characteristics. The analytical results have shown the need to use advanced methods of speed control. In contrast, further analysis has been presented while using V/f Control of 3-phase PWM-Inverter fed IM. Both open and closed loop control schemes have been presented and discussed. The simulation results have shown that the system performance is highly improved when using closed loop V/F control scheme while maintaining maximum constant torque.

Keywords: Variable Frequency Drives, Scalar V/F Control, Speed Control, Induction Machine

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I. SUMMARY

This report is mainly concerned with the speed control of three phase induction motors (IMs) using variable frequency drive (VFD). Detailed study of conventional two levels, three-leg voltage source inverter (VSI) is adopted using pulse width modulation (PWM). The proposed control strategy adjusts theIM speed by changing both the voltage magnitude and frequency of the VSI. This approach is so-called "constant V/F" where the ratio of voltage magnitude and frequency is kept constant in order to maintain the magnetic flux which in turns keep fixed torque under varied speed conditions.

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This report is organized in 5sections, as follows;

- Section I, an introduction of the subject studied in this report has been submitted, describing a brief overview of induction motors, different control methods of IM speed control, research motivation, objectives, and report organization.
- SectionII, this section has illustrated the basics of AC induction machines in terms ofconstruction, principle of operation, speed-torque characteristics, and operating modes. Different methods which used forspeed control of AC induction motors have been discussed. The merits of variable frequency drives have been highlighted for speed control applications in contrast with the classical control methods. Thereby, the necessity of modern and efficient control strategies have been addressed to govern the speed of induction machines.
- Section III, this sectionintroduced Pulse Width Modulated 3-Ph voltage source inverter under

different load conditions for both single and three phase inverters.

- Section IV, it presents detailed study for V/f Control of PWM-Inverter fed Induction Motors. Uncontrolled characteristics have been addressed and compared in contrast with the V/f controlled induction motors using open and closed control schemes. The best performance of speed control has been attained under closed loop control scheme.
- SectionV, this sectiondiscusses the obtained results and presents the final conclusions of the proposed study. Suggestions and recommendations for future work have been addressed.

Nomenclatures

Cf : Filter capacitance
Ea : Back e.m.f of armature
f_(Cut_off) : Cut-off frequency of LC filter
Ia : Armature current
Lf : Filter inductance
LR : Rotor leakage inductance
LS : Stator leakage inductance
ma : Amplitude modulation ratio
mf : Frequency modulation ratio
P : total number of motor poles
Pdev : Developed power
Ra : Armature Resistance
Rr : Rotor resistance
Rs : Stator resistance
S : Slip of induction motor
T : Produced Torque
Tb : Full-Load torque
Tph :The number of turns per phase
n : Rotor speed in rpm
nr : Rotor speed in rpm
ns : Synchronous speed
Vcnt : Reference signal amplitude
Vtri : Triangular carrier signal amplitude
Vs : Input supply DC voltage
Φm : Air gap flux

List of Abbreviations

EMF Electromagnetic Force
FOC Field Oriented Control
IGBT Insulated gate bipolar transistor
IM Induction Motor/Machine
MMF Magneto-Motive Force
MOSFET Field-effect transistor
PWM Pulse Width Modulation
RPM Revolution per minute
SCIM Squirrel-Cage Induction Motor
SM Synchronous Motor
SPWM Pulse Width Modulation
VC Vector Control
VCVSI Voltage-Controlled Voltage Source Inverter
VFD Variable Frequency Drive
VSI Voltage Source Inverter

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II. INTRODUCTION

1.1 Statement of Problem

This report discusses the operation of three phase induction motors (IM) and the respective speed control methods using variable frequency drives (VFD). Few classical control methods have been proposed for speed control of IMs, e.g. changing applied voltage, rotor resistance control which is applicable only with slip ring type IMs, pole changing machines, and stator frequency variations. However, all these methods are prone to inherent demerits namely,infeasibility with wide ranges of controlled speed, the incompatibility with different types of induction machines, in addition to their incompliance with constant torque and power saving applications, e.g. fans, blowers, pumps, and HVAC, where loading effect of IMs is tolerable.

1.2 Motivation

Accordingly, modern speed control methods have been discussed in literature to overcome the above mentioned design issues. Scalar V/f control is one of these recent strategies. It adjusts theIM speed by changing both the voltage magnitude and frequency of the supplied voltage using variable frequency drive (VFD) or voltage source inverter (VSI). In this approach, the ratio of the voltage magnitude and frequency is kept constant in order to maintain fixed magnetic flux of the IM which in turns maintain theproduced torque under varied speed conditions[1].

The motivations beyond this study and development of scalar V/f control proposed in this report are summarized in the following:

- It obviates the need to use slip ring IM needed for changing the rotor resistance in order to manipulate the speed-torque characteristics. On the contrary, scalar controlled squirrel IM become more appropriate. This eliminated the maintenance issues relevant to rings and brushes.
- It overcomes the limitation of speed control of classical methods which could only adjust the motor speed with a limited ranges. Nevertheless, scalar V/f control can achieve varied and wide range of speed.
- It provides compatibility with different types of IMs.
- It provides more feasibility and better cost effective solution especially with considering computability ofsquirrel cage IM. This feature is superiorcontrary to classical control methods, i.e. changeable poles and slip ring IMs. Therefore, it is a remarkable advantage considering that squirrel cage is more widespread and simpler due to the lack of brushes and slip rings, and lower cost expenses.
- Not only speed control is achieved, but also limited starting current of IM can be enhanced using Scalar V/f control.

Additionally, V/f scheme enhances constant torque which is suitable for power saving of centrifugal applications , e.g. fans, blowers, pumps, and HVAC, where reduction of rotor speed leads to dramatic mitigation of the power consumption.According to the affinity laws as depicted in Figure 1.1, the flow is proportional to shaft speed, while the head (pressure) is proportional to the square of shaft speed, and the consumed power is proportional to the cube of shaft speed. Therefore, for instance, if the full speed is halved, then the consumed power is eighth the original full load power. Thus, energy is reduced by 10 to 60 percent if the loadis operated between 40 to 80 percent of full speed.

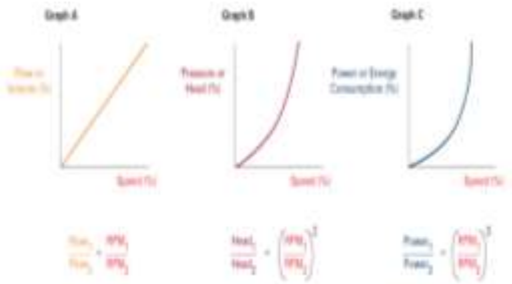


Figure IV.1Affinity laws

1.3 Report objectives

The main objective of this report is to introduce different methods of IM speed control with the involvement of classical control methods in contrast with scalar V/f control scheme. The superiority of scalar V/f control over classical methods would be discussed.The transient behavior of thelatteris not ideal.However the steady state response is satisfactory with the applications where loading effect is tolerable, e.g. fans, blowers, pumps and HVAC. In these applications, quick response and accuracy of speed control are not decisive factors compared with the expected power savings obtained by using VFD to control the speed over wide range according to the application and desired operating conditions.

A dedicated case study is introduced illustrating the mathematical modeling of induction motor and respective characteristics. Verification and validation of the proposed modelingshall be submitted using time domain simulations via MATLAB/Simulink. This way, the system performance of uncontrolled induction motor will be investigated during transient and steady state operation in terms of the rotor and stator currents, motor speed, and developed electro-magnetic torque characteristics. The analytical results would depict the need to use advanced methods of speed control for IMs.

Moreover, a Pulse Width Modulated (PWM) single andthree phase voltage source inverters (VSI) are introducedand discussed showing the topology structure of two level, three leg VSI in terms of both the power and control circuits. Simulation results using MATLAB/Simulink would be presented to illustrate the system performance under linear loading conditions in line with the adopted simulation parameters.

Hence, further analysis is presented to discuss scalar V/f Control of 3-phase PWM-Inverter fed IM. The naming "Scalar" is traced back to the fact that only the magnitude of the magnetic flux is controlled by manipulating scalar quantities, namely the voltage source magnitude and frequency. Meanwhile, the voltage and magnetic flux angles are not considered as state variables in this control regime. The scalar variablescan be obtained either by directmeasurement or calculations which are further used in the control strategy with both open loop and closed loop feedback formats. Both open and closed loop control schemes are addressed and discussed. The simulation results using MATLAB/Simulink are presented to show the system performance development when using closed loop V/F control scheme while maintaining maximum constant torque.

1.4 Main contributions

I. Simulations of an Induction Motor to illustrate the uncontrolled operating characteristics, including speed, torque, rotor and stator currents.
II. Development of MATLAB/Simulink models for a PWM Inverter.
III. Development of a V/f Control scheme for controlling the Induction motor with both Open Loop and Closed Loop schemes using MATLAB/Simulink.
IV. Comparison of the proposed schemes against the operational characteristics of uncontrolled induction.
V. Introducing the conclusions and future work suggestions in accordance with the obtained results.

1.5 Reportorganization and outlines

Following-up the above mentioned research motivations andobjectives of this report is organized in 5sections, as follows;

- Section.1, an introduction of the subject studied in this report has been submitted, describing a brief overview of induction motors, different control methods of IM speed control, research motivation, objectives, and report organization.
- Section.2, this section has illustrated the basics of AC induction machines in terms of construction, principle of operation, speed-torque characteristics, and operating modes. Different methods which used for speed control of AC induction motors have been discussed. The merits of variable frequency

drives have been highlighted for speed control applications in contrast with the classical control methods. Thereby, the necessity of modern and efficient control strategies have been addressed to govern the speed of induction machines.

- Section.3, this sectionintroduced Pulse Width Modulated 3-Ph voltage source inverter under different load conditions for both single and three phase inverters.
- Section.4, it presents detailed study for V/f Control of PWM-Inverter fed Induction Motors. Uncontrolled characteristics have been addressed and compared in contrast with the V/F controlled induction motors using open and closed control schemes. The best performance of speed control has been attained under closed loop control scheme.
- Section.5, this sectiondiscusses the obtained results and presents the final conclusions of the proposed study.Moreover, suggestions and recommendations for future work have been addressed.

III. INTRODUCTION OF INDUCTION MACHINESAND SPEED CONTROL METHODS

1.6 Introduction

Electrical motors represents the most significant power consumers in the industry . Many types of electrical motor exist as shown in Figure 2.1. This report is mainly concerned about induction motors as they are the most widespread in the world among all types. It is used in many applications including industrial, commercial, residential household appliances, and transportation.

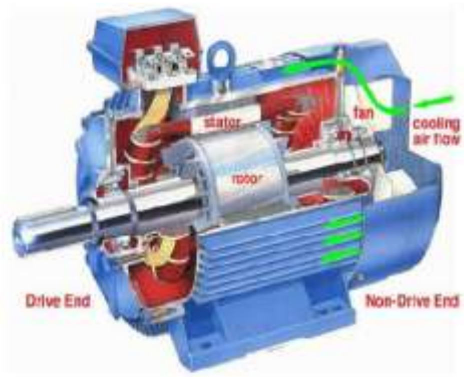
Figure 2.1 Types of electrical motors

The superiority of IMs over the other motor types, i.e. DC motors and synchronous motors (SM), is attributed to few reasons which summarized below:

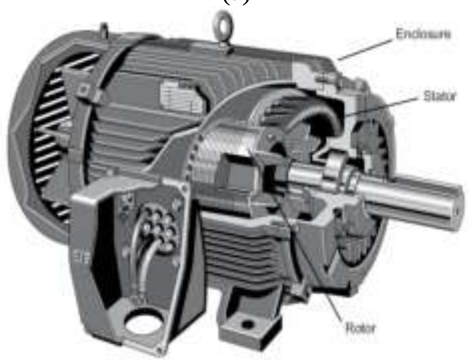
I. More cost effective and less-expensive than DC and Synchronous Motors.
II. Squirrel-Cage Induction Motors (SCIMs) are very robust and ruggedly maintained which facilitates its usage with various environmental conditions and prolonged time durations. Additionally, these motors overcome the hazardous and maintainability issues belonged to commutators and brushes that used with DC and AC synchronous motors.
III. IMs possess high efficiency
IV. The maintenance costs of IMs are small owing to the construction simplicity.
V. Provision of adequate starting torque.

1.7 Construction of AC IMs

As depicted in Figure 2.2AC IM is composed of three main parts, namely the rotor, stator, and enclosure.



(a)



(b)

Figure 2.2 Construction of AC IM: (a) Cut-way view,(b) External View

Stator construction

The stationary part of AC IM is the stator. The stator core is configured by a hollow cylindermade of many thin laminated sheets which are used to reduce electromagneticlosses. The stator windings are fabricated of insulated wires which are inserted into the metal laminations as shown in Figure 2.3.These coils are directly supplied from a three phase electrical power source.

Figure 2.3 Stator Windings contracture through laminations

Rotor construction

Whereas, the rotating part of the IM is the rotor body which is considered as a basic element that specifies the induction motor type . There are two ultimate types of rotor body as depicted in Figure 2.4, namely:squirrel cage rotor and Wound type rotor.

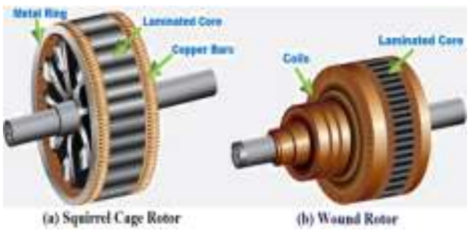


Figure 2.4 Types of AC IM: (a) Squirrel Cage Rotor, (b)Wound Rotor type

Wound type or Slip Ring IM type

The rotor is wound by the coils' conducting wires. These coils are connected to an external variable resistors through slip rings and brushes. At the end of the rotor ,these rings are installed to render asliding contact with three phase brushes as depicted in Figure 2.5. Thus, commutation of the rotorcircuit phases is done when the rotor rotates while being interfaced with the external circuit. This configuration facilitates the change of the rotor resistance and subsequently the rotor current in order to control the speed either by increase or decrease within a limited range.

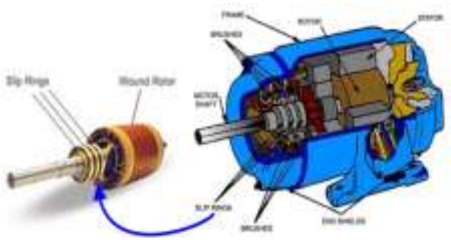


Figure 2.5 Slip ring rotor type

Squirrel cage induction motor type

Instead of conductor wires of the wound rotor, a copper or aluminum bars are skewed and evenly spaced to form a cylinderwhich encased over a slight air gap with the stator. These conducting bars are then shorted altogether through a tightened ring which brazed at the end sides of the rotor. This types obviates the need of slip rings and brushes, so it provides remarkable features in terms of lower expenses, more rugged and robust construction, higher reliability, and reduced maintainability.

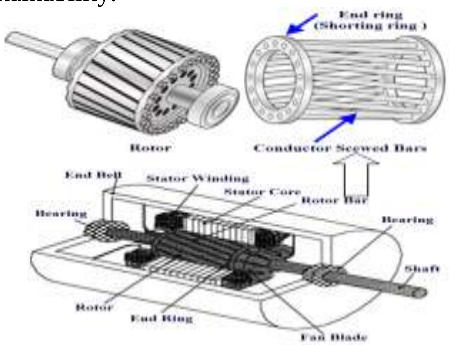


Figure 2.6 Squirrel-cage Ac IM

The enclosure

Finally, the motor composition is externally protected from the outer environmental ingressions by the enclosure which consists of a frame (or yoke) and two end brackets for bearing housings. The enclosure accommodates the stator mounting inside which the rotor is fitted with a slight air gap clearance as demonstrated in Figure 2.7.

Figure 2.7 Enclosure assembly of AC induction motor

Principle of operation

When the stator windings are supplied from a three phase power source , then a rotating magnetic fieldis produced with a displacement of 120° (electrical degrees) in space through the coils (aa', bb', and cc ') as shown in Figure 2.8.Thismagnetic flux rotates with the synchronous speed Ns which is given by Eq. 2.1.

$$n_s = \frac{120 \times f_s}{P} \quad (2.1)$$

where, fsis the frequency of the supplied voltage, and Pis the total number of poles.

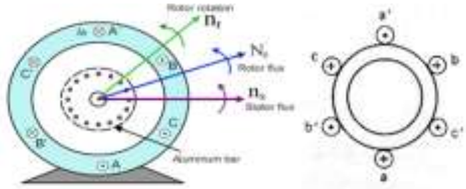


Figure 2.8 Squirrel Cage Rotor AC Induction Motor Cutaway View

The rotating magnetic flux produced by the stator cuts the rotor which induces a current in the rotor windings. According to Lenz's law, the direction of induced rotor currents would be opposite to the cause that producesthem. Accordingly, a mechanical torque is produced making a rotation of the rotor via the interaction between the electromagnetic fluxes of stator and rotor.While rotating in the same direction, the rotor speedapproaches the synchronous speed Nsof the stator magnetic field and thus the relative speed among rotor and stator filedis reduced.Actually, the relative speed between synchronous speed and rotor rotational speedis considered as the driver of the rotor which is so called the slip (s) as described in Eq . 2.2. Hence,according to Eq .2.4, the rotational speed of the rotornr always remains less than the synchronous speedns.This reveals the referring ofIMas asynchronous motors.

$$s = \frac{N_s - N_r}{N_s} \quad (2.2)$$

where, n_r is the rotational speed of the rotor, while the speed of the magnetic field induced in the rotor N_2 is given by Eq 2.3.

$$N_2 = s.n_s \quad (2.3)$$

$$n_r = (1 - s) \times N_s \quad (2.4)$$

The smaller the slip, the more reduction of the induced voltage in thestatoror back electromagnetic force (emf), thus theconverted energy into torque is reduced as well. This causes the torque production to drop off, and themotor will reach a steady state at the equilibrium point where the load torque is matched with the motor torque.Note that the torque production is governed by the angle formed between the rotor and the stator magnetic fluxes. Additionally, it can be noticed that IMsare considered as self-starter, where no external excitationor self-excitation is needed as manifested in DC or AC synchronous motors.

1.8.1 The equivalent circuit of Three phase IM

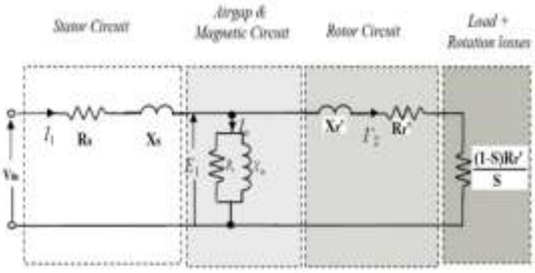


Figure 2.9 Equivalent circuit of AC induction motor

The equivalent circuit of IM is depicted in Figure **Error! Reference source not found.**, where X_m= Magnetizing Reactance, X_s= Stator Reactance, X_r= Rotor Reactance, R_s= Stator Resistance, R_r= Rotor Resistance, S= slip ratio, R_c= Magnetizing resistance, and V_{in}= Supplied voltage.

The induced voltage at stator or back emf is given by Eq. IV.1.

$$E_1 = 4.44\, f_s \varphi_m T_{ph} K_w \quad \text{(IV.1)}$$

where, f_s is the supplied frequency, φ_m is the air gap flux, T_{ph} is the number of turns per phase, and K_w is the winding factor. The equation above can be simplified as follows:

$$E = K_E . f_s \varphi_m \quad \text{(IV.2)}$$

where, K_E is a constant.As given in Eq. IV.2, the magnetic flux can be controlled by either changing the applied voltage or frequency.Increasing the voltage would augment the magnetic flux of stator provided that the frequency is constant.On the contrary, increasing the applied frequency (i.e.increasing rotor speed considering Eq. **Error! Reference source not found.** while the applied voltage is constant, would lead to magnetic flux reduction. In this sense, a collapse in thedeveloped torque would be existent as well considering that the torque is given by Eq. IV.3.

$$T = K_T . \varphi_m . I_1 \quad \text{(IV.3)}$$

where, K_T is a constant.

typical torque-speed characteristics

Based on the equivalent circuit shown in Figure**Error! Reference source not found.**, the typical torque-speed characteristics of the IM are presented as shown in Figure IV.**2**. When the IM is started and the machine is in stand-still condition, then most of the energy is consumed by the magnetizing circuit and the backemf ($E_1 \simeq 0.0$). This way, the drawn stator current I_1 at starting is significant $I_1 \simeq$ 7 times of full-load current (I_{FL}) and the starting torque is around 1.5

times of the motor rated value as shown in Figure IV.**2**.

As long as the rotor speeds-up, the drawn current is reduced slightly and eventually dropped when achievingthe full load speed (or base speed) N_{FL}at steady state which is close to the rated synchronous speed n_s, ,i.e. when S is ranged from .01 to .05. Thus, the rotor current is reduced down to the full-load value (I_{fl}) and the full load torque is developed as given by Eq. IV.4and Eq.IV.5, respectively.

$$I_2 = \frac{V_{in}}{(R_S + \frac{R_r}{S}) + j.(X_S + X_r)} \qquad (IV.4)$$

$$T = \pm\frac{P_{dev}}{\omega_S} = \pm\frac{I_2{}^2 . \frac{R_r}{S}}{\omega_S} \qquad (IV.5)$$

$$= \pm\frac{1}{\omega_S} . \frac{3V_{in}{}^2}{[(R_S + \frac{R_r}{S})^2 + (X_S + X_r)^2]} . \frac{R_r}{S}$$

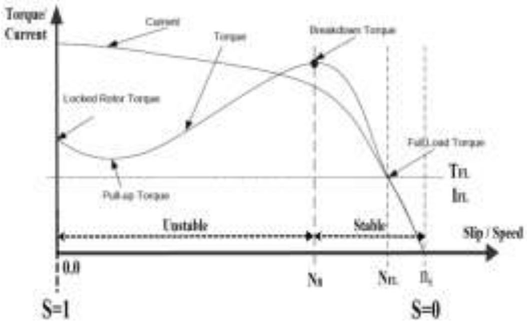


Figure IV.2Typical toque-speed characteristics of IM

If the mechanical load exceeds the full-load torque T_{FL} value, then the additional torque is developed at the expense of the rotor speed which is dropped and the slip ratio increases accordingly. However, the over-loading is bounded by the limits of the stable region as indicated in Figure IV.**2** at the breakdown torque. The latter is the torque beyond which the IM cannot handle extra loading and can be achieved atabout 80% of the synchronous speedn_s. Its value is equivalent to 2.5 times of the full load torque T_{FL}. Any further loading of the IM would lead to rapid fall of the torque andmotor stalling within the highlighted unstable region.

Modes of operation

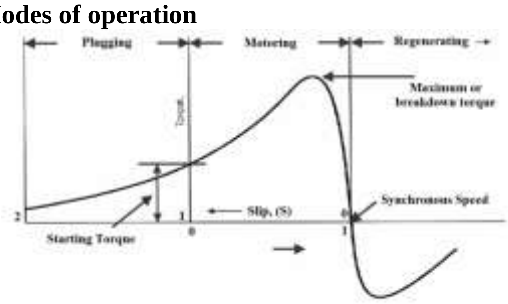


Figure IV.3Modes of operation

As shown in Figure IV.**3**, the IM operation can be classifiedaccording to three operating modes, namely: motoring, regenerative, and plugging which are elaborated below.

Motoring (0 < S < 1)

In normal motor operation, the rotor revolves in the same direction of rotation of the magnetic fieldproduced by the stator currents.According to the equivalent circuit shown in Figure **Error! Reference source not found.**, the power flow diagram of IM can be described as given in Figure IV.**4**, ,where P_{ag} : P_{RCL} : P_m= 1: S : (1- S), i.e. the developed mechanical power P_m= (1-S) P_{ag}.

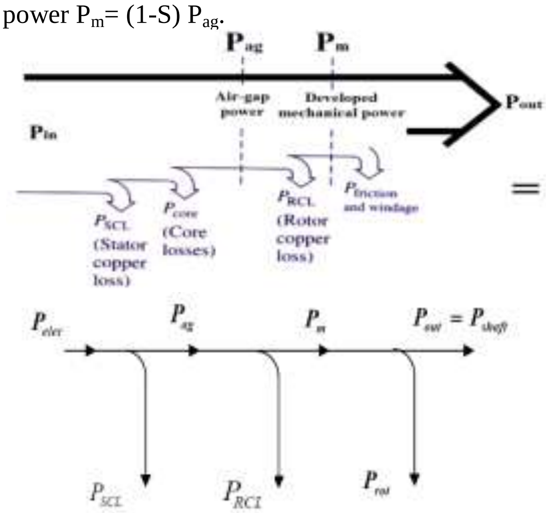


Figure IV.4Power flow diagram in motoring mode of IM

Regenerating S < 0 (Negative slip)

The induction machine can operate as a generator if its rotor is driven by a prime mover at a speed higher than the synchronous speed (resulting in negative slip), while its stator terminals are connected to a three-phase supply. Thus, the kinetic energy of the drive system will be fed back to the supply through a reverse power flow as shown in the figure below.

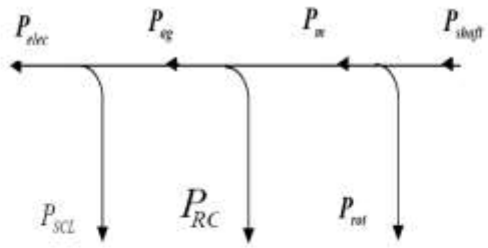


Figure IV.5Power flow diagram in regenerative mode

Plugging (Braking) S > 1

The plugging operation is achieved by changing the phase sequence of the terminal three phase source which feeds the IM. Accordingly, the magnetic field of the stator would inversely rotate leading to braking of the motor speed which comes rapidly to zero. Moreover, acceleration in the opposite direction would take place unless the supply is disconnected at the zero speed.

Classical speed control methods

The following section illustrates few classical method which usedto govern the speed control of AC induction motors[2] as demonstrated in Figure IV.**6**.

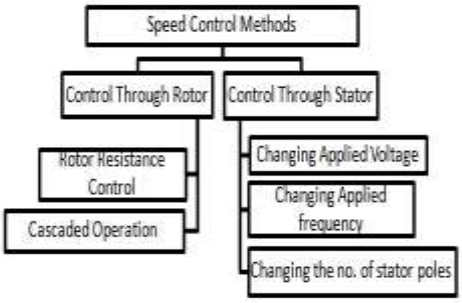


Figure IV.6 Classical or conventional speed control methods for IMs

Rotor Resistance Control

This methods is only usable with wound rotor type. As illustrated earlier in Figure **Error! Reference source not found.**, the rotor winding are commutated through rings and brushes. Thus, the rotor three phase windings make direct contact with an external resistors' circuit in order to control the rotor current, see Figure IV.**7**.

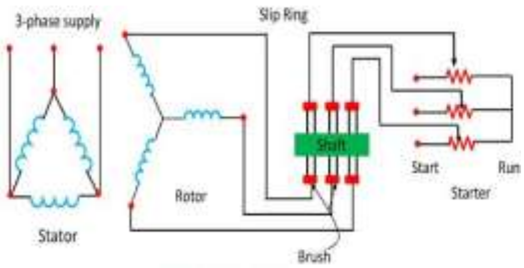


Figure IV.7 Speed control by varying therotor resistance of a wound type IM

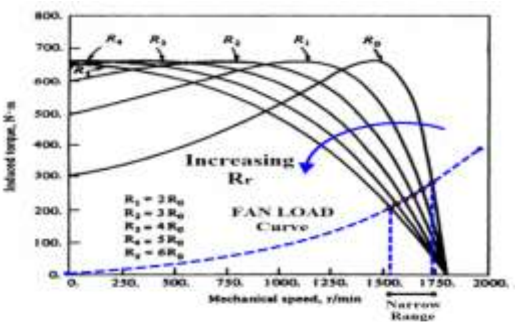


Figure IV.8 Toque-Speed curves under rotor resistance control

Varying the rotor resistance does not affect the maximum developed torque, but only changes the speed at which this torque occurs as shown in Figure IV.**8**. Moreover, the starting torque is enhanced by increasing the rotor resistance while the starting current is decreased.However, this method can only be used with wound rotor type. Moreover, the speed control range is narrow as demonstrated in Figure IV.**8**, where lower rotor speeds are achieved by increasing the rotor resistance. This leads to higher rotor copper losses and hence lower motor efficiency.

Cascaded or Tandom Operation

In this method, two induction motors are mounted on the same shaft. One of the two motors must be of slip ring type which is called main motor. The second motor is called auxiliary motor.The stator of the main motor is connected to the three phase supply. While the supply of the auxiliary motor is derived at a slip frequency from the slip rings of the main motor. This is called cascading of the motors. If the torque produced by both act in the same direction, cascading is called cumulative cascading. If torques produced are in opposite direction, cascading is called differential cascading. The speed of the speed of the cascaded set is described by Eq. IV.6.

$$N = \frac{120 \times f_s}{P_1 \pm P_2} \qquad \text{(IV.6)}$$

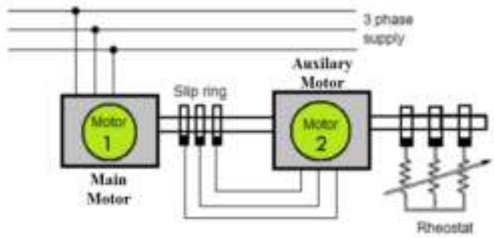


Figure IV.9 Speed control by varying therotor resistance of a wound type IM

where, P_1&$P_2$is the no. of the stator poles belonged to the main and the auxiliary motor, respectively. Note that the sign (±) is adjusted according to the mode of operation. The positive sign is assigned in case of cumulative cascading, whereas the negative sign is used with the differential cascading. This method is also rarely used due to following disadvantages :

- It requires two motors which makes the set expensive.
- Smooth speed control is not possible.
- Narrow range of speed control, where only two speed values can be adjusted according to the mode of operation.

- Operation is complicated.
- The starting torque is not sufficient to start the set.
- Set cannot be operated if $P_1 = P_2$.

Changing the applied voltage

The developed torque is proportional to the square of the applied voltage ($T \propto V_{in}^2$). Therefore, the torque-speed curves change considerably with the applied voltage variations in accordance with Figure IV.**10**. It is clear that the speed varies in a narrow range by reducing the applied voltage. Thus, this method possesses few disadvantages:

- The motor efficiency is of low order under decreased voltage.
- Limited range of speed control with small slip operated motors.
- Low power factor.
- Incompatible with constant toque applications, e.g. mixers.
- Used only in low power applications, mainly centrifugal pumps, fans, and blowers.

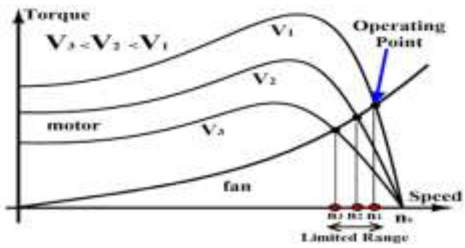


Figure IV.10 Speed control by changing the applied voltage

Changing the applied frequency

From Eq. IV.3, the torque is dependent of the armature current as well as the magnetic flux. Considering that the armature current is approximately constant at steady state, then the only influencing parameter is φ_m which lead to dropping in the produced torque when the rotor speed exceeds the base speed as shown in Figure IV.**11**.

Additionally, if the frequency is decreased at constant applied voltage, then flux augmentation and saturation may occur due to reduced magnetizing reactance at low frequencies leading to high drawn currents from the stator and heating

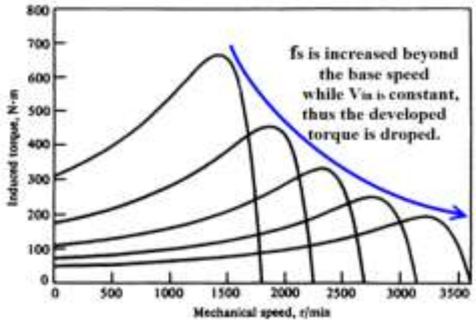


Figure IV.11 Toque-Speed curves of varied applied frequency increasing beyond the base speed, while constant voltage is maintained

Changing the no. of stator poles

Recalling Eq. **Error! Reference source not found.**, the synchronous speed can be controlled directly through either changing the applied frequency or the number of stator poles, where ($n_s = 120 \times f_s / P$). Thus, the windings arrangement for coil groups of armature phases are modified to change the total number of stator poles as shown in Figure IV.**12**. This method is employed only with squirrel cage induction motor which adapts itself with induced poles generated by armature windings.

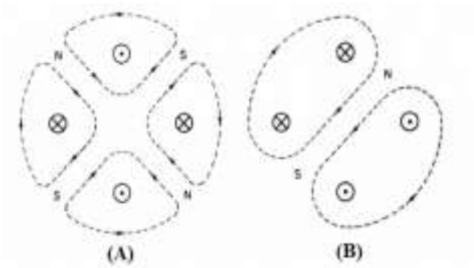


Figure IV.12 Stator Pole Switching: from (A) four poles – to (B) two poles

The ultimate drawback of the this method is that the speed can only be halved or doubled by switching between different stator poles. Thus, it does not guarantee wide range of controllability. The advantages and demerits of all the above mentioned methods are summarized in Table IV.1.

Table IV.1Summary of the conventional speed control methods

	Method	Advantage	Disadvantage
1	Rotor Resistance Control	• Varying the rotor resistance does not affect the maximum developed torque, but only changes the speed at which this torque occurs. • The starting torque is enhanced by increasing the rotor resistance, also the starting current is reduced effectively.	• Can only be used with wound rotor type. • Increasing the rotor resistance for lower speed leads to higher rotor copper losses and hence lower motor efficiency.
2	Cascaded Operation	• Rotor resistance can be controlled in the auxiliary motor which limits the magnitude of the slip ring currents and enhance the start current.	• Two motors set is expensive and costly construction. • Only two speed values can be adjusted according to the mode of operation either cumulative or differential cascading. Thus, wide range of wide speed control is not possible. • Operation is complicated. • The starting torque is not sufficient to start the set.
3	Changing the applied voltage	• Simple implementation using auto-transformers or variable resistors at stator three phase terminals.	• Both motor efficiency and power factorare reduced under decreased applied voltage. • Limited range of speed control. • Incompatible with constant toque applications, e.g. mixers. • The speed is controlled below the base speed at the expense of lowering both the starting and maximum torque developed. • Compatible with only flow/pumping applications with low power ratings.
4	Changing the applied frequency	• Provision of wide range of speed control.	• Reduction of the produced torque when the rotor speed exceeds the base speed. • Flux saturation may be encountered when the frequency is decreased leading to heating and high drawn currents from stator.
5	Changing the number of stator poles	• Compatible with squirrel cage IM which adapts itself with induced poles generated by armature windings.	• The speed can only be halved or doubled by switching between different stator poles.

Necessity of advanced methods for speed control of IM

To overcome the above mentioned limitations of classical techniques of speed control, scalar V/f method has been proposed in literature. In this method, the magnitude of the applied voltage is proportionally controlled in line with the frequency using variable frequency drive (VFD). Recalling Eq. IV.2, the air-gap flux is directly proportional to the stator applied voltage and inversely proportional to the frequency. Thus, keeping constant V/f ratio leads to fixing themagnetic flux which in turn maintain the developed torque as well. Accordingly, the following aspects can be offered:

- Wide range of speed control of IM.
- Salutation of the air-gap flux is avoided via the employment of variable voltage magnitude and frequency which produces an acceptable fixed torque at steady state, see Eq. IV.3.
- Compatible with all types of AC induction motors, including squirrel-cage IM opposing to the other methods which requires special construction, external rotor circuit, slip rings and brushes, or multiple-set of motors.

In DC machines, the produced torque is a function of two perpendicular vector components, namely filed current I_f and armature current I_a as depicted in Figure IV.**13**. In this configuration, these two vectors are decoupled and completely independent. Thus, the torque can be controlled through the armature current while fixing the field circuit current.

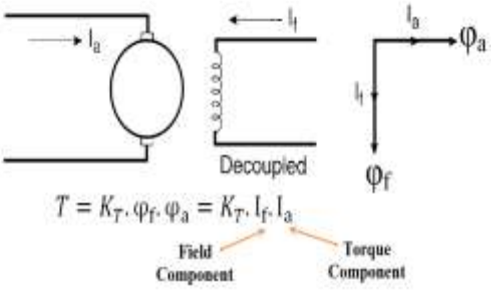


Figure IV.13 Separately excited DC motor

To avail an analogy with this concept, a generalized d-q model of AC induction motor is introduced as per the equivalent circuit shown in Figure IV.**14**, hence the developed toque is controlled according to Eq. IV.7.

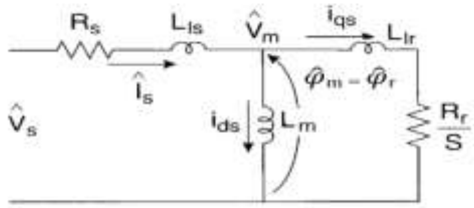


Figure IV.14 Equivalent circuit in the (d-q) generalized frame for induction motor

$$T = k_t^{'} . \widehat{\varphi_r} . i_{qs} = k_t^{'} . i_{ds} . i_{qs} \quad \text{(IV.7)}$$

Nevertheless, the current components i_{dqs} are not perpendicular similar to DC machines considering that direct-axis component i_{ds} is inductive, while the quadrate-axis component is not purely resistive due to the rotor leakage reactance I_{lr}. This way, imitation of the torque-speed characteristics of DC machine is not applicable by only manipulating the scalar quantities of control variables i_{ds}. Thus, the angles of control variable should considered to precisely control the torque especially under heavy loading applications where the rotor speed is influenced, see FigureIV.15. Therefore, scalar V/f control only fits with low power applications where loading effect is tolerable, e.g. pumps, fans, blowers and HVAC. It can be exploited to guarantee steady state operation in terms of the produced torque and speed control, whereas the dynamic performance is sluggish and imprecise till reaching the steady state.Moreover, it can be noticed that open loop control schemes are less effective in adjusting the speed which may deviate to lower levels at higher loading conditions.

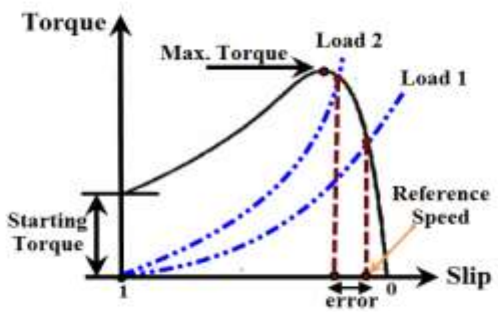


Figure IV.15 Loading effect on variable speed control

Concluding remarks

All the aforementioned classical methods are prone to many limitations and inherent demerits namely, infeasibility with wide ranges of controlled speed, the incompatibility with different types of induction machines, in addition to their incompliance with constant torque and power saving applications. Moreover, the modeling of IMs is challenging due to their non-linear characteristics and behavior which resulted from electrical parameters oscillations due to operational temperature limits and saturation. Accordingly, these limitations render the speed control of IMs more complex which imposes the need of advanced control algorithms to control the speed regardless of the non-linearity of system performance. One of these control strategies is vector control (VC) or field oriented control (FOC). This control strategy is remarkable as control both voltage magnitude and phase angle so that the flux linkage/torque is maintained constant while precisely controlling the IM speed. However, this control method is rather complicated and requires a high speed embedded micro-controllers.

Alternatively, a scalar V/f control method is introduced in this report an alternative solution for non-vector controlleddrive schemes. It adjusts theIM speed by changing both the voltage magnitude and frequency of the supplied voltage using variable frequency drive (VFD) or voltage source inverter (VSI).In this approach, the ratio of the voltage magnitude and frequency is kept constant in order to maintain fixed magnetic flux of the IM which in turns maintain theproduced torque under varied speed conditions[1]. Therefore, This approach guarantees satisfactory steady state performance, but the dynamic response is rather sluggish. Thereby, it is more appropriate for the power saving applications where slow transient response in matching with reference speed is neither crucial nor influenced by the loading effect of IM, such as: fans, blowers, pumps, and HVAC applications. Moreover, being a simpler control strategy it requires less computational capabilities by the used embedded system while achieving satisfactory steady state performance at fixed output torque.

IV. SINGLE AND THREE PHASE PWM VOLTAGE SOURCE INVERTERS

The function of an inverter is to convert the DC input voltage to an AC output voltage of desired magnitude and frequency . This sectionintroduces the electrical topology of single and three phase voltage source inverters(VSI) in terms of both the power and switching circuits as a preliminary stage for the next sections.

Single phase full wave bridge

The shown circuit below in Figure IV.1consists of four switching devices, 3-wire DC source comprising two capacitor at the DC link. The principle of operation is such that the transistors pairs (Q_1-Q_2) and (Q_3-Q_4)are switched on and off alternately. Each pair provides an opposite polarity of theinput DC voltage (Vs) across the load.

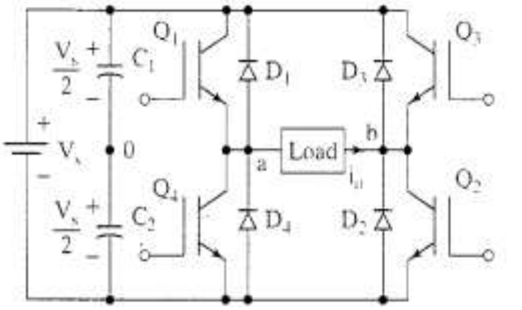


Figure IV.1 Single phase voltage source inverter using full wave bridge

When the pairs Q_1- Q_2 are turned on while Q_3-Q_4 are switched offas shown in Figure IV.2, thenthe output voltage (V_{out} = V_s) and the peak reverse voltage of (Q_3-Q_4 = V_s). On the contrary, the operating conditions are inversely triggered through the switchesQ_3-Q_4in contrast with Q_1-Q_2as per Figure IV.1.

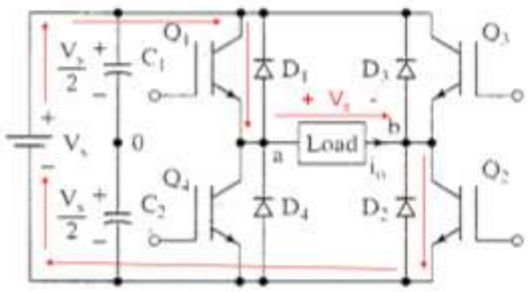


Figure IV.2 Single phase VSI:(Q_1- Q_2)are turned on, while(Q_3-Q_4) are switched off

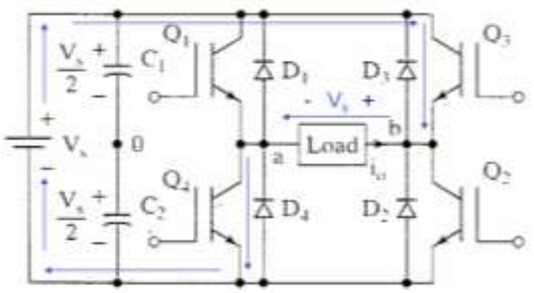


Figure IV.3 Single phase VSI: (Q_3-Q_4)are turned on, while (Q_1- Q_2) are switched off

As can be seen from Figure IV.4, the output voltage of the single phase VSI yield an alternating polarity of the input DC link voltage (V_s).

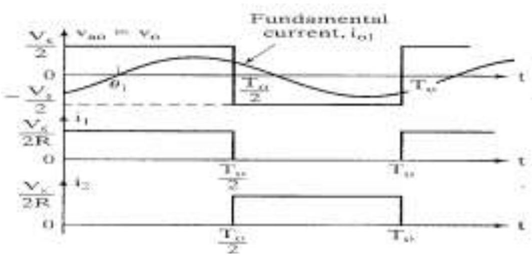


Figure IV.4The output voltage of the single phase VSI

The output RMS voltage V_{oaRMS} for resistive loads is given by Eq. IV.1IV.1IV.1IV.1IV.1IV.1

$$V_{ao\,rms} = \sqrt{\frac{2}{T_o}\int_0^{\frac{T_o}{2}} \left(\frac{V_s}{2}\right)^2 dt} = \frac{V_s}{2} \qquad \text{(IV.1)}$$

Three phase voltage source inverter

Similarly, three phase voltage source inverters operate with the same concept. However, the power circuit is quite different as it is composed of six switching devices as shown in Figure IV.5

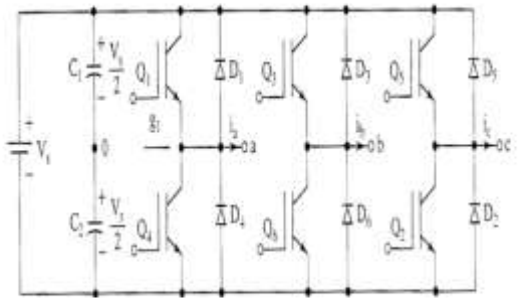


Figure IV.5The power circuit of three leg-two level voltage source inverter

The switching elements of VSIcan be classified with two main groups of semiconductors, namely: metal oxide semiconductor field-effect transistor (MOSFET) and insulated gate bipolar transistor(IGBT) as shown in Fig. IV.6. IGBThas been selected in this report for such purpose because they are faster (in terms of allowable switching frequency) compared to BJTs which are limited to (10KHz). Besides, they have better allowable voltage and current ratings (2000 V, 400 A) that are relatively higher than MOSFETs which are limited by (1000 V , 40 A) [3].

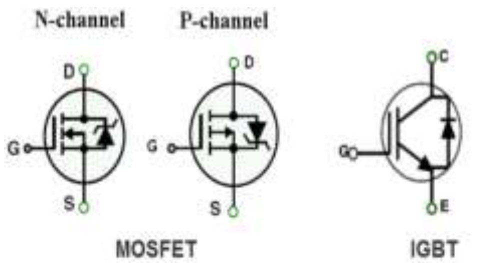


Figure IV.6Different semi- conductors used as switching elements

Analogous to single phase VSI, the switching sequences to alternate the polarity of the input DC voltage are shown in Table IV.1 for the same respect with three phase VSI

Table IV.1 Switching sequences of three phase VSI using 180° conduction

	180° commutation			
Intervals (degree)	**Transistor "On"**	**Polarities**		
		a	**b**	**c**
0-60°	Q1, Q6, Q5	+	—	+
60-120°	Q1, Q6, Q2	+	—	—
120-180°	Q1, Q3, Q2	+	+	—
180-240°	Q4, Q3, Q2	—	+	—
240-300°	Q4, Q3, Q5	—	+	+
300-360°	Q4, Q6, Q5	—	—	+

The equivalent circuit under each commutation mode of the switching devices within the range of 180° conduction are shown in Figure IV.7.

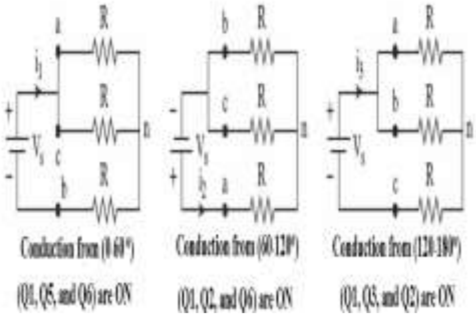


Figure IV.7Equivalent circuits in the conduction range from (0 to 180^o)

Accordingly, the output line and phase voltage waveforms are obtained as depicted in Figure IV.8 and IV.9 respectively in response to the switching sequence.

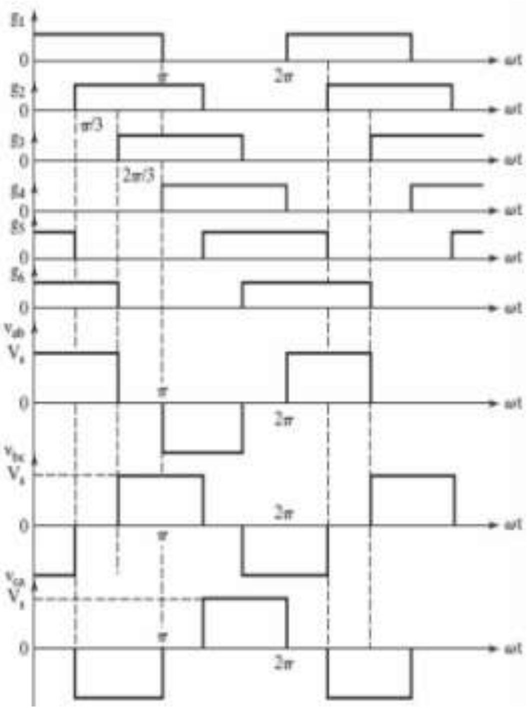


Figure IV.8Gate signals and output line voltage waveforms for 180^o Conduction

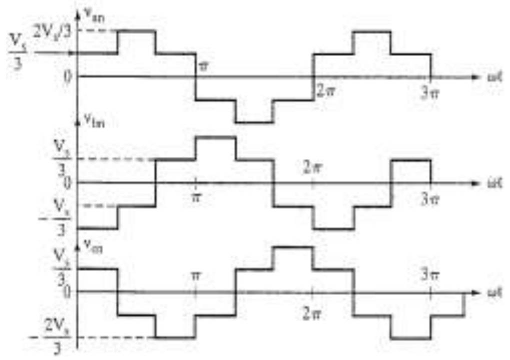


Figure IV.9 Output phase voltage waveforms for 180^o Conduction

The output Fourier series of the line voltages supplying a three phase Y-Load is given by the following equations:-

$$V_{ab}(t) = \sum_{n=1,3,5,..}^{\infty} \frac{4V_s}{\sqrt{3}n\pi} sin\left(\frac{n\pi}{3}\right) sin\, n\,(\omega t) \quad \text{(IV.2)}$$

$$V_{bc}(t) = \sum_{n=1,3,5,..}^{\infty} \frac{4V_s}{\sqrt{3}n\pi} sin\left(\frac{n\pi}{3}\right) sin\, n\left(\omega t - \frac{2\pi}{3}\right) \quad \text{(IV.3)}$$

$$V_{ca}(t) = \sum_{n=1,3,5,..}^{\infty} \frac{4V_s}{\sqrt{3}n\pi} sin\left(\frac{n\pi}{3}\right) sin\, n\left(\omega t - \frac{4\pi}{3}\right) \quad \text{(IV.4)}$$

Gating pulse modulation of the VSI

The output voltage waveforms of ideal inverters should be sinusoidal. However, the actual output voltage of inverters contains harmonics. For high power applications, low distorted sinusoidal waveforms should be produced to avoid harmful impacts on the local load. The power quality is affected by the short circuit path of harmonic currents which in turn reduces the capacity of the VSI to supply other loads [4].

IMs are considered as a low power factor linear loads which are prone to current harmonics distortion.In practice, the particular effect of current distortion relys on the magnitude of certainharmonics' order rather than the total harmonic distortion. With regards to third harmonic and its multiples (3rd , 9th ,… etc.), it causes a sharp increase in the zero sequence current. Accordingly, current overload occurs in the neutralwire for star connected loads, while large circulating currents and increased heating take place for delta connected loads. Whereas, the presence ofnegative-sequence harmonics (5th , 11th, 17th,.. etc.) which are 120° out of phase from fundamental current component, would produce an opposing magnetic field against shaftrotation of supplied motors which causes heating and harmful mechanical vibrations.

Therefore, in order to produce the desired AC sinusoidal waveform with minimized harmonics, the switching patterns of the power circuit must be modulated in a suitable manner. Many switching techniques are used for the gate signals of the three phase VSI in order toregulate the output voltage. Hence, the output voltage becomes of a lower harmonics contents except for the AC sinusoidal fundamental component. This facilitates better power quality and reduced harmonics. Additionally, the system requires smaller AC filter components which makes the design less bulky and inexpensive compared to a square wave output voltage. Sinusoidal pulse width modulation (SPWM) is one of the well-known technique which is commonly used in power electronics applications and has been selected for implementation in this report. The latter is dependent of two signals referredas control and carrier signals. The latter can be in the form of saw-tooth or triangular waveforms. These two signals are compared with each other as shown in Figure . Then, a modulated signal for the switching of IGBT is generated, as per Figure IV.10(a), (b) and (c). The more efficientswitching, the morecloseness of the output voltage to a sine wavecan be attained[3]-[5]as depicted in Figure IV.11.

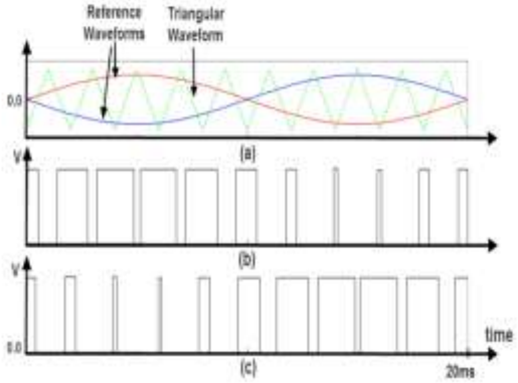


Figure IV.10(a) Comparison between carrier and control signals, (b) Gating pulses for switch S1, (c) Gating pulses for switchS2

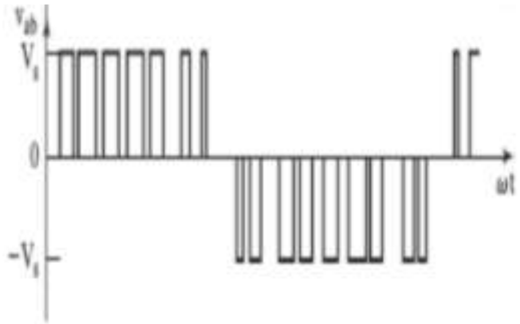


Figure IV.11The output line voltage by implementation of SPWM gate pulses

The VSI producesan output voltage with a frequency equals to that ofthe control signal f_{cnt}.In addition, theoutput voltage contains harmonics at the frequency of the triangular carriersignal (switching frequency). Therefore, there are two main equations which govern PWM inverter with regards to its output voltage and frequency; as submitted below.

$$m_a = \frac{V_{cnt}}{V_{tri}} \qquad \text{(IV.5)}$$

$$m_f = \frac{f_{tri}}{f_{cnt}} \qquad \text{(IV.6)}$$

Where,V_{cnt} is the reference signal amplitude and $V_{tri}$is the triangular carrier signal amplitude, $f_{tri}$is the frequency of the triangular carrier waveform which is responsible for to the switching speed of IGBTs of the VSI, while f_{cnt} is the frequency of the reference signal. While $m_a$is the amplitude modulation ratio, whereas m_f is the frequency modulation ratio.

The amplitude modulation ratio (m_a) is used to adjust the RMS value at the fundamental frequency of the inverter output line voltage as derived by Eq. 3.3 [3].

$$V_{LL1,rms} = \frac{\sqrt{3}}{2\sqrt{2}} \times m_a \times V_{dc} \qquad \text{(IV.7)}$$

It is a preference to keep $m_a$between zero and one in order to avoid over-modulation. In this range, the amplitude of a fundamental frequency component of the output voltage varies linearly, therefore this range is also known as linear range. If m_a goes beyond one , then increased harmonics are manifested due to over-modulation. Another drawback is that the amplitude of a fundamental frequency component of an output voltage will no more vary linearly [5]. If switching frequency is high, then it is easierto filter out undesired harmonicsas shown in Figure IV.10(c). Therefore it is suggested in [6]that either switchingfrequency should be less than 6kHz or higher than 20kHz in order to have the desiredsine wave ofoutput voltage. One more consideration for selection of the switching frequency, is that frequency modulation $m_f$should be kept as an integer and multiple of 3 in order to suppress odd multiple of 3 and even harmonics. Knowing that if m_f is not integer, then sub-harmonics at output voltage may exist. In addition, DC components and even harmonics may be present at the output in this case.

Selection of the DC bus voltage magnitude

The value of the DC bus voltage is selected so that the magnitude of the output voltage fundamental component can be varied by ± 10% while operating with linear PWM (where m_a is equal or smaller than one). The relationship between the dc bus voltage and the fundamental component of the line-to-line output voltage (V_{LL}) is given by:

$$V_{DC} = \frac{2\sqrt{2}}{\sqrt{3}} \times \frac{V_{LLrms}}{m_a} \qquad \text{(IV.8)}$$

In order to have V_{LLrms} = 419.16 while assuming that$m_a$is kept at 0.9, then V_{DC} is required to be equal to 760.55 V. Accordingly, the dc bus voltage magnitude is selected as 800V to compensate for system power losses, since power switches are not ideal besidesthe voltage drop across the output filter inductor.

Selection of the power switches

It is very important to designate the current and voltage ratings of the power switches in order to avoid damaging them. Assuming that the DC bus voltage is constant, and that the output current is free of harmonics at maximum loading. Then, the output RMS current is given by:

$$I_{orms} = \frac{S_{3ph}}{\sqrt{3} \times V_{LLrms}} \qquad \text{(IV.9)}$$

Where, S_{3ph} is the rated apparent power, and V_{LLrms} is the RMS value of the fundamental component of the switched voltage. Hence, the peak ratings of each gate switch can begiven by Eq. IV.10and IV.11as submitted below.

$$V_T = V_{DC} \qquad \text{(IV.10)}$$

$$I_T = \sqrt{2} \times I_{orms} \qquad \text{(IV.11)}$$

Where, V_T and I_T are the maximum voltage and current rating of each switch respectively.

Design of LC Filter

The factors which decides theselection of passive components are based on their availability, i.e. size of inductor(economical perspective), and the control bandwidth.Knowing that corner frequency or the synonymously called the resonant frequency (ω_0) is given by Eq. IV.12

$$\omega_o = \frac{1}{\sqrt{(L_f \times C_f)}} \qquad \text{(IV.12)}$$

The cut-off frequency is hence is adjusted by :

$$f_{Cut\_off} = \frac{1}{2\pi\sqrt{(L_f \times C_f)}} \qquad \text{(IV.13)}$$

Where, $L_f$and C_T are the inductance and capacitance of the AC filter, respectively.

V. PROPOSED SCALAR CONTROL SCHEMESFOR MOTOR DRIVES

Scalar control is speed control method used with both (AC and DC) motor drives due to variation in the magnitude of the control variables. There are two control variableswhichsubmitted in scalar control , namely: " Magnitude of (flux) " and " Magnitude of (voltage)"[1], [2], [7], [8], [9].

Scalar Control of DC-Motor

There are two types of DC-motor speed control, namely armature control and field control or flux control. The former is regulated by controlling the armature voltage and flux linkage as given by Eq. V.1 and V.2, respectively, meanwhile the latter is controlled by the varying the current of the field circuit as derived by Eq. V.3.

$$E_a = V_a - I_a \times R_a \qquad \text{(V.1)}$$

Also,

$$E_a \propto \boldsymbol{n} \times \boldsymbol{\varphi} \qquad \text{(V.2)}$$

$$T \propto I_a \times \boldsymbol{\varphi} \qquad \text{(V.3)}$$

where, E_a is the back e.m.f of the DC motor, I_a is the armature current, n is the motor speed, T is the produced torque, and R_a is the armature resistance.

Modes of operation:-

As can be seen from Eq. V.2, if the field current is regulated at constant value which yields fixed magnetic flux, then the motor speed can be controlled by varying the armature applied voltage. Similarly the torque can be controlled by regulating the armature current at constant flux operating condition. Subsequently, two modes of operation can be used for DC-motor control as illustrated in Figure V.1.

I. Mode (1) is referred as armature control or constant torque region, where the speed control is performed by varying applied voltage by keeping constant value of flux magnitude and regulating the stator current.

II. On the other hand, Mode (2) is so called constant Horse Power (H.P.) region. From Eq.V.2,andV.3, when the stator voltage is maintained at its rated value while regulating the stator current, thus the consumed H.P. is maintained constant as obviously given by Eq. V.4.

$$H.P. \propto [\boldsymbol{n}\times\boldsymbol{T}] \propto \left[\left(\frac{E_a}{\boldsymbol{\varphi}}\right)\times(I_a\times\boldsymbol{\varphi})\right] \propto E_a \times I_a \qquad (V.4)$$

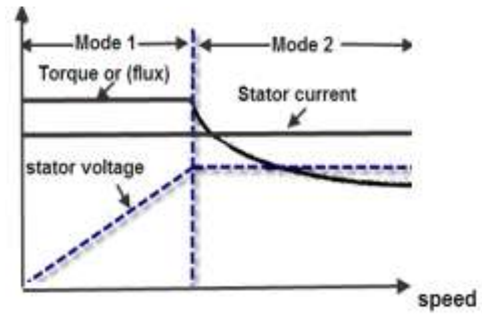


Figure V.1 Modes of operation over wide range of DC motor speed

Hence, under this condition, the speed control is performed by only varying the magnetic flux through the field current circuit. The block diagram of scalar speed control of DC motors is demonstrated in Figure V.2.

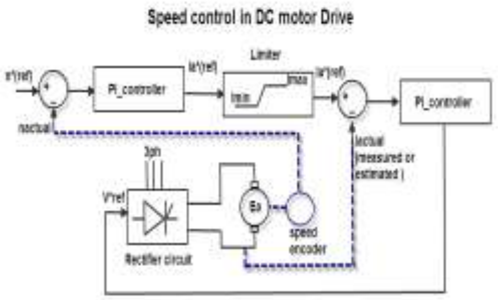


Figure V.2 Block diagram for speed control in DC motor drives[8]

Scalar Control of variable frequency driven AC IMs

By recalling the equivalent circuit of IM shown in Figure **Error! Reference source not found.**, in addition to Eq. IV.1and IV.3, the following formulas can be derived.

$$E_a \propto f_s \varphi \qquad (V.5)$$

$$T \propto . \varphi . I_a \qquad (V.6)$$

It can be noticed from Eq. V.5 and V.6 that both flux and torque are functions of (frequency and voltage), thus an inherent coupling between speed and torque exists, so they cannot be controlled independently. Knowing that air gap flux is the integral of the applied voltage $V_A$which impressed across the magnetizing inductance as described below:

$$\lambda_{ag} = \int V_A \, dt = \int V_A \sin(\omega t)\, dt = -\frac{V_A}{\omega}\cos(\omega t) \qquad (V.7)$$

Thus, by assuming that the air gap voltage is sinusoidal, then to have a constant air gap flux a constant volts/Hz ratio is to be controlled by fixing the ratio among voltage magnitude and frequency which is-so called "V/f control". It is obvious that scalar control is simple to be implemented and practically it produces good steady state performance.

However, considering that the air gap flux linkages deviate from their set-point valuesin both magnitude and phase. In the meantime, scalar control schemes only consider the magnitude of the control variables (i.e. voltage and magnetic flux) while disregardingthe phase angle monitoring of these variables. Therefore, its interior dynamic performance is neither precise nor quick enough when compared with vector control.Thereby, scalar control is used in variable-speed applications in which loading effect of the motor speed is tolerable, e.g. pumping and cooling applications where the quick and precise control of the speed is not quite sensitive. There are two types of scalar V/f control method, namely open loop and closed (V/f) control schemes.

Modes of operation of scalar V/f control

There three modes of operation, two modes are analogous to DC-motor drives in line with an additional operating mode which illustrated below:

I. Mode (1) is referred as armature control or constant torque region, where the speed control is performed by varying both the voltage magnitude and frequency producing constant value of flux magnitude while regulating the stator current.
II. On the other hand, Mode (2) is so called constant Horse Power (H.P.) region or weakening-field region. In this mode, the stator voltage is adjusted at its rated value while regulating the stator current. Thus, the speed control is obtained by varying the frequency above its rated value f_{rated}. This way, the speed is increased at the expense of collapsed flux/torque while the output H.P is maintained constant at the rated value.
III. Finally, Mode (3) maintains the stator voltage at its rated value and regulates the slip speed just below its pull-out torque value.

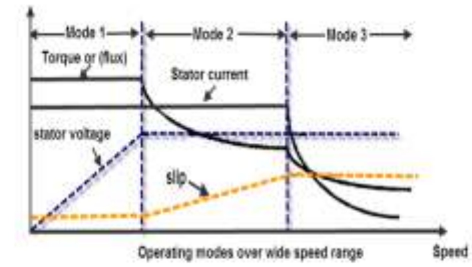


Figure V.3 Torque-Speed and power curves Scalar V/f control[8]

The implemented scalar (V/f) control can be set linear or parabolic in accordance with the load type as shown in Figure V.4

1) Linear V/f : used with [linear loads, i.e. T_L=Kω_r]
2) Parabolic V/f : used with [fans or pump-type loads T_L=Kω_r^2]

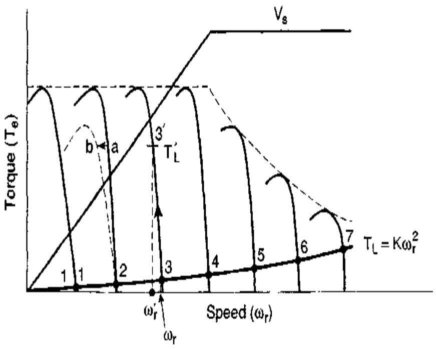


Figure V.4 Torque-Speed characteristics oflinear and parabolic V/f control[8]

Speed control using open loop V/f control of a voltage-fed inverter

The block diagram of the open V/f control loop is presented in Figure V.5. The required speed set-point is commanded to the speed controller in terms of the applied frequency $\omega_e^*\approx\omega_r$as the primary control variable.Correspondingly, this reference speed ω_e^* is multiplied by the gain (G) based on which the commanded phase voltage magnitude $V_S^{*\prime}$ is generated while maintaining a constant V/f ratio for fixed air gap flux. Note that at low speed ranges, the voltage drop across the stator resistance cannot be neglected, so a boost voltage (V_o)should be considered for compensation of this drop. Thereby, V_o been added to the reference voltage $V_S^{*\prime}$ to generate the modified reference of the voltage magnitude (V_S^*). At higher slip speed ranges, the effect of the boost voltage is negligible.

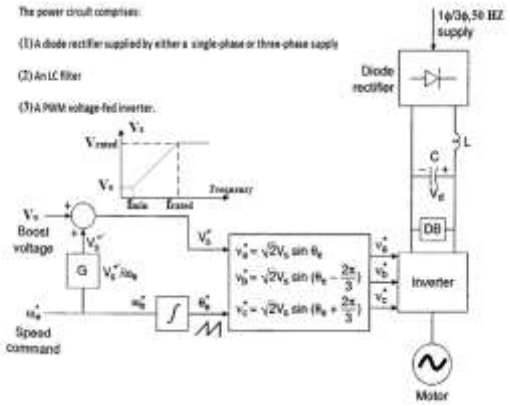


Figure V.5 Block diagram for the speed control using open loop V/f control of VSI[8]

Recalling FigureIV.15, scalar V/f control only fits with low power applications with small loading effect, e.g. pumps, fans, blowers and HVAC. Therefore, at no-load torque, the slip is very small, and the speed is nearly the synchronous speed. However, if the motor is loaded, then simple open-loop Vs/f (or V/Hz) is less effective in adjusting the speed which may deviate to lower levels at higher loading conditions. Thus, open loop is only used at light loading when the speed response is not a concern as the error in speed resulted from slip of the motor is considered acceptable.

Speed control using closedloop V/f control of a voltage-fed inverter

According to Figure V.6, the block diagram of the V/f closed control loop is presented. It is shown that ($\Delta\omega_{rm}$) which is the error between the reference rotor speed ω_{rm}^* and actual measured speed (ω_{rm}), is passed through a proportional-integral (PI) controller and slip limiter which is used to govern the positive and negative slip speed in accordance with the torque load and pull-out torque limits, respectively. Hence, a slip command ω_{slip} which is considered as the slip compensation. The latter is added to the actual measured speed ω_{rm} to get the reference frequency command ω_e^* after considering the slip compensation. Correspondingly, ω_e^* is multiplied by a gain (k) and aggregated with the boost compensation value within the V/f function generator which is the same as open loop scheme to consider voltage drop compensation at low frequency ranges. Eventually, the error in voltage magnitude is passed through a PI controller to obtain the voltage command(V_S^*).

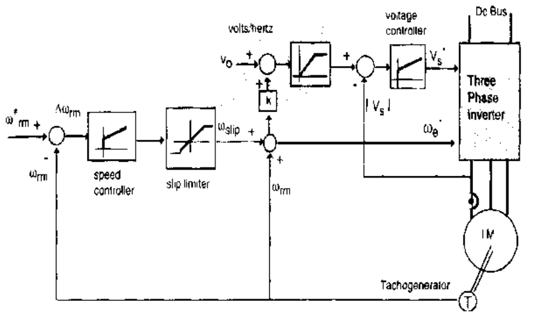


Figure V.6 Block diagram for speed control using closedloop V/f control with slip regulation[8]

This method provides good steady state response, but transient response is unexpected in terms of the produced torque especially under varying loading. In other word, this approach is considered as open loop torque control in line with a closed loop speed control. Additionally, it strongly requires a precise measurement of the rotor speed to get the slip. In negative slip mode of operation, the regenerated power must either be dissipated in a braking resistor or fed back to the AC mains.

Simulation of the proposed method using MATLAB/Simulink

In this subsection, time domain simulationsof ACIM are presented using MATLAB/Simulink to test the system performance against three case studies which proposed as follows:-

I. Uncontrolled fed Induction motor by three phase VSI.
II. Using open loop V/f control scheme to govern the IM speed under varied load torque.
III. Using closed loop V/f control scheme to govern the IM speed under varied load torque.

Through the above referred simulation case studies, the system performance of uncontrolled induction motor is investigated during transient and steady state operation in terms of the rotor and stator currents, motor speed, and developed electro-magnetic torque characteristics.Then, further simulations are presented usingV/f speed control schemes with both open and closed structures as illustrated earlier. Accordingly, an analytical assessment and discussion of the simulation results are introduced showing system performance while preservingmaximum constant torque in contrast with the uncontrolled machine. Note that all the used simulation parameters are submitted in Appendix A, e.g. characteristics of the motor under study, switching circuit, LC filter, nominal and operating conditions. Furthermore, the simulation sequence has been carried out based on the following Table V.1.

Table V.1 Simulation time sequences

	Simulation time in (sec)	
	from 0.0 to 4.0	from 4.0 to 10.0
Motor loading torque	T=0.2*Tb=4.38 n.m	$T=T_b$= 21.9 n.m

Case I: Uncontrolled inverter-fed asynchronous motor.

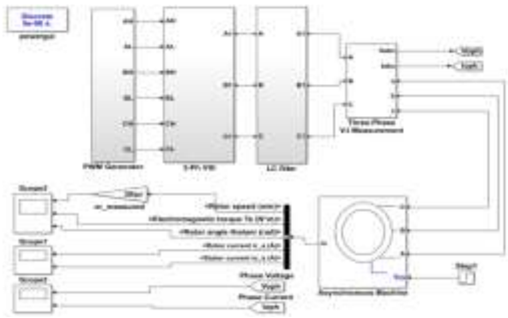


Figure V.7Block Diagram of 3ph-inverter fed IM under varying load torque

As shown in the figure above, the Simulink file contains three sub-blocks, namely PWM Generator, 3-Ph VSI, and LC filter, besides the 3-ph IM. Each sub-block of the latter isillustrated hereinafter.

PWM Generator Sub-Block

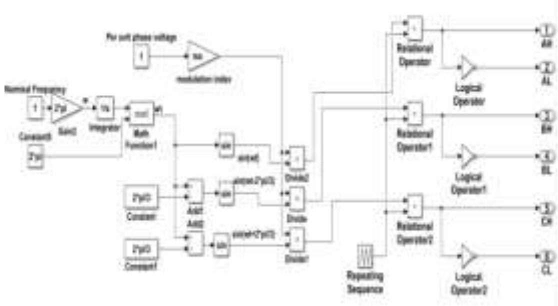


Figure V.8 Block Diagram of PWM-Generator Sub-Block

The Sub-Block entitled as "3-Ph VSI"

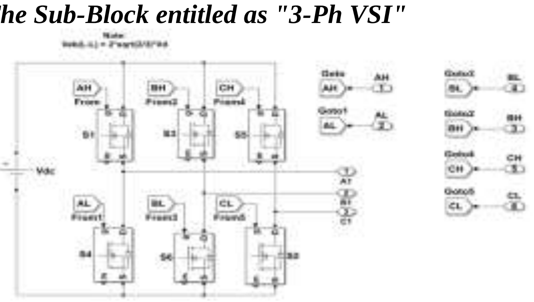


Figure V.9Block Diagram of 3-Ph VSI

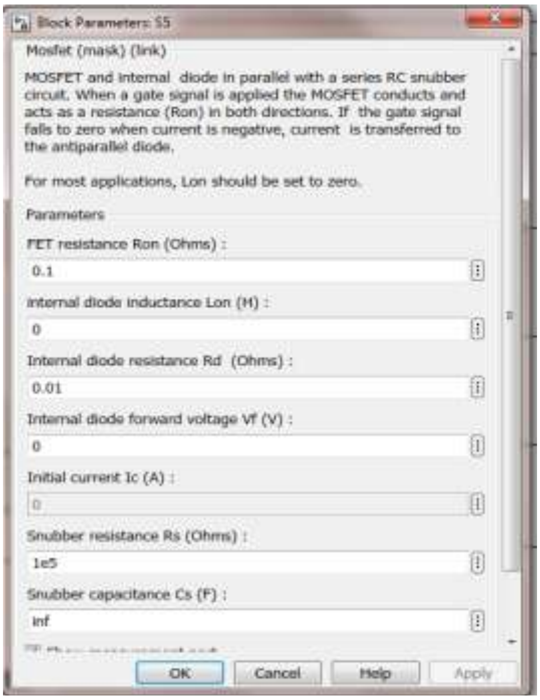


Figure V.10Block of Mosfet switching device in MATLAB/Simulink

Sub-Block entitled as "LC filter"

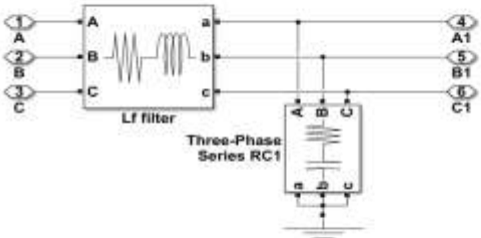


Figure V.11Block Diagram LC filter sub-block

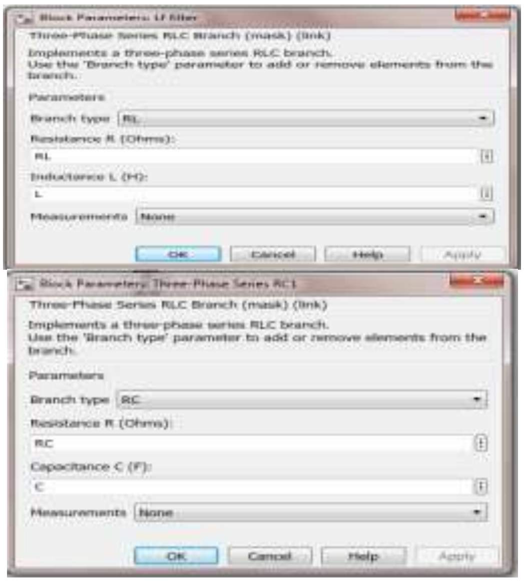


Figure V.12Block of series RLC branches in MATLAB/Simulik for the LC filter

Three phase IM sub-block

The proposed 3-ph IM used in the case study is characterized by the following ratings: 4KW, line- to line voltage is 400V, frequency is 50Hz and rated speed is 1430 RPM. Other parameters are shown in the following MATLAB/Simulink blocks.

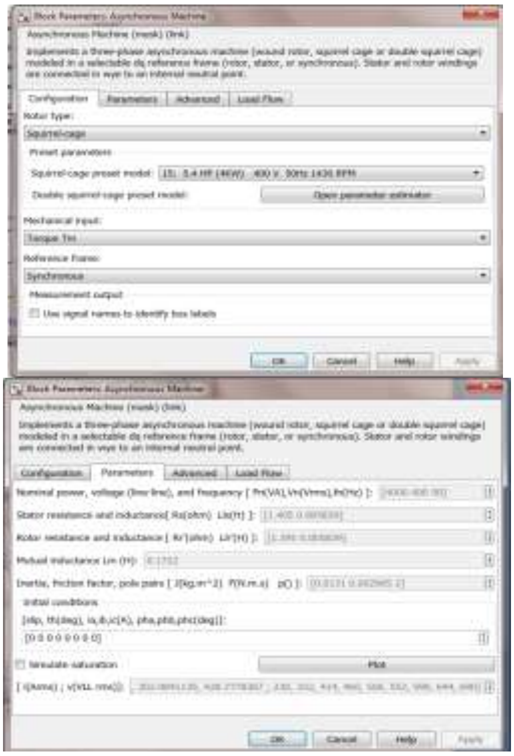


Figure V.13The parameters of the IM sub-block

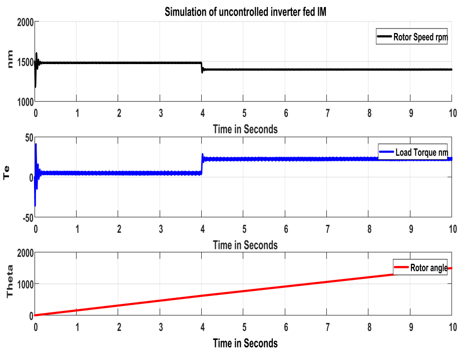


Figure V.14Response of uncontrolled inverter fed IM in terms of: Rotor Speed, Load torque, and rotor angle

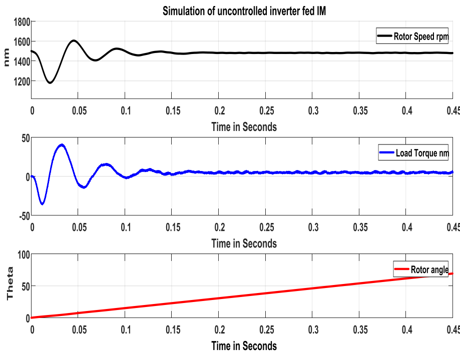


Figure V.15Zoom-in figure for the response of uncontrolled inverter fed IM during the time interval from 0 to 0.45 sec

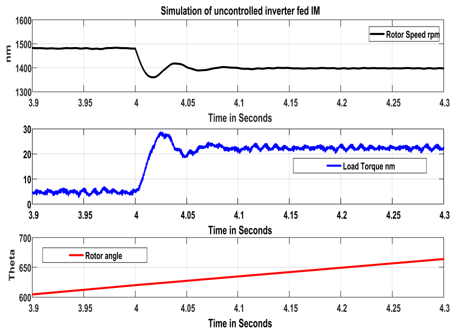


Figure V.16Zoom-in figure for the response of uncontrolled inverter fed IM during the time interval from 3.9 to 4.3 sec

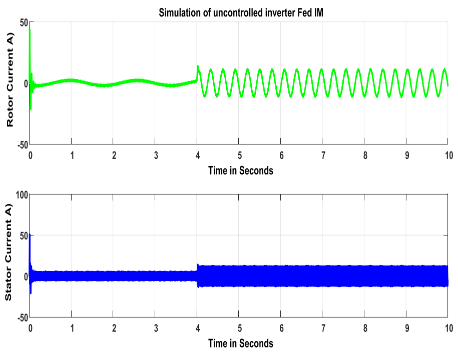


Figure V.17 Response of uncontrolled inverter fed IM in terms of rotor and stator phase current

Figure V.14, V.15, V.16, and V.17 show the response of uncontrolled IM which supplied from three phase VSI without having any means of speed control. As can be noticed from, With reference to the zoomed-in figures, the response of the motor in terms of the speed and electromagnetic torque is too oscillatory despite of being driven with the fifth value of the full load torque (≈4.4 n.m)in accordance with Table V.1. Furthermore, the peak overshoot also approaches about twice the rated full-load torque during both the starting and transient instants where the transition to full-load torque takes place at the fourth second of this simulation.

Case II: Using open loop V/f control scheme to govern the IM speed under varied load torque.

The same operating conditions are used in this case study, but the open loop V/f control scheme is proposed for the speed control in accordance with the reference set point which commanded by the user as shown in the following figures.

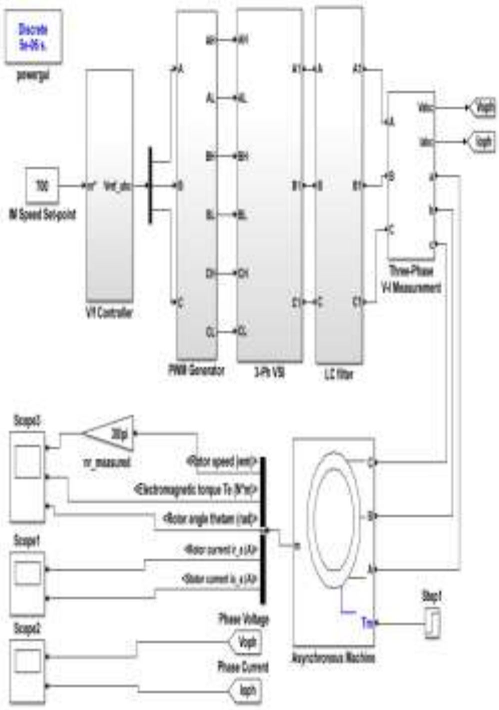


Figure V.18Block Diagram of open loop V/f control scheme in the created MATLAB/Simulink file

The sub-block entitled as "V/f Controller" is the only block which has been additionally added to the earlier simulation file in order to configure the proposed to control method.

The sub-block entitled as "V/f Controller"

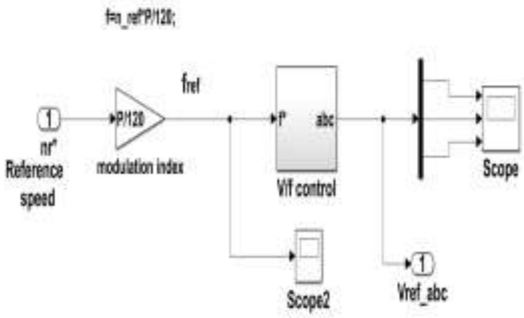


Figure V.19Diagram of V/f controller sub-block in the created MATLAB/Simulink file

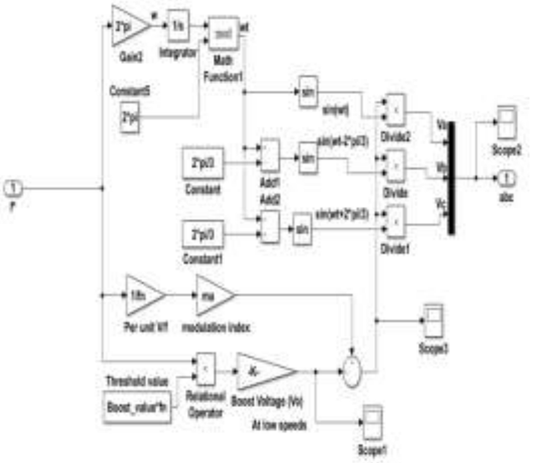


Figure V.20Sub-division of the V/f controller sub-blocks

Note that the sub-block "PWM Generator" receives the three phase reference signals of the voltage as shown in case study I. The reference speed set point adopted in the simulation is 700 RPM under varying load torque in accordance with Table V.1.

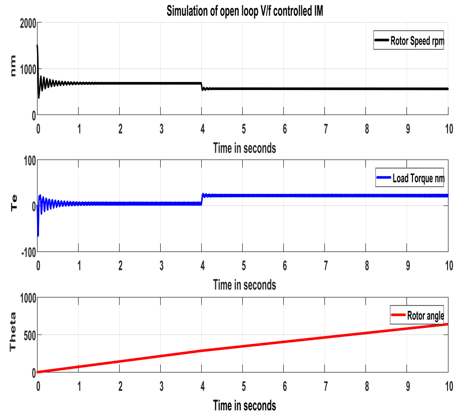


Figure V.21Response of open loop V/f controlled IM in terms of: Rotor Speed, Load torque, and rotor angle

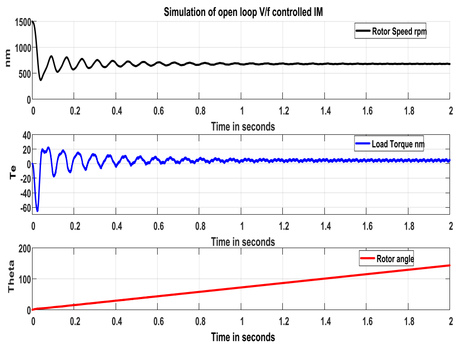


Figure V.22Zoom-in figure for the response of open loop V/f controlled IM during the time interval from 0 to 2 sec

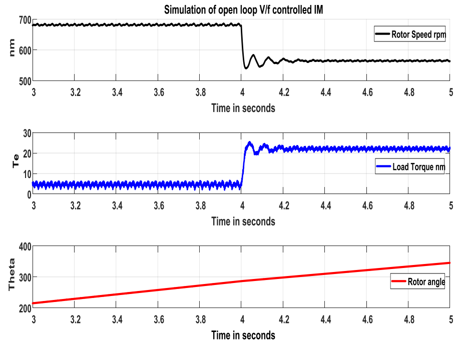


Figure V.23Zoom-in figure for the response of open loop V/f controlled IM during the time interval from 3 to 5 sec

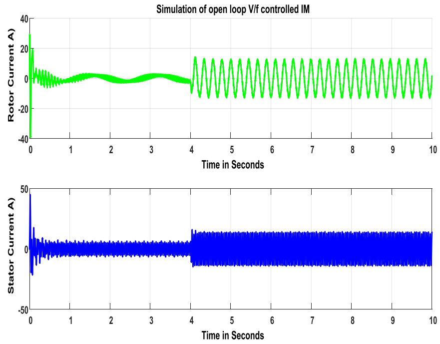


Figure V.24 Response of open loop V/f controlled IM in terms of rotor and stator phase current

As shown in Figure V.21,V.22,V.22V.23, andV.24, the speed control become feasible with this scheme. However, the transient response in terms of the rotor speed and electromagnetic torque is still oscillatory but with lower rate of change and smaller overshoots when compared with Case I. Moreover, the loading effect is witnessed due to varying load torque at the fourth second of this simulation, where the speed is decreased at the expense of increasing the torque as obvious in Figure 4.23. This recall the fact that closed loop V/f control would be much better to regulate the speed in case of higher loading effect while matching with the reference set-point.

Case III: Using closed loop V/f control scheme to govern the IM speed under varied load torque.

Similarly, the last case study is on the same track as shown in the following figures.

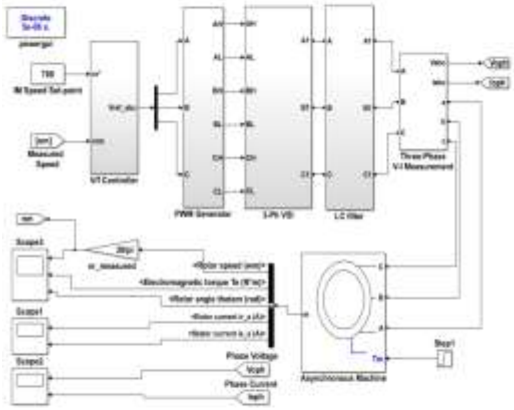


Figure V.25Block Diagram of closed loop V/f control scheme in the created MATLAB/Simulink file

As obvious, the motor speed is measured and fed-back the V/f controller as shown in the previous figure. The sub-block entitled as "V/f controller" is an updated version of the earlier simulation case study II as shown below, while the other sub-blocks are the same.

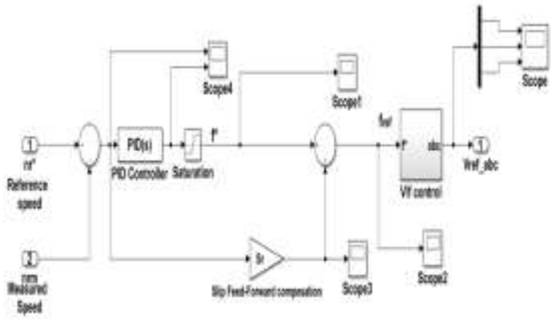


Figure V.26Block Diagram of V/f controller sub-block in the created Simulink file

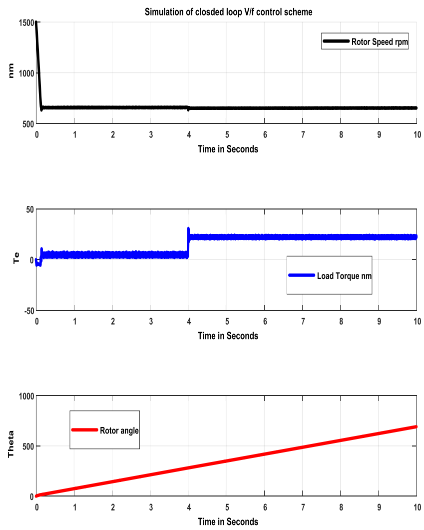


Figure V.27Response of closed loop V/f controlled IM in terms of: Rotor Speed, Load torque, and rotor angle

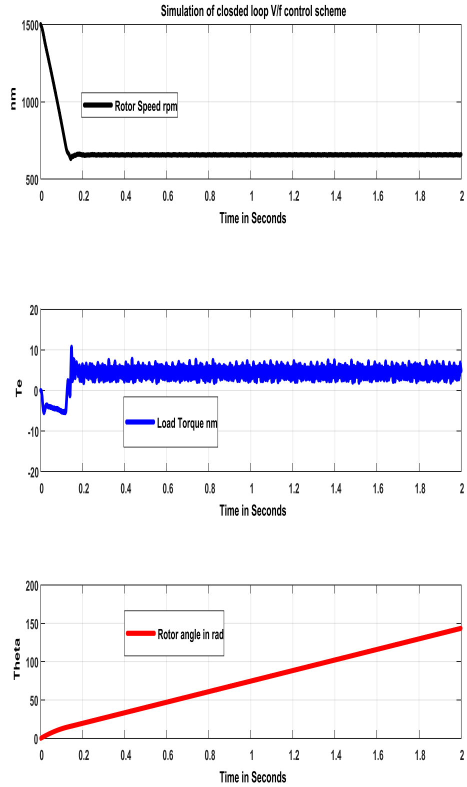


Figure V.28Zoom-in figure for the response of closed loop V/f controlled IM during the time interval from 0 to 2 sec

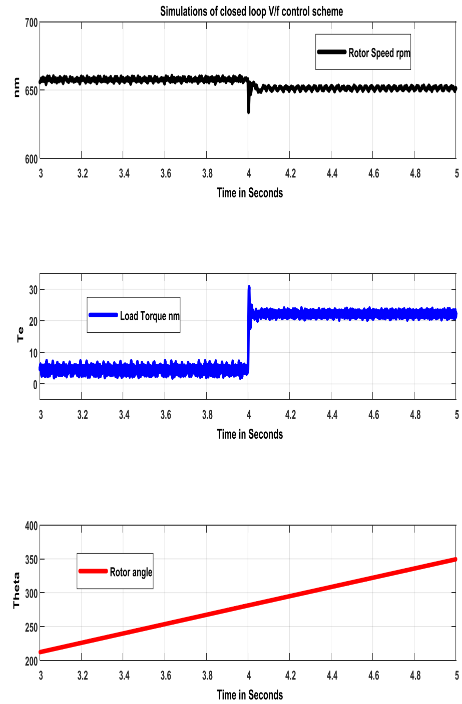


Figure V.29Zoom-in figure for the response of closed loop V/f controlled IM during the time interval from 3 to 5 sec

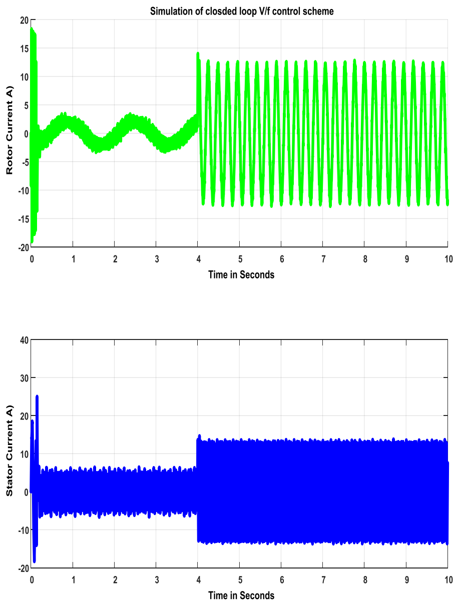


Figure V.30 Response of closed loop V/f controlled IM in terms of rotor and stator phase current

As depicted in Figure V.27,V.28,V.29, andV.30, the system transient and steady state response becomes highly improved while using the closed loop V/f control. The steady state error in rotor speed due to the loading effect is less significant and negligible when compared with Case II as shown in FigureV.27 and V.29. Furthermore, the oscillations of the rotor speed have been strictly damped during the transient instants, i.e. the starting and the fourth second of the simulation time. Additionally, the rising time of the controller to match with the reference speed is lower than Case II which prove the superiority of the closed loop structure over the open loop one. However, as clear in Figure V.27, the electromagnetic torque and stator current oscillates repeatedly. This in fact is traced back to that V/f control only consider the magnitudes as control variables while neglecting the phase angles of the voltage and flux linkage. Accordingly, the transient and steady state response of only the speed is improved while the torque response remains almost the same. For this reason, V/f control is only feasible with low power applications, e.g. pumping and fans. However, if precise control of both the speed and torque are mandatory in some applications, then vector control method would be more appropriate.

VI. CONCLUSION AND FUTURE WORK

Conclusion

In this report, detailed studies and analysis have been introduced regarding the speed control methods of induction motors using variable frequency drives. A brief introduction of induction machines and the classical methods have been well illustrated. Moreover, highlights on the limitations and drawbacks of classical methods have been introduced as preliminary stage of the study motivation and objectives. Both single and three phase inverters have been elaborated in terms of the power circuit, switching circuit, harmonics reduction through gate signals modulation using using SPWM. The criteria of selecting the DC bus voltage and LC filter design has been addressed. Eventually, scalar V/f control schemes have been submitted showing their relevant merits and demerits.

Both open and closed loop V/f controlled IMs have been investigated by means of simulation using MATLAB/Simulink in contrast with the uncontrolled machine condition. The results and discussions have shown and proven that closed loop V/f control scheme is superior in terms of the transient and steady state response of the motor speed. On the contrary, open loop scheme is prone to limitations in the steady state response especially during increased or varying loading torque. Furthermore, the dynamic response of closed loop V/f control is much better as it depicted lower rising and settling times compared to open loop structure.

Thereby, the former is more appropriate for the power saving applications, such as: fans, blowers, pumps, and HVAC applications, where precision of speed control is neither crucial nor heavily influenced by the loading effect of IM. Moreover, being a simpler control strategy it requires less computational capabilities by the used embedded system while achieving satisfactory steady state performance at fixed output torque. Nevertheless, if precise control of both the speed and torque are mandatory as witness some applications, e.g. servo drives, then vector control method would be more appropriate.

Future work

The following topics are suggested for a future work :

- Implementation and analysis of more advanced speed control methods, e.g. vector control and direct torque control for compatibility with the needs of quick and precise speed control, e.g. servo motor application and highly loaded VFDs.

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Appendix A

```
%% This MATLAB mfile summarized all the used simulation parameters, such as the characteristics of the IM motor under study, switching circuit, LC filter, nominal and operating conditions.
clear all; close all; clc;
%% Mains Voltage Source parameters
%%%%%%%%%%%%%%
f=50;          %Mains Frequency
Vph=220;       % Phase voltage
VLLrms =Vph*sqrt(3);    % Line Voltage =380 Vrms
%% Motor data
%%%%%%%%%%%%%%%%%
% rated values
fn=60; % Rated/Maximum Allowable frequency
Pn=3730; % Rated/Maximum power of the motor in VA
PF=0.9; % Power factor
Prated=PF* Pn; % Rated Power in Watt
Vn=460; % Rated/Maximum Allowable line voltage in RMS
P=4;   % Total No. of poles
j=0.02;    % Inertia
% Magnetizing Parameters
Lm=0.2037;   % Mutual Inductance in (H)
Xm=2*pi*f*Lm;   % Mutual Reactance
% Stator Parameters
Rs=1.115; % Stator Resistance
Lls=0.005974; % Leakage Inductance of stator in (H)
Xls= 2*pi*f* Lls;     % Stator Reactance
% Rotor Parameters
Rr=1.083; % Rotor Resistance
Llr=0.005974 ;% Leakage Inductance of the rotor in (H)
Xlr= 2*pi*f* Llr ; % Rotor Reactance
% Full Load torque calculations
Sr=0.025; % slip ratio
ws=4*pi*f/P;          %Synchronous speed: ws=4*pi*50/4=157.07 rad/sec
wm=(1- Sr)*ws;   % Rotor speed in rad/sec
Tb= Prated /wm;      % Full load torque = 3730*0.9/153.14325=21.92 (nm)
wm_slip= Sr *ws;     % Radial Slip Speed (wm_slip)=0.025*125.663=3.926 rad/sec
%% Calculation of the drop voltage accross the stator resistance
Irated=Prated/(3*Vph); % Rated Current
Vdrop_Stator= Irated*Rs; % Voltage drop accross stator resistance
Boost_value=Vdrop_Stator/Vph;
%% SPWM Switching
%%%%%%%%%%%%%
fsw=5250;    % Switching frequency
Ts= 1/fsw;   % Sampling time
ma=0.9;  % amplitude modelation index
%DC link
%%%%%%%%
Vdc= 700;
VDC= 2*sqrt(2)/sqrt(3)*VLLrms*ma ;    % DC-link voltage = 2*sqrt(2)/sqrt(3)*380/0.9= 558 V
%% Filter Design
%%%%%%%%%%
fc=0.2 *fsw; % i.e. cut-off frequency=1050
RC=0.1; % Equivalent Series Resistance of the Capacitance of the used LC filter
RL=0.5; % Equivalent Series Resistance of the inductance of the used LC filter
C=20e-6; % Proposed capacitance the used LC filter
L= 1/(2*pi* fc)^2/ C; %i.e. L=1.148e-3;
```

Eng.Ahmad AL-Enezi" Scalar Controlled Three Phase Induction Motors using Variable Frequency Drives" International Journal of Engineering Research and Applications (IJERA) , vol. 9, no. 9, 2019, pp. 44-69