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Thème

Real time V/f control of single-phase induction motor by using PWM technique

Soutenu le14/06/2021. Devant le jury composé de :

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Dedication

I dedicate this modest work to:

My parents
My wife

My children: Iyad, Ouayss, Anass, Assile and Ariyam

My brothers and My sisters

My family and all my relatives

All my friends:

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To my brothers and sisters

for all my family

who supported me all the time

All my friends

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I dedicate this humble work to my dear parents

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And to all the people who

Contribute to the success of this work

AymenZekri

ملخص

في هذا العمل ، تم تحقيق التحكم في الوقت الفعلي ***V / f*** للمحرك الحثي أحادي الطور باستخدام تقنية **PWM** خطوة بخطوة في ثلاثة أجزاء على النحو التالي:

في الجزء الأول ، تم تقديم المفاهيم الأساسية وكيفية تشغيل المحرك الحثي أحادي الطور ومبدأ عمله. بالإضافة إلى ذلك ، تم تقديم أنواع عديدة من هذه الآلات والدوائر المكافئة لها. بالإضافة إلى ذلك ، تم شرح الخصائص الميكانيكية للسرعة وعزم الدوران للمحرك الحثي أحادي الطور. في نهاية هذا الجزء ، نقدم مجالات التطبيق ومزايا وعيوب هذا المحرك.

في الجزء الثاني ، تم الكشف عن صيغ النماذج الرياضية اللازمة لنمذجة المحرك الحثي أحادي الطور والمحول العاكس. وهكذا ، تم تقديم عرض توضيحي لنموذج بارك**Park** لمحرك غير متزامن أحادي الطور مع مكثف دائم. بالإضافة إلى ذلك ، تم تقديم تقنية **PWM** للتحكم في العاكس عن طريق التحكم ***V / f*** للمحرك التعريفي.

في الجزء الأخير ، قمنا بمحاكاة النظام واستخراج نتائجه ، ثم تحليله والتحقيق التجريبي من أهمية الثابت ***V/ f*** في التحكم في المحرك المدروس. تم تنفيذ جزء المحاكاة بواسطة برنامج **MATLAB / SIMULINK** وكذلك الجزء التجريبي والتحقق من صحة التحكم ***V/f*** بناءً على تقنية تعديل عرض النبضة (**PWM**) للعاكس المتصل بالمحرك الحثي أحادي الطور الذي نتحكم فيه بواسطة **Arduino.**

قدم الاختبار التجريبي كفاءة التحكم ***V/f*** لمحرك تحريض أحادي الطور باستخدام تقنية **PWM**للعاكس أحادي الطور. بالإضافة إلى أهمية ***V/f***الثابت لضمان استمرارية عمل المحرك بالحفاظ على قيمة الثابت***V/f***دائمًا أكبر من القيمة الحرجة.

الكلمات المفتاحية :

محرك تحريضي احادي الطور , العاكس , تقنية تعديل عرض النبضة, تحكم بالاردوينو , نموذج بارك , تحكم ***V/f*** .

Abstract

In this work, the real time *V/f* control of single phase induction motor by using PWM technique has been realized step by step in three parts as follow:

In the first part, the essential concepts and operation of the single-phase induction motor and its working principle were presented. In addition, many types of this type of machine and its equivalent circuits have been presented. In addition, the torque-speed characteristics of the single-phase induction motor have been explained. At the end of this part, we present the fields of application and the advantages and disadvantages of this motor.

In the second part, the formulations of the mathematical models necessary for the modeling of the single-phase induction motor and the inverter were exposed. Thus, the demonstration of the Park model of a single-phase asynchronous motor with a permanent capacitor was presented. In addition, the PWM technique to control the inverter by V / f control of the induction motor was presented.

In the last part, we simulate the system and extract its results, then analyze it and experimentally validate the importance of the constant V / f in the control of the induction motor. The simulation part carried out by the MATLAB / SIMULINK software and also the experimental part and validation of a V / f control based on the pulse width modulation (PWM) inverter connected to the single-phase induction motor controlled by Arduino.

The experimental test presented the efficiency of *V/f* control for a signal phase induction motor using the PWM technique for a single-phase inverter. In addition, the importance of the constant *V/f* to ensure the continuity of operation after keeping the value always greater than the critical value.

key words:

Single Phase Induction Motor, Inverter, PWM Technique, Arduino Control, Park Module, V/f Control

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Symbol List

I	current
cos (x)	cosine is in mechanical position inside the motor
x	is the mechanical position inside the motor
ω	is the electrical angular speed
F	is the flux magnitude
t	is the time
C_{St}	starting capacitor
C_{run}	running capacitor
Z	impedance
R	resistance
X	reactance
Z_b	The impedance of 'backward'
Z_f	The impedance of 'forward running'
V_f	voltage of forward
V_b	voltage of backward
N	number of turne
f	frequancy
Ø	flux in core (webers)
L_{ps}, L_{as}	The specific inductances of the main and auxiliary phase.
L_{r1}, L_{r2}	The specific inductances of the two fictitious rotor phases.
R_{ps}, R_{as}	The resistances of the main and auxiliary phase of the stator.

R_{r1}, R_{r2}	The fictitious resistances of the two rotor phases.
I_{as}	Stator auxiliary winding current (E.A)
i_{ps}	Stator main winding current (E.P)
$i_{r1} i_{r2}$	Les courants des deux phases rotoriques.
i_{pas}	Le vecteur d'état actuel du stator
i_{r12}	Le vecteur d'état du courant rotorique
V_{ps}	La tension de l'enroulement principal (E.P) du stator
V_{as}	La tension d'enroulement auxiliaire (E.A) du stator
V_{r1}	La tension de la 1ère phase du rotor
V_{pas}	Le vecteur d'état de tension du stator
V_{r12}	Le vecteur d'état de la tension rotorique
V_{sd}, V_{sq}	Direct and quadrature stator and rotor voltages
V_{dc}	direct voltage
V_c	voltage at terminal capacitance
V_{sdq}, V_{rdq}	stator voltage and quaratic direct rotor
V	voltage
θ	the electrical angle between one stator phase and another rotor.
V_{r2}	The voltage at the 2nd phase of the rotor
θ_s	the angle stator
θ_r	the angle rotor
θ_a	represents the rotation angle of the coordinate system
ψ_{ps}, ψ_{as}	The total flows passing through the main and auxiliary winding.
ψ_{r1}, ψ_{r2}	The total fluxes passing through the fictitious rotor windings.

M_{pr} The amplitude of the mutual induction between the main winding and a winding fictitious rotor.

M_{ar} The amplitude of the mutual induction between the auxiliary winding and a winding fictitious rotor.

L_s, L_r MAS cyclic stator and rotor inductors, respectively

L Inductor

C_{et} electromagnetic torque

M_{sr} mutual cyclic inductance

P Number of pole pairs

Ω_m The mechanical angular speed of the rotor.

Ω_r angular speed of the rotor

J The moment of inertia of the rotor and any load attached to it.

Ωm Electric angular speed of the rotor($\omega m= d\theta/dt$)

f_v The viscous friction coefficient of the engine.

C_r The resistive torque of the load.

R_{pas} Resistors between the main and auxiliary phase of the stator.

R_{r12} The resistance matrix of the rotor between the two phases

ψ_{pas} the stator flux state vector

ψ_{r12} the stator flux state rotor

ψ_{sdq}. Direct and quadrature stator and rotor fluxes.

IM Induction motor

General Introduction

General Introduction

An electric motor is an electric machine that converts electrical energy into mechanical energy. In normal motoring mode, most electric motors operate through the interaction between an electric motor's magnetic field and winding currents to generate force [1]. Electric motor is classified into different types based on different criteria. The induction motor categorized as AC motors powered by AC power sources and the single-phase motor-powered bay single phase supply source and three phase motors powered by three phase supply sources.

The construction of the single-phase induction motor is as follows: the stator has laminated construction, made up of stampings. The stampings are slotted on its periphery to carry the winding called stator winding or main winding. This is excited by a single-phase AC. supply. The laminated construction keeps iron losses to minimum. The stampings arc made up of material like silicon steel which minimizes the hysteresis loss. The stator winding is wound for certain definite number of poles means when excited by single phase AC supply, stator produces the magnetic field which creates the effect of certain definite number of poles. Manufacturing Researchers encountered "the control of variable electric machines". Because electric motors are backed by high performance, increased reliability and low cost [2]. There are probably more single-phase AC induction motors in use today than the total of all the other types put together because they are least expensive, lowest maintenance is required. To achieve better efficiency induction motor has to be controlled by some control techniques. Among different methods of control, Variable frequency drives serve the purpose to a good extent for low dynamic requirements. Even today it is commonly used for the open-loop speed control. Most single-phase induction motors are unidirectional. Using microcontroller-based control systems, one can add speed variation to the system [3,4].

In the single-phase mode it is required to use a split-phase capacitor motor. It is important to remark that the capacitor is designed for the nominal speed and consequently the performance is not optimized for variable-speed operation. The use of a start capacitor motor is not recommended for adjustable-speed motor drive systems due to the presence of the centrifugal switch that changes the motor characteristics during the operation [5].

The induction motors generally run at a constant speed which changes slightly when mechanical loads are applied to the motor shaft. Due to its simplicity, robustness and low cost, this type of motor is the most widely used and, in practical terms, is quite suitable for almost all types of machines. Currently it is possible to control the speed of induction motors by frequency inverters [6].

These constraints have therefore directed research in the field of variable speed towards alternating current machines, and more particularly towards induction machines. Those-these have many advantages: reduced manufacturing cost, relatively simple, with stands over loads, higher rotational speed and does not require maintenance permanent. The disadvantage of this category of machines lies in the complexity of their operation, because they behave like multivariable, nonlinear and strongly coupled, hence the difficulty of their control [7]. Thanks to recent technological advances in power electronics and Micro-computers, the problems inherent in its alternative machine controls It has been fixed, making DC machines less commonly used.

As part of this study, we chose to work in the MATLAB / Simulink environment, so that it facilitates us to achieve the results with precision and within short deadlines. In addition, the experimental test was released for the validation of the effectiveness of the subject of our project. The context of this project presented in three chapters is as follows:

The first chapter of this study, presents generalities on the machines asynchronous and the operating principle of single-phase induction machines. Next, we will do a brief presentation of the main configurations of the single-phase motors. At the end, the fields of application of single-phase induction motors and their advantages and disadvantages have been given.

The second chapter is devoted to the modeling of the motor as well as the inverter, where the dynamic model of machine describes the transient and the steady state behavior of the induction machine. This model can be used to simulate the single-phase induction motor drives and evaluate their transient performances including that of using the V/f control technique. So, it is important to be able to model the single-phase induction motor in order to predict these phenomena. Various models will be developed and the d-q axis model for the study of transient behavior will be tested and proven to be reliable and accurate. Then, the modeling technique for the inverter model by finding the relationship of the output in terms of the input, finding mathematical formulas describing the transient voltage and current, for applied PWM control.

In the third chapter, is the object of this study deals with the method of realization of a variable speed drive which aims to obtain variable frequency for studied motor step by step as follows: the single-phase induction motor has been simulated by the software MATLAB / SIMULINK and a practical part of a *V/f* control based on the Pulse Width Modulation (PWM) inverter connected to the single-phase induction motor controlled by Arduino. Then, the simulation results show the importance of *V/f* control for the best performance operating in a single-phase motor. The experimental test presented the efficiency of *V/f* control for a signal phase induction motor using the PWM technique for a single-phase inverter. In addition, the importance of the constant *V/f* to ensure the continuity of operation in single phase induction motor.

CHAPTER I
Generality of the single-phase induction motor

I.1 Introduction

The concept of induction motor was introduced by Arago in 1824. From Aragon's experiment, it is known that when a permanent magnet is rotated around a copper or aluminum disk, the disk is attracted to the magnet and rotates in the same direction as the rotation of the magnet. Subsequently, this phenomenon was explained by Faraday's law of electromagnetic induction. This principle forms the basic working principle of the induction motor [8].

Single-phase induction motors are used in applications such a sheathing, ventilation, and air conditioning both in residential and industrial areas. These applications, especially those with lower nominal power, utilize fixed-speed drives. The single-phase induction motor runs approximately at its rated speed when it is directly connected to an ac supply. However, many applications need variable speed operation, which results in energy-saving and efficiency. In applications like the centrifugal pump, a 20% reduction in speed results ∼in 50% savings in energy. To control the speed of these motors, a motor drive, and control system with different methods can be used. An induction motor's speed can be changed by the supply frequency and by the number of poles of the motor. The control methods incorporate the change of frequency to control the motor speed [9].

I.2 Features and Types of Single-Phase Induction Motors

I.2.1 Features:

There are many benefits to single-phase motors. For starters, single-phase motors are less expensive to manufacture than most other types of motors. Single-phase motors typically require very little maintenance, don't often require repairs, and when they do, they are fairly easy to complete. Single-phase motors will last for years as well, and usually most failures from single-phase motors are a result of inappropriate application rather than a manufacturing defect from the motor itself [10].

I.2.2 Types of Single-Phase Induction Motors

Due to the rotating magnetic field of the stator, the induction motor becomes self-starting. There are many methods of making a single-phase induction motor as self-starting one.

Based on the starting method, single phase induction motors are basically classified into the following types.

- Split-phase motor
- Capacitor start motor

- Permanent capacitor run motor
- Capacitor start capacitor run motor
- Shaded pole motor

The rotating magnetic field is produced when there is minimum two alternating fluxes, having a phase difference between them.

The resultant of these two fluxes produces a rotating flux which rotates in space in one particular direction. So, in all the above methods or say types of induction motors, the additional flux other than main flux should have a certain phase difference with respect to main or stator flux.

If the phase difference is more, starting torque will be more. So, the starting torque of the motor depends on the rotating magnetic field and thereby, additional means (whether it is an auxiliary winding or anything).

Once the motor picks up the speed, this additional winding is removed from the supply. This is the basic principle followed by all these types of single-phase induction motors.Let us discuss these types of motors in brief.

I.2.2.1 Split Phase Induction Motor

Fig.I.1. a Split Phase Induction Motor

This is one of the most widely used types of single-phase induction motors. The essential parts of the split phase motor include main winding, auxiliary winding and a centrifugal switch.

This is the simplest arrangement to set up a rotating magnetic field by providing two winding on the same stator core as shown in figure.

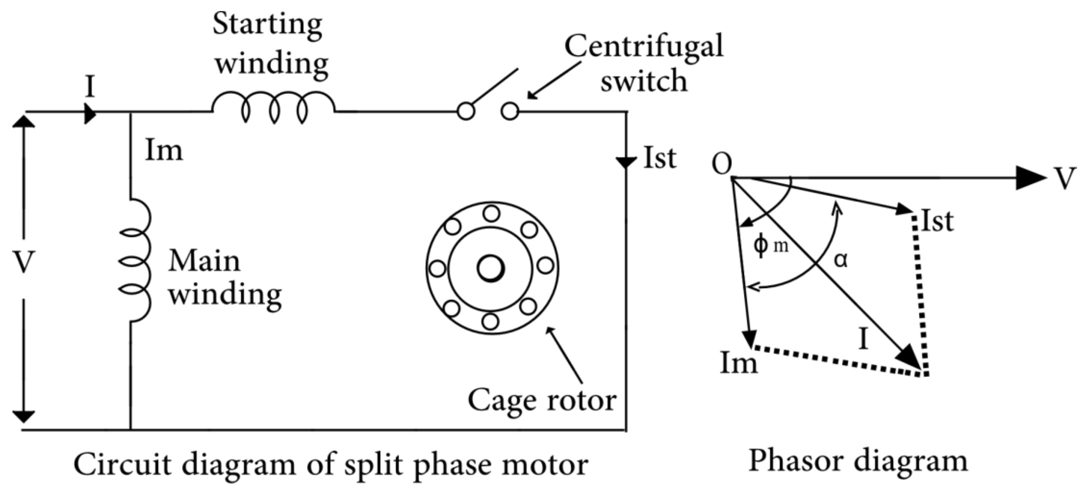


Fig.I.1. b Split-phase-induction-motor-circuit-diagram

The auxiliary or starting winding carries a series resistance such that its impedance becomes highly resistive in nature.

It is not wound identical to the main winding but contains fewer turns of much smaller diameter as compared to main winding.

This will reduce the amount of start current lags the voltage. The main winding is inductive in nature in such that current lags the voltage by some angle. This winding is designed for the operation of 75 % of synchronous speed and above.

These two windings are connected in parallel across the supply. Due to the inductive nature, current through main winding lags the supply voltage by a large angle while the current through starting winding is almost in phase with voltage due to resistive nature.

Hence there exists a phase difference between these currents and thereby phase difference between the fluxes produced by these currents. The resultant of these two fluxes produces rotating magnetic field and hence the starting torque.

The centrifugal switch is connected in series with the starting winding. When the motor reaches 75 to 80 percent of synchronous speed, the centrifugal switch is opened mechanically and thereby auxiliary winding is out of the circuit. Therefore, the motor runs only with main winding.

Split phase motors give poor starting torque due to small phase difference between main and auxiliary currents. Also, the power factor of these motors is poor. These are mainly used for easily started loads such as blowers, fans, washing machines, grinders, etc.

I.2.2.2 Capacitor Start Induction Motor

This motor is similar to the split phase motor, but in addition a capacitor is connected in series to auxiliary winding. This is a modified version of split phase motor.

Since the capacitor draws a leading current, the use of a capacitor increases the phase angle between the two currents (main and auxiliary) and hence the starting torque. This is the main reason for using a capacitor in single phase induction motors.

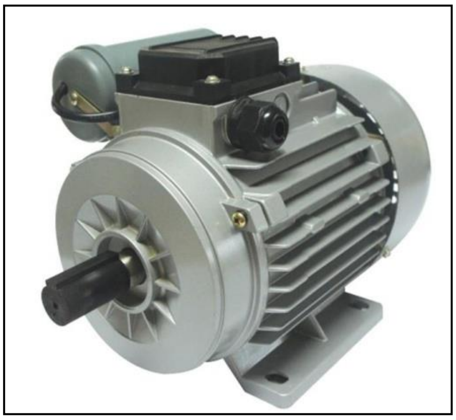


Fig.I.2. a Capacitor start induction motor

Here the capacitor is of dry-type electrolytic one which is designed only for alternating current use. Due to the inexpensive type of capacitors, these motors become more popular in wide applications.

These capacitors are designed for definite duty cycle, but not for continuous use. The schematic diagram of capacitor start motor is shown in figure below.

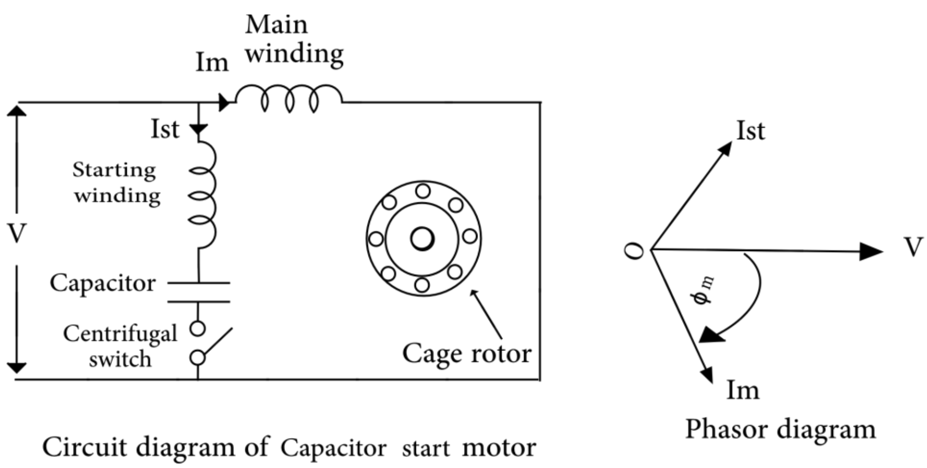


Fig.I.2. b Circuit diagram of capacitor start motor

The operation of this motor is similar to the split phase motor where the starting torque is provided by additional winding.

Once the speed is picked up, the additional winding along with capacitor is removed from the circuit with the help of centrifugal switch. But the difference is that the torque produced by this motor is higher than split phase motor due to the use of capacitor.

Due to the presence of a capacitor, the current through auxiliary winding will leads the applied voltage by some angle which is more than that of split case type.

Thus, the phase difference between main and auxiliary currents is increased and thereby starting torque.

The performance of this motor is identical to the split phase motor when it runs near full load RPM. Due to the capacitor, the inrush currents are reduced in this motor.

These motors have very high starting torque up to 300% full load torque. However, the power factor is low at rated load and rated speed.

Owing to the high starting torque, these motors are used in domestic as well as industrial applications such as water pumps, grinders, lathe machines, compressors, drilling machines, etc.

I.2.2.3 Permanent capacitor induction motor

This motor is also called as a capacitor run motor in which a low capacitor is connected in series with the starting winding and is not removed from the circuit even in running condition. Due to this arrangement, centrifugal switch is not required.

Fig.I.3. a Permanent capacitor induction motor

Here the capacitor is capable of running continuously. The low value capacitor produces more leading phase shift bur less total starting current as shown in phasor diagram.

Hence, the starting torque produced by these motors will be considerably lower than that of capacitor start motor. The schematic circuit of this motor is shown in figure below.

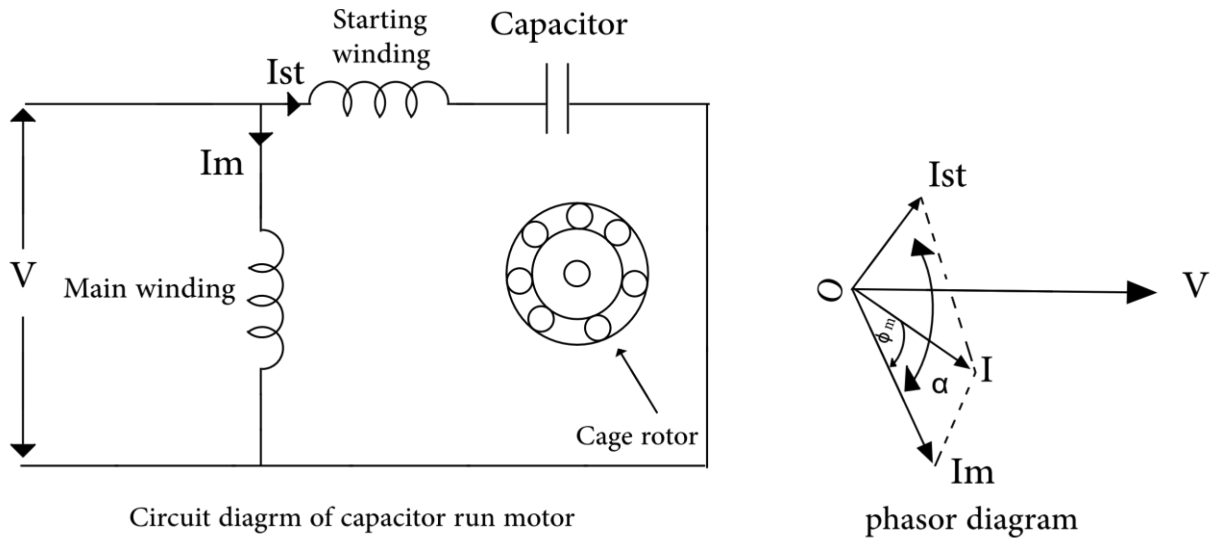


Fig.I.3. b Circuit diagram of capacitor run motor

In this, the auxiliary winding and capacitor remains in circuit permanently and produce an approximate two-phase operation at rated load point. This is the key strength of these motors.

This will result better power factor and efficiency. However, the starting torque is much lower in these motors, typically about 80 percent of full load torque.

Due to the continuous duty of auxiliary winding and capacitor, the rating of these components should withstand running conditions and hence permanent capacitor motor is more than equivalent split phase or capacitor start motors. These motors are used in exhaust and intake fans, unit heaters, blowers, etc.

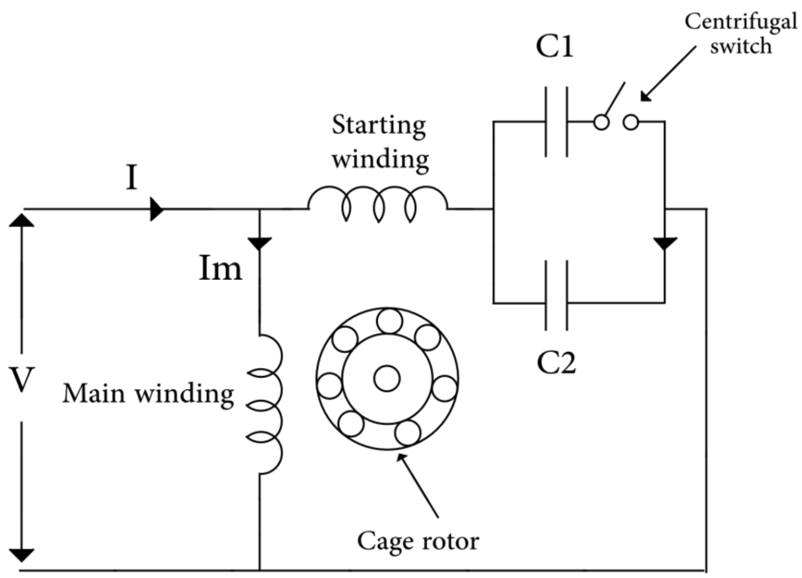
I.2.2.4 Capacitor start and capacitor run induction motor

These motors are also called as two-value capacitor motors. It combines the advantages of capacitor start type and permanent capacitor type induction motors.

This motor consists of two capacitors of different value of capacitance for starting and running. A high value capacitor is used for starting conditions while a low value is used for running conditions.

Fig.I.4. a Capacitor start and capacitor run induction motor

It is to be noted that this motor uses same winding arrangement as capacitor-start motor during startup and permanent capacitor motor during running conditions. The schematic arrangement of this motor is shown in figure below.



Circuit diagram of capacitor start capacitor run motor

Fig.I.4. b Circuit diagram of capacitor start capacitor run motor

At starting, both starting and running capacitors are connected in series with the auxiliary winding. Thus, the motor starting torque is more compared with other types of motors.

Once the motor reaches some speed, the centrifugal switch disconnects the starting capacitor and leaves the running capacitor in series with auxiliary winding.

Thus, both running and auxiliary windings remain during running condition, thereby improved power factor and efficiency of the motor.

These are the most commonly used single phase motors due to high starting torque and better power factor. These are used in compressors, refrigerators, air conditioners, conveyors, ceiling fans, air circulators, etc.

I.2.2.5 Shaded pole induction motor

This motor uses entirely different technique to start the motor as compared with other motors so far, we have discussed now.

This motor doesn’t use any auxiliary winding or even it doesn’t have a rotating field, but a field that sweeps across the pole faces is enough to drive the motor. So, the field moves from one side of the pole to another side of the pole.

Fig.I.5. a Shaded pole induction motor

Although these motors are of small ratings, inefficient and have low starting torque, these are used in a variety of applications due to its outstanding features like ruggedness, low initial cost, small size and simple construction.

A shaded pole motor consists of a stator having salient poles (or projected poles), and a rotor of squirrel cage type. In this, stator is constructed in a special way to produce moving magnetic field.

Stator poles are excited with its own exciting coils by taking the supply from a single-phase supply. A 4-pole shaded pole motor construction is given in below figure.

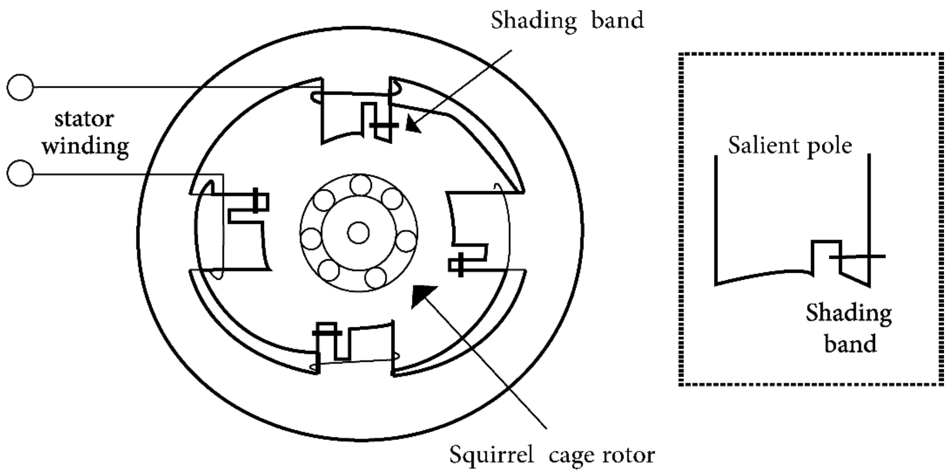


Fig.I.5. b Pole shaded pole motor construction

each salient pole is divided into two parts; shaded and un-shaded. A shading portion is a slot cut across the laminations at about one third distance from one edge, and around this a heavy copper ring (also called as shading coil or copper shading band) is placed.

This part where shading coil is placed is generally termed as shaded part of the pole and remaining portion is called as un-shaded part as shown in figure. Let us discuss how the sweeping action of the field takes place.

When an alternating supply is given to the stator coils, an alternating flux will be produced. The distribution of flux in the pole face area is influenced by the presence of copper shading band [11].

I.3 Construction of Single-phase induction motors

The single-phase induction machine is the most frequently used motor for refrigerators, washing machines, clocks, drills, compressors, pumps, and so forth.

I.3.1 Stator of single-phase induction motor

The single-phase motor stator has a laminated iron core with two windings arranged perpendicularly. One is the main and other is the auxiliary winding or starting winding [12].

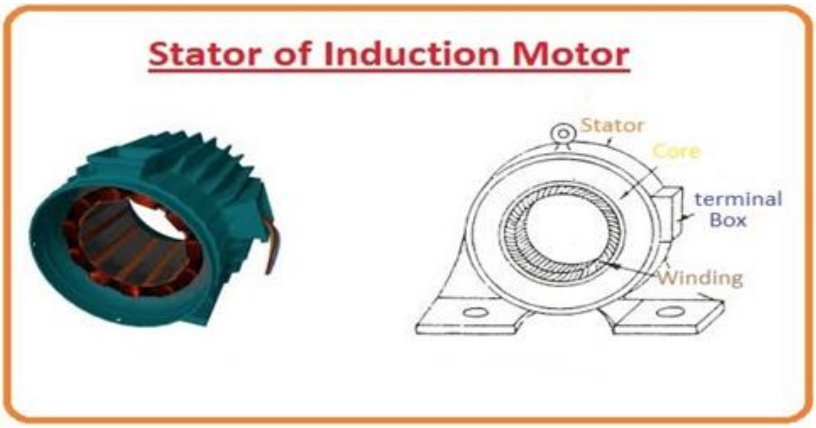


Fig.I.6 Stator of single-phase induction motor

I.3.2 Rotor of single-phase induction motor

- The rotor of the induction motor is its rotating part which rotates in the magnetic field. There are two types of rotors of single-phase induction motor first one is wound and the other is squirrel cage rotor.

  Let's discuss both types one by one.

I.3.2.1 Squirrel cage rotor of Single-phase induction motor

- This type of rotor comprises of a sequence of conductor bars which are arranged in a cylindrical shape structure in the different slots.
- All these are connected with the slip ring on both sides. This assembly is said to be squirrel cage because its shape is like a squirrel [13].

I.3.2.2 Wound rotor of single-phase induction motor

It is a cylindrical core type, designed with steel lamination includes slots for holding the wires that are equally spaced at 1200 separately & allied in a Y-configuration. The terminals of these windings are taken out to connect with the three slip rings along with brushes on the shaft [14].

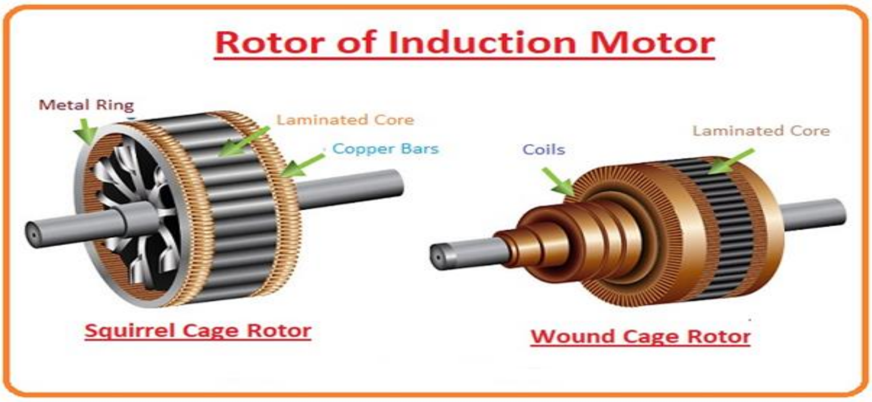


Fig.I.7 Types of rotors of single-phase induction motor

I.4 Working principle of the single-phase induction motor

In the normal operation case, the auxiliary winding of the SPIM is connected to the single-phase power supply at the starting moment, while is disconnected when the rotor reaches 75%–80% of the synchronous speed [15]. Therefore, only the main winding is connected to the power supply after the machine comes to the steady-state operation.

The following analyzes the performance of the SPIM when only the main winding is connected to the power supply. When the single-phase AC current $i = \sqrt{2Icos(wt)}$ is flowing through the main winding, a single-phase pulsating flux can be produced as,

$$F(x,t)=f\ cos\ (x)\ cos\ (wt) \quad \text{(I.1)}$$

where f is the instantaneous flux, F is the flux magnitude, x is the mechanical position inside the motor, ω is the electrical angular speed, and t is the time. It can be observed that the flux axis is fixed in the space, but the flux magnitude varies all the time (t) at different mechanical position (x).

By adopting the trigonometric Eq. (I.1) can be rewritten as,

$$f(x,t) = \frac{F}{2}cos(x - wt) + \frac{F}{2}cos(x + wt) \quad \text{(I.2)}$$

According to Eq. (I.2), it can be seen that the pulsating flux in Eq. (I.1) can also be considered as the combination of the two rotating fluxes in opposite directions, one is the positive rotating flux as,

$$f_{+}(x,t) = \frac{F}{2}cos(x + wt) \quad \text{(I.3)}$$

And the other one is the negative rotating flux as,

$$f_{-}(x,t) = \frac{F}{2}cos(x + wt) \quad \text{(I.4)}$$

Based on these explanations, one conclusion can be obtained, i.e., one pull-sating flux with sinusoidal distribution in space and simultaneously with sinusoidal time-varying magnitude, can be divided into two rotating fluxes with the same rotating speed and magnitude but in opposite directions. The magnitude of each rotating flux is the half of the original one.

Therefore, based on this conclusion, the SPIM can be regarded as two three- phase induction machines working in a coaxial connection. They are injected with three-phase current of the same magnitude but opposite phase sequence. As a result, two rotating fluxes are produced with the same magnitude but in opposite rotating directions, the positive direction rotating flux produces the positive direction electromagnetic torque T +, while the negative direction rotat- ing flux produces the negative direction electromagnetic torque T- as it is shown in figure.I.8, figure.I.9 shows the mechanical character of the SPIM when only the main winding is connected to the single-phase power supply. It can be observed that the equivalent two three-phase induction motors have symmetric speed n-torque T performance as shown in dotted lines T- and T +. The torque of the SPIM T_{SPIM} can be obtained as the sum of T- and T +. Several conclusions can be drawn in the following based in figure. I.9.

(1) In the case of n = 0, T- and T + have the same value but in opposite direction and the total torque of SPIMT_{SPIM} is equal to zero, indicating zero starting torque for the SPIM, and the motor cannot start on its own when only the main winding is connected to the power supply.

(2) The negative torque T- reduces the total torque T_{SPIM} and the output power, thus a lower motor efficiency can be the consequence.

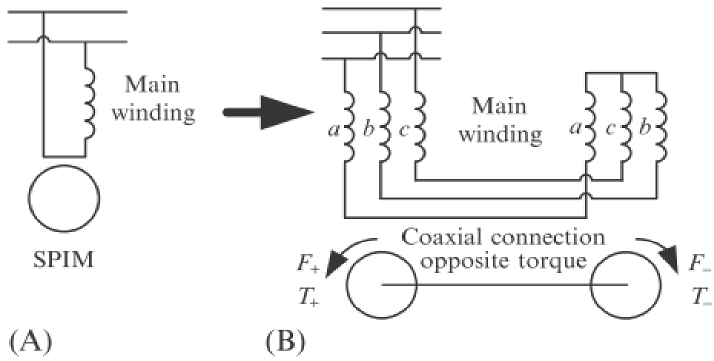


Fig.I.8 The single-phase induction motor (SPIM)

In figure.I.8 shows the single-phase induction motor (SPIM) is equivalent as two three-phase induction motors in a coaxial connection, but opposite direction torque. (A) Conventional SPIM; (B) two three-phase induction motors.

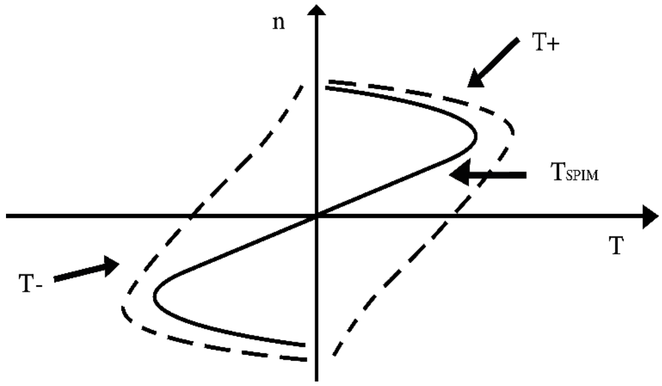


Fig.I.9 Mechanical characteristics (torque-speed) of the SPIM

Figure.I.9 presents the mechanical characteristics (torque-speed) of the SPIM when only the main winding is connected to the single-phase power supply.

In order to solve the starting problem of the SPIM, besides the main winding, an auxiliary winding is added with a series connection of a starting resistor, a start- ing capacitor, or using both starting and running capacitors, as shown in figure.I.10 [16].

Figure.I.10. A show the schematics of the SPIM with auxiliary winding includ- ing the starting resistor. Since the starting resistance R_{st} is larger than the con-ductance of the auxiliary winding, the phase angle θ_a is small. The phase angles

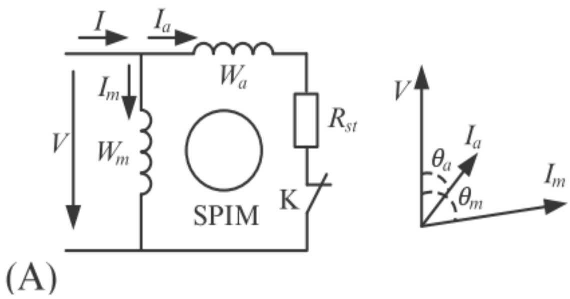


Fig.I.10. a Schematics of the SPIM with both main winding and auxiliary winding

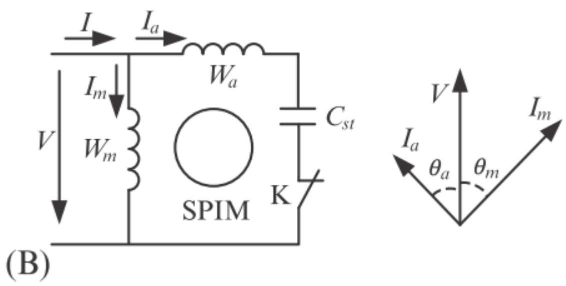


Fig.I.10. b Shows the schematics of the SPIM with the starting capacitor C_{St} in the auxiliary winding.

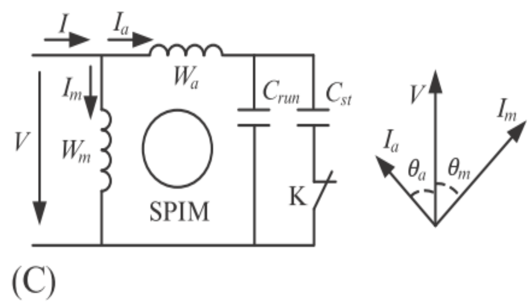


Fig.I.10.c Shows the schematics of the SPIM with both starting capacitor C_{Stand} running capacitor C_{run} in the auxiliary winding.

Figure.I.10. a shows Schematics of the SPIM with both main winding and auxiliary winding, (A) starting resistor; (B) starting capacitor; (C) starting capacitor and running capacitor. difference between θ a and θ m is smaller than 90 degrees, thus the starting torque is small and it is relatively difficult for the motor to start.

Figure.I.10. b shows the schematics of the SPIM with the starting capacitor C_{St} in the auxiliary winding. Due to the adoption of C_{St}, the auxiliary winding cur- rent I_a is phase leading θ_a of the supply voltage V. By appropriately choosing the starting capacitance, $\theta_a+\theta_m= 90$ degrees can be achieved, thus giving a suffi- cient starting torque and also a smaller starting current.

Figure.I.10.c shows the schematics of the SPIM with both starting capacitor $C_{St}$and running capacitor C_{run} in the auxiliary winding. This case is similar to the case in figure.I.10. B, but with an additional running capacitor $C_{run}$to ensure a better operation efficiency, power factor, and output power.

In conclusion of these discussions, the main winding and the auxiliary winding are displaced at ~ 90 electrical degrees, the different parameters of both windings determine that the currents flowing through these windings having different phase angles, and then an oval airgap flux can be produced consequently.

This oval flux can be divided into two rotating fluxes with opposite directions and different values, ie., $F_+>F_-$, so the positive and negative direction torques are different, ie., $T_+>T_-$, and as a result, the SPIM is able to start up with the implementation of the auxiliary winding.

I.5 Equivalent circuit of single-phase induction motor

Equivalent circuit for single-phase induction motor There are several types:

* Without Core Loss

* With Core Loss

I.5.1 Equivalent circuit of a single-phase induction motor without core loss

A single-phase motor may be looked upon as consisting of two motors, having a common stator winding, but with their respective rotors revolving in opposite directions. The equivalent circuit of such a motor based on double-field revolving theory is shown in Figure.I.11. Hence, the single-phase motor has been imagined to be made-up of (i) one stator winding and (ii) two imaginary rotors. The stator impedance is $Z = R_1 j.\ X_1$. The impedance of each rotor is (r_2. j.x_2) where r_2 and x_2 represent half the actual rotor values in stator terms (ie .x_2 stands for half the standstill reactance of the rotor, as referred to stator). Since iron loss has been neglected, the exciting branch is shown consisting of exciting reactance only. Each rotor has been assigned half the magnetizing reactance (i_{exm} represents half the actual reactance). The impedance of 'forward running' rotor is

$$Z_{f}=\frac{jx_0(\frac{r2}{s}+jx_2)}{\frac{r2}{s}+j(x_0+x_2)} \quad (I.5)$$

and it runs with a slip of s. The impedance of 'backward' running rotor is,

$$Z_{b}=\frac{jx_m(\frac{r2}{2-s}+jx_2)}{\frac{r2}{2-s}+j(x_m+x_2)} \quad (I.6)$$

and it runs with a slip of (2 − s). Under standstill conditions, $V_f = V_b$, but under running conditions V_f is almost 90 to 95% of the applied voltage.

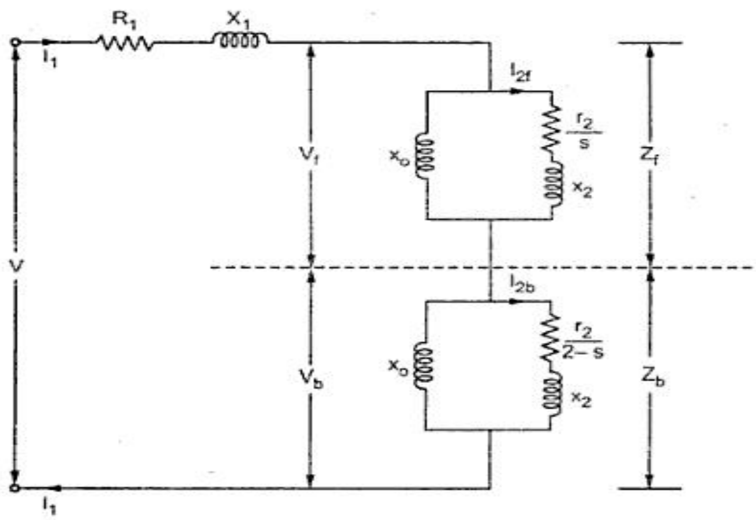


Fig.I.11 Equivalent circuit without core loss

I.5.2 Equivalent circuit–with core loss

The core loss can be represented by an equivalent resistance which may be connected either in parallel or in series with the magnetising reactance as shown in figure.I.12. Since under running conditions V_f is very high (and V_b is correspondingly, low) most of the iron loss takes place in the 'forward motor' consisting of the common stator and forward-running rotor. Core-loss current I_w = core loss / Vf . Hence, half value of core-loss equivalent resistance is $r_C = V_f / I_w$. As shown in Fig.I.12 a, r_C has been connected in parallel with x_m in each rotor [17].

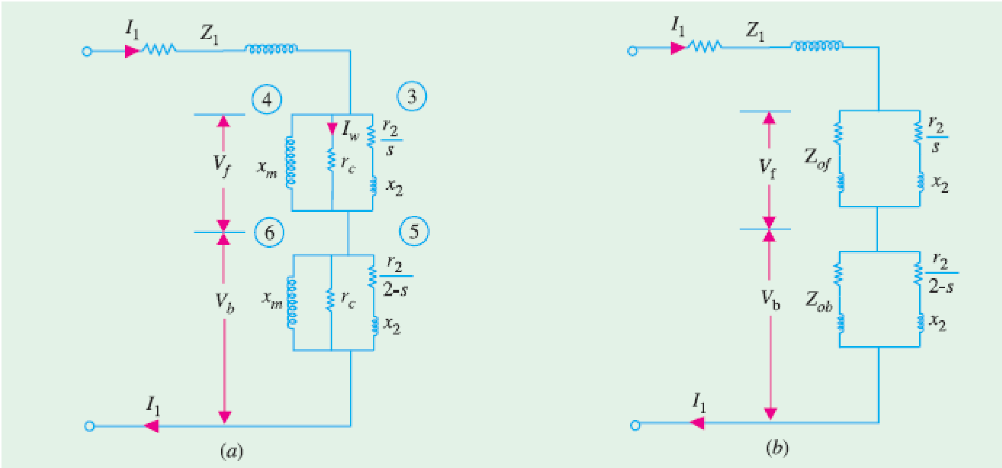


Fig.I.12 Equivalent circuit–with core loss

I.6 Capacitor start capacitor run motor

The Capacitor Start Capacitor Run Motor has a cage rotor, and its stator has two windings known as Main and Auxiliary Windings. The two windings are displaced 90 degrees in space. There are two capacitors in this method one is used at the time of the starting and is known as starting capacitor. The other one is used for continuous running of the motor and is known as run capacitor.

So, this motor is named as capacitor start capacitor run motor. This motor is also known as Two value capacitor Motor. Connection diagram of the Two valve capacitor motor is shown below

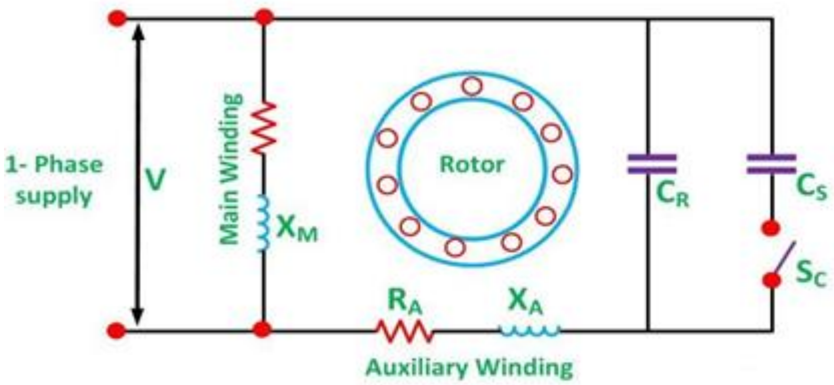


Fig.I.13 Capacitor start capacitor run motor.

There are two capacitors in this motor represented by C_S and C_R. At the starting, the two capacitors are connected in parallel. The Capacitor Cs is the Starting capacitor is short time rated. It is almost electrolytic. A large amount of current id required to obtain the starting torque. Therefore, the value of the capacitive reactance X should be low in the starting winding. Since,

$$X_A = 1/(2.\pi.f.C_A) \quad \text{(I.7)}$$

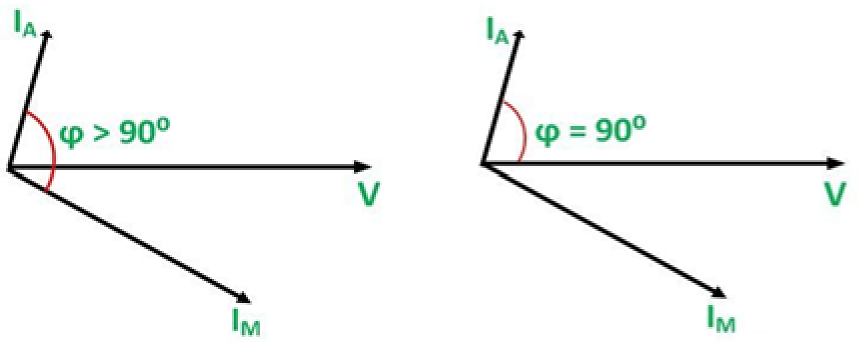
the value of the starting capacitor should be large.

The rated line current is smaller than the starting current at the normal operating condition of the motor. Hence, the value of the capacitive reactance should be large. Since

$$X_R = 1/(2\pi f C_R) \quad \text{(I.8)}$$

the value of the run capacitor should be small.

As the motor reaches the synchronous speed, the starting capacitor Cs is disconnected from the circuit by a centrifugal switch Sc. The capacitor C_R is connected permanently in the circuit and thus it is known as RUN Capacitor. The run capacitor is long time rated and is made of oil filled paper [18].



(a) **(b)**

Fig.I.14 (b) shows the phasor diagram when at the starting both the capacitor are in the circuit and the phasor when the starting capacitor is disconnected

Fig.I.14 (a) shows the phasor diagram when at the starting both the capacitor are in the circuit and $\phi > 90^\circ$. (b) shows the phasor when the starting capacitor is disconnected, and ϕ becomes equal to 90˚.

I.7 Torque-speed curve characteristic

In single phase induction motor is similar in construction to that of a poly phase induction motor with difference that its stator has only one winding. If such a stator is supplied with single phase alternating current, the field produced by it changes in magnitude and direction sinusoidally.

Thus, the magnetic field produced in the air gap is alternating one but not rotating as a result these kinds of motors are NOT SELF-STARTING Figure.I.15 show the torque–speed characteristic of single-phase induction motor.

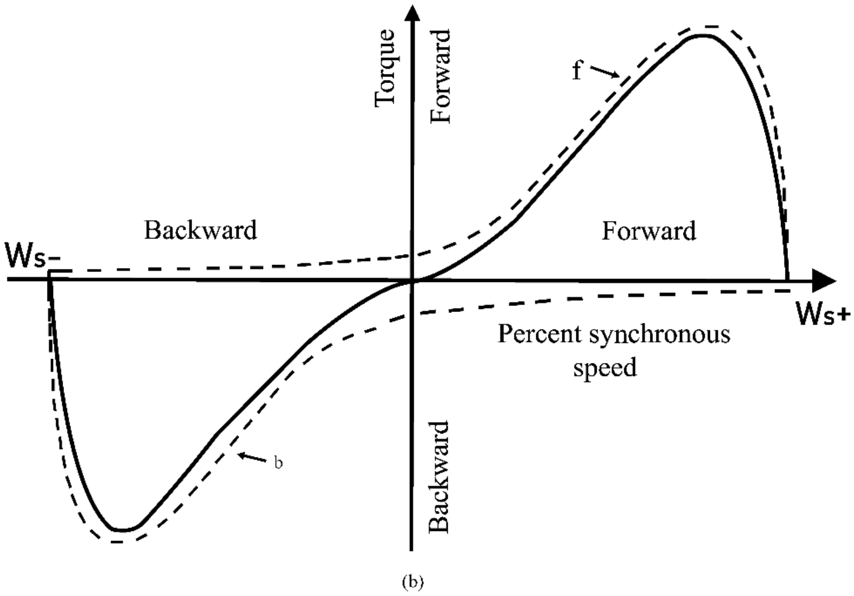


Fig.I.15 Torque-speed characteristics

Such an alternating filed is equivalent to two field of equal magnitude rotating in opposite direction at equal speed as explained below [19].

I.8 Comparison between Single Phase and Three Phase Induction Motors

1. Single phase induction motors are simple in construction, reliable and economical for small power rating as compared to three phase induction motors.
2. The electrical power factor of single-phase induction motors is low as compared to three phase induction motors.
3. For the same size, the single-phase induction motors develop about 50% of the output as that of three phase induction motors.
4. The starting torque is also low for single phase asynchronous motors (induction motor).
5. The efficiency of single-phase induction motors is less compared to that of three phase induction motors [20].

I.9 Applications of Single-Phase Induction Motor

Depending on the type of machine and application you require, some motors will work better than others. If you are running smaller equipment that requires less horsepower, a single-phase motor will work best for your needs.

- ✓ These are some advantages of the single-phase induction motor that are described here.
- ✓ The Single-phase motor is the main part of the different pumps used in our homes and industries.
- ✓ Different compressors also used a single-phase induction motor.
- ✓ The ceiling fans in our homes also consists of the single-phase motor.
- ✓ Different juicer machines and blenders are consisting of the single-phase induction motor
- ✓ Different toys and robots also used induction motors for their movements.
- ✓ Vacuum cleaners also consist of the induction motors.
- ✓ Drilling machines are also used single-phase induction motor for their operation [21].

Single-phase induction motors are not self-starting without an auxiliary stator winding driven by an out of phase current. The auxiliary winding of a permanent-split capacitor motor has a capacitor in series with it during starting and running. Single-phase motors don’t create a magnetic field on their own, so they must be switch activated in order to make the rotor move. This type of motor is only able to operate once the rotor is set in motion and a magnetic field is created [22].

I.10 Advantages and Disadvantages of Single-Phase Motors

Each type of motor has its own unique advantages and disadvantages .

If you are thinking about using a single-phase motor in an application, we are sure that you are wondering whether you’ve made the right choice or not as there are a handful of other motors available that may be able to perform the same or a similar function, this wonderment is not unfounded. We have outlined some of the main advantages and disadvantages that you should be aware of when using such a unit [23].

I.10.1 Advantages

There are many benefits to single-phase motors. For starters, single-phase motors are less expensive to manufacture than most other types of motors. Single-phase motors typically require very little maintenance, don’t often require repairs, and when they do they are fairly easy to complete. Single-phase motors will last for years as well, and usually most failures from single-phase motors are a result of inappropriate application rather than a manufacturing defect from the motor itself .

I.10.2 Disadvantages

While single-phase motors are simple mechanics-wise, this does not mean that they are perfect and nothing can go wrong. On occasion they have been known to run slow, overheat, or even fail to start, overheat or run slow. If a shock is felt while touching the motor, there is a problem with the motor that will need to be repaired immediately [24].

I.11 Conclusion

In this chapter, we have presented the concepts essential to the understanding of the operation of the single-phase induction motor and its working principle. Furthermore, the five types of this machine and its equivalent circuits. In addition, the torque-speed characteristics of the single-phase induction motor have been explained.

Ultimately, the fields of application of single-phase induction motors and their advantages and disadvantages have been given.

CHAPTER II

Modeling of the single-phase induction motor connected to the inverter

II.1 Introduction

In this chapter, our study is broken down into two parts, the first part is presented the Modeling of single-phase induction motor and what we will see in this research and the second part built around modeling of inverter.

Dynamic model of machine describes the transient and the steady state behavior of the induction machine. This model can be used to simulate the asynchronous motor drives and evaluate their transient performances including that of using the scalar control techniques. This model is also used when developing high performance control techniques for the asynchronous motor drives such as *V/f* control, vector control or direct control. During start-up and other motoring operations, this motor draws large currents, produce oscillatory torques, voltage dips and can even generate harmonics in the power system. So, it is important to be able to model the single-phase induction motor in order to predict these phenomena. Various models will be developed and the d-q axis model for the study of transient behavior will be tested and proven to be reliable and accurate.

It has been shown that the speed of rotation of the d, q axis can be arbitrary although there are three preferred speeds or reference frames [25].

This part introduces the modeling technique for the inverter model by finding the relationship of the output in terms of the input, finding mathematical formulas describing the transient voltage and current, for applied PWM control.

II.2 Model of single-phase induction motor with permanent capacitor

Single phase induction motor is widely used in household applications (washing machine, ventilator, etc.) and industrial (driving pumps, conditioners air ...).

The single-phase induction motor is supplied by a single-phase AC network. The circuits Magnetic stator and rotor as well as the motor cage are identical to those of the polyphase motor.

The stator has two windings, a so-called working main winding (E.P) which generally occupies 2/3 (or 1/2) of the stator slots and an auxiliary winding (E.A) which occupies the remainder of the slots.

For the modeling of this kind of motor, we adopt the same simplifying assumptions than in the case of a three-phase asynchronous motor studied previously. With these assumptions, referring to the equivalent diagram in figure.II.1.

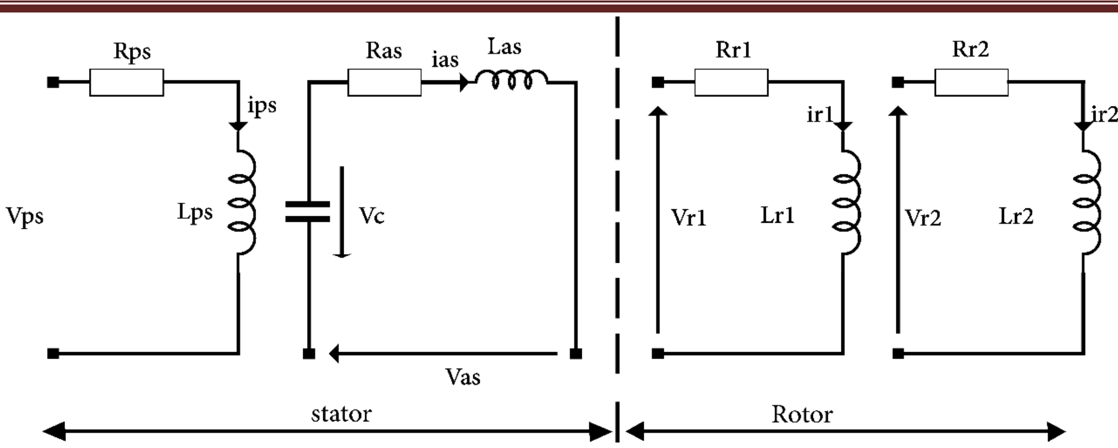


Fig.II.1 Equivalent diagram of a single-phase asynchronous motor with capacitor Permanent.

With:

L_{ps}, L_{as}: The specific inductances of the main and auxiliary phase.

L_{r1}, L_{r2}: The specific inductances of the two fictitious rotor phases.

R_{ps}, R_{as}: The resistances of the main and auxiliary phase of the stator.

R_{r1}, R_{r2}: The fictitious resistances of the two rotor phases.

II.3 Real Axis Model of single-phase induction motor

Fig.II.2 represents the stator and rotor windings of a single-phase induction motor permanent capacitor.

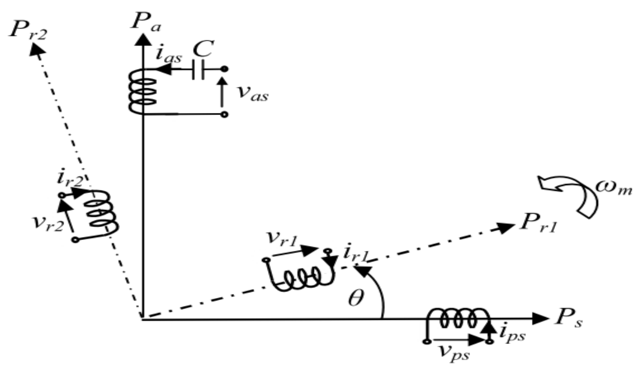


Fig.II.2 Real model of a single-phase asynchronous motor with permanent capacitor

II.3.1 Voltage equations

Based on the equivalent diagram of the single-phase asynchronous capacitor motor permanent represented by figure.II.1 and on the representation of its different winding illustrated by figure.II.2, the electrical operating equations of this motor are written as following:

Voltage equations of the main and the auxiliary winding in the stator:

$$v_{ps} = R_{ps}\, i_{ps} + \frac{d\psi_{ps}}{dt} \qquad (II.1)$$

$$v_{as} = R_{as}\, i_{as} + \frac{d\psi_{as}}{dt} + v_c \qquad (II.2)$$

Equation of the rotor voltage:

$$v_{r1} = R_{r1} i_{r1} + \frac{d\psi_{r1}}{dt} \qquad (II.3)$$

$$v_{r2} = R_{r2} i_{r2} + \frac{d\psi_{r2}}{dt} \qquad (II.4)$$

In matrix form :

$$[v_{pas}] = [R_{pas}][i_{pas}] + \frac{d}{dt}[\psi_{pas}] + [v_c] \qquad (II.5)$$

$$[v_{r12}] = [R_{r12}][i_{r12}] + \frac{d}{dt}[\psi_{r12}] \qquad (II.6)$$

So:

$$[v_{pas}] = [v_{ps} \quad v_{as}]^T \qquad (\mathrm{II}.7)$$

$$[i_{pas}] = [i_{ps} \quad i_{as}]^T \qquad (\mathrm{II}.8)$$

$$[v_{r12}] = [v_{r1} \quad v_{r2}]^T \qquad (\mathrm{II}.9)$$

$$[i_{r12}] = [i_{r1} \quad i_{r2}]^T \qquad (\mathrm{II}.10)$$

$$[v_c] = [0 \quad v_c]^T \qquad (\mathrm{II}.11)$$

$$[R_{pas}] = \begin{bmatrix} R_{ps} & 0 \\ 0 & R_{as} \end{bmatrix} \qquad (\mathrm{II}.12)$$

$$[R_{r12}] = \begin{bmatrix} R_{r1} & 0 \\ 0 & R_{r2} \end{bmatrix} \qquad (\mathrm{II}.13)$$

II.3.2 Flux equations

Based on the representation of the windings of this type of single-phase motor of the figure.II.2, the flow equations for this engine are written:

$$\begin{cases} \psi_{ps} = L_{ps} i_{ps} + M_{pr} i_{r1} \cos\theta - M_{pr} i_{r2} \sin\theta \\ \psi_{as} = L_{as} i_{as} + M_{ar} i_{r1} \sin\theta + M_{ar} i_{r2} \cos\theta \\ \psi_{r1} = L_{r1} i_{r1} + M_{pr} i_{ps} \cos\theta + M_{ar} i_{as} \sin\theta \\ \psi_{r2} = L_{r2} i_{r2} - M_{pr} i_{ps} \sin\theta + M_{ar} i_{as} \cos\theta \end{cases} \quad \text{(II.14)}$$

In matrix form

$$\begin{bmatrix} \psi_{ps} \\ \psi_{as} \\ \psi_{r1} \\ \psi_{r2} \end{bmatrix} = \begin{bmatrix} L_{ps} & 0 & M_{pr} \cdot \cos\theta & -M_{pr} \cdot \sin\theta \\ 0 & L_{as} & M_{ar} \cdot \sin\theta & M_{ar} \cdot \cos\theta \\ M_{pr} \cdot \cos\theta & M_{ar} \cdot \sin\theta & L_{r1} & 0 \\ -M_{pr} \cdot \sin\theta & M_{ar} \cdot \cos\theta & 0 & L_{r2} \end{bmatrix} \begin{bmatrix} i_{ps} \\ i_{as} \\ i_{r1} \\ i_{r2} \end{bmatrix} \quad \text{(II.15)}$$

θ: angle between the stator and the rotor.

ψ_{ps}, ψ_{as}: The total flows passing through the main and auxiliary winding.

ψ_{r1}, ψ_{r2}: The total fluxes passing through the fictitious rotor windings.

M_{pr}: The amplitude of the mutual induction between the main winding and a windingfictitious rotor.

M_{ar}: The amplitude of the mutual induction between the auxiliary winding and a windingfictitious rotor.

II.3.3 Expression of the electromagnetic torque

$$C_{et} = \frac{P}{2} [I]^T \left\{ \frac{d}{d\theta} [L] \right\} [I] \quad \text{(II.16)}$$

With

$$[I]^T = [i_{ps} \quad i_{as} \quad i_{r1} \quad i_{r2}] \quad \text{(II.17)}$$

$$[L] = \begin{bmatrix} [L_s] & [M_{sr}] \\ [M_{sr}] & [L_r] \end{bmatrix} \quad \text{(II.18)}$$

$$[M_{sr}] = \begin{bmatrix} M_{pr} \cdot \cos\theta & -M_{pr} \cdot \sin\theta \\ M_{ar} \cdot \sin\theta & M_{ar} \cdot \cos\theta \end{bmatrix} \quad \text{(II.19)}$$

$$[M_{sr}]^T = \begin{bmatrix} M_{pr} \cdot cos\,\theta & M_{ar} \cdot sin\,\theta \\ -M_{pr} \cdot sin\,\theta & M_{ar} \cdot cos\,\theta \end{bmatrix} \quad (II.20)$$

$$[L_s] = \begin{bmatrix} L_{ps} & 0 \\ 0 & L_{as} \end{bmatrix} \quad (II.21)$$

$$[L_r] = \begin{bmatrix} L_{r1} & 0 \\ 0 & L_{r2} \end{bmatrix} \quad (II.22)$$

So, after direct calculation, the expression of the electromagnetic torque becomes:

$$C_{et} = P \cdot \left[-M_{pr}(i_{r1} \cdot sin\,\theta + i_{r2} cos\,\theta)i_{ps} + M_{ar} \cdot (i_{r1} \cdot cos\,\theta + i_{r2} \cdot sin\,\theta)i_{as}\right] \quad (II.23)$$

II.3.4 Mechanical equation

The fundamental law of dynamics applied to the rotor shaft of the motor and any attached load gives [26].

$$J\frac{d\Omega_m}{\partial t} = C_{em} - f_v\Omega_m - C_r \quad (II.24)$$

By replacing C_{et} in (II. 21)by its expression given by (II. 20)we obtain:

$$\frac{d\Omega_m}{dt} = \frac{P}{J}\left[-M_{pr}(i_{r1} \cdot sin\,\theta + i_{r2}\,cos\,\theta)i_{ps} + M_{ar}(i_{r1}\,cos\,\theta + i_{r2}\,sin\,\theta)i_{as}\right] - f_v\frac{\Omega_m}{J} - \frac{C_r}{J}\Omega_r$$

(II. 22)

J: The moment of inertia of the rotor and any load attached to it;

f_v: The viscous friction coefficient of the engine;

C_r : The resistive torque of the load.

II.4 Park model of the single-phase permanent capacitor motor

The coefficients of the differential equations thus obtained are variable and the analytical solution of the system comes up against practically insurmountable difficulties. To obtain a system of equations with constant coefficie27nts, the stator and rotor windings are transformed into orthogonal windings according to the park transformation Eq.II.23.

Park's matrix in the case of the asynchronous motor single-phase is defined by

$$[P(\theta_a)] = \begin{bmatrix} \cos\theta_a & \sin\theta_a \\ -\sin\theta_a & \cos\theta_a \end{bmatrix} \quad (II.25)$$

For the transformation of the stator winding, we have

$\theta_a = \theta_s$ (II.26)

$[V_{sdq}] = [P(\theta_s)].[V_{pas}]$ (II.27)

$$[P(\theta_s)] = \begin{bmatrix} \cos\theta_s & \sin\theta_s \\ -\sin\theta_s & \cos\theta_s \end{bmatrix} \quad \text{(II.28)}$$

For the transformation of the rotor winding, we have

$\theta_a = \theta_r$ (II.29)

$[V_{rdq}] = [P(\theta_r)].[V_{r12}]$ (II.30)

$$[P(\theta_r)] = \begin{bmatrix} \cos\theta_r & \sin\theta_r \\ -\sin\theta_r & \cos\theta_r \end{bmatrix} \quad \text{(II.31)}$$

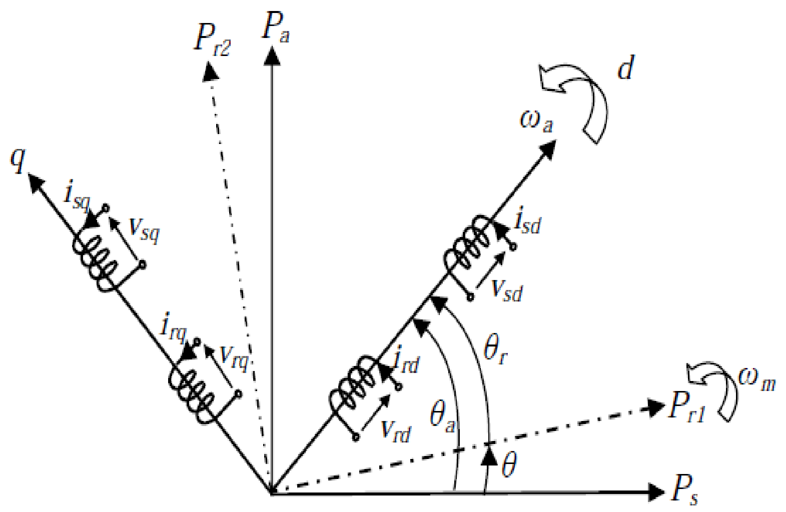


Fig.II.3 Representation of the Park transformation of the single-phase motor Permanent capacitor

In our case, the frame of reference must be fixed in the part where the asymmetry is found, the frame of reference will be linked to the stator, $\theta_a = 0$, that is the system *(d, q)* will be merged with the axis (P_s, P_a) It follows that

$$\theta = -\theta_r, \frac{d\theta_r}{dt} = -\frac{d\theta}{dt} = -\omega r = \omega_m \quad \text{(II.32)}$$

Therefore

$$[P(0)] = [P_s] = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad \text{(II.33)}$$

$$[P(\theta_r)] = [P_r] = \begin{bmatrix} \cos\theta_r & -\sin\theta_r \\ \sin\theta_r & \cos\theta_r \end{bmatrix} \quad \text{(II.34)}$$

II.4 .1 Voltage equations

By multiplying the expression (II. 5) by *[Ps]* given by the equation (II.33) we obtain

$$[v_{pas}] = [R_{pas}].[i_{pas}] + \frac{d}{dt}[\psi_{pas}] + [v_c] \quad \text{(II.35)}$$

$$[P_s][V_{pas}]=[R_{pas}][P_s][i_{pas}]+[P_s]\frac{d}{dt}[\psi_{pas}]+[P_s][V_c] \quad \text{(II.36)}$$

$$[V_{sdq}]=[R_{pas}]\ [i_{sdq}]+[P_s]\frac{d}{dt}\{\ [P_s]^{-1}\ [\psi_{sdq}]\ \}\ [V_{cdq}] \quad \text{(II.37)}$$

From were

$$[V_{sdq}]=[R_{pas}].\ [i_{sdq}]+\frac{d}{dt}\ [\psi_{sdq}]+\ [V_{cdq}] \quad \text{(II.38)}$$

And

$$[V_{sdq}]=\ [V_{sd}V_{sq}]^T;\ [i_{sdq}]=\ [i_{sd}i_{sq}]^T;[\ \psi_{sdq}]=[\ \psi_{sd}\psi_{sq}]^T \quad \text{(II.39)}$$

$$[v_{r12}] = [R_{r12}].[i_{r12}] + \frac{d}{dt}[\psi_{r12}] \quad \text{(II.40)}$$

For the rotor equation, by multiplying the expression (II.40) by *[Pr]* given by the equation (II.38), we obtain

$$[V_c]=\ [V_{cd}V_{cq}]^T=[0\ \ V_{cq}]^T \quad \text{(II.41)}$$

$$[V_{rdq}]=\ [R_{r12}]\ [P_r]\ [i_{r12}]\ +\ [P_r]\frac{d}{dt}\ [\psi_{r12}\ ] \quad \text{(II.42)}$$

$$[V_{rdq}]=\ [R_{r12}].[i_{rdq}]+\ [P_r]\ \frac{\partial}{\partial t}\ \{\ [P_r]^{-1}\ [\psi_{rdq}]\ \} \quad \text{(II.43)}$$

$$[V_{rdq}]=\ [R_{r12}].[i_{rdq}]+\ \frac{d}{dt}\ [\psi_{rdq}]\ +\ [P_r\ ]\ \{\ \frac{\partial}{\partial t}\ \ [P_r]^{-1}\}\ [\psi_{rdq}] \quad \text{(II.44)}$$

We show that

$$[P_r]\ \{\ \frac{d}{dt}\ \ [P_r]^{-1}\}\ =\frac{d\theta}{dt}\begin{bmatrix}0 & -1\\ 1 & 0\end{bmatrix} = -\frac{d\theta}{dt}\begin{bmatrix}0 & -1\\ 1 & 0\end{bmatrix} \quad \text{(II.45)}$$

Which give

$$[V_{rdq}]=\ [R_{r12}].\ [i_{rdq}]+\ \frac{d}{dt}\ [\psi_{rdq}]\ -\ \omega_m\begin{bmatrix}0 & -1\\ 1 & 0\end{bmatrix}[\psi_{rdq}] \quad \text{(II.46)}$$

With

$$[V_{rdq}]=\ [V_{rd}V_{rq}]^T;\ [i_{rdq}]=\ [i_{rd}i_{rq}]^T;[\ \psi_{rdq}]=[\ \psi_{rd}\psi_{rq}]^T \quad \text{(II.47)}$$

In matrix form

$$\begin{bmatrix} V_{sd} \\ V_{sq} \\ V_{rd} \\ V_{rq} \end{bmatrix} = \begin{bmatrix} R_{ps} & 0 & 0 & 0 \\ 0 & R_{as} & 0 & 0 \\ 0 & \omega_m M_{ar} & R_{r1} & \omega_m L_{r2} \\ -\omega_m M_{pr} & 0 & -\omega_m L_{r1} & R_{r2} \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} + \begin{bmatrix} L_{ps} & 0 & M_{pr} & 0 \\ 0 & L_{as} & 0 & M_{ar} \\ M_{pr} & 0 & L_{r1} & 0 \\ 0 & M_{ar} & 0 & L_{r2} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} + \begin{bmatrix} 0 \\ V_c \\ 0 \\ 0 \end{bmatrix} \quad (II.48)$$

II.4.2 Flux equations

The flux link vector linked to the currents in a frame of reference linked to the stator is as follows:

$$\begin{bmatrix} \psi_{sd} \\ \psi_{sq} \\ \psi_{rd} \\ \psi_{rq} \end{bmatrix} = \begin{bmatrix} L_{ps} & 0 & M_{pr} & 0 \\ 0 & L_{as} & 0 & M_{ar} \\ M_{pr} & 0 & L_{r1} & 0 \\ 0 & M_{ar} & 0 & L_{r2} \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} \quad (II.48)$$

After transformation of the system (II.48),the rotor winding being short-circuited, the following equations are obtained

$$\begin{cases} V_{sd} = R_{ps} i_{sd} + \frac{d}{dt}\psi_{sd} \\ V_{sq} = R_{ps} i_{sq} + \frac{d}{dt}\psi_{sq} + V_c \\ 0 = R_{r1} i_{rd} + \frac{d}{dt}\psi_{rd} + \omega_m \psi_{rq} \\ 0 = R_{r2} i_{rq} + \frac{d}{dt}\psi_{rq} + \omega_m \psi_{rd} \end{cases} \quad (II.49)$$

By eliminating $i_{rq} i_{rq}$ and $\psi_{sd}\psi_{sq}$from relation (II. 49) and this is based on relation (II. 46) and also L_{r1}=L_{r2}=L_r et R_{r1}=R_{r2}=R_r and R_{r1}=R_{r2}=R_r which is moreover the case in a squirrel cage motor, we get

$$\begin{cases} V_{sd} = R_{ps} i_{sd} + \frac{M_{pr}}{L_r}\frac{d}{dt}\psi_{rd} + \left(L_{ps} - \frac{M_{pr}^2}{L_r}\right)\frac{di_{sd}}{dt} \\ V_{sq} = R_{ps} i_{sq} + \frac{M_{ar}}{L_r}\frac{d}{dt}\psi_{rq} + \left(L_{as} - \frac{M_{ar}^2}{L_r}\right)\frac{di_{sq}}{dt} + V_c \\ 0 = \frac{R_r}{L_r}\psi_{rd} - \frac{R_r}{L_r}M_{pr} i_{sq} + \frac{d}{dt}\psi_{rd} + \omega_m \psi_{rq} \\ 0 = \frac{R_r}{L_r}\psi_{rq} - \frac{R_r}{L_r}M_{ar} i_{sq} + \frac{d}{dt}\psi_{qr} - \omega_m \psi_{rd} \\ 0 = i_{sq} - C\frac{d}{dt}V_c \end{cases} \quad (II.50)$$

II.4.3 Expression of electromagnetic torque

By taking into account the expression (II.51) with the use of the expression (II.46) we deduce the final expression of the electromagnetic torque.

$$C_{et} = P.\,[-M_{pr}(i_{r1}.\sin\theta + i_{r2}.\cos\theta) i_{ps} + M_{ar}(i_{r1}.\cos\theta + i_{r2}.\sin\theta) i_{as}] \quad (II.51)$$

$$C_{et} = \frac{P}{L_r}(M_{ra}\psi_{rd}i_{sq} - M_{rp}\psi_{rp}i_{sd}) \quad \text{(II.52)}$$

II.4.4 Mechanical equation of the machine

By replacing the electromagnetic torque from relation (II.52) in equation (II.53) we find

$$J\frac{d\Omega_m}{dt} = C_{et} - f_v\Omega_m - C_r \quad \text{(II.53)}$$

$$\frac{dQ_m}{dt} = \frac{P}{JL_r}(M_{ra}\psi_{rd}i_{sq} - M_{rp}\psi_{rp}i_{sd}) - \frac{f}{j}\Omega_r - \frac{C_r}{j} \quad \text{(II.54)}$$

By adding equation (II.54) to equation (II.50) and arranging the equations in the form of a state space, the model of the single-phase asynchronous motor with permanent capacitor supplied with voltage in a linked frame of reference stator is given as follows [26].

$$\begin{cases} \frac{di_{sd}}{dt} = -\frac{R_{ps}}{\sigma_{dr}L_{ps}}i_{sd} - \frac{P\omega_m M_{ar}M_{pr}}{L_r L_{ps}\sigma_{rd}}i_{sq} + \frac{M_{pr}R_r}{L_r L_{ps}\sigma_{rd}}i_{rd} + \frac{PM_{pr}\omega_m}{L_r L_{ps}\sigma_{rd}}i_{rq} + \frac{V_{sd}}{L_{ps}\sigma_{dr}} \\ \frac{di_{sq}}{dt} = \frac{P\omega_m M_{ar}M_{pr}}{L_r L_{as}\sigma_{rq}}i_{sd} - \frac{R_{as}}{\sigma_{rq}L_{as}}i_{sq} - \frac{PM_{ar}\omega_m}{L_r L_{as}\sigma_{rq}}i_{rd} + \frac{M_{ar}R_r}{L_r L_{as}\sigma_{rq}}i_{rq} + \frac{V_{sq}}{L_{as}\sigma_{qr}} - \frac{V_c}{L_{as}\sigma_{qr}} \\ \frac{di_{rd}}{dt} = \frac{M_{pr}R_{ps}}{L_r L_{ps}\sigma_{rd}}i_{sd} - \frac{R_r}{L_{as}\sigma_{rq}} - \frac{PM_{ar}\omega_m}{L_r\sigma_{rd}}i_{sq} - \frac{P\omega_m}{\sigma_{rd}}i_{rq} - \frac{M_{pr}}{L_r L_{ps}\sigma_{dr}}V_{sd} \\ \frac{di_{rq}}{dt} = \frac{PM_{pr}\omega_m}{L_r\sigma_{rq}}i_{sd} + \frac{P\omega_m}{\sigma_{rq}}i_{rd} + \frac{M_{ar}R_{as}}{L_r L_{as}\sigma_{rq}}i_{sq} - \frac{R_r}{L_r\sigma_{rq}}i_{rq} - \frac{M_{ar}}{L_r L_{as}\sigma_{rq}}V_c + \frac{M_{ar}}{L_r L_{as}\sigma_{rq}}V_{sq} \\ \frac{d\omega_m}{dt} = \frac{P}{J}(M_{ar}i_{rd}i_{sq} - M_{pr}i_{rq}i_{sd}) - \frac{f}{J}\omega_m - \frac{C_r}{J} \\ \frac{dV_c}{dt} = \frac{1}{C}i_{qs} \end{cases}$$

(II.55)

And

$$C_{et} = P(M_{ar}i_{rd}i_{sq} - M_{pr}i_{rq}i_{sd}) \quad \text{(II.56)}$$

II.5 Inverter

A device that converts DC power into AC power at desired output voltage and frequency is called an Inverter. The purpose of inverter is to take DC power from a battery source and convert it into AC. These inverters widely used in industrial application such as uninterruptible power supply (UPS), AC motor drives, standby power supply, etc. The inverters are usually operated on Pulse Width Modulation (PWM) technique. The PWM is very advance and useful technique in that the pulse width is very by using different method. PWM Inverters are used to gate rated output voltage according to the load. The output voltage change with change in load. so, By using the PWM technique we can correct the change in output voltage by changing the width of pulse. Because the width is depending on frequency and frequency depends on voltage and synchronous speed in induction motor as shown below equation,

$$\omega_s = \frac{2\pi f}{p} \qquad (II.57)$$

And,

$$V = 4.44T\,\Phi\, m\, f \qquad (II.58)$$

So, as shown above equation we can control the speed of motor and output voltage by change in switching frequency, Inverter can be classified in two ways according to its operation

- Voltage source inverter
- Current source inverter

II.5.1 Different types of single-phase inverter

For single phase applications, single phase inverter is used. There are mainly two types of single-phase inverter [27].

a) Half bridge
b) Full bridge

II.5.1.1 Half bridge inverter

The power circuit and output waveform are as shown in the figure. The inverter circuit consist two power switches as shown in figure.II.4

The switches can be transistors, MOSFET, IGBT, etc. Two switches shown by S_1 and S_2. Two diodes are connecting parallel to power switch to block the reverse voltage. If we use MOSFET as power switch then there is no need to use parallel diode due to its internal construction.

The basic operation of half bridge inverter can divide into two parts:

If switch S_1 is on for $\frac{T}{2}$ Period then the output voltage is $\frac{V_{dc}}{2}$.

If switch S_2 is on for $\frac{T}{2}$ 2 Period then the output voltage is $-\frac{V_{dc}}{2}$.

The switching operation is done in such that two switch is not on at same time, if it is then two switch short circuit across the DC input, which is cause high flow of current that is very harmful for power switches.

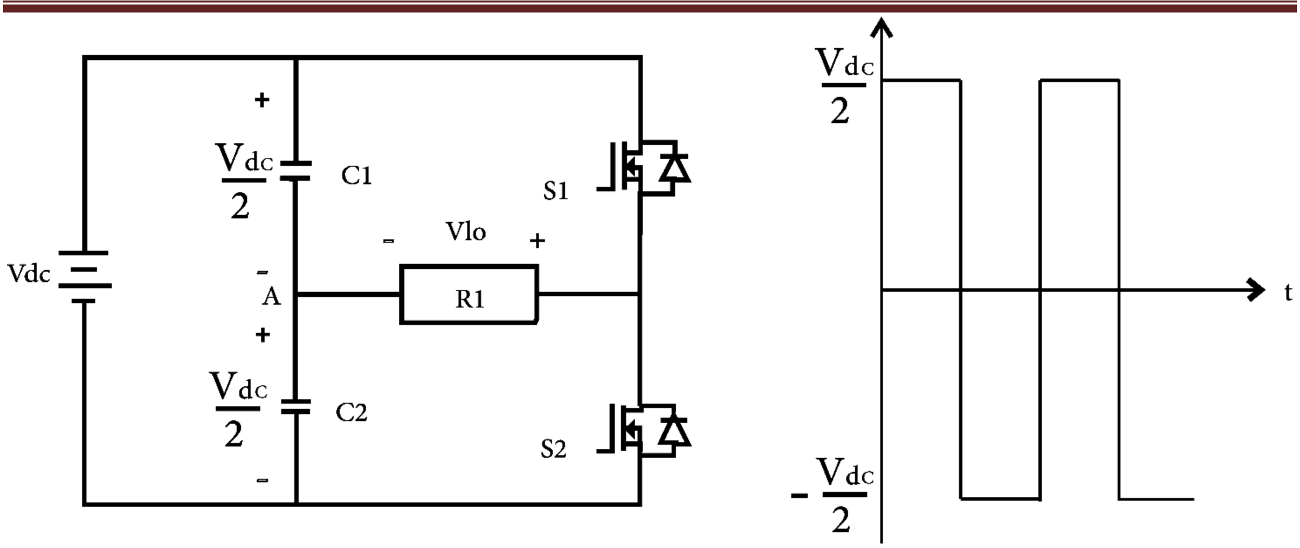


Fig.II.4 Half Bridge Inverter

Table.II.1 Switching states of half bridge inverter

S_1	S_2	V_0
ON	OFF	$\frac{V_{dc}}{2}$
OFF	ON	$-\frac{V_{dc}}{2}$

II.5.1.2 Full bridge inverter

A single-phase full bridge inverter circuit and its output wave form are shown in figure.II.5 It consists of four power switches and it is used in higher power ratings application.

The four switches are named as S_1, S_2, S_3 and S_4 as shown in figure.II.5 The operations of single-phase full bridge inverter can be divided into two cases.

- Switches S_1 and S_4 are turned on and kept on for one half period and S_2 and S_3 are turned off. At that time the output voltage across the load is equal to V_{dc}.

- When S_2 and S_3 are turned on, the switches S_1 and switches S_4 are turned off, then at this time the output voltage is equal to $-V_{dc}$.

The output voltage will change alternately from positive half period and negative half period.

Same like in half bridge inverter, to prevent short circuit across DC supply occurred, the switches S_1 and S_4 must be in ‘on’ state while S_2 and S3 must be in ‘off’ state. To avoid such type of problem dead time is given in between two switching operation [28].

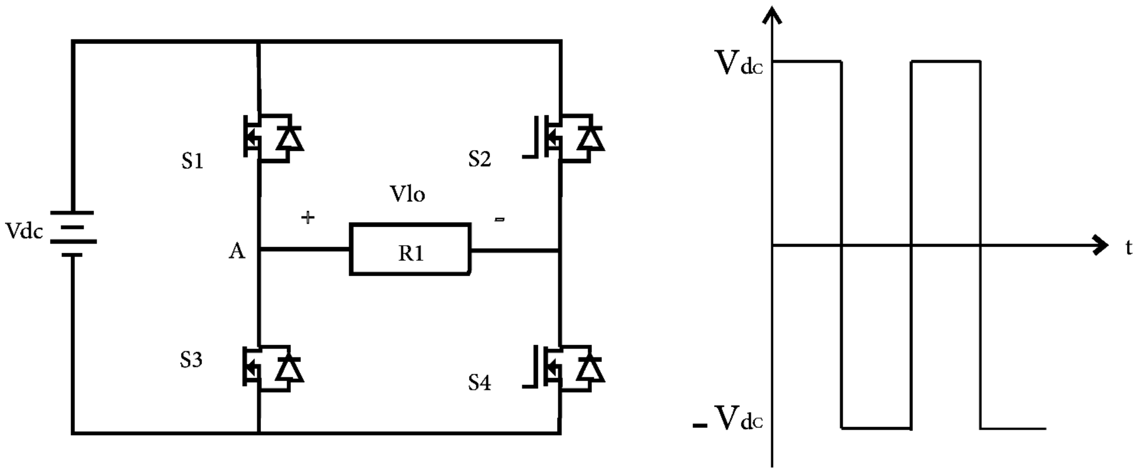


Fig.II.5 Full Bridge Inverter

- Switching state

Table.II.2 Switching states of full bridge inverte

S_1	S_2	S_3	S_4	V_a	V_0	V_{a0}
ON	OFF	OFF	ON	$V_{dc}/2$	$-V_{dc}/2$	V_{dc}
OFF	ON	ON	OFF	$-V_{dc}/2$	$V_{dc}/2$	$-V_{dc}$
ON	OFF	ON	OFF	$V_{dc}/2$	$V_{dc}/2$	0
OFF	ON	OFF	ON	$-V_{dc}/2$	$-V_{dc}/2$	0

II.6 Modeling of single-phase inverter:

In this part, the mathematical model of the single-phase inverter will be developed according to each situation of the switches.

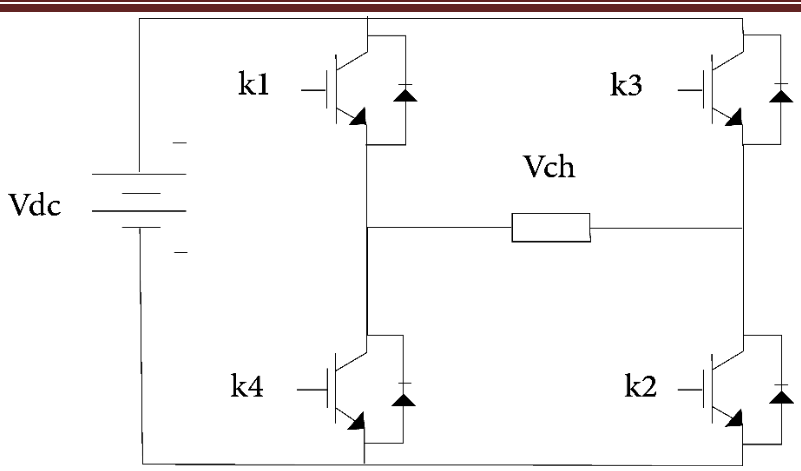


Fig.II.6 Circuit of Single-Phase inverter

$$V_{Lo}=\begin{cases} -V_{dc} & k1 \quad k2 \quad Closed \\ V_{dc} & k3 \quad k4 \quad Closed \\ 0 & k1 \quad k4 \quad Closed \\ 0 & k3 \quad k2 \quad Closed \end{cases} \tag{II.59}$$

For more simplification we have S_1 related to K_1 and K_4 and S_2 related to K_3 and K_2 where:

Table.II.3 Situation of switches K_1-K_4 according Signal S_1-S_2

Signal		K_1	K_4
S_1	0	0	1
	1	1	0
Signal		K_3	K_2
S_2	0	0	1
	1	1	0

According to table.II.3 and equation II.5, We can develop the single-phase inverter mathematical model as below:

$$V_{Lo}=\begin{cases} 0 & S1=0, \quad S2=0 \\ -V_{dc} & S1=1, \; S2=0 \\ 0 & S1=1, \; S1=1 \\ V_{dc} & S1=0, \; S1=1 \end{cases} \tag{II.60}$$

$$V_{Lo}= V_{dc} \; [-1 \;\; 1] \begin{bmatrix} S1 \\ S2 \end{bmatrix} \tag{II.61}$$

$$V_{Lo}= V_{dc} \; [-S_1 \quad +S_2] \tag{II.62}$$

II. 7 PWM for single phase inverter

The Pulse Width Modulation (PWM) is a technique which is characterized by the generation of constant amplitude pulse by modulating the pulse duration by modulating the duty cycle. Analog PWM control requires the generation of both reference and carrier signals that are feed into the comparator and based on some logical output, the final output is generated. The reference signal is the desired signal output maybe sinusoidal or square wave, while the carrier signal is either a sawtooth, or triangular wave at a frequency significantly greater than the reference. The DC to AC power converters is known as Inverters. An inverter is a circuit which converts a dc power into an ac power at desired output voltage and frequency. The ac output voltage could be fixed or variable frequency. This conversion can be achieved either by controlled turn on and turn off devices (e.g., BJT's, MOSFETs, IGBTs, MCTs, SITs, GTOs, and SITHs) or by forced commutated thyristors, depending on applications. The output voltage waveforms of ideal inverter should,be,sinusoidal.

The voltage waveforms of practical inverters are, however, no sinusoidal and contain certain harmonics. Square wave or quasi-square wave voltages are acceptable for low and medium power applications, and for high power applications low, distorted, sinusoidal waveforms are required. The output frequency of the inverter is determined by the rate at which the semiconductor devices are switched on and off by the inverter control circuitry and consequently, an adjustable frequency ac,output,is,readily,provided.

The square wave inverters need switching devices. These switching devices can either be thyristors or transistors and or other power semiconductor devices. Due to their mode of operation, losses in these semiconductor devices are very small and consequently they have a higher efficiency with much more power handling capability. There are three basic configurations of single-phase square wave inverters are centre – tapped load, centre -tapped supply and bridge configuration.

By sequentially switching them on and off, the voltage across the load changes polarity cyclically and produces an alternating voltage / current. The main drawback of the centre-tapped configuration is that it needs a centre-tapped transformer/supply and higher voltage ratings transistors. This limitation can be overcome by bridge type inverters. In bridge inverters, there are four transistors for single phase operation instead of two as in centre-tapped inverters. The transistors are operated in such way that when T_1 is on, T_4 is off and vice-versa. Similarly, transistors T_2 and T_3 are switched in a complementary manner. When transistors T_1 and T_2 conduct, a positive voltage appears across the load and when T_3 and T_4 conduct, a negative voltage is developed. If the time periods of T_1 and T_2 are analogous with those of T_3 and T_4, a square wave is produced across the load. However, if the switching of T_1, T_2 and T_3, T_4 is shifted in phase, the width of the positive and negative halves is controlled and the voltage across the load is controlled [30].

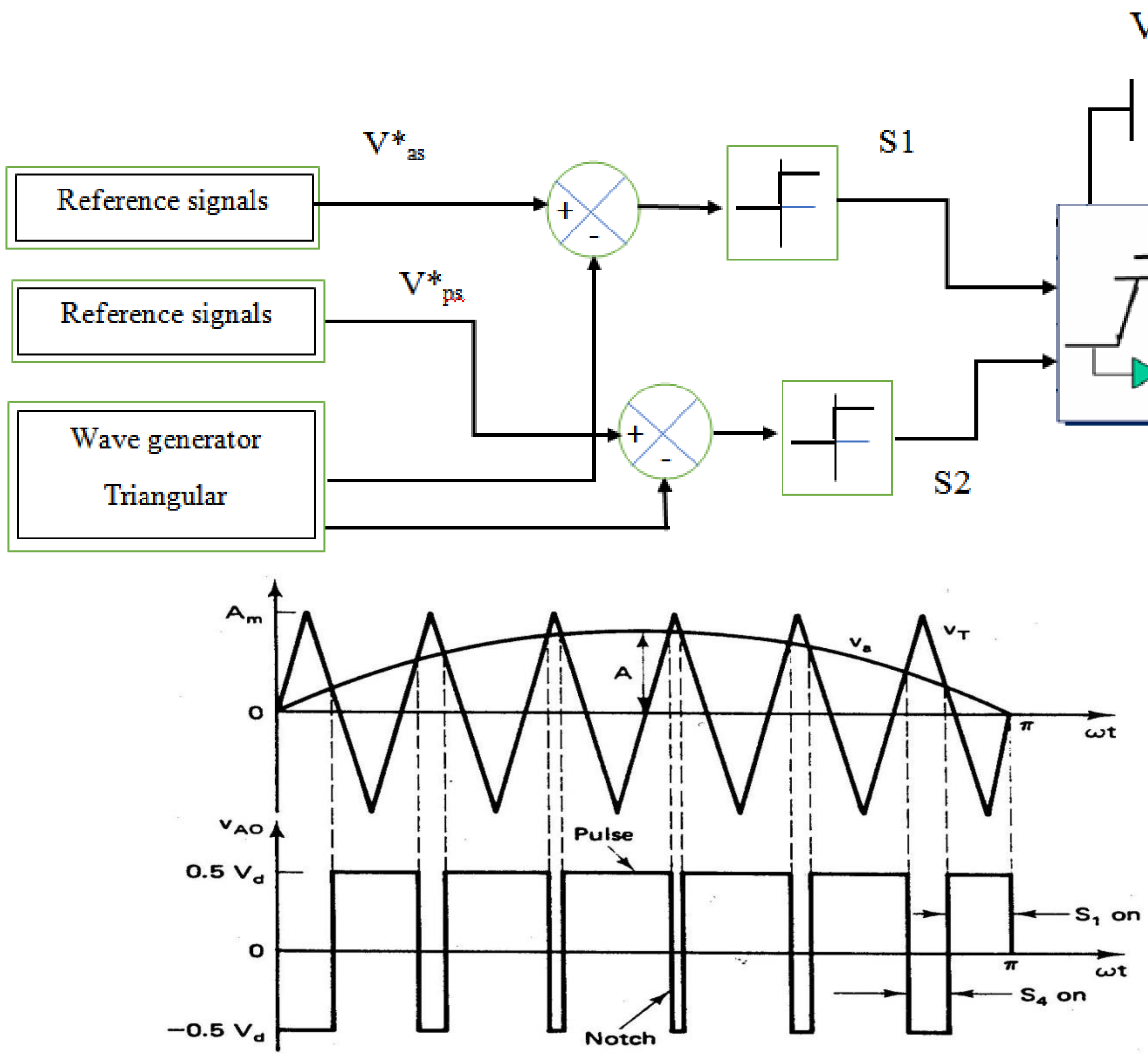


Fig.II.7 PWM for single phase inverter

II.*8 V/f* control of induction motor

According to Faraday (principle of electromagnetism), the variation in magnetic flux gives birth to an induced electromotive force (voltage) which, according to Lenz, opposes the Source which gave birth to it.

$$v(t) = -N\frac{d\phi}{dt} = V_m \sin(\omega t) \Rightarrow \phi(t) = \frac{V_m}{N\omega}\cos(\omega t)$$
$$\Rightarrow \phi_{\max} = \frac{V_m}{N\omega} = \frac{V_m}{N2\pi f} = \left(\frac{1}{2\pi N}\right)\left(\frac{V_m}{f}\right) = k\left(\frac{V_m}{f}\right) \quad \text{(II.63)}$$

If *V* is kept constant:

• When f decreases, the flux increases: risk of saturating the machine (undesirable).

• When f increases, the flux decreases: poor performance in torque.

The torque is directly linked to the flux.

The following constraints must therefore be respected When f is lower than the nominal frequency fn, the flux must be maintained at its maximum value, so the developed torque is also maximum

$$f < f_n \Rightarrow \left(\frac{V}{f}\right) = \text{cst} \tag{II.64}$$

This speed is called the constant torque function.

When f is greater than the nominal frequency fn, the supply voltage must be kept constant and equal to its nominal value. This is to prevent possible breakdown of the insulation.

$$f > f_n \Rightarrow V = \text{cst} \tag{II.65}$$

This regime is called: constant power function. $P = T\omega$.

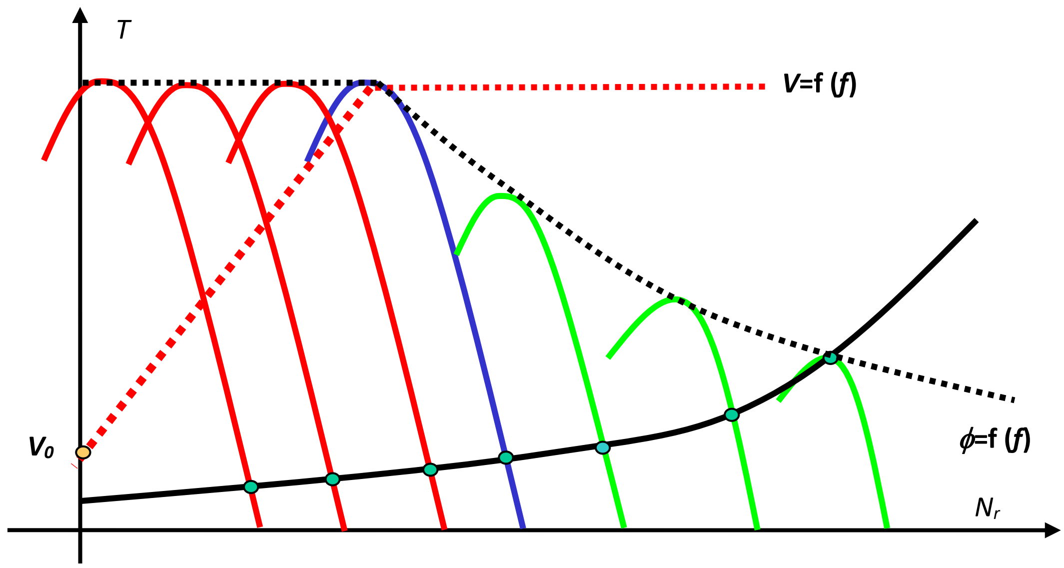


Fig.II.8 Variable frequency torque & speed characteristics.

The motor is a load for the inverter. The rectifier block transforms ac to dc, providing the dc link to the inverter. A filter capacitor is used between to smoothen the dc waveform. The inverter block produces variable frequency and variable voltage which is fed to the motor. The ratio of voltage and frequency is maintained constant and speed control by *V/f* method can be achieved [29].

II.9 Conclusion

In this part, the formulations of the mathematical models necessary for modeling of the single-phase induction motor and the inverter has been exposed. Thus, the demonstration of the park model for a single-phase induction motor with a permanent capacitor has been presented. On the other hand, the different types of single-phase inverters were explained.

In addition, PWM technique for inverter and *V/f* control of asynchronous motor were presented.

In the next chapter, we will simulate the system, extract its results, analyze them and experimentally validate the importance of the constant V/f in the asynchronous motor control.

CHAPTER III

Simulation and validation of V/f control for single-phase connected to PWM inverter

III.1 Introduction

Usually, when an electrical machine is simulated in software simulators its steady-state model is considered, but for electric motor studies the transient behavior is also important. One of the advantages of circuit simulators over Simulink is the ease of modeling transients for electric machines and motors and the inclusion of drive controls in the simulation. As long as the equations are known, any Simulink control problem or algorithm can be modeled for testing and verifying its effectiveness in virtual time. However, real-time experiments are very important for the validation of any theatrical idea because many effects cannot be taken into account in virtual time. Therefore, in this chapter, simulation and validation of V/f control for single phase induction motor connected to PWM inverter will be performed.

III.2 The simulation diagram of single-phase induction motor

In below the figure (III.1) shows the overall simulation diagram of single-phase induction motor using MATLAB-Simulink, in case, of the frame of reference linked to the stator, $\theta_a = 0$, that is the system (d, q) and according the mathematical model that presented in (Equation II.50) in chapter II.

After the MATLAB Simulink, enter all the necessary data, which are electrical parameters, L and torque load ... etc.

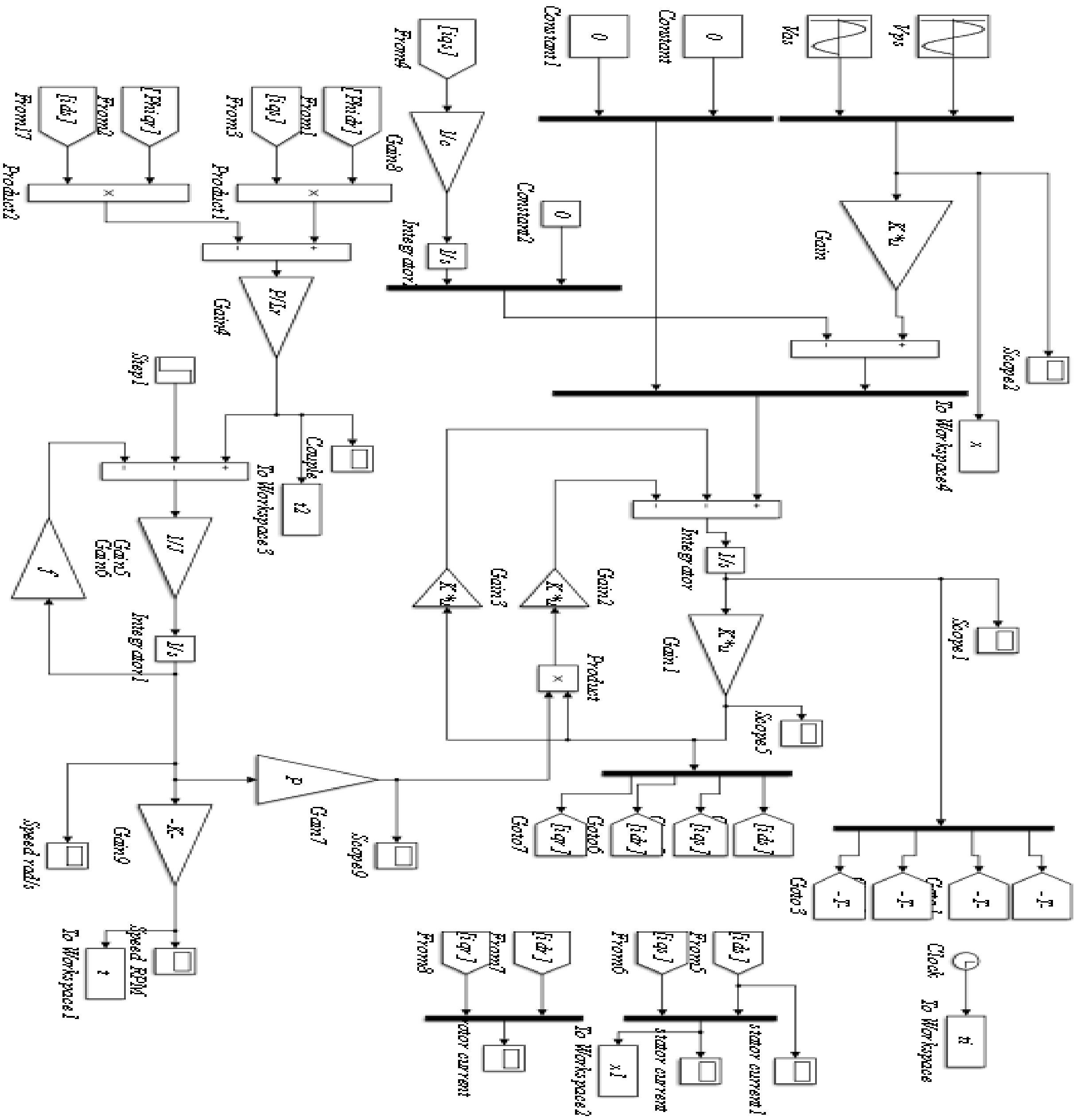


Fig.III.1simulation diagram for single phase induction motor

Notice: The results of this simulation are identical to the park transformations related to the reference stator ie approximation to α,β transformations

III.3 Simulation results and interpretation

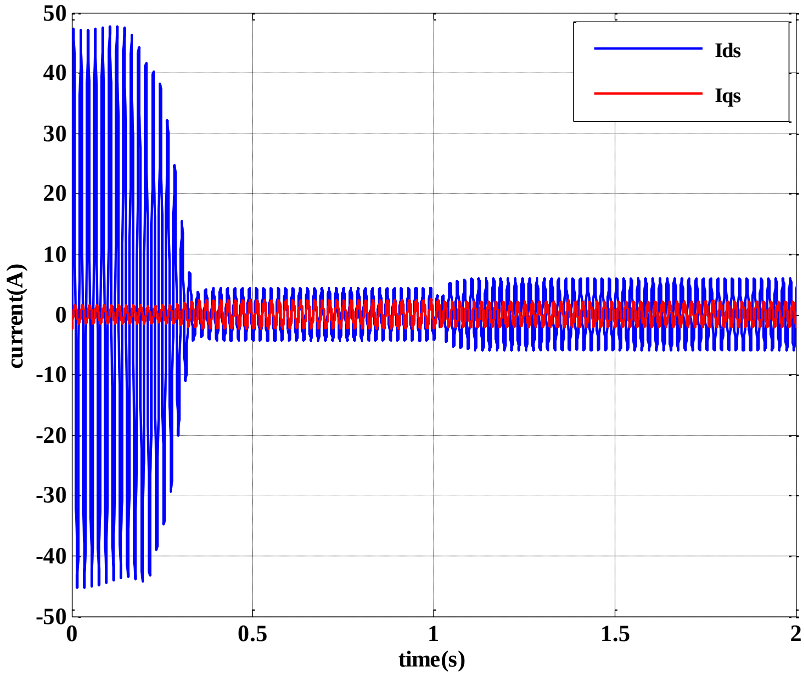


Fig.III.2 Stator currents in axis d q.

Figure III.2 shows the transient currents in the proposed asynchronous motor. In the figure, we can see that thepeak value of the starting currents is very high compared to the nominal value.

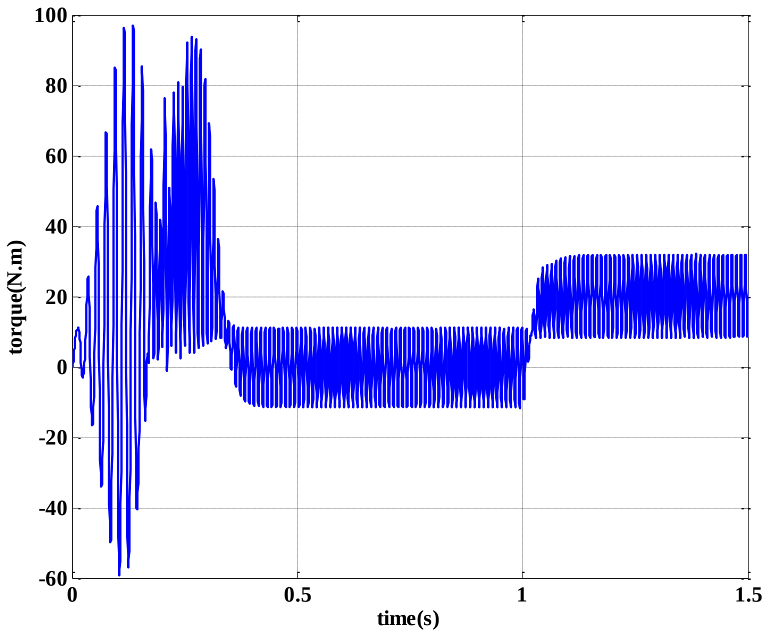


Fig.III.3 Evolution of instantaneous electromagnetic torque as a function of time

The shape of the torque shown in figure (III.3) is marked by significant oscillations during the transient regime since it rises to 3 times the nominal torque of the machine.

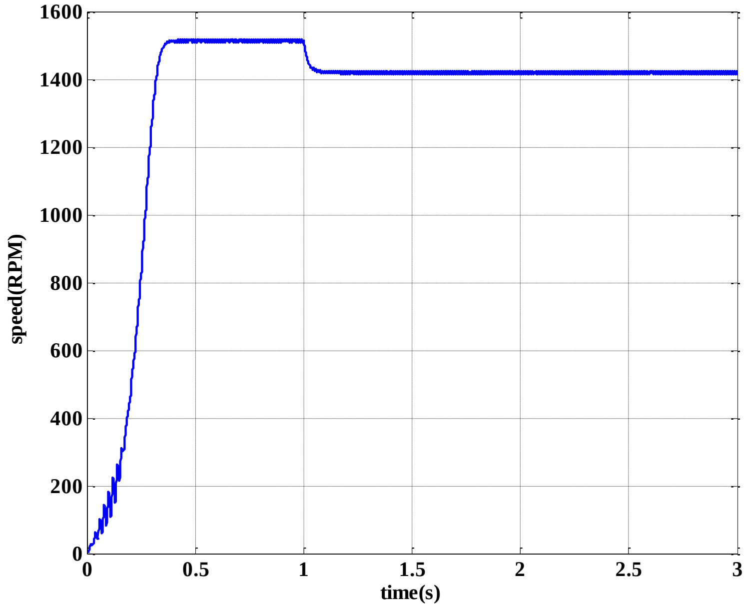


Fig.III.4 Evolution of speed as a function of time

The oscillations of the torque are also felt on the evolution of the speed which in steady-state stabilizes at 150 rad / s or 1400 rpm, (the motor has a pair of poles). When applied the load in the instant t=1s, we notice that the current increases at this moment, also the torque develop, and speed drops due to the slippage caused by the load.

III.4The model simulation diagram of single-phase induction motor connected to the inverter

The inverter is a very important device for the control of the induction motor, in this part, we have associated the inverter with the last simulation of single-phase IM. In figure III.5, the simulation diagram of single-phase induction motor and inverter has been presented. Also, in figure 6 the detail of the Simulink full bridge inverter according the developed model in chapter II.

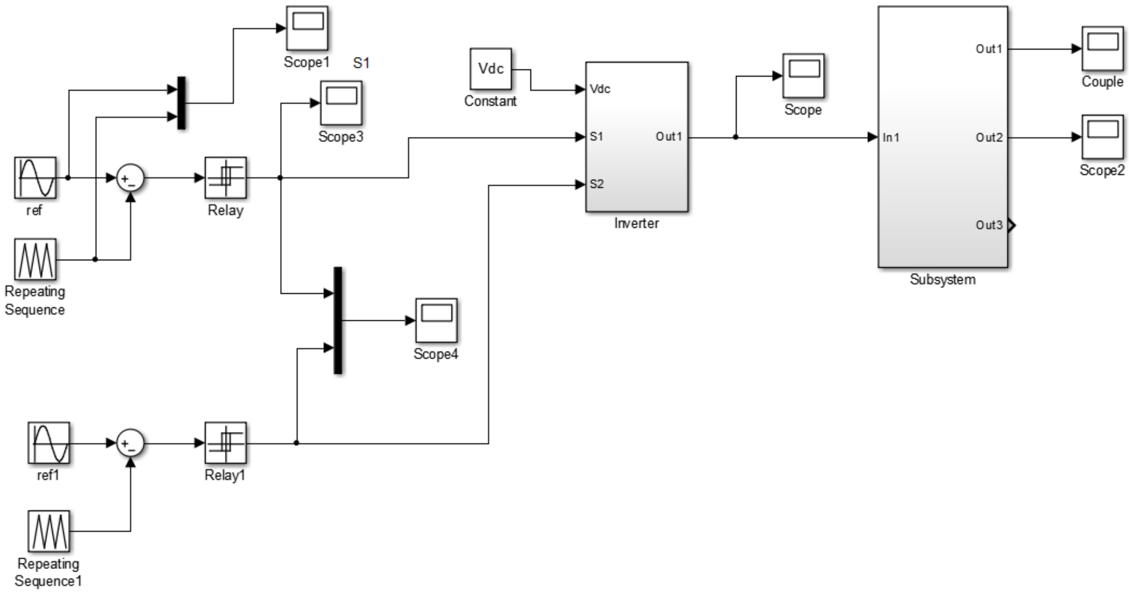


Fig.III.5 simulation diagram of single-phase induction motor and inverter

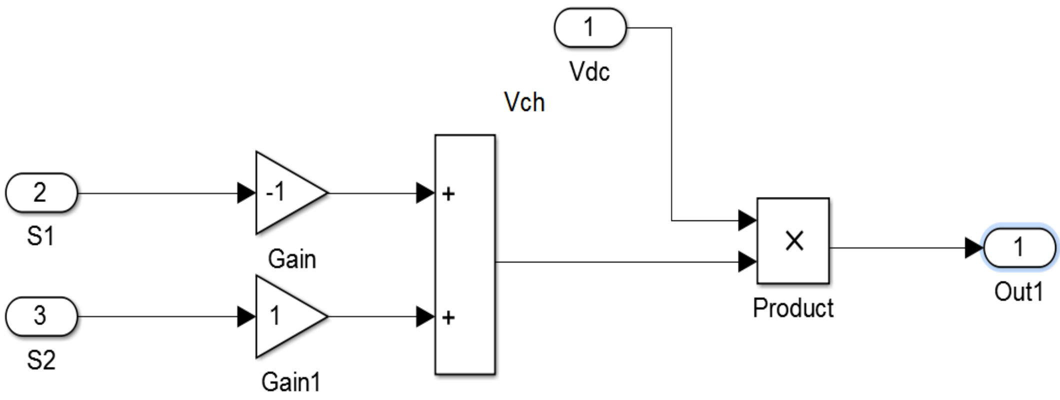


Fig.III.6 Full bridge of single-phase inverter simulation diagram

III.5 Simulation results and interpretation

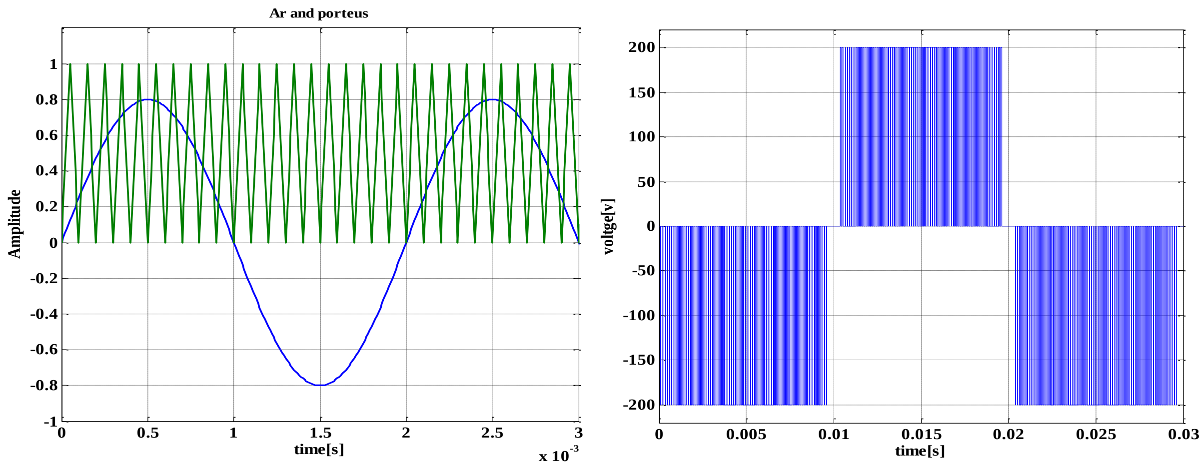


Fig.III.7 PWM high side with voltage simulation results for A_r = *0.8*, f_{ref} = 50

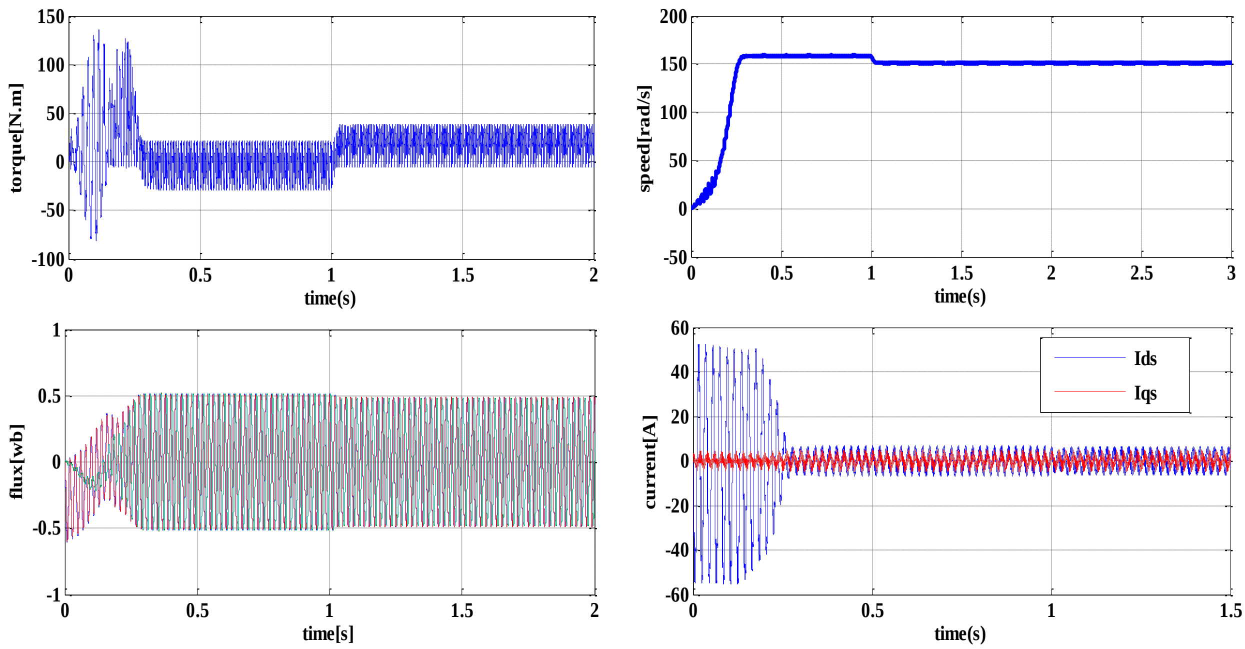


Fig.III.8 Speed, torque, current and flux simulation results for *Ar = 0.8*, f_{ref} *= 50*

The figure shows the simulation results for an asynchronous motor in the normal state when $f_{ref} = 50$ *and* $Ar = 0.8$, the width of the tension pulse is about 0.01 s, since when applying a load at the moment 1 s we observe a deceleration of the motor speed accompanied by an increase in current and torque, As well as a decrease in magnetic flux.

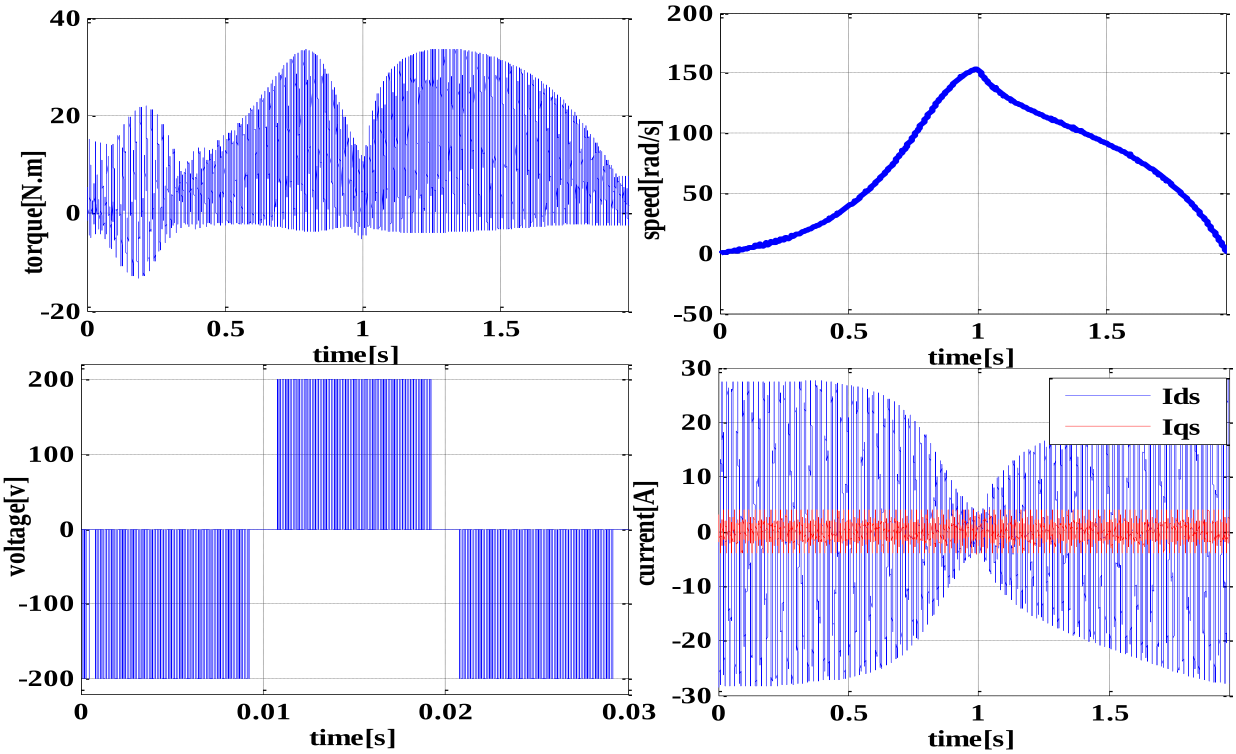


Fig.III.9 Speed, torque, current and voltage simulation results for $Ar = 0.4$, $fref = 50$

In this case, we set $f_{ref} = 50$ and change $Ar = 0.4$ where we initially notice an increase in velocity, a ripple in torque followed by an increase, as well as a decrease in the value of the current and a stabilization in the width of the tension pulse, and after applying a load at the moment 1 s, we notice a **dropout** of the motor where the Speed up to zero, followed by an increase in current as well as an increase in torque. In this case the dropout because *V/f* constant is not respected.

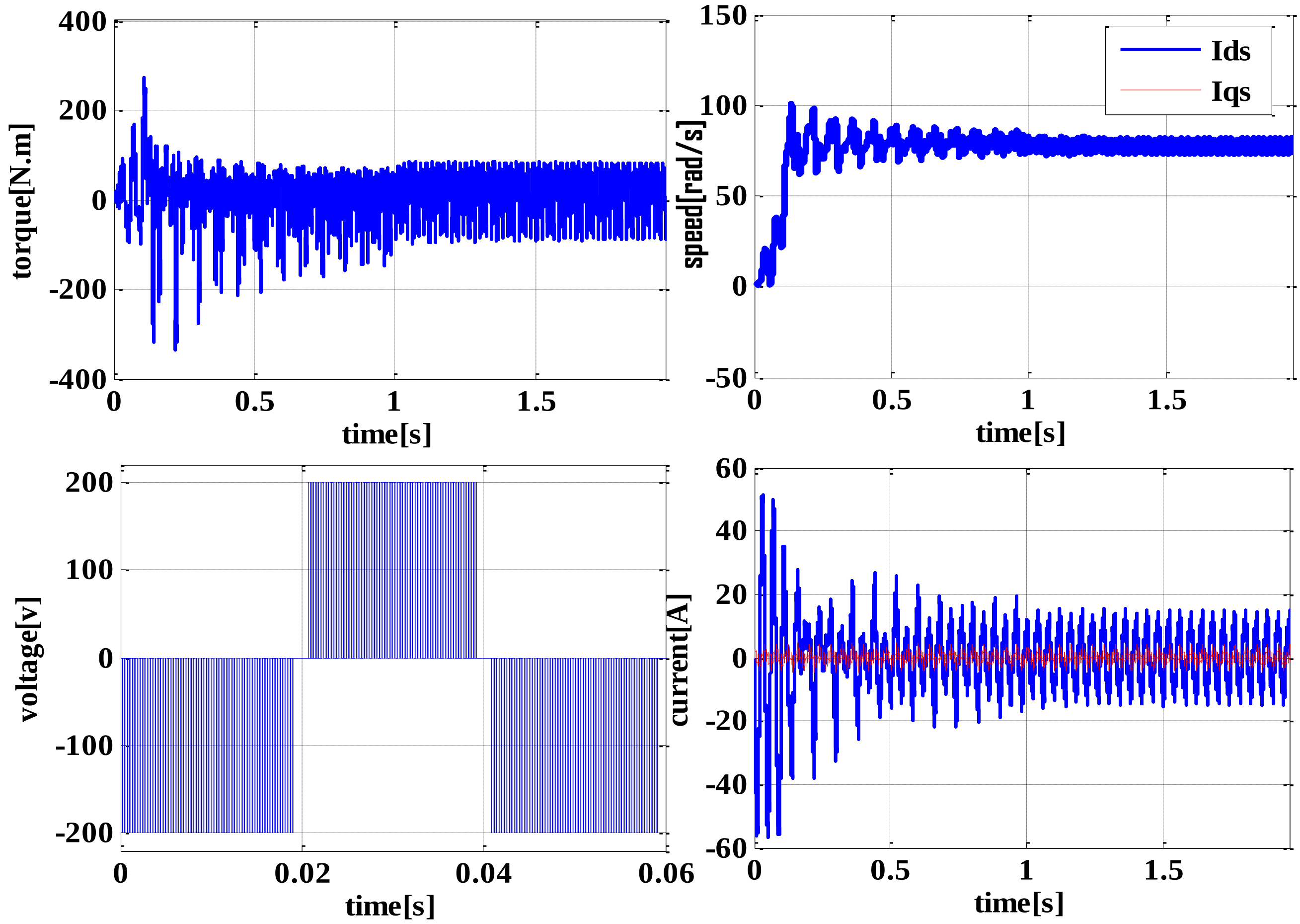


Fig.III.10 Speed, torque, current and voltage simulation results for *Ar = 0.8*, f_{ref} *= 25*

The figure shows the simulation results for an asynchronous motor in the normal case when f_{ref}= 25 and *Ar* = 0.8, where we notice an increase in the impulse width and the motor does not work efficiently, that is, the speed has not reached its normal state, as well as the instability of the torque, but when the load is applied at the time for 1 second, we observe a slowdown in the motor speed accompanied by an increase in current and torque

III.6 The global model simulation diagram of single-phase induction motor, inverter and *V/f* control

In this part, we will simulate the pulse width modulation as well as the *V / f* control and see how it affects the efficiency and response of the motor.

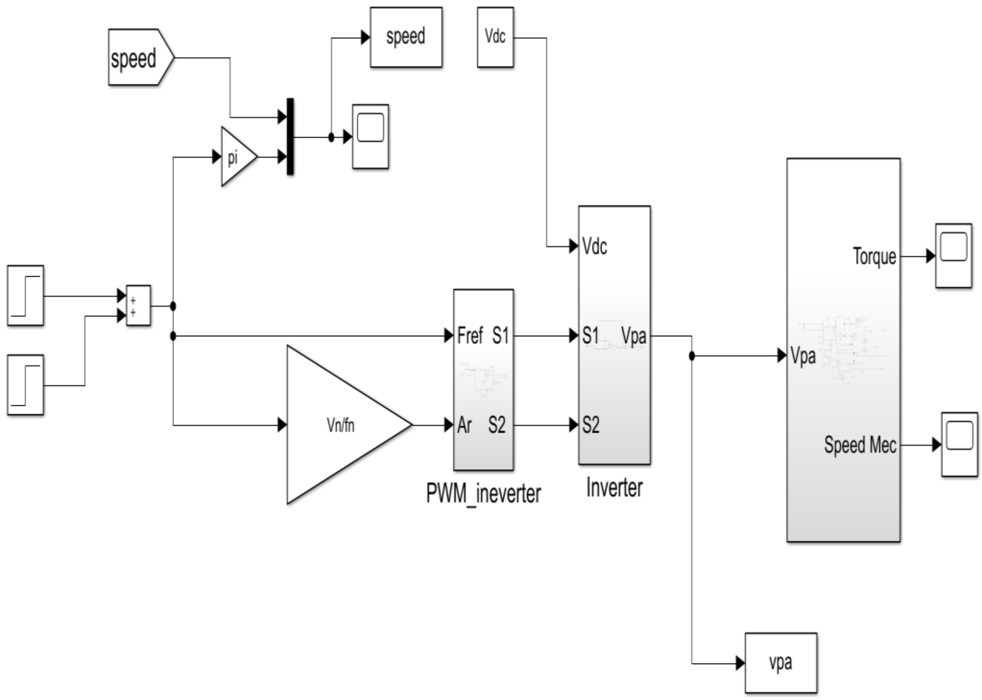


Fig.III.11 Simulation diagram of *V/f* control for single-phase induction motor

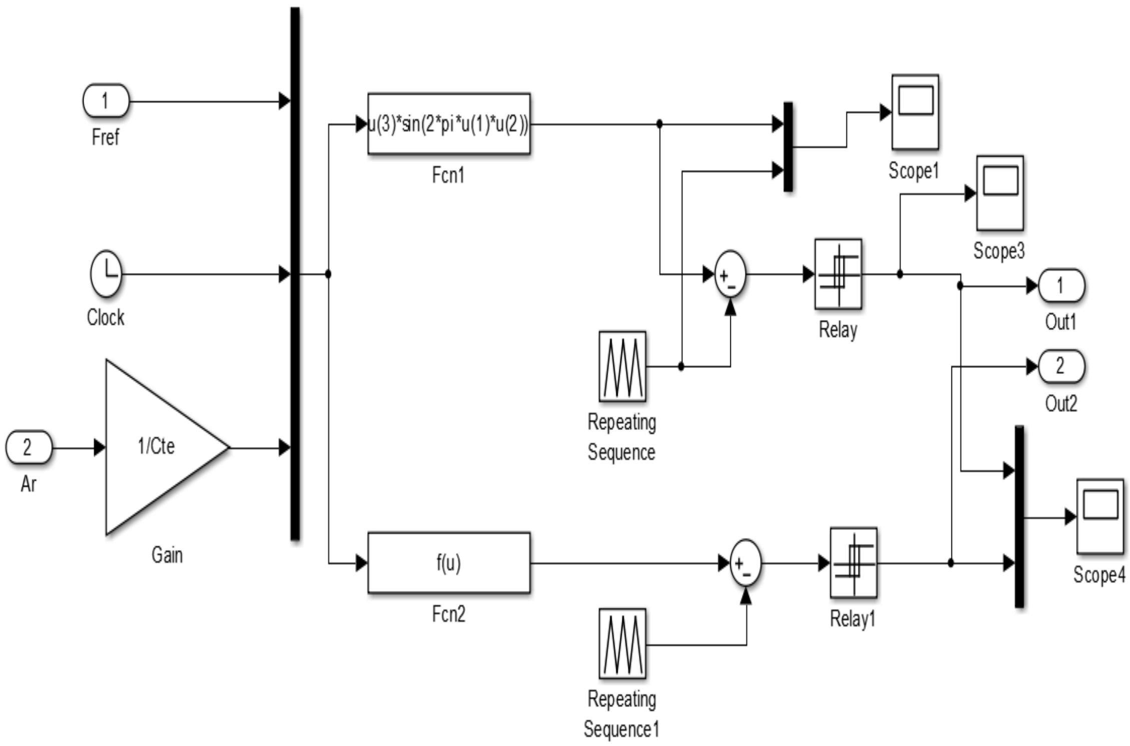


Fig.III.12 Diagram of PWM_inverter simulation inside

III.7 Simulation results and interpretation

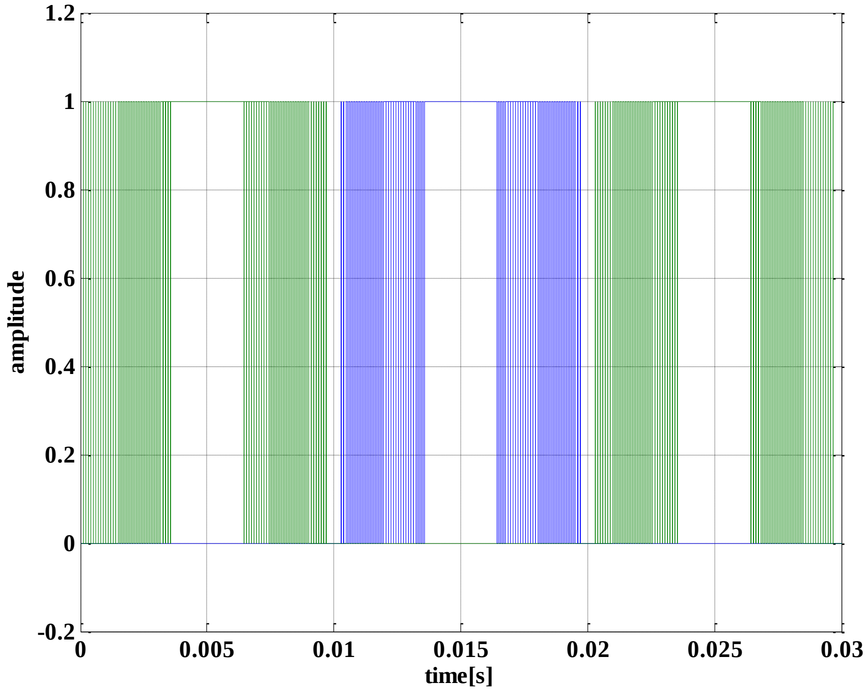


Fig.III.13 PWM high side ineverter

This picture shows the control signal of the inverter, as it shows the method of switching between circuit breakers, as the output S1 controls two opposite circuit breakers, as well as S2.

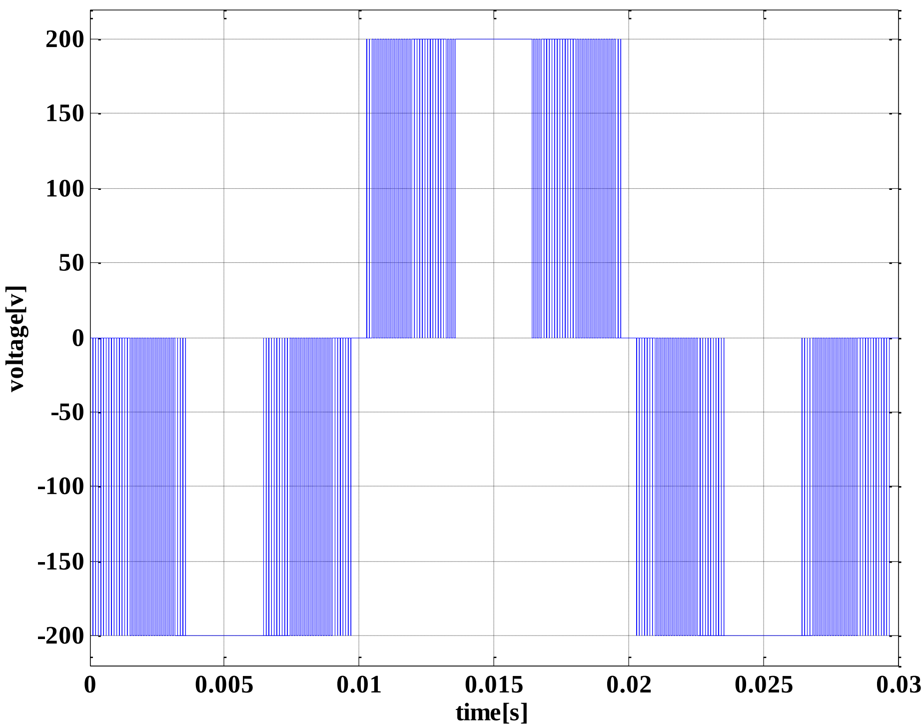


Fig.III.14 Evolution of voltage as a function of time

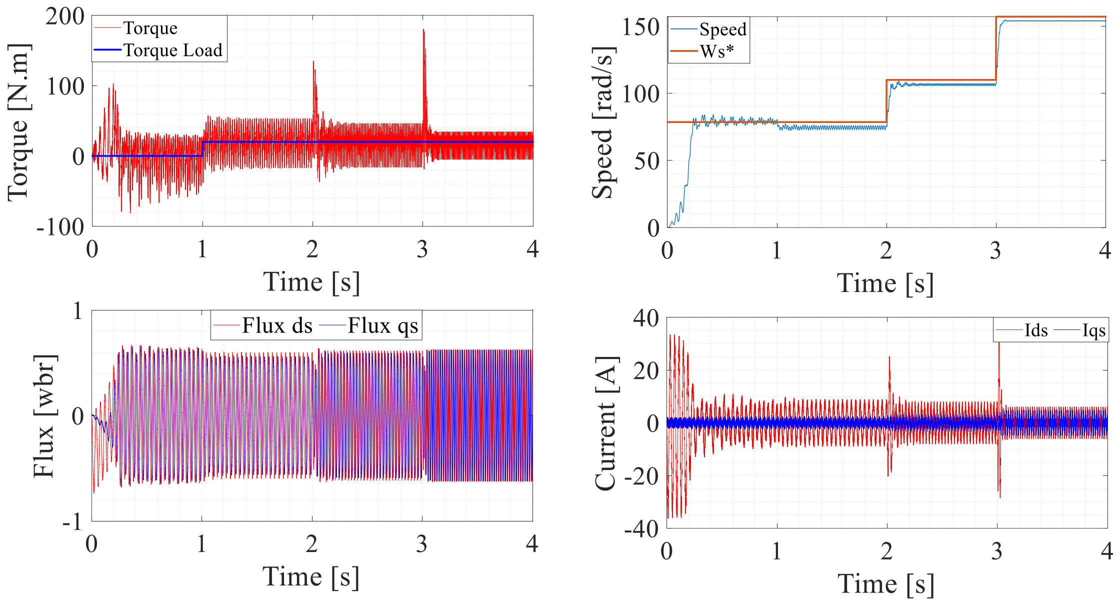


Fig.III.15 Open-loop V/f control results for torque, speed, flux and current in single-phase IM using a PWM inverter

In Figure III.14 above, we have the results of open loop V/f control results for torque, speed, flux, and current in single-phase IM using a PWM inverter. Regarding the speed results, we have the measured speed equal to the synchronous speed when the time is between 0 and 1 s because this case without load and the slip is zero. However, after 1 s we have applied a load to the motor, so the motor slip is taken into account, for the latter, there is a difference between the measured speed equal to the synchronous.

About the torque results, we have very important torque ripplewhen increase the speed.As for the current results after application of the load (20 Nm at 1s after idling), we see that the current increases at this moment.

In addition, when starting up, the current records are recorded at their highest value and then recorded as low in the steady state period.

As for the magnetic flux, it records 0.8 wb, and when a load is applied at 1 s, we notice a decrease in the flux value.

III.8 Expremental validation

In this section, we will implement the studied PWM $V\,/\,f$ control using the fluid bench test: Bridge rectifier and filter for inverter DC bus, single phase induction motor, single phase voltage inverter, AC transformer, controller by arduino-mega, laptop PC and oscilloscope.

The object of this experiment is the validation of the importance of $V/f = cte$ in the single-phase induction motor.

III.9 Test bech organisation

The following figure shows a practical implementation model of various parts for vrified the effectivness of V/f control. The consisting of this organisation are voltage source connected , a rectifier bridge, a filter capacitor and a controlled for generate the PWM signals for the inverter.

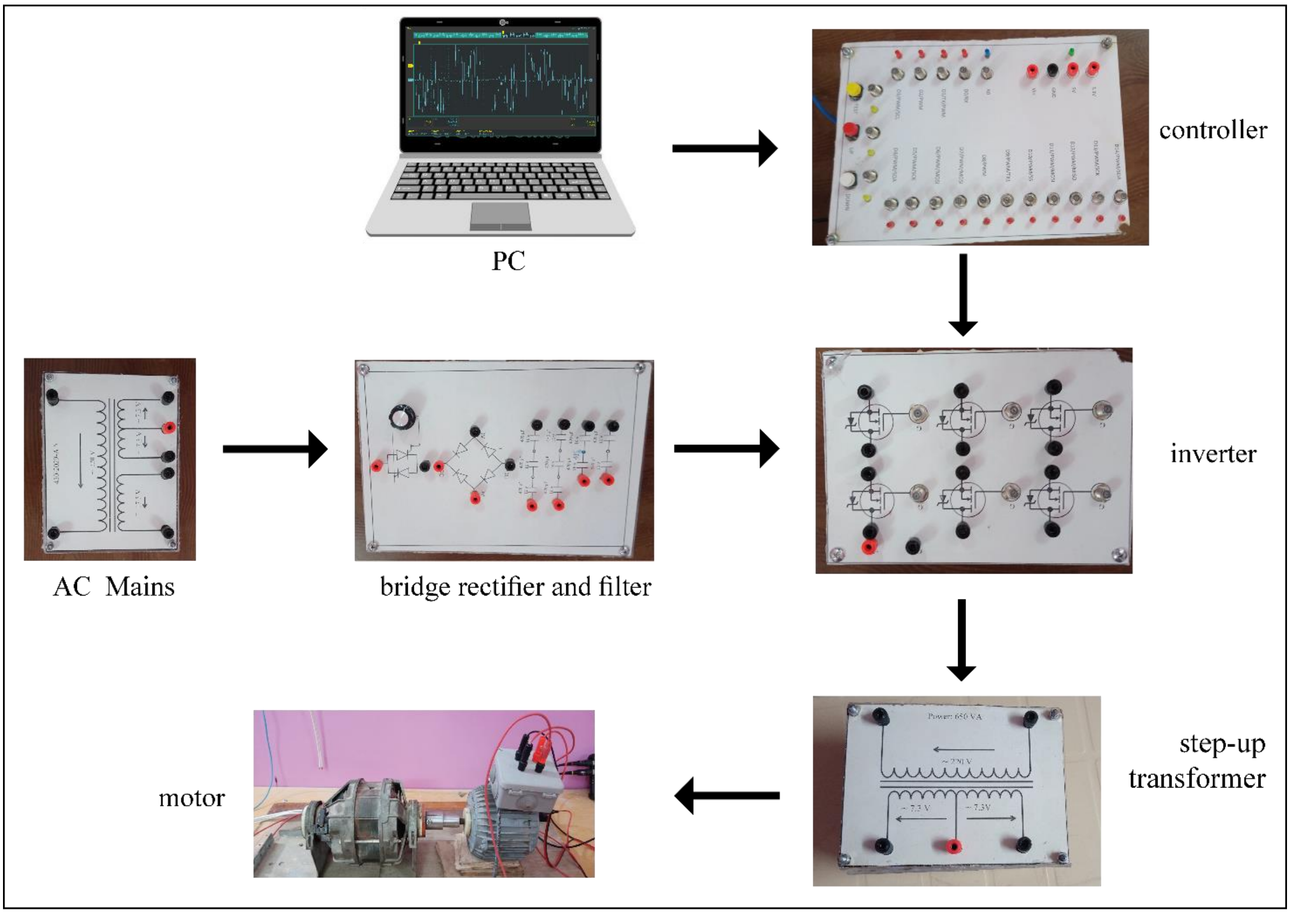


Fig.III.16 Organization of the test bench

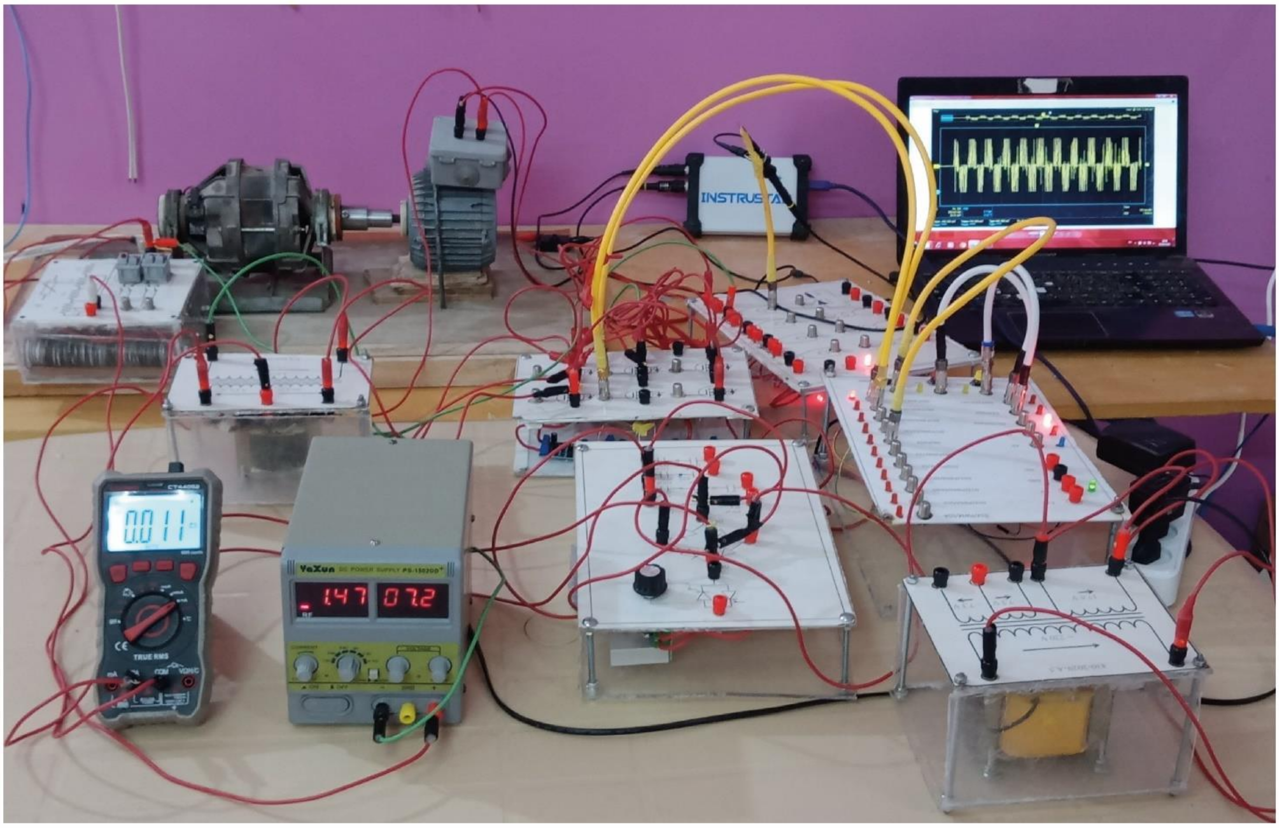


Fig.III.17 Test bench-experiment setup for real-time *V/f* control

III.9 Design summary

III.9.1 AC Mains

Step-down transformer ,its role is to reduce the tension as it lowers the voltage from 220*V* to 31.1*V* so that we can feed the bridge rectifier.

III.9.2 Bridge rectifier

An electrical device that periodically converts alternating current (AC) that reverses direction into direct current (DC) that flows in only one direction. We fed the rectifier input with 32.1V AC to get a constant current to feed the inverter).

III.9.3 Filter

The chemical capacitor is used for charging and discharging in rectifier circuits that convert the variable current into a constant current, as it filters the output voltage.

III.9.4 Inverter

It is an electrical device that converts direct current into alternating current that is controlled.

III.9.5 Controller

It is an electronic development board consisting of an open-source electronic circuitwith a microcontroller programmed (Arduino- mega) by a computer. The the PWM signal generated by Arduino has been verified by the oscilloscope

III.9.6 Pc Laptop

The laptop computer used to upload Arduino program and checking the results

III.10 Different excremental results of the motor

In the following table, we have presented the values of A_r the reference and (frequency) in order to get the current, voltage and state of the motor in rotation or not.

Table.III.1 Different excremental results of the motor

Ar	*f(Hz)*	$I_{rms}(A)$	*V(v)*	*V/f*	Speed [*RPM]*	state of motor
0.3	12	0.13	85	7	270	Operated
0.3	20	0.23	115	5.75	475	Operated
0.3	32	0.23	125	3.9	0	dropout
0.6	12	0.27	116	9.6	290	Operated
0.6	20	0.41	148	7.4	490	Operated
0.6	32	0.27	132	4.1	0	dropout
0.9	12	0.46	143	11.9	324	Operated
0.9	20	0.53	157	7.85	510	Operated
0.9	32	0.537	175	5.4	770	Operated

- We notice from the table that there is a direct relationship between Ar and voltage, the more Ar increases the value of the voltage.
- With regard to the results of the cases of the motor, we note that the values of *(V/f)* are related to the value of the constant whose value ($\frac{V}{f} = \frac{220}{50} = 4.4 = constant$) is, whenever the value of *(V/f)* is equal to or greater than the constant, we note the work of the motor, and whenever the value of *(V/f)* is less than the constant, we notice the occurrence of dropout of motor.

III.11 Experimental results

In this part we show the current and control signals of PWM for different reference amplitude and frequency (variable) which we will explain in relation to the results (state of motor) presented in the table. In the next result of the current, we have: **1 [V]=1 [A]**

Notes: About the waveform of the current results, it is not like the simulation results because the parameters used in the simulation for the motor power of 4kW and the induction motor used in real-time are 150 watts. On the other hand, the controller used (Arduino) generates a frequency lower than 5KHz for the PWM.

In the case of Ar=0.3 and f=12 Hz

Fig.III.18 The current with *f=12 Hz*

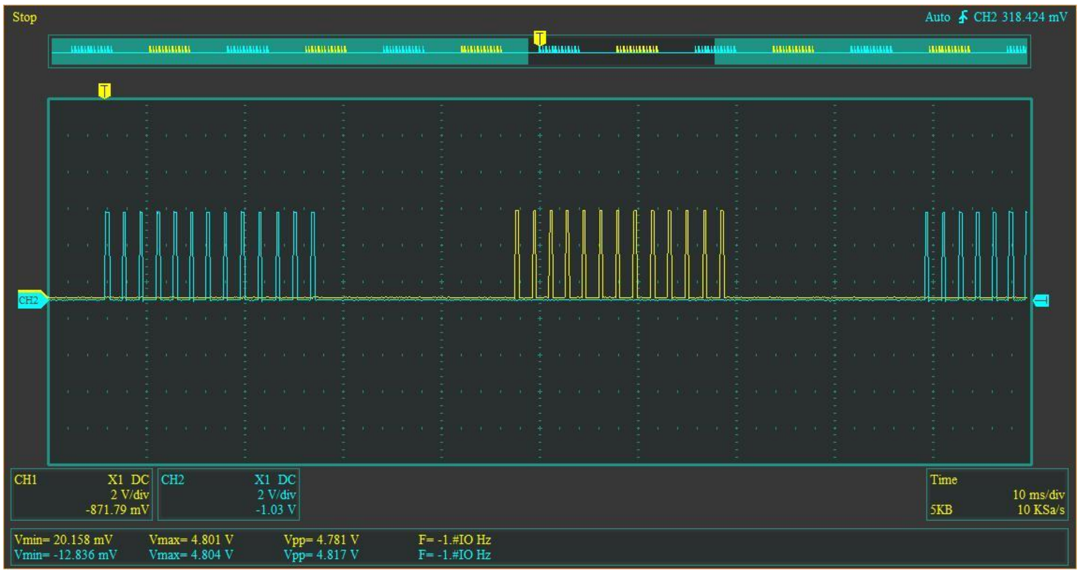


Fig.III.19PWM Signal with *f=12 Hz*

Figure.III.18 and Figure.III.19 present respectively, the inverter output current and their PWM control signals by Arduino, the measured RMS currents are 0.13A and12Hz frequency for the reference control signals of PWM method. In this case the motor working

In the case of Ar=0.3 and f=32 Hz

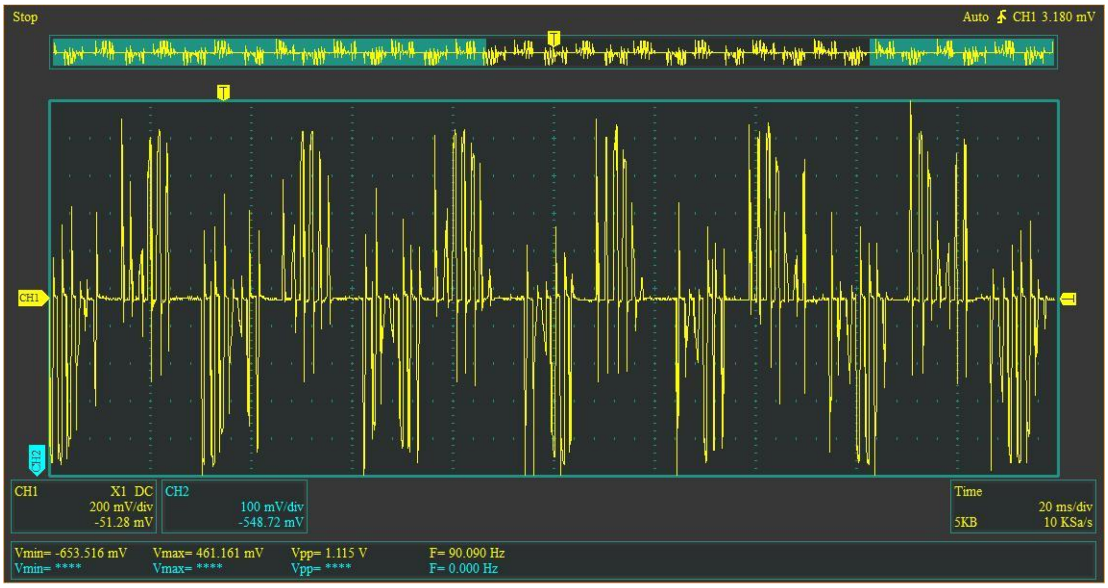


Fig.III.20 The current with *f=32 Hz*

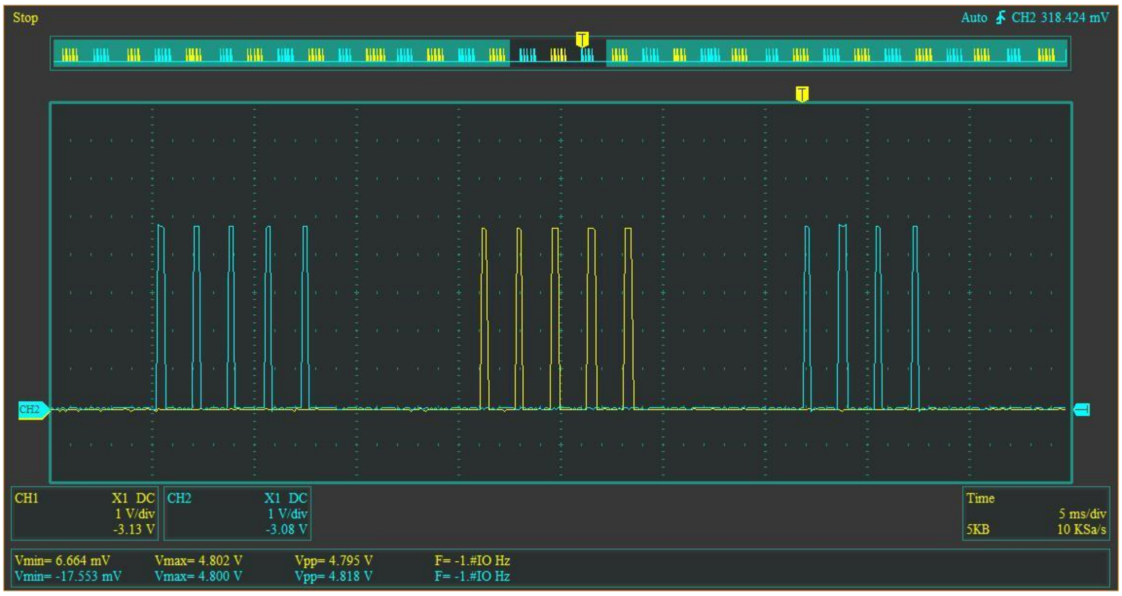


Fig.III.21 PWM Signal with *f=32 Hz*

Figure.III.20 and Figure.III.21 present respectively, the inverter output current and their PWM control signals by Arduino, the measured RMS currents are 0.23A and 32Hz frequency for the reference control signals of PWM method. In this case the motor dropout

In the case of Ar=0.6 and f=20 Hz

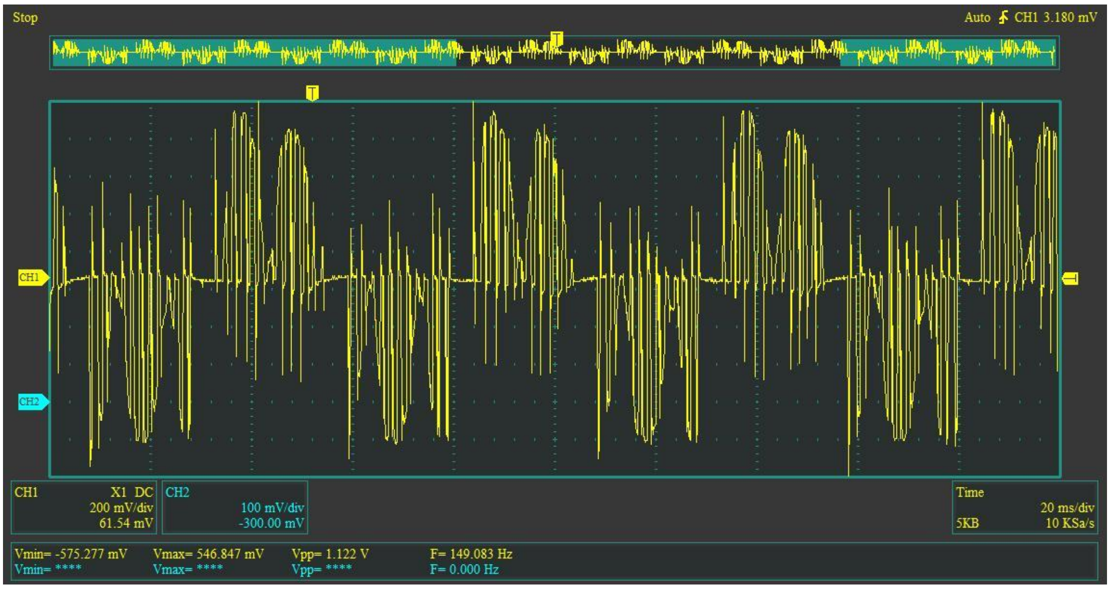


Fig.III.22 Current for *f=20 Hz*

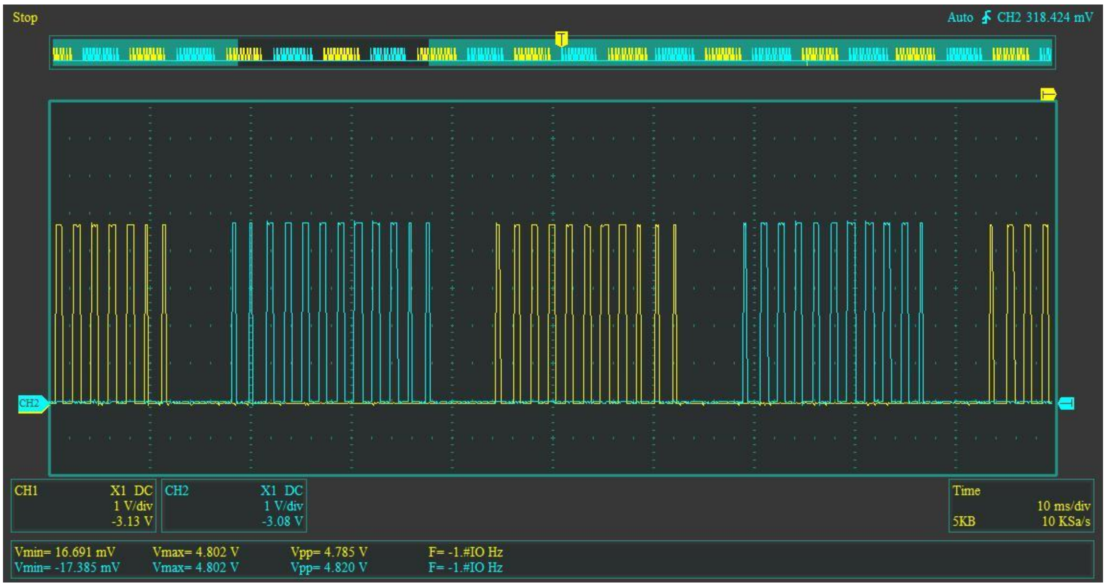


Fig.III.23 PWM Signal for *f=20 Hz*

Figure.III.22 and Figure.III.23 present respectively, the inverter output current and their PWM control signals by Arduino, the measured RMS currents are 0.41A and20Hz frequency for the reference control signals of PWM method. In this case the motor working

In the case of Ar=0.6 and f=32 Hz

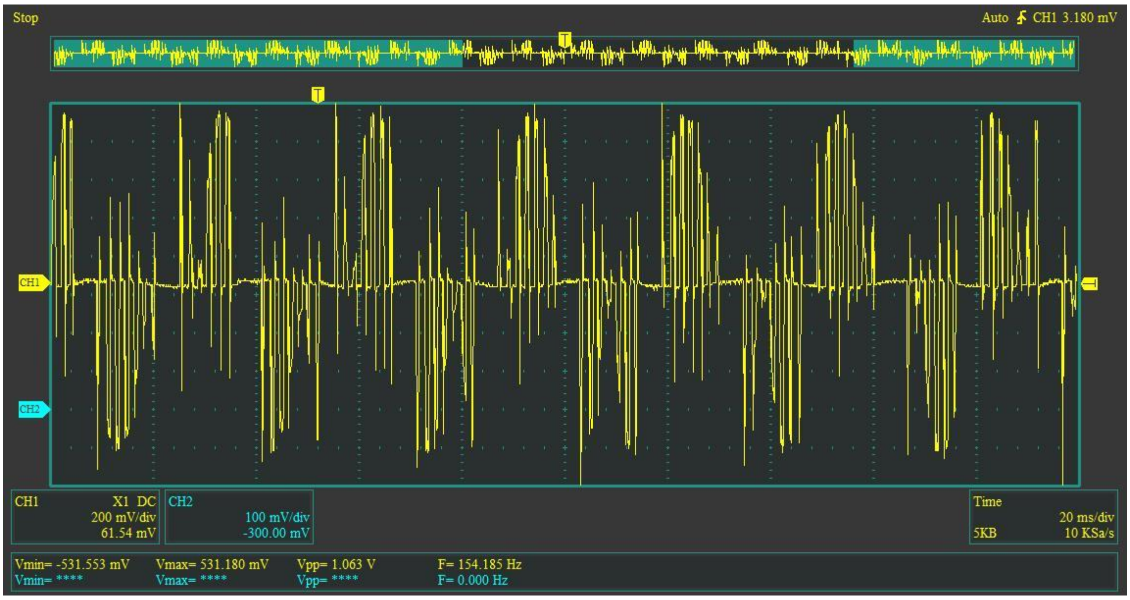


Fig.III. 24 Current for *f=32 Hz*

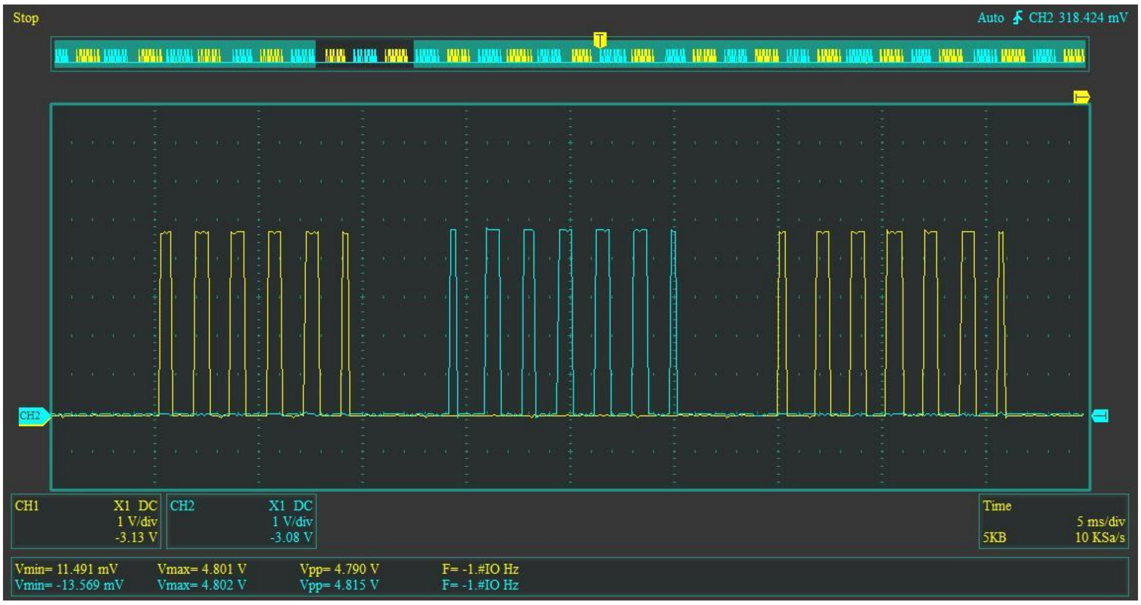


Fig.III.25 PWM Signal for *f=32 Hz*

Figure.III.24 and Figure.III.25 present respectively, the inverter output current and their PWM control signals by Arduino, the measured RMS currents are 0.27A and 32Hz frequency for the reference control signals of PWM method. In this case the motor dropout

In the case of Ar=0.9 and f=12 Hz

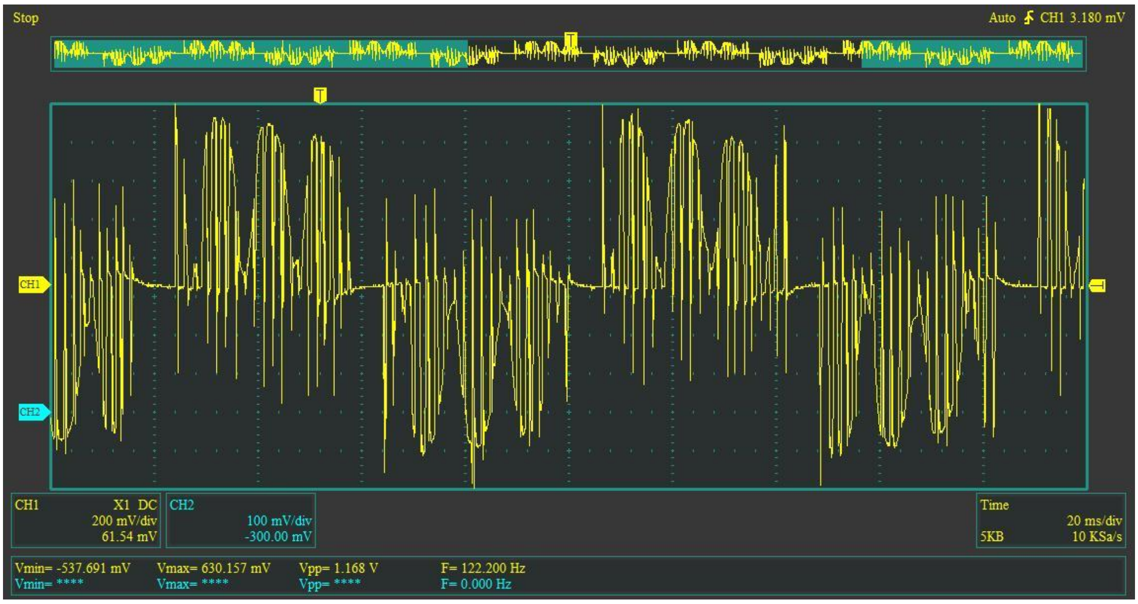


Fig.III.26 Current for *f =12 Hz*

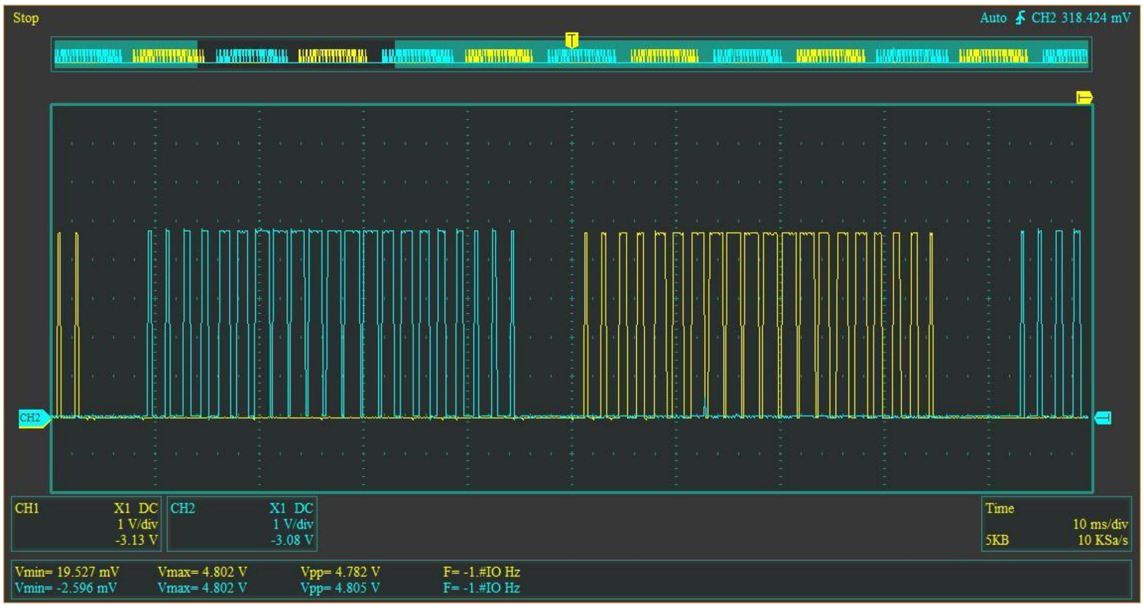


Fig.III.27 PWM Signal with *f=12 Hz*

Figure III.26 and Figure III.27 present respectively, the inverter output current and their PWM control signals by Arduino, the measured RMS currents are 0.46 A and 12Hz frequency for the reference control signals of PWM method. In this case the motor is working

In the case of Ar=0.9 and f=20 Hz

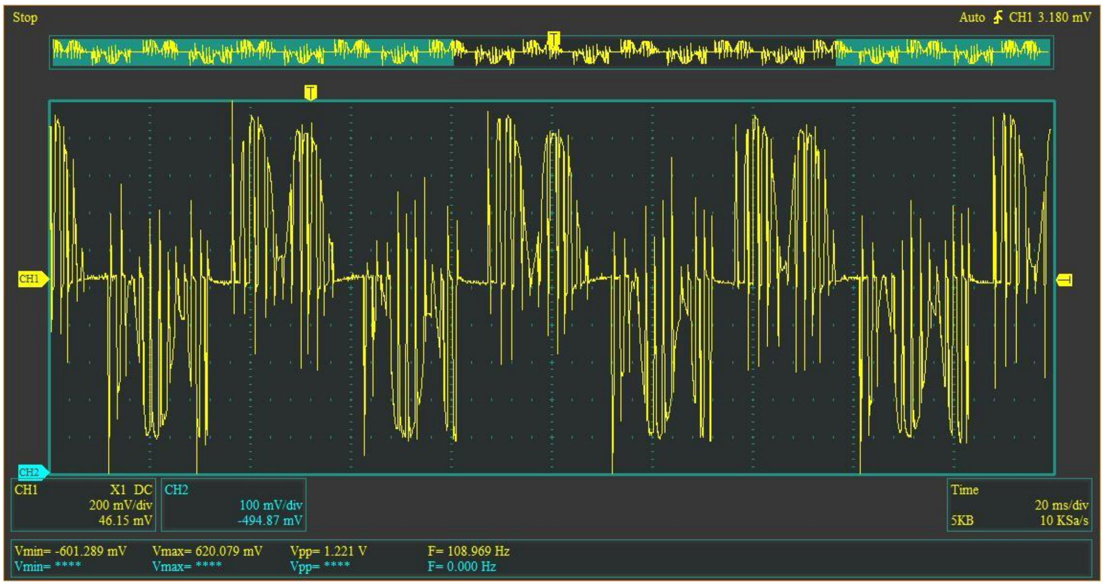


Fig.III.28 the current with *f*=20 Hz

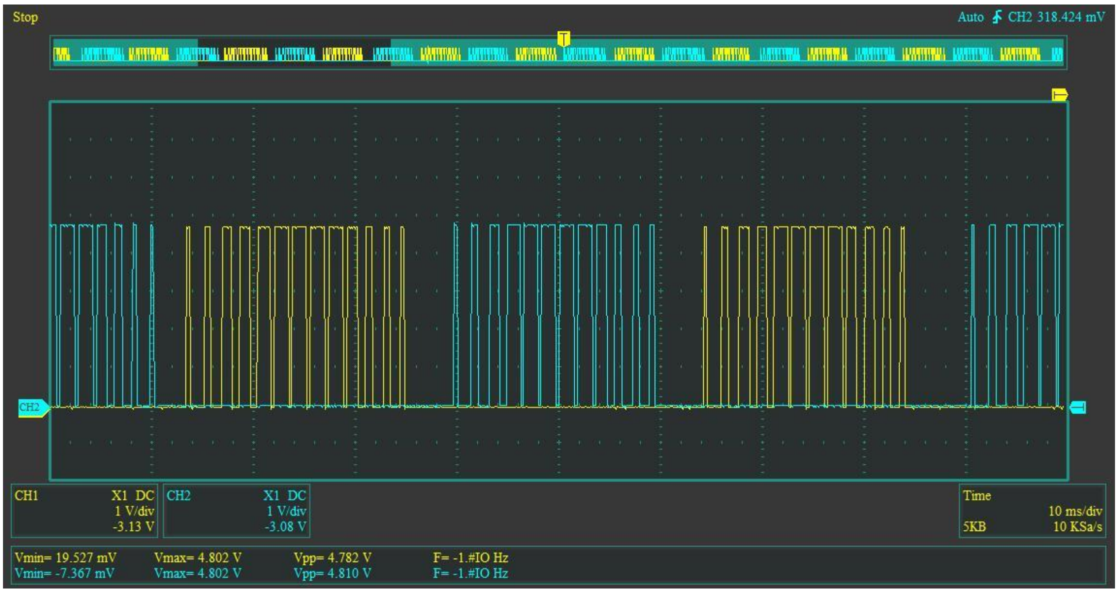


Fig.III.29 PWM Signal with *f=20 Hz*

Figure III.28 and Figure III.29 present respectively, the inverter output current and their PWM control signals by Arduino, the measured RMS currents are 0.53 A and 20Hz frequency for the reference control signals of PWM method. In this case the motor is working

III.12 Conclusion

In this chapter, the single-phase induction motor has been simulated by the software MATLAB / SIMULINK and a practical part of a *V/f* control based on the Pulse Width Modulation (PWM) inverter connected to the single-phase induction motor controlled by Arduino.

The simulation results show the importance of *V/f* control for the best performance operating in a single-phase motor. The experimental test presented the efficiency of *V/f* control for a signal phase induction motor using the PWM technique for a single-phase inverter. In addition, the importance of the constant *V/f* to ensure the continuity of operation after keeping the value always greater than the critical value.

General conclusion

General Conclusion

The aim of our project for a master's degree was to theoretically and practically study, simulate and realize the practice of *V/f* control based on PWM of a single-phase AC motor based primarily on a test bench with a single-phase inverter.

In the first chapter, we made a general study of the single-phase motor, where we shed light on its most important characteristics, advantages and disadvantages in terms of working with the difference between it and three phases, and mentioned some of its most important types and areas of use.

In the second chapter, we presented the modeling of the single-phase induction motor, the inverter, and the equivalent circuits in order to obtain mathematical equations and understand how they work. We also touched on the inverter and mentioned its two types: half bridge and full bridge, and in addition to that we mentioned the control of the pulse width modulation signal from the controller side, as well as the inverter and the method of switching of its power electronic circuit.

In the third chapter, we simulated the motor and observed its results before and after applying the load. Then we added an inverter to the motor in order to control and track the results of speed and torque.... etc. Then, we implemented *V/f* control on the inverter and tracked its behavior before and after applying the load, and we also carried out the practical work of the *V/f* control by implementing the inverter and practically controlling and tracking the results with the oscilloscope.

Ultimately, this work allowed us to extend our knowledge in the field of power electronics and the control of electric motors for better performance in the operation of VSD variable speed drives.

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