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Palestine Polytechnic University

College of Engineering

Department of Electrical Engineering

Industrial automation Engineering

Graduation Project

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Modeling of AC servo motor drive

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ABSTRACT:

Servo motors are synchronous machines through which a different angle can be obtained with high accuracy when the motor is running through specific pulses through which the motor running time is controlled, as the rotating part of the motor rotates to reach the desired angle when set through a closed control loop.

The goal of this project is to build a model to control the speed and angle of the servo motor, the motor is controlled by PLC where the number of pulses is set that works to determine the angle, speed and direction of rotation of the motor, and the closed loop control process is performed by the encoder sensor to read the speed and position. This data is sent via the sensor to the drive system, which processes this data and sends faults to the PLC.

This project demonstrates the results using MATLAP simulation, in which different curves of angles and velocities were shown, and ISPSOFT 3.09 software was used to control the programming and operation of the PLC to simulate the main controller and system using COMMGR 1.1 software. Driver settings have been modified using PANATERM software.

الملخص:

المحركات التنفيذي هي عبارة عن الات متزامنة يمكن الحصول من خلالها على زاوية مختلفة وبدقة عالية عند تشغيل المحرك عن طريق نبضات محددة يتم من خلالها التحكم في زمن تشغيل المحرك حيث يدور الجزء الدوار للمحرك للوصول للزاوية المطلوبة عند ضبط من خلال التحكم بالحلقة المغلقة.

الهدف من هذا المشروع هو بناء نموذج للتحكم في سرعة و وزاوية المحرك المؤازر ، تم التحكم في المحرك عن طريق PLC حيث يتم ضبط عدد النبضات التي تعمل على تحديد الزاوية والسرعة واتجاه دوران المحرك ، و يتم عملية التحكم الحلقة المغلقة عن طريق مجس encoder لقراءة السرعة والموقع ، ويتم ارسال من خلال المجس هذه البيانات الى نظام القيادة الذي يعمل على معالجة هذه البيانات وارسال الاخطاء الى PLC .

يظهر هذا المشروع النتائج عن طريق استخدام محاكاة برنامج MATLAP ، حيث تم اظهار منحنيات لزاوية وسرعات مختلفة، وتم استخدام برنامج ISPSOFT 3.09 وهو جهاز يتم من خلاله التحكم في برمجة وتشغيل PLC ، ولعمل محاكاة بين جهاز التحكم الرئيسي والنظام باستخدام برنامج COMMGR 1.1, وتم ضبط اعدادات Driver باستخدام برنامج PANATERM.

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Chapter one

Introduction:

A servomotor is a structural unit of a servo system and is used with a servo drive. The servomotor includes the motor that drives the load and a position detection component, such as an encoder.

The servo systems vary the controlled amount, such as position, speed, or torque, according to the set target value (command value) to precisely control the machine operation.

Several control system algorithms have been applied in control system engineering. The one of the interesting term in that application is position control. Position control for servo motor exists in a great variety of automatic processes. However, the performance of servo motor is influenced by uncertainties such as nonlinear properties, mechanical parameter variation, external disturbance, unstructured uncertainty due to nonideal field orientation in the transient state and unmodelled dynamics. From a practical point of view, complete information about uncertainties is difficult to acquire in advance. To deal with these uncertainties . [1]

A closed-loop tension control system with the programmable logic controller (PLC) with function modules as its control kernel, the alternating current (AC) servo motor as execute element and the radius-following device to accomplish the real-time radius compensation. The mechanism of the tension control system is analyzed and the numerical model is set up. The compensation technique of the radius of the scroll is analyzed.[2]

A synchronous electric motor is an AC motor in which, at steady state, the rotation of the shaft is synchronized with the frequency of the supply current; the rotation period is exactly equal to an integral number of AC cycles. Synchronous motors contain multiphase AC electromagnets on the stator of the motor that create a magnetic field which rotates in time with the oscillations of the line current. The rotor with permanent magnets or electromagnets turns in step with the stator field at the same rate and as a result, provides the second synchronized rotating magnet field of any AC motor. A synchronous motor is termed doubly fed if it is supplied with independently excited multiphase AC electromagnets on both the rotor and stator. [3]

Problem Statement:

The lack of a servo motor control unit in the leadership lab at Palestine Polytechnic University, and knowledge of the mechanism of servo work and control.

Objectives:

1) Provides a servo motor controller in the driving lab.
2) Provides an easy control system for three-phase servo motor in the following
    - Speed control.
    - Position Control.
    - Torque control.
3) Help teachers explain experiments and explain engine operation methods.
4) Provide an integrated system with easy control and easy maintenance system.

Project Scope:

The scope of this project is:

1) Understanding of the servo motor control background, analyzing the problem and investigated plc controller theory which has been applied to the servo motor system.
2) Design and implementation of servo motor driver using PLC controller.
3) Implementation servo drive control on the servo motor control by using MATLAB simulation.

Time Table:

This table it shows the work plan for this project.

Time	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15
Reading research and collecting information about servo motor and its control circuits	■	■	■	■											
Design and simulation of the motor and the control circuit			■	■	■	■	■								
Choose the pieces to be used in the project					■	■									
Write a project summary						■	■	■	■	■					
Building the control circuit, programming the project control unit, and designing an educational board										■	■	■	■	■	
Analysis of the results														■	■
conclusions and recommendations														■	■
Documentation											■	■	■	■	■

Time table for introduction

Estimated Cost:

#	the name of piece	The price of the cat in the market is local
1	Servo motor (synchronous)	500 $
2	Servo driver	1200 $
3	Interior collage board	20 $
4	External collage board	40 $
5	PLC controller system (delta)	300 $
6	Connection wires complete system	40 $
	sum	2100 $

Chapter Two

Modeling servo motor and encoder

A Servo motor is a rotary actuator that allows for precise control of angular position, velocity and acceleration. Servos are found in many places: from toys to home electronics to cars and airplanes.

Servo motor is an automatic device that uses error sensing feedback to correct the performance of a mechanism. The term correctly applies only to the systems where the feedback or error correction signals help to control mechanical position or other parameters. A common type of servo provides position control. Servos are commonly electrical or partially electronic in nature, using an electric motor as the primary means of creating mechanical force. Other types of servos use hydraulics, pneumatics, or magnetic principles. Usually, servos operate on the principle of negative feedback, where the control input is compared to the actual position of the mechanical system as measured by some sort of transducer at the output. Any difference between the actual and wanted values (error signal) is amplified and used to drive the system in the direction necessary to reduce or eliminate the error. Servomotors are available as AC or DC motors. Today, servo motor are used in automatic machine tools, satellite tracking antennas, remote control airplanes, automatic navigation systems on boats and planes, and antiaircraft gun control systems.[1]. Fig (2.1) shows the construction of a standard servo motor.

Fig (2.1): Construction of a standard servo motor

Servo motor mechanism:

As the name suggests, a servo motor is a servomechanism. More specifically, it is a closed –loop servomechanism that uses position feedback to control its motion and final position. The input to its control is some signal, either analogue or digital, representing the position commanded for output shaft. The motor is paired with some type of encoder to provide position and speed feedback. In the simplest case, only the position is measured. The measured position of output is compared to the command position, the external input to the controller. If the output position that required, an error signal is generated which then causes the motor to rotate in either direction, as needed to bring the output shaft to the appropriate position. As the position approach, the error signal reduces to zero and the motor stops. The very simplest servo motor use position-only sensing via a potentiometer and bang-bang control of their motor, the motor always rotates at full speed (or stopped).this motor not widely used in industrial motion control, but they form the basis of simple and cheap servos for radiocontrolled models. More sophisticated servo motors measure both the position and also the speed of the output shaft. They may also control the speed of their motor, rather than always running at full speed. Both of these enhancements, usually in combination with a PID control algorithm, allow the servo motor to be brought to its commanded position more quickly and more precisely, with less overshooting.[1]

Types of AC servo motors:

Induction-type AC servo motor.

Synchronous-type AC servo motor.

This research is based on a Synchronous motor.

Synchronous motors:

Type of synchronous motors

- Wound field.
- Permanent magnet.
- Synchronous reluctance.
- Hysteresis motors.

Permanent magnet synchronous motor will be studied.

2.1 Permanent magnet synchronous motor (PMSM):

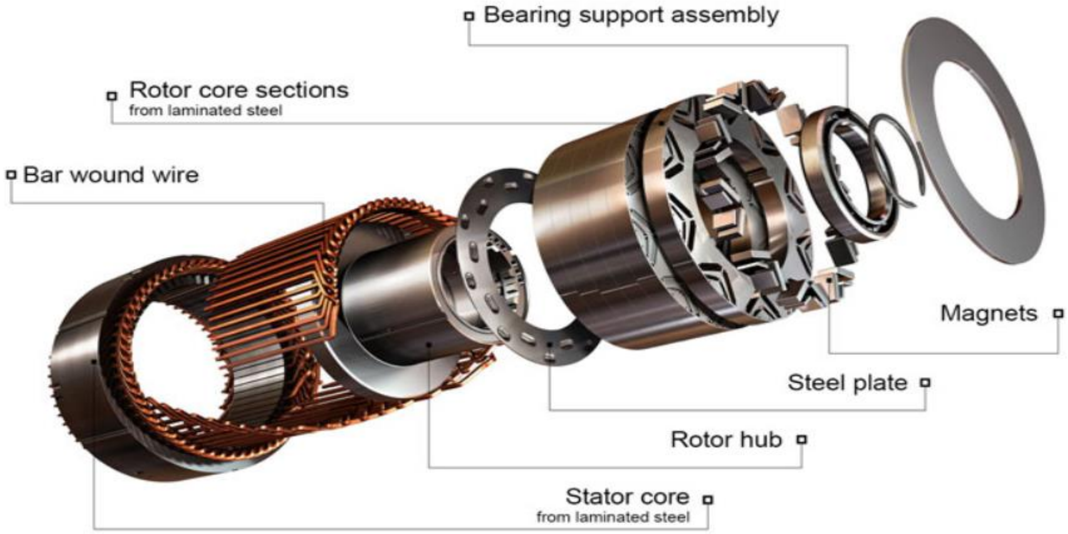


Fig (2.2): Permanent Magnet Synchronous Motor of generally (PMSM) modelling.

A permanent magnet synchronous motor: is a synchronous electric motor whose inductor consists of permanent magnets, like any rotating electric motor, consists of a rotor and a stator. The stator is the fixed part. The rotor is the rotating.

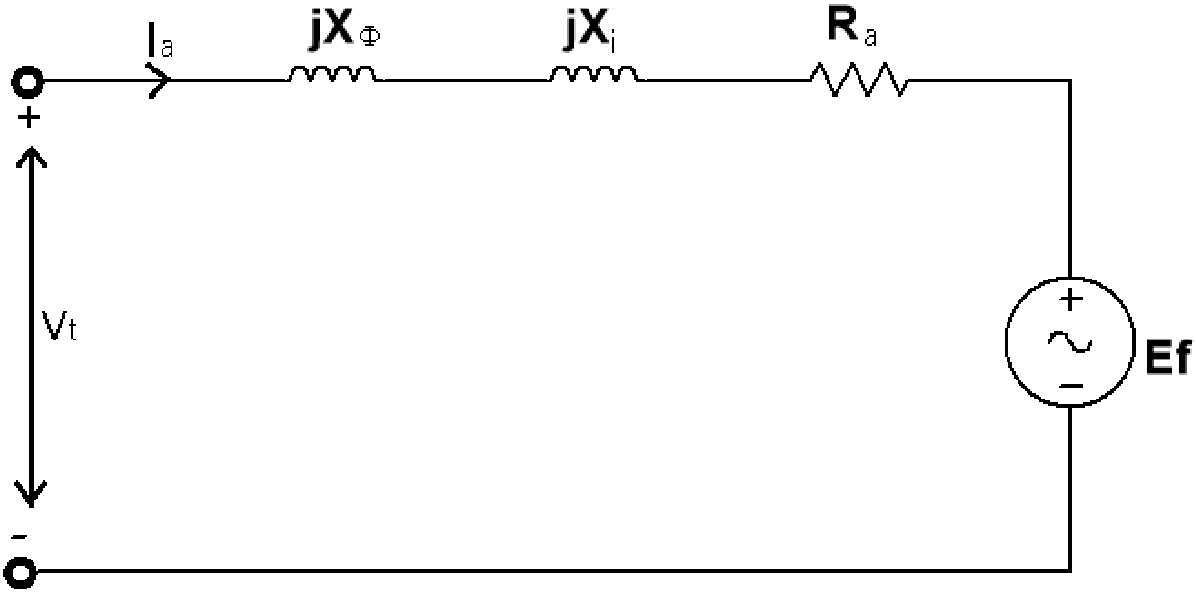


Fig (2.3): Per-phase equivalent circuit for a synchronous motor.

Where the voltage terminal of synchronous motor is

$$V_t = E_a + I_a (R_a + jXi + jX\Phi) \quad \textbf{(2.1)}$$

$I * \cos\Phi = Ia = \text{constant}$

Where I_a is the active component of armature current and

$I_a . Z_s = \text{constant}$

2.1.1 Synchronous Motors characteristics and Features

- The rotation of a synchronous motor is established by the phase sequence of the three-phase AC applied to the motor stator. As with a three-phase induction motor, synchronous motor rotation is changed by reversing any two stator leads. Rotor polarity has no effect on rotation.
- Synchronous motors are often direct-coupled to the load and may share a common shaft and bearings with the load.
- Large synchronous motors are usually started across the- line. Occasionally, reduced voltage starting methods, such as autotransformer or part-winding starting, may be employed.

- Equivalent circuit and phasor diagram of a synchronous motor per phase

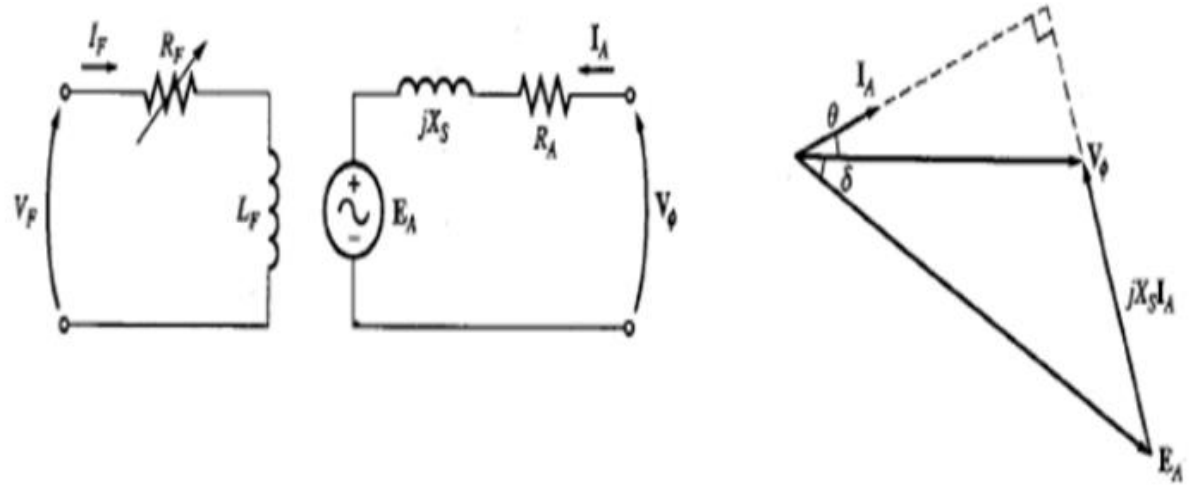


Fig (2.4): Equivalent circuit and phasor diagram of a synchronous motor per phase

The Equivalent circuit equation for a synchronous motor is thus

$V_{\emptyset} = E_A + jx_s I_a + R_a I_a$ **(2.2)**

$E_A = V_{\emptyset} - jx_s I_a - R_a I_a$ **(2.3)**

Synchronous speed

$\mathrm{n} = \frac{120*\mathrm{F}}{\mathrm{P}}$ **(2.4)**

The parameter of motor

Panasonic	
Model NO.	$MSMD042P1S$
INPUT 3**Φ**AC	$106\ V$
	$2.6\ A$
RATED OUTPUT	$0.4\ KW$
RATED FREQ.	$200\ HZ$
RATED REV.	$3000\ r/min$
Rated torque	$1.3\ N.m$
d-axis inductance (L_d)	$6.81\ mH$
q-axis inductance (L_q)	$6.81\ mH$
Rotor permanent magnet flux (λ_M)	$0.1674\ v\ s\ rad^{-1}$
Inertia of the mechanical system (J_M)	$0.018 * 10^{-4}\ kg.m^2$
Viscous friction coefficient (B_M)	$1.3671 * 10^{-3}\ Nm\ s\ rad^{-1}$
Stator resistance per phase (R_S)	$20\ \Omega$

The rated speed

$$\mathrm{n} = \frac{120 * 200}{8} = 3000\ \mathrm{rpm}$$

$$p_m = \sqrt{3}\, V_l\, I\, PF$$

$$400 = \sqrt{3} * 106 * 2.6\, PF$$

$$PF = 0.83$$

$$PF = \cos\theta = 0.83$$

$$\theta = 33.9\ leading$$

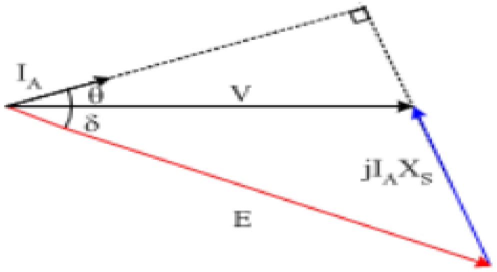


Fig (2.5): phasor diagram of a synchronous motor per phase

2.1.2 Methods of starting

As just stated, the purpose of starting method is to bring rotor speed close to synchronous speed. One widely used method is to start the synchronous motor as an induction motor with field unexcited and damper winding serving as a squirrel-cage rotor. Following four points should be noted about this starting method:

1. The starting torque and current can be increased and reduced respectively, by increasing the damper winding resistance. For successful pull-in, the motor speed while running as an induction motor must be close to synchronous speed. For this the damper winding resistance must be as low as possible. Further, for damping hunting oscillations, damper winding resistance must be low. The damper winding resistance is chosen to provide a compromise between these contradictory requirements.

2. During acceleration as an induction motor, because of large number of turns in field winding, the induced voltage in the field winding may reach several thousand volts, thus overstressing the insulation of the winding and increasing the voltage rating of the field supply converter. This undesirable situation is eliminated by keeping the field circuit. Closed through a small discharge resistance before dc excitation is applied. The discharge resistance permits a circulating current to flow through the field winding. Though

induced voltage is still present, the actual potential difference between terminals or between turns is reduced to a safe value.

The field closed through a discharge resistance, acts somewhat as a cage winding and modifies the starting and pull-in-torques. An increase in the field circuit resistance increases the starting torque. On the other hand, a decrease in discharge resistance reduces the potential difference appearing in the field circuit. The value of discharge resistance is chosen to obtain a compromise between these two contradictory requirements.

3. Dc excitation should not be applied during acceleration as an induction motor because while it produces no net motoring torque, it does produce braking torque (braking torque is produced by the currents that are induced in stator by the Dc field). Dc field should be applied only after the motor has reached close to full speed.

4. When rotor has salient pole construction, the damper winding can have conductors only over the pole arc. This leads to a dip in the speed-torque curve at half of synchronous speed.

5. When started with full supply voltage, the starting current can be 7 to 10 times of full load value. Except in small size motors, such a high starting current causes fluctuation in supply voltage. In case of large size motors, such a high starting current may cause a large drop in the terminal voltage, thus reducing the already low starting torque further. Starting current can be reduced by employing any one of the reduced voltage starting methods employed for induction motors. Reduction in starting current is obtained at the expense of reduction in starting torque. When started at a reduced voltage, the transition to full voltage can be made before or after the pull-in. Former is preferred as it improves pull-in performance due to two reasons:

    a. with full voltage the speed attained as induction motor is closer to synchronous speed and
    b. The pull-in torque increases in proportion to voltage squared consequently pull- in can be achieved faster and with larger motor loads.

Another method of starting is to use a low power auxiliary motor coupled to the synchronous motor shaft. With the help of auxiliary motor, the rotor speed is brought near, synchronous speed and then de field is switched-in. This method has a very low starting torque.

2.1.3 Braking of Synchronous Motor:

- Dynamic braking

As shown in Fig. (2.6), the motor can work in regenerative braking only at synchronous speed. Therefore, regenerative braking cannot be used for stopping or decelerating a load. Dynamic braking is obtained by disconnecting stator from-the source and connecting it to a three-phase resistor. Machine works as a synchronous generator and dissipates generated energy in the braking resistor. The per phase equivalent circuit for a per unit speed k is shown in Fig. (4.5) The per unit speed k is given by

$$\mathrm{k} = \frac{\mathrm{w_m}}{\mathrm{w_{ms}}} \qquad \textbf{(2.5)}$$

The speed torque curve is shown in Fig (4.4). The motoring operation is obtained when δ is positive and E lags being V, whereas regenerative braking is obtained when & is negative or E leads V. The maximum torque T_{max} (also known as pull-out torque), is reached at $\delta = \pm 90°$, If the load torque exceeds T_{max}, the machine pulls out of synchronism. In order to prevent damage due to excessive current, automatic circuit breakers are provided to disconnect the machine when it comes out of synchronism.

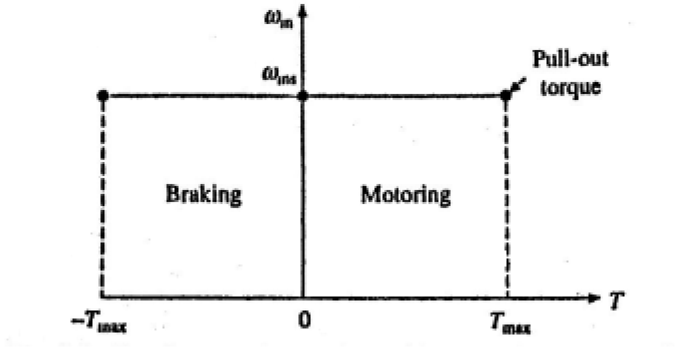


Fig (2.6): speed torque characteristic with a fixed frequency supply.

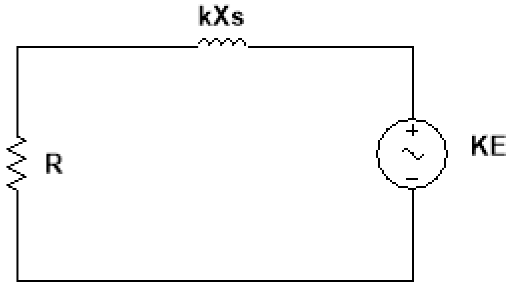


Fig (2.7): Dynamic braking equivalent circuit.

Braking current is given by $I_{sb} = \frac{kE}{\sqrt{R_B^2+(KX_S)^2}}$ **(2.6)**

Braking power $P_B = 3I_S^2R_B$ **(2.7)**

Braking torque $T_B = \frac{P_B}{kw_{ms}}$ **(2.8)**

Gives final equation $T_B = \frac{3R_BkE^2}{w_{ms}(R_B^2+k^2\ x_s^2)}$ **(2.9)**

→ Substitute in equations:

$$\mathrm{k} = \frac{\mathrm{w_m}}{\mathrm{w_{ms}}} = \frac{1500}{3000} = 0.5$$

$$\mathrm{I_{sb}} = \frac{0.5 * 106}{\sqrt{1.33^2 + (0.5 * 7)^2}} = 14.1711\ \mathrm{A}$$

$$\mathrm{P_B} = 3 * 10^2 * 1.33 = 399\ \mathrm{W}$$

$$\mathrm{T_B} = \frac{399}{0.5 * 3000} = 0.266\ \mathrm{N.m}$$

Since, synchronous react rice is large compared to braking resistance, for most Speed range, the variation of current and torque is not large. Therefore, a single section of resistance is enough. At zero speed, the induced voltage, and therefore, armature current and torque are zero. As the torque is available in whole speed and it is zero at zero speed, dynamic braking is suitable for stopping motor. Range theoretically, plugging can also be employed. However, it is not used in practice. Plugging torque is produced by damper winding. Because of its low resistance, while current drawn from the supply is very large, the braking torque produced is much smaller compared to that produced by dynamic braking. In case of large motors, high plugging current can create a severe disturbance in supply lines.

2.1.4 Losses:

Various losses occurring in the motor are:

1. Armature copper loss $I_a^2\ R_a$.
2. Iron and friction losses.

2.2 V/f Control of Permanent Magnet Synchronous Motors

Permanent Magnet Synchronous Motor is characterized by high power density, high efficiency and high reliability, and it is superior in many applications. V/f control for PMSM is able to get rid of the expensive rotor position sensor, and it is of great research value. V/f control method for PMSM. Firstly, the reason for the instability of the traditional open-loop V/f control is analyzed. A speed closed loop is introduced to avoid the instability of the system. Meanwhile, in order to enhance the efficiency of the system, a reactive power closed-loop is proposed, which is added to the system. Finally, experimental results are provided to validate the effectiveness of the proposed V/f control method.[2]

The increasing energy cost demands for more efficient motion control systems in domestic and industrial applications. Power electronics and control can contribute to increase the efficiency of present systems, but it can also be dealt with new efficient solutions for applications. Instead of using constant speed using variable speed drives in motion control applications the efficiency of the systems can be increased. The most common control methods used in drives are V/f control, vector control and direct torque control in continuous running applications, a small increase in efficiency means a huge energy savings per year. These continuous running applicants, fanions are mainly pumping and compressors for heating, ventilating and air conditioning applications. In these applications where high dynamics are not required, a simple digital implementation of V/f control can be used instead of more complex vector or direct torque control with the same performance the workhorse for these applications has been the induction motor for years. The induction motor is a well-known motor, a cheap motor, and does not require position sensor to implement a low-cost control for this kind of applications. But efficiency can be improved if the induction motor is substituted by a permanent magnet synchronous motor (PMSM). However, in permanent magnet synchronous motors, the stator currents have to be synchronized with the rotor permanent magnet in order to produce the required torque and not to lose synchronization. For this purpose a rotor position sensor is required. The need of a rotor position sensor increases the cost and reduces the reliability. Self-synchronization can be achieved using damper windings, but due to cost, efficiency and high-cost, they are generally not implemented in PMSMs. Therefore, it is necessary to develop new control strategies for PMSMs to avoid the use of the rotor position sensor. Because heating, ventilating and air conditioning applications do not demand for a high-performance control, the V/f control strategy is suitable for these drives. However, even using a V/f control strategy for permanent magnet synchronous motors, there is a need in synchronization for stator currents with the rotor magnet position.[3]

2.3 Equations of permanent magnet synchronous motors

The Park transformation is useful when modeling a PMSM, since there is no angle dependent terms appear in equations, providing easy analysis of the system [4]. With the electrical equations in Park variables, it is easy to obtain an expression for the motor generated torque as a function of electrical variables. This produced mechanical torque links the electrical world with the mechanical world, and completes the model of the system. The model equations of the permanent magnet synchronous motor in Park variables are:

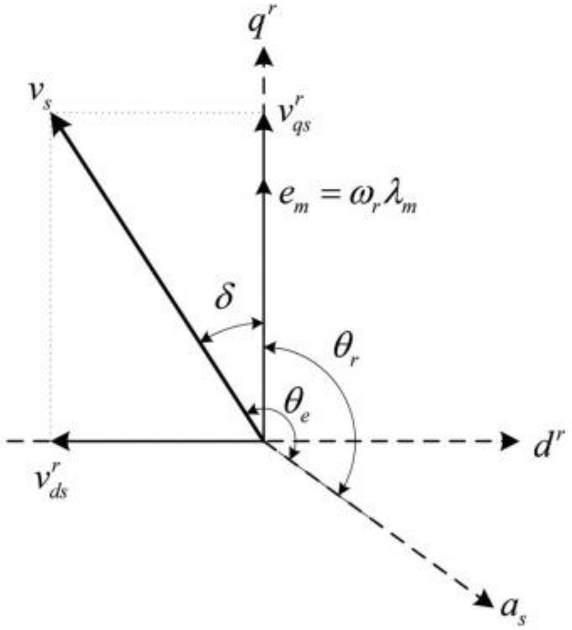


Fig (2.8): Load angle

Sometimes, it is useful to define a new variable called load angle [5]. The load angle is the angle between the stator electrical applied voltage and the emf generated by rotor magnets when rotating, as can be seen in Figure (2.8). With this new equation, the system equations in state space variables are defined as

$$\mathrm{i}_{\mathrm{ds}}^{\mathrm{r}} = -\frac{\mathrm{R_s}}{\mathrm{L_d}}\mathrm{i}_{\mathrm{ds}}^{\mathrm{r}} + \mathrm{w_r}\frac{\mathrm{L_q}}{\mathrm{L_d}}\mathrm{i}_{\mathrm{qs}}^{\mathrm{r}} + \frac{\mathrm{v_s}*\sin\delta}{\mathrm{L_d}}$$

$$\mathrm{i}_{\mathrm{ds}}^{\mathrm{r}} + \frac{\mathrm{R_s}}{\mathrm{L_d}}\mathrm{i}_{\mathrm{ds}}^{\mathrm{r}} = \mathrm{w_r}\frac{\mathrm{L_q}}{\mathrm{L_d}}\mathrm{i}_{\mathrm{qs}}^{\mathrm{r}} + \frac{\mathrm{v_s}*\sin\delta}{\mathrm{L_d}} \tag{2.10}$$

$$\mathrm{i}_{\mathrm{qs}}^{\mathrm{r}} = -\frac{\mathrm{R_s}}{\mathrm{L_d}}\mathrm{i}_{\mathrm{qs}}^{\mathrm{r}} - \mathrm{w_r}\frac{\mathrm{L_d}}{\mathrm{L_q}}\mathrm{i}_{\mathrm{ds}}^{\mathrm{r}} - \frac{\lambda_{\mathrm{m}}}{\mathrm{L_q}}\mathrm{w_r} + \frac{\mathrm{v_s}*\cos\delta}{\mathrm{L_q}} \tag{2.11}$$

$$\mathrm{w_r} = \frac{3}{2}(\frac{\mathrm{n}}{2})^2\frac{1}{\mathrm{J_m}}\lambda_{\mathrm{m}}\mathrm{i}_{\mathrm{qs}}^{\mathrm{r}} + \frac{3}{2}\left(\frac{\mathrm{n}}{2}\right)^2\frac{1}{\mathrm{J}}\left(\mathrm{L_d} - \mathrm{L_q}\right)\mathrm{i}_{\mathrm{ds}}^{\mathrm{r}}\mathrm{i}_{\mathrm{qs}}^{\mathrm{r}} - \frac{\mathrm{B_m}}{\mathrm{J_m}}\mathrm{w_r} - \frac{\mathrm{n}}{2\mathrm{J}}\mathrm{T_L} \tag{2.12}$$

$\delta = w_e - w_r$

$\delta = \frac{2\pi 1500}{60} - \frac{2\pi 3000}{60}$

$\delta = 157 - 314 = -157$

i_{ds}^{r} =-$\frac{20}{6.81m}i_{ds}^{r} + 314\ \frac{6.81m}{6.81m}\ 15 + \frac{220\sin -157}{6.81m}$

$i_{ds}^{r} = 2.69\ A$

$$i_{qs}^{r} = -\frac{R_s}{L_d}i_{qs}^{r} - w_r\frac{L_d}{L_q}i_{ds}^{r} - \frac{\lambda_m}{L_q}w_r + \frac{v_s * \cos\delta}{L_q}$$

$$i_{qs}^{r} = -\frac{20}{6.81m}i_{qs}^{r} - 314\frac{6.81m}{6.81m}2.69 - \frac{0.1674}{6.81m}314 + \frac{220 * \cos -157}{6.81m}$$

$i_{qs}^{r} = 13.0369A$

The above equations are the state space model, but this model contains non-linear terms. To analyze the stability of the system, a linear model must be obtained.

Stability analysis:

The non-linear model can be linearized by substituting each variable as [5]

$\mathrm{x_i} = \mathrm{x_i} + \Delta\,\mathrm{x_i}$

Where xi is the variable, $\mathrm{x_i}$ is the steady state value, and $\Delta\,\mathrm{x_i}$ is a perturbation from the steady state value. Then, the linearized system is

$\mathrm{x} = \mathrm{A(x)} + \Delta\mathrm{x} + \mathrm{B(X)}\Delta\mathrm{u}$

Applying this linearization technique to the state space model of the permanent magnet synchronous motor, the linearized model is obtained as

$$\begin{Bmatrix} \Delta\dot{i}^r_{ds} \\ \Delta\dot{i}^r_{qs} \\ \Delta\dot{\omega}_r \\ \Delta\dot{\delta} \end{Bmatrix} = \begin{pmatrix} -\frac{R_s}{L_d} & \frac{L_q\omega_{r0}}{L_d} & \frac{L_q I^r_{qs}}{L_d} & -\frac{V_s\cos\delta_0}{L_d} \\ -\frac{L_d\omega_{r0}}{L_q} & -\frac{R_s}{L_q} & -\frac{1}{L_q}\left(L_d I^r_{ds} + \lambda_m\right) & -\frac{V_s\sin\delta_0}{L_q} \\ \frac{3}{2}\left(\frac{n}{2}\right)^2\frac{1}{J_m}\left(L_d - L_q\right)I^r_{qs} & \frac{3}{2}\left(\frac{n}{2}\right)^2\frac{1}{J_m}\left(\lambda_m + \left(L_d - L_q\right)I^r_{ds}\right) & -\frac{B_m}{J_m} & 0 \\ 0 & 0 & -1 & 0 \end{pmatrix} \begin{Bmatrix} \Delta i^r_{ds} \\ \Delta i^r_{qs} \\ \Delta\omega_r \\ \Delta\delta \end{Bmatrix} + \begin{pmatrix} -\frac{\sin\delta_0}{L_d} & 0 & 0 \\ \frac{\cos\delta_0}{L_q} & 0 & 0 \\ 0 & 0 & -\frac{n}{2J_m} \\ 0 & 1 & 0 \end{pmatrix} \begin{Bmatrix} \Delta v_s \\ \Delta\omega_e \\ \Delta T_l \end{Bmatrix}$$

V/f open loop control

When the motor is operated at open loop V/f control, the applied voltage and frequency are constant, that is

$\Delta v_s = 0$

$\Delta w_e = 0$

The stability of the system is determined by the eigenvalues of the state matrix $\mathrm{A(x)}$. In open loop V/f control strategy with no-load, the motor produces no torque. Then, $I_{qs}^{r} = 0.$ In order to minimize the losses, I_{ds}^{r} is also 0. In this case, the applied voltage must only compensate the emf in the q axis, $v_s = w_r \lambda_m = v_{qs}^{r}\ and\ v_{ds}^{r} = 0.$ Substituting this steady state conditions in the state matrix A(X) it is possible to obtain the stability characteristic of the system. Figure (2.10) shows the root locus diagram of the permanent magnet synchronous motor in an open loop V/f control at no-load as a function of stator frequency ω_e. For this figure the motor data can be found in Appendix A. As seen in Figure (2.10), the motor becomes unstable above 100 Hz operation, i. e. half of the rated frequency. The most left poles are the named stator poles, and represent the fast electrical stator dynamics [6, 5]. The most right poles are named the rotor poles, and represent the slow mechanical dynamics. A poor coupling between the rotor and stator poles causes this instability [7, 8].

Figure (2.11) shows the dominant poles at different load levels. As seen, the stability characteristic is not modified with the load level. Figure (2.12) shows this instability in a real system. As seen, at low frequency, the motor is stable (Figure (2.12) (a)), but when increasing the frequency the motor becomes unstable (Figures (2.12) (b) and (2.12) (c)).

- Calculations equations showing results on drawings

$$\mathrm{w} = \frac{4\pi \mathrm{f}}{\mathrm{p}}$$

$\mathrm{p} = 8.$

$$\text{Fig (2.12)(a)}: \mathrm{w} = \frac{4 * 3.14 * 50}{8} = 78.5\ \mathrm{rad/s}$$

$$\text{Fig (2.12)(b)}: \mathrm{w} = \frac{4 * 3.14 * 100}{8} = 157\ \mathrm{rad/s}$$

$$\text{Fig (2.12)(c)}: \mathrm{w} = \frac{4 * 3.14 * 200}{8} = 314\ \mathrm{rad/s}$$

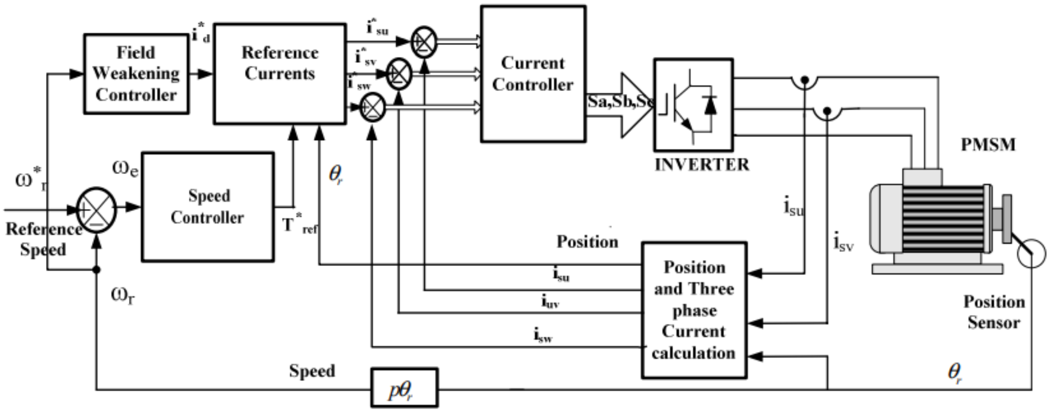


Fig (2.9): PMSM vector-controlled drive with constant flux operation

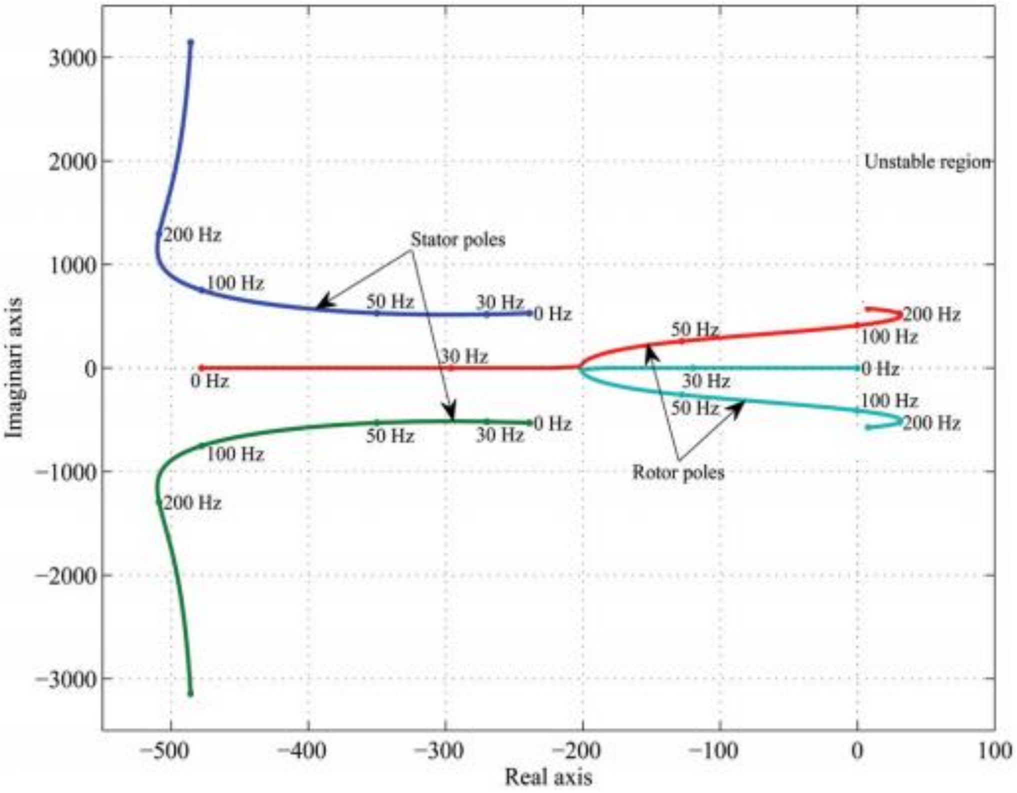


Fig (2.10): Root locus of the permanent magnet synchronous motor operating at no-load in an open loop V/f control strategy.

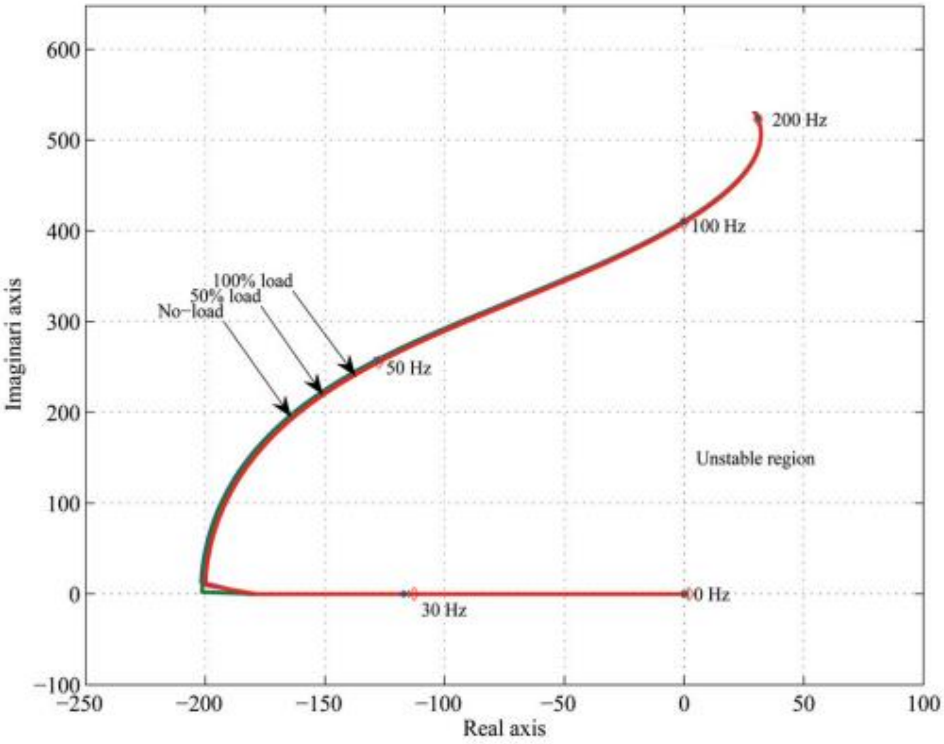


Fig (2.11): Root locus of the permanent magnet synchronous motor operating at different load levels in an open loop V/f strategy.

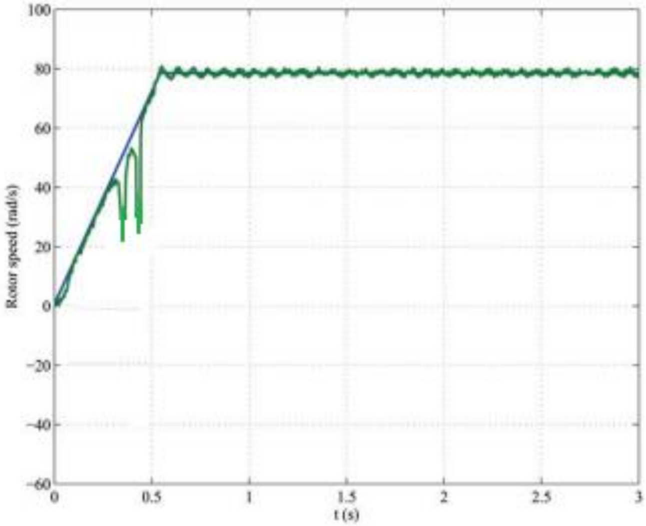


Fig (2.12) (a): Rotor speed at 50 Hz stator frequency.

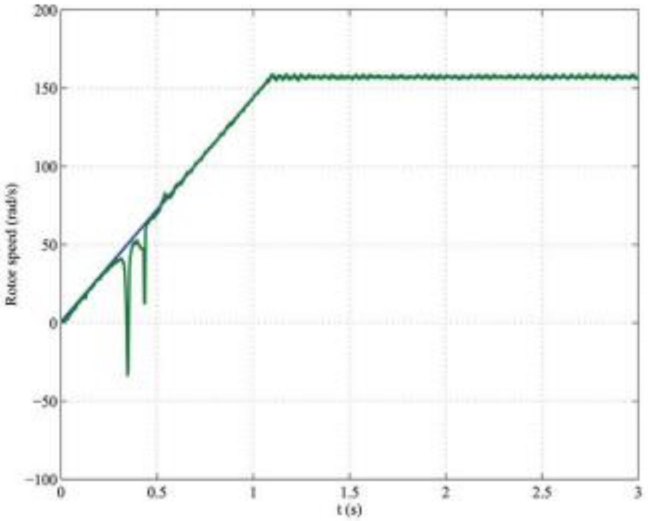


Fig (2.12) (b): Rotor speed at 100 Hz stator frequency.

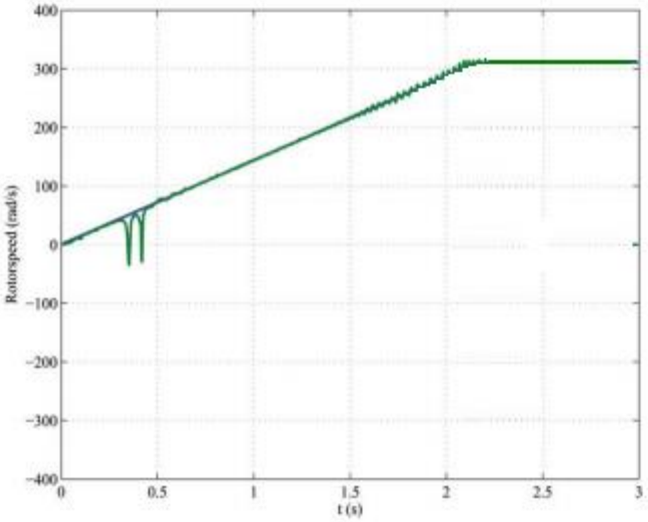


Fig (2.12) (c): Rotor speed at 200 Hz stator frequency.

Fig (2.12): Rotor speed at different stator frequencies in the open loop V/f control strategy.

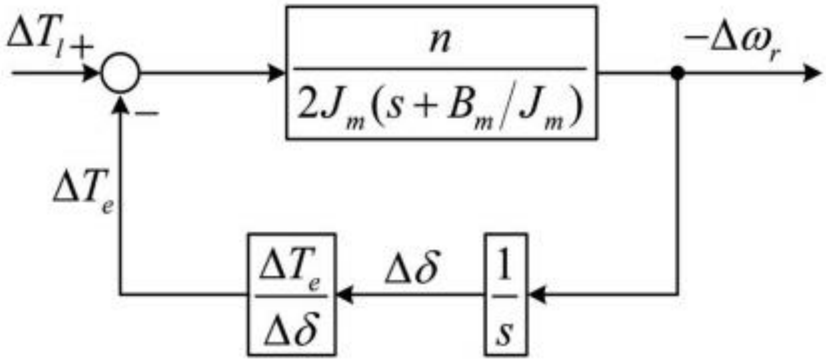


Fig (2.13): Block diagram of the small signal model operating at V/f open loop control strategy

2.3 Mathematical modeling of PMSM

In PMSM the inductances vary as a function of the rotor angle. The two-phase (d-q) equivalent circuit model is used for analysis. The space vector form of the stator voltage equation in the stationary reference frame is given as:

$$v_s = r_s i_s + \frac{\lambda_s}{dt} \quad \textbf{(2.13)}$$

where r_s , v_s , i_s , and λ_s are the resistance of the stator winding, complex space vectors of the three phase stator voltages, currents, and flux linkages, all expressed in the stationary reference frame fixed to the stator, respectively. They are defined as:

$v_s = [v_{sa}(\mathrm{t}) + \mathrm{a}_1 v_{sb}(\mathrm{t}) + a_2 v_{sc}(\mathrm{t}) \;\;]$

$i_s \; = [i_{sa}(\mathrm{t}) + \mathrm{a}_1 i_{sb}(\mathrm{t}) + a_2 i_{sc}(\mathrm{t}) \;\;]$

$$\lambda_s = [\lambda_{sa}(\mathrm{t}) + \mathrm{a}_1\lambda_{sb}(\mathrm{t}) + a_2\lambda_{sc}(\mathrm{t})\ \ ] \quad \textbf{(2.14)}$$

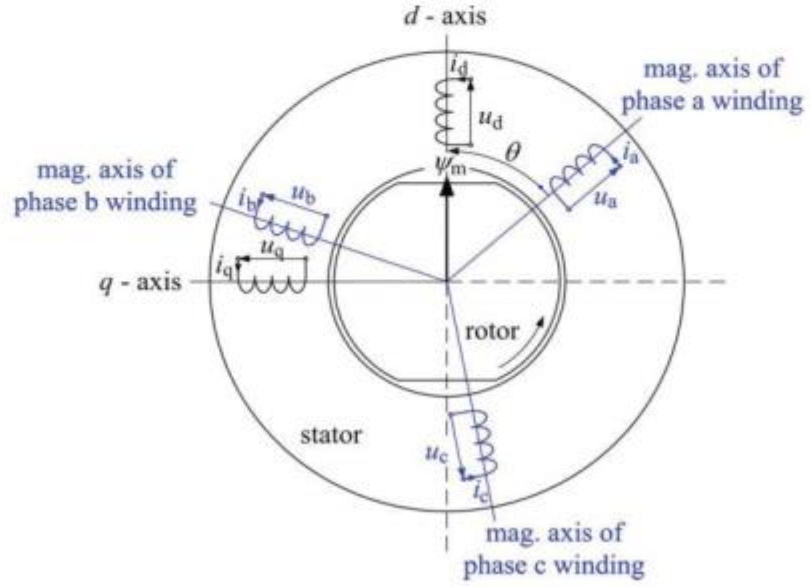


Fig (2.14): Schematic representation of a two-pole, three-phase permanent magnet synchronous machine.

Fig. (2.14) illustrates a conceptual cross-sectional view of a three-phase, two-pole surface mounted PMSM along with the two-phase d-q rotating reference frame. Symbols used in (4.5) are explained in detail below: a , and a_2 are spatial operators for orientation of the stator windings. v_{sa}, v_{sb}, v_{sc}. are the values of stator instantaneous phase voltages. i_{sa}, i_{sc}, i_{sb} are the values of stator instantaneous phase currents. λ_{sa}, λ_{sb}, λ_{sc} are the stator flux linkages and are given by:

$$a = e^{\frac{j2\pi}{3}}$$

$$a_2 = e^{\frac{j4\pi}{3}} \quad \textbf{(2.15)}$$

Current Controller Design

The error between reference speed and measured speed is send to a PI controller. Since d and q axis controller are identical tuning of q axis controller is sufficient. Structure of q axis current controller is shown in Fig. (2.15).

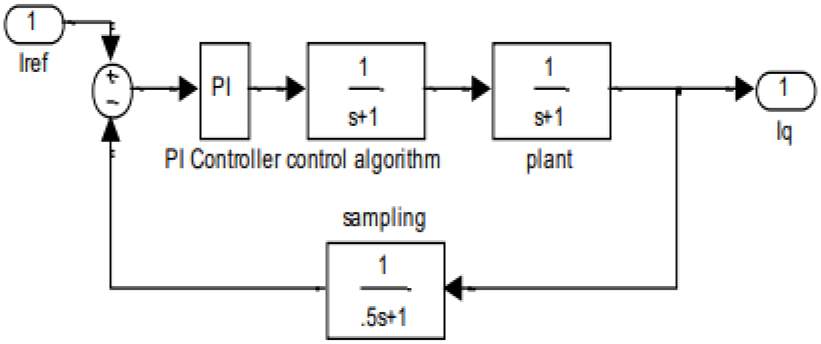


Fig (2.15): Q axis current controller.

PI controller offers a zero steady state error. Its transfer function is

$$\mathrm{Gc(s) = U(s)/E(s)}$$

$$= \mathrm{k_{pi}} + \frac{\mathrm{k_{ii}}}{\mathrm{s}}$$

$$= \mathrm{k_{pi}}(1 + \frac{\mathrm{T_{ii}s}}{\mathrm{T_{ii}s}}) \qquad \textbf{(2.16)}$$

Where $\mathrm{k_{pi}}$ is proportional gain, $\mathrm{k_{ii}}$ is integrator gain $\mathrm{T_{ii}}$ integrator time constant. It is a ratio between $\mathrm{k_{pi}}$ and $\mathrm{k_{ii}}$.

$$T_{ii} = \frac{\mathrm{k_{pi}}}{\mathrm{k_{ii}}} \qquad , \quad T_s = 0.2ms$$

$$G_{pe}(s) = i_q(s)/U_q(s)$$

$$= 1/R_s + s\, l_s \qquad \textbf{(2.17)}$$

$$= 1/\mathrm{R_s}\,(1 + \mathrm{sL_s}/\mathrm{R_s})$$

$$= \mathrm{k}/\left(1 + \mathrm{T_q}\right)\mathrm{k}$$

$$= 1/\mathrm{R_s} \qquad \text{-}R_s - \text{stator resistance}$$

$\mathrm{T_q} = \mathrm{L_s}/\mathrm{R_s} = 0.116$ sec Is the time constant of the motor the feedback is the delay introduced by digital to analog conversion? It is a first order transfer function with time constant $\mathrm{T_s}$

$$G_{sam}(s) = 1/(T_s s + 1)$$

Thus modified q axis controller with unity feedback is shown in Fig. (2.16) below [9]

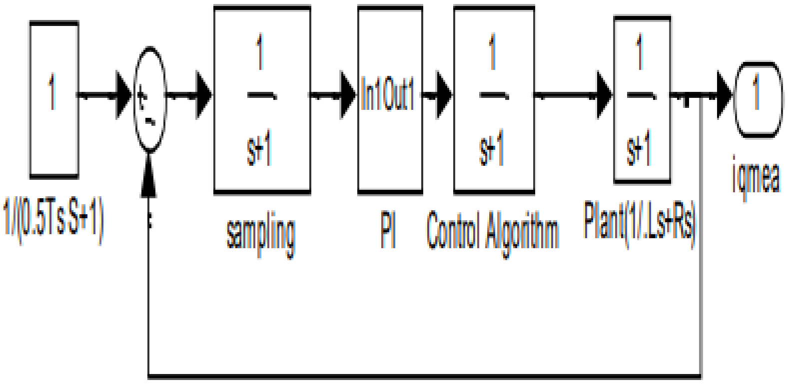


Fig (2.16): Modified q axis current controller.

The modelling of PMSM to obtain the transfer function between output and command input which was derived as follows [10]

R_S = stator resistance Ω, ohm.

L_q, L_d = quadrature and direct axis inductance [H, Henry].

∅ = rotor magnetic flux [Wb, weber].

P = number of pole pairs.

I_q, I_d = quadrature and direct axis currents [A, Amperes].

E_b = back emf [V, Volts].

p = derivative with respect to time.

T_e = electromagnetic torque [N − m, newton meters].

T = load torque [N − m, newton meters].

J = moment of inertia [Kg − m2].

B = friction coefficient.

W_e = angular rotation [rad/sec].

K_t = torque constant.

λ_q, λ_d = flux linkages Wb, weber.

λ_{af} = mutual flux between magnet and stator.

Where Kt is torque constant, by solving all the equations the PMSM transfer function can be written as Transfer Function of PMSM:

-Transfer Function of PMSM:

$$\frac{w_r(s)}{v_q(s)} = \frac{4.705S+2.219}{S^3+7.504S^2+3.36S+2.702} \qquad \textbf{(2.18)}$$

2.3.1 PI controller design Transfer:

The integral action is proportional to the integral of the control error

$$u(t) = k_i \int_0^t e(\tau)\, d\tau \qquad \textbf{(2.19)}$$

Ki is the integral gain. It appears that the integral action is related to the past values of the control error. The value of Ki and $Kp\ are$ given below

$$k_i = \frac{-w\ \sin\theta}{|G(jw)|} \qquad \textbf{(2.20)}$$

$$k_p = \frac{\cos\theta}{|G(jw)|} \qquad \textbf{(2.21)}$$

The overall transfer function of PI controller is shown below

$$G_C(S) = K_P + \frac{K_i}{s} \qquad \textbf{(2.22)}$$

→$k_p = 3.1132$ →$k_i = 1.5046$

PI controller $\mathrm{T.F} = \frac{3.1132s+1.5046}{s}$ **(4.23)**

The overall transfer function including PI controller is shown below

$$\mathrm{T.F} = \frac{14.647s^2+13.987s+3.3387}{s^4+7.504s^3+3.36s^2+2.702s}$$

2.3.2 Ziegler's Nicholas PI, PID controller method

The Ziegler-Nichols rule is a heuristic PID tuning rule that attempts to produce good values for the three PID gain parameters:

1. K_p: The controller path gain.
2. T_i: The controller's integrator time constant.
3. T_d: The controller's derivative time constant.

Given two measured feedback loop parameters derived from measurements:

1. The period T_u of the oscillation frequency at the stability limit.
2. The gain margin Ku for loop stability with the goal of achieving good regulation.

The PID tuning

$$k_p = 0.6T_u \quad \textbf{(4.24)}$$

$$k_i = \frac{2k_p}{T_u} \quad \textbf{(4.25)}$$

$$k_d = k_p \frac{T_u}{8} \quad \textbf{(4.26)}$$

$$k_u = \frac{1}{|G(jw)w_{cr}|} \quad \textbf{(4.27)}$$

$$\mathrm{T_u} = \frac{2\pi}{\mathrm{w}} \quad \textbf{(4.28)}$$

Tuning rules work entirely well when you have a simple controller, a framework that is straight, monotonic, and slow, and a reaction that is commanded by a solitary shaft exponential "slack" or something that demonstrations a great deal like one.

Real plants are probably not going to have a flawless first arrange slack trademark, however this estimation is sensible to depict the recurrence reaction roll off in a dominant part of cases. Higher-arrange shafts will present an additional stage move, be that as it may. Regardless of the possibility that they don't influence the state of the pickup roll off much, the stage move matters a ton to circle dependability. You can't rely on a solitary "slack" post to coordinate both the plentifulness roll off and the stage move precisely.

So, the Ziegler-Nichols display presumes an extra anecdotal stage conformity that does not mutilate the expected greatness roll off. At the strength edge, there is a 180-degree stage move around the criticism circle (Nyquist's security rule). A first request slack can contribute close to 90 degrees of that stage move.

Whatever remains of the watched stage move must be secured by the manufactured stage change. The stage modification is dared to be a straight line somewhere around zero and the basic recurrence where 180 degrees of stage move happens. A "straight line" stage move relates to an immaculate time delay.

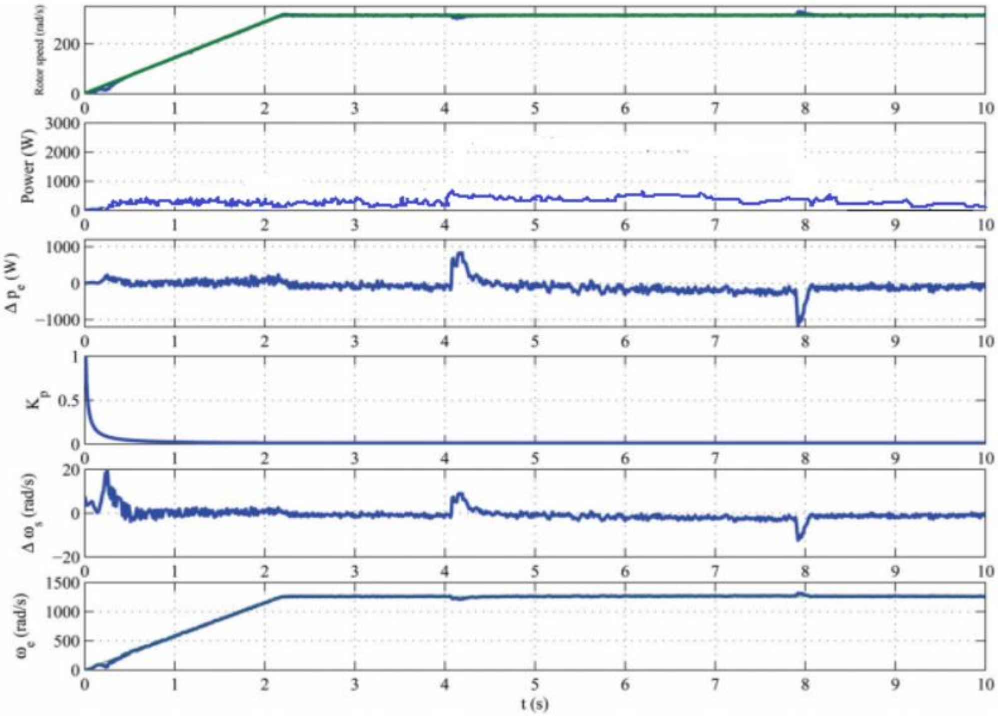
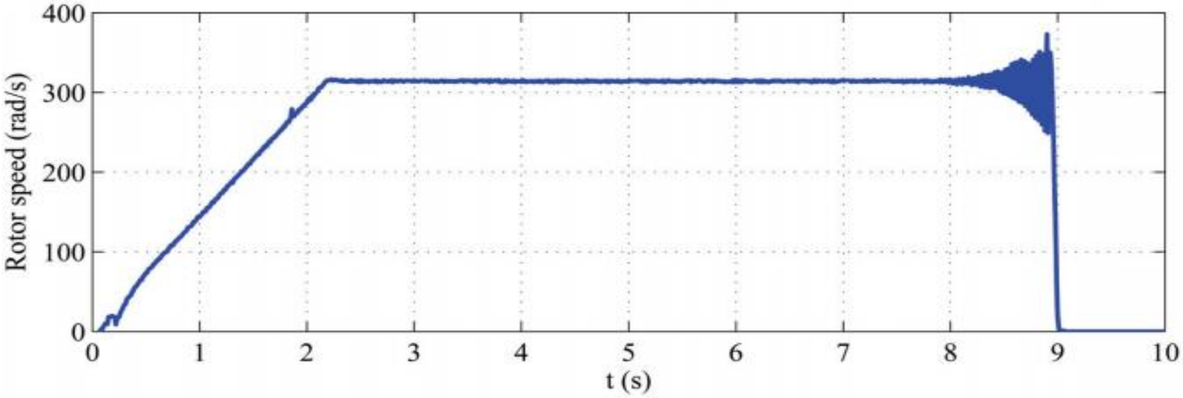
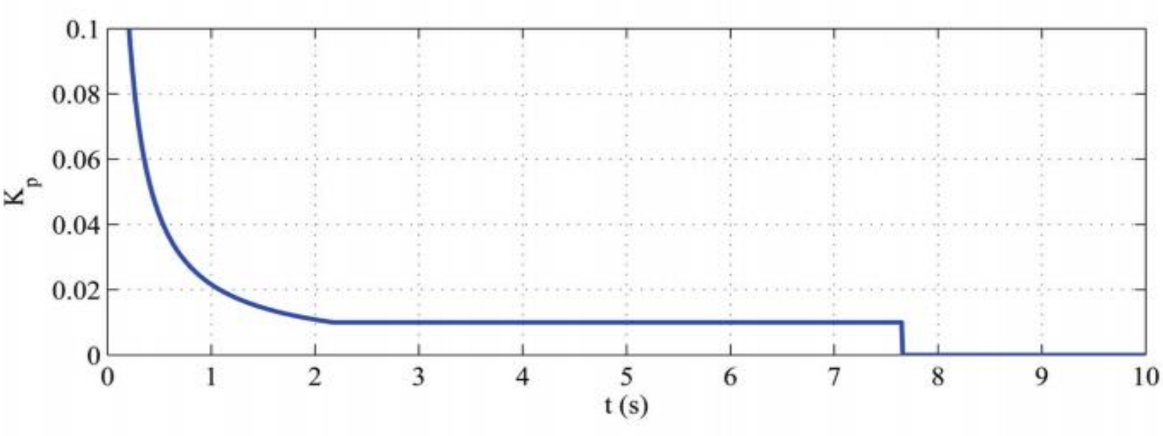


Fig (2.17): Rotor speed, input power perturbation, Kp, frequency perturbations Δωe and excitation frequency of the motor when operating at rated speed (200 Hz) with a load step.

step is applied, generating an input power perturbation. The stabilization loop compensates this perturbation, reducing the excitation frequency, and maintaining synchronism. At time 8 s, the torque is released, generating an input power perturbation. In this case, the stabilizing loop reacts increasing excitation frequency, to not to lose synchronization. In these torque steps, the variation of the rotation speed is less than 5 % of the rated speed during less than 200m_s. These performances are good enough for HVAC applications. The variation of rotor speed when the stabilizing loop is removed can be seen in Figure (2.18). At time 7.5 s, the Kp is made zero, removing the stabilizing loop. Instantaneously, the motor loses synchronization.



Rotor speed



(b) K_p

Fig (2.18): Rotor speed variation when K_p = 0

Unstable, even at no-load, from a certain excitation frequency lower than the rated speed. Then, it is necessary to have a stabilizing loop in the system. This stabilizing loop can be implemented by means of an speed measurement system, increasing cost, and complexity. The objective of this work is to develop a sensor less stabilizing loop. The presented strategy uses input power perturbations to stabilize the system. After adding the stabilizing loop, the V/f operation of the permanent magnet synchronous motor is stable for all the frequency range, and for any load torque applied to the motor. Future research includes the estimation of the initial rotor position. Here, the motor is started from a known position, but for real applications, the rotor can be at any position. The stabilizing method developed uses some motor parameters. The variation of this parameters with temperature or even aging, must be studied. Increasing speed in PMSM over the rated speed means field weakening. For the operation above rated speed in HVAC applications is of interest, this method must be studied.

2.4 The AC servo motors

A servo motor is a linear or rotary actuator that provides fast precision position control for closed-loop position control applications. Unlike large industrial motors, a servo motor is not used for continuous energy conversion. Servo motors have a high-speed response due to low inertia and are designed with small diameter and long rotor length. Servo motors work on servo mechanism that uses position feedback to control the speed and final position of the motor. Internally, a servo motor combines a motor, feedback circuit, controller and other electronic circuit.

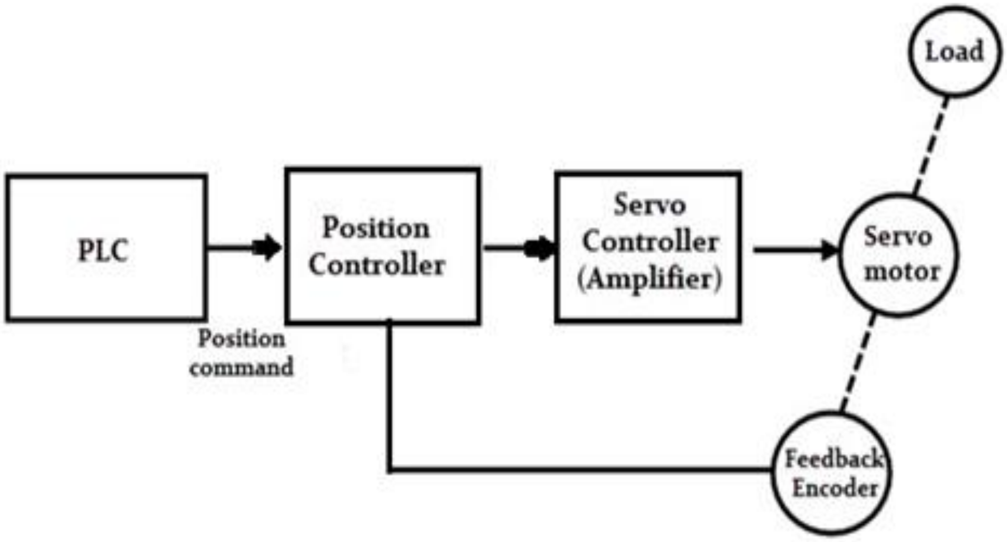


Fig (2.19): The block diagram of AC servo motor system using programmable logic controllers.

It uses encoder or speed sensor to provide speed feedback and position. This feedback signal is compared with input command position (desired position of the motor corresponding to a load), and produces the error signal (if there exist a difference between them).

The error signal available at the output of error detector is not enough to drive the motor. So, the error detector followed by a servo amplifier raises the voltage and power level of the error signal and then turns the shaft of the motor to desired position.

2.4.1 Servo motor in general

The main difference between AC and DC motors is that the magnetic field generated by the stator rotates in the case of AC motors. A rotating magnetic field is key to the operation of all AC motors. The principle is simple. A magnetic field in the stator is made to rotate electrically around and around in a circle. Another magnetic field in the rotor is made to follow the rotation of this field pattern by being attracted and repelled by the stator field.

Because the rotor is free to turn, it follows the rotating magnetic field in the stator.

It illustrates the concept of a rotating magnetic field as it applies to the stator of a three-phase AC motor. The operation can be summarized as follows:

- Three sets of windings are placed 120 electrical degrees apart with each set connected to one phase of the three-phase power supply.
- When three-phase current passes through the stator windings, a rotating magnetic field effect is produced that travels around the inside of the stator core.
- Polarity of the rotating magnetic field is shown at six selected positions marked off at 60-degree intervals on the sine waves representing the current flowing in the three phases, A, B, and C.
- Simply interchanging any two of the three-phase power input leads to the stator windings reverses direction of rotation of the magnetic field.
- The number of poles is determined by how many times a phase winding appears.

There are two ways to define AC motor speed. First is synchronous speed. The synchronous speed of an AC motor is the speed of the stator's magnetic field rotation. This is the motor's ideal theoretical, or mathematical, speed, since the rotor will always turn at a slightly slower rate. The other way motor speed is measured is called actual speed. This is the speed at which the shaft rotates. The nameplate of most AC motors lists the actual motor speed rather than the synchronous speed.

2.4.2 Synchronous-type AC servo motor

Consist of stator and rotor. The stator consists of a cylindrical frame and stator core. The armature coil wound around the stator core and the coil end is connected to with a lead wire through which current is provided to the motor.

The rotor consists of a permanent magnet and hence they do not rely on AC induction type rotor that has current induced into it. And hence these are also called as brushless servo motors because of structural characteristics.

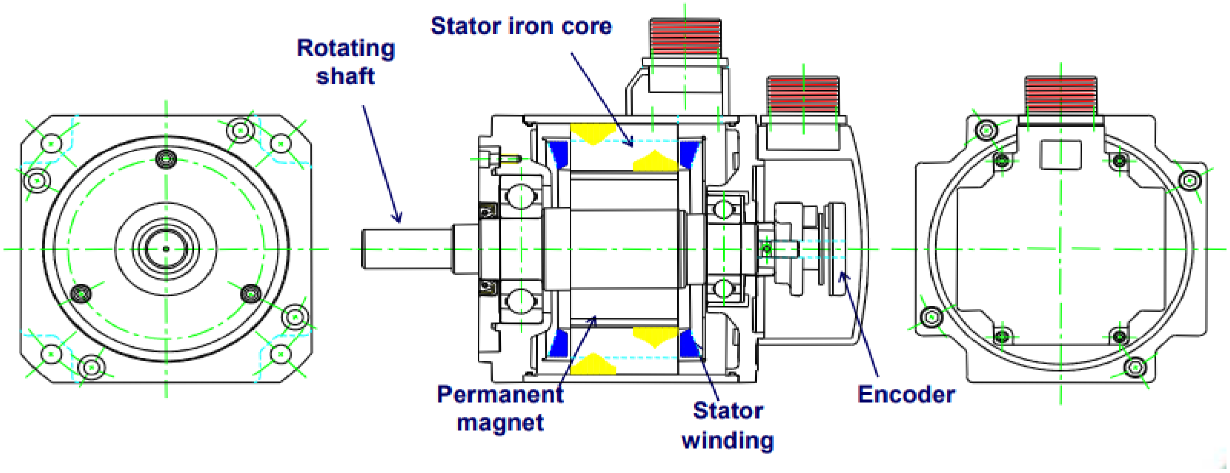


Fig (2.20): Synchronous Servo motor components

The magnetic force is be made by permanent magnet and the current is used to generate torque. Then high torque and efficiency are available at low current and small size. It has no brush so there is little noise/vibration and no dirt. And high precision control is available with high resolution encoder.

When the stator field is excited, the rotor follows the rotating magnetic field of the stator at the synchronous speed. If the stator field stops, the rotor also stops. With this permanent magnet rotor, no rotor current is needed and hence less heat is produced.

Also, these motors have high efficiency due to the absence of rotor current. In order to know the position of rotor with respect to stator, an encoder is placed on the rotor and it acts as a feedback to the motor controller.

Stator in synchronous motor

Stator is composed of the core and winding which generates torque. The essential technologies are to apply the iron core and insert much coil to the equal area. Divided core / centralized winding type which can insert much coil to the equal area has been on the rise with the progress of forming and winding technologies. Especially, the design using FEM technology becomes usual to minimize the torque ripple and cogging torque. Then, servo motor becomes small-sized and high-precision.

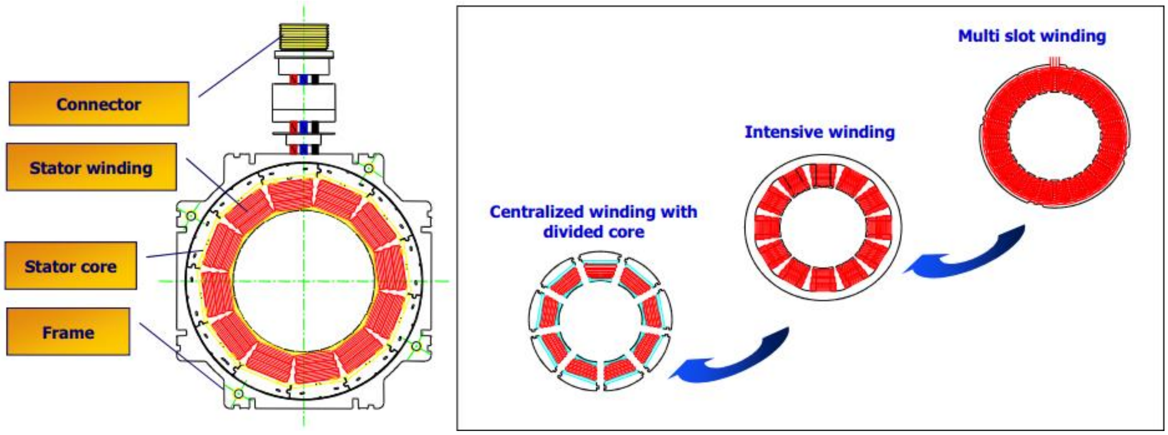


Fig (2.21): Stator in synchronous motor

Rotor in synchronous motor

The rotor part is composed of shaft and rotor core and permanent magnet. It can generate high power at the same size depending on the performance of permanent magnet. So selecting and applying permanent magnet is the essential technology. Especially, it is designed to minimize cogging torque through with stator.

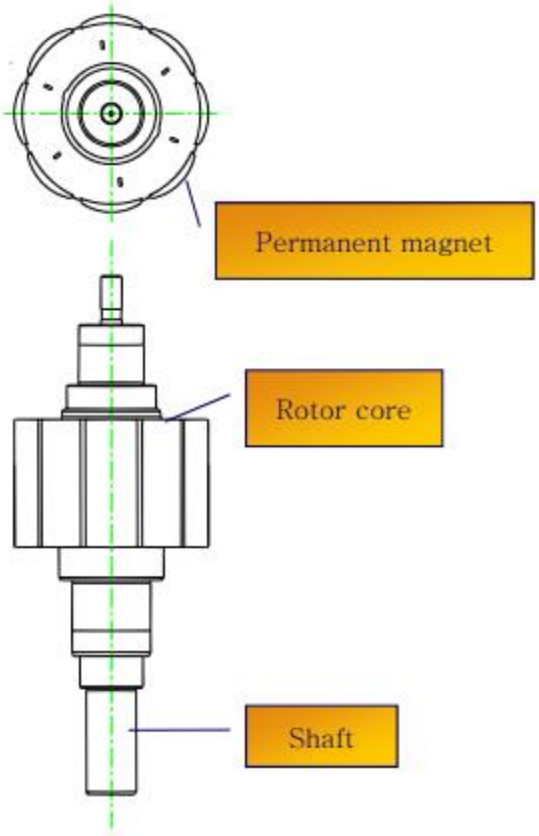


Fig (2.22): Rotor in synchronous motor

Theory of Incremental Encoder in synchronous motor

Sensors is a device that detects the state of the environment such as energy, heat, light, magnet, supersonic, etc. and convert them to electric signals. An encoder is a sensor for converting rotary motion or position to a series of electronic pulses. Rotary encoders serve as measuring sensors for rotary motion and for linear motion when used in conjunction with mechanical measuring standards such as lead screws, and convert rotary motion which incremental or absolute into electrical signals. They are both effective and low cost feedback devices.

An encoder is an electrical mechanical device that converts linear or rotary displacement into digital or pulse signals. The most popular type of encoder is the incremental encoder also known as optical encoder, which consists of a rotating disk, a light source, and a photo detector (light sensor). The disk, which is mounted on the rotating shaft, has patterns of opaque and transparent sectors coded into the disk shown on Fig (2.23). As the disk rotates, these patterns interrupt the light emitted onto the photo detector, generating a digital or pulse signal output.

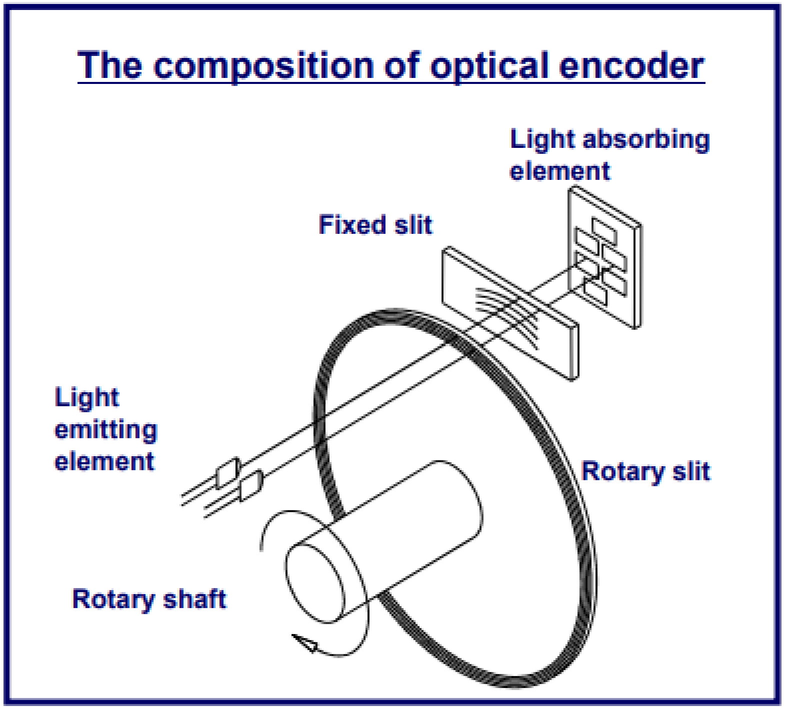


Fig (2.23): Simple Diagram of Incremental Encoder

An incremental encoder generates a pulse for each incremental step in rotation. Although the incremental encoder does not output absolute position, it can provide high resolution at an acceptable price. For example, an incremental encoder with a single code track, referred to as a tachometer encoder, generates a pulse signal whose frequency indicates the velocity of displacement.

However, the output of the single-channel encoder does not indicate direction. To determine direction, a two-channel, or quadrature, encoder uses two detectors and two code tracks. The most common type of incremental encoder uses two output channels A and B to sense position. Using two code tracks with sectors positioned 90° out of phase; the two output channels of the quadrature encoder indicate both position and direction of rotation. If A leads B, for example, the disk is rotating in a clockwise direction. If B leads A, then the disk is rotating in a counter-clockwise direction.

Therefore, by monitoring the number of pulses and the relative phase of signals A and B, the position and direction of rotation can be track. In addition, some quadrature detectors include a third output channel, called INDEX, yield single pulse per revolution, which is useful in counting full revolutions. It is also useful as a reference to define a home base or zero position. This single pulse can be used for precise determination of a reference position as shown in Fig (2.24).

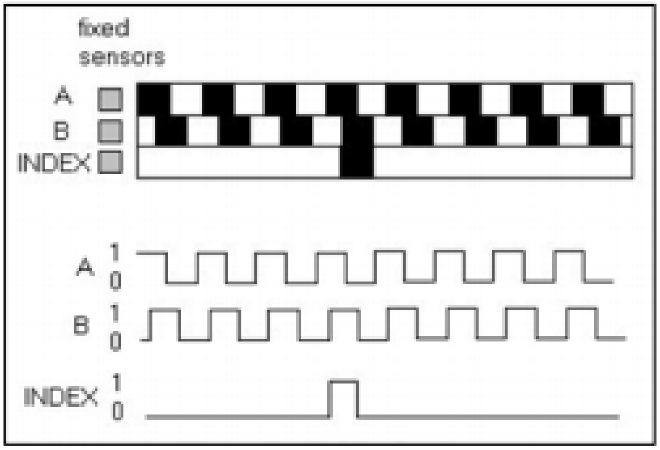


Fig (2.24): Output pulse from incremental encoder

Working of AC Servo Motor

The schematic diagram of servo system for induction motor is shown in the figure below. In this, the reference input at which the motor shaft has to maintain at a certain position is given to the rotor of synchro generator as mechanical input theta. This rotor is connected to the electrical input at rated voltage at a fixed frequency.

The three stator terminals of a synchro are connected correspondingly to the terminals of control transformer. The angular position of the two-phase motor is transmitted to the rotor of control transformer through gear train arrangement and it represents the control condition alpha.

Initially, there exist a difference between the synchro generator shaft position and control transformer shaft position. This error is reflected as the voltage across the control transformer. This error voltage is applied to the servo amplifier and then to the control phase of the motor.

With the control voltage, the rotor of the motor rotates in required direction till the error becomes zero. This is how the desired shaft position is ensured in AC servo motors.

Alternatively, modern AC servo drives are embedded controllers like PLCs, microprocessors and microcontrollers to achieve variable frequency and variable voltage in order to drive the motor.

Mostly, pulse width modulation and Proportional-Integral-Derivative (PID) techniques are used to control the desired frequency and voltage. The block diagram of AC servo motor system using programmable logic controllers, position and servo controllers is given below.

2.6 AC servo motors & DC servo motors

The difference between AC and DC servo motors boils down to electrical currents and the unique way that the current works in each motor type. Due to these differences, each motor is suited to somewhat different applications. While the applications of both AC and DC motors are regularly encountered in daily activities, the functions of AC motors are generally more prevalent in people's domestic and work lives.

2.6.1 Advantages of AC servo motors over DC servo motors

The following list of AC servo motor advantages illustrates the reasons for the motor's widespread use and ongoing popularity:

Table (2.1): Difference between the DC and AC Servo Motors

--	DC Servo Motors	AC Servo Motors
1.	It delivers high power output	Delivers low output of about 0.5 W to 100 W
2.	It has more stability problems	It has fewer stable problems
3.	It requires frequent maintenance due to the presence of commutator	It requires less maintenance due to the absence of commutator
4.	It provides high efficiency	The efficiency of AC servo motor is less and is about 5 to 20%
5.	The life of DC servo motor depends on the life on brush life	The life of AC servo motor depends on bearing life
6.	It includes permanent magnet in its construction	The synchronous type AC servo motor uses permanent magnet while induction type doesn't require it.
7.	These motors are used for high power applications	These motors are used for low power applications

Efficiency

AC motors are built for long-lasting performance in some of the most challenging applications. In an AC motor, there are few moving parts. When the motor is active, the relative lack of moving metal parts allows for slower wear and a low probability of sudden failure. These traits give AC motors extended longevity, which makes this motor type ideal for field applications in which machines and vehicles are expected to perform for hours on end, far away from repair facilities.

By the same token, the longevity of the AC motor makes it the ideal motor type for machines and appliances that are used daily in the service industry, such as cappuccino makers and vending machines.

Quietness

AC motors are relatively quiet in their operation. The simple design and small number of parts in an AC motor translate to a low-volume function, regardless of whether you use the motor for mid-paced or fast operations. The quietness of AC motors makes them preferable for the vast majority of machine operations that take place close to workers and crowds of people.

Longevity

AC motors are built for long-lasting performance in some of the most challenging applications. In an AC motor, there are few moving parts. When the motor is active, the relative lack of moving metal parts allows for slower wear and a low probability of sudden failure. These traits give AC motors extended longevity, which makes this motor type ideal for field applications in which machines and vehicles are expected to perform for hours on end, far away from repair facilities.

By the same token, the longevity of the AC motor makes it the ideal motor type for machines and appliances that are used daily in the service industry, such as cappuccino makers and vending machines.

Flexibility

Another key feature of the AC motor is its flexibility, which allows it to instantly go into motion at the flick of a switch and reverse at the turn of the lever. In machines that are built for both forward and reverse functions, the AC servo motor is the best option for smooth and seamless performance.

The flexibility of AC motors also makes this the ideal motor type for applications that involve a variety of users, such as luxury items and devices that are used by people from all walks of life. In a recliner, for example, an AC motor makes it possible for the user to adjust the sitting position in a variety of angles.

Versatility

As one of the most widely used motor types on the market, AC servo motors are available in a vast range of shapes and sizes, from OEM models to customized variations. As such, AC servo motors are available for a wide variety of applications. If you need a solution for a particular component that no longer functions with its original motor, chances are you can find a replacement AC servo motor that will activate the device and restore it to its original level of performance.

Constant Speed

AC servo motors are specifically designed to operate at constant speeds. This makes the AC servo motor the preferred option for any operator or manufacturer who needs a motor to run at the same speed throughout an application, regardless of the load. If you run a machine to operate a mild or medium load, the AC motor will run at a constant speed throughout the designated operation.

Chapter 3

Modeling of servo drive

A servo drive receives a command signal from a control system, amplifies the signal, and transmits electric current to a servo motor in order to produce motion proportional to the command signal. Typically, the command signal represents a desired velocity, but can also represent a desired torque or position. A sensor attached to the servo motor reports the motor's actual status back to the servo drive. The servo drive then compares the actual motor status with the commanded motor status. It then alters the voltage, frequency or pulse width to the motor so as to correct for any deviation from the commanded status.

3.1 Driver for servo motor components

The following figure shows the internal driver components

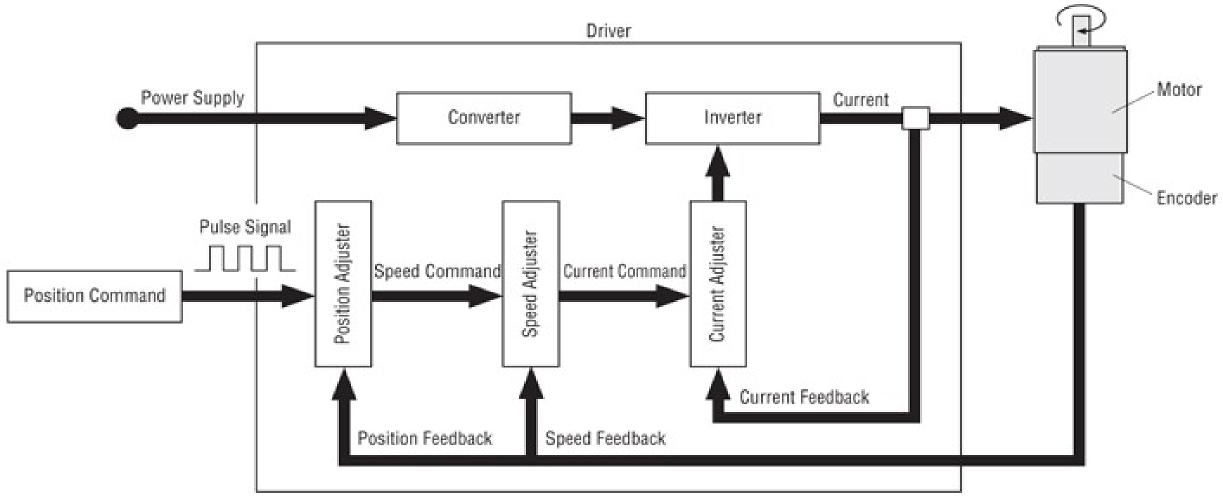


Fig (3.1): internal driver components

The driver consists of

1. Converter
2. Inverter
3. Feedback of control
    - Speed control
    - Position control
    - Current control

3.2 Converter (rectifier) and Inverter

3.2.1 Converter (rectifier)

AC to DC converter, firing angle, R, RL, RLE loads, Power electronics concerns the application of electronic principles into situations that are rated at power levels rather than signal level. The development of new power semiconductor devices, new circuit topologies with their improved performance and their fall in prices have opened up wide field for the new applications of power electronic converters. Power electronic converters are used for the conversion of AC to DC, DC to AC, AC to AC and DC to DC power. Any power semiconductor device can act as a switch. Mostly thyristor used as a power switch in power converters. The thyristor can be triggered at any angle α in positive half cycle and the output voltage can be controlled.

Type of Converter (rectifier)

1) Single-phase rectifiers

- Half-wave rectification.
- Full-wave rectification.

2) Three-phase rectifiers

- Three-phase, half-wave circuit.
- Three-phase, full-wave circuit using center-tapped transformer.
- Three-phase bridge rectifier uncontrolled.
- Three-phase bridge rectifier controlled.

In the driver (MBDDT2210)

The source of electricity is single phase

The rectifier used is full wave rectifier

The following figure shows the rectifier used

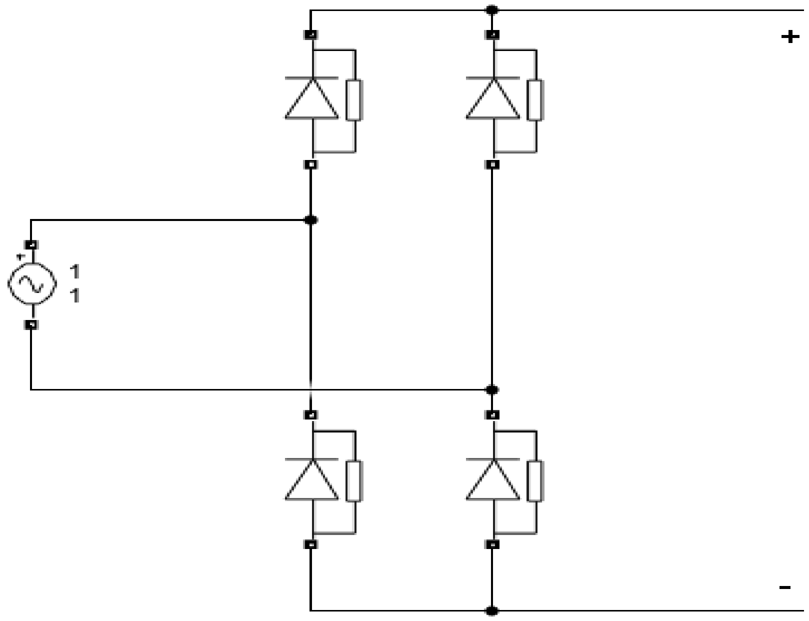


Fig (3.2): full wave rectifier

Equation of full wave rectifier

$\text{Average voltage, vaverage} = 2\text{Vm}/\pi$

$\text{RMS Voltage, Vrms} = \text{Vm}/\sqrt{2}$

$\text{Average voltage, vaverage} = 2 * 220/\pi$

$\text{Average voltage, vaverage} = 140.127\text{V}$

$\text{RMS Voltage, Vrms} = 220/\sqrt{2}$

$\text{RMS Voltage, Vrms} = 155.56\text{V}$

$\text{Voltage DC, VDC} = 0.9 * \text{VRMS}$

$\text{VDC} = 140\text{V}$

$\text{Average Current, Iaverage} = 2\text{Im}/\pi$

$\text{RMS Current, Irms} = \text{Im}/\sqrt{2}$

Center tap rectifier, Transformer utilization factor (TUF) = 0.693

Bridge rectifier, Transformer utilization factor (TUF) = 0.812

Ripple factor = 0.482

Maximum efficiency = 81.2%

Form factor = 1.11

peak factor = √2

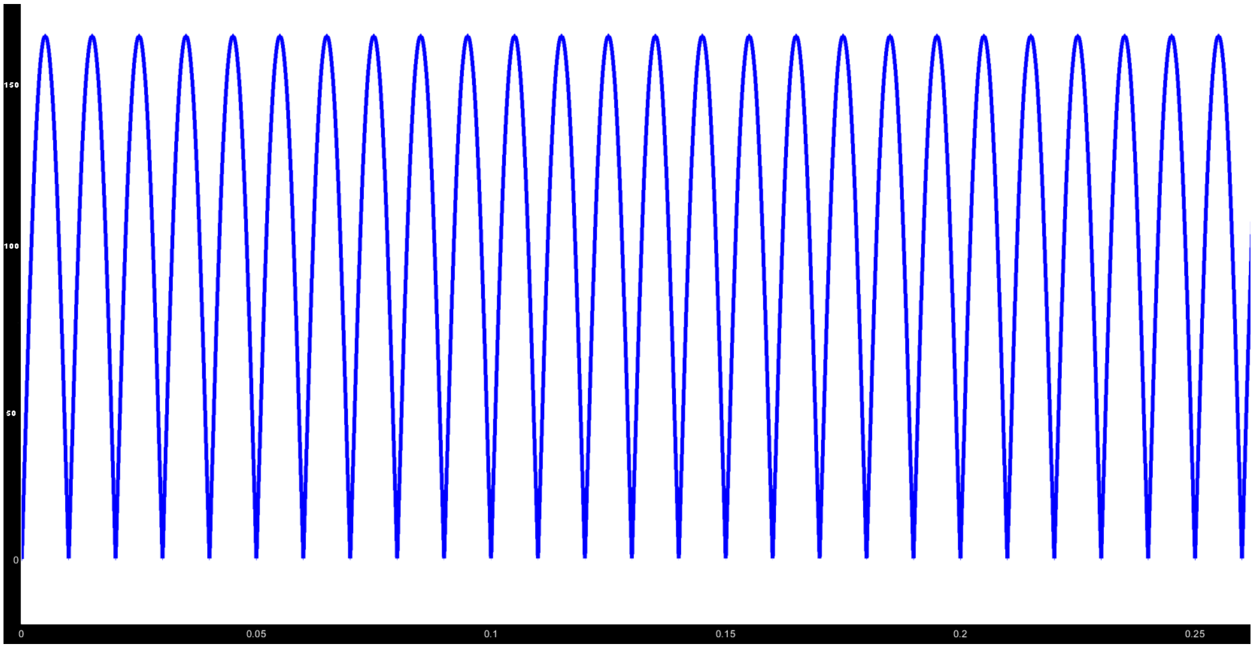


Fig (3.3): *The output result from the full wave rectifier*

3.2.2 Inverter

A power inverter, or inverter, is a power electronic circuit or circuitry that changes direct current (DC) to alternating current (AC).[5]

The input voltage, output voltage and frequency, and overall power handling depend on the design of the specific device or circuitry. The inverter does not produce any power; the power is provided by the DC source.

A power inverter can be entirely electronic or may be a combination of mechanical effects (such as a rotary apparatus) and electronic circuitry. Static inverters do not use moving parts in the conversion process.

Power inverters are primarily used in electrical power applications where high currents and voltages are present; circuits that perform the same function for electronic signals, which usually have very low currents and voltages, are called oscillators. Circuits that perform the opposite function, converting AC to DC, are called rectifiers.

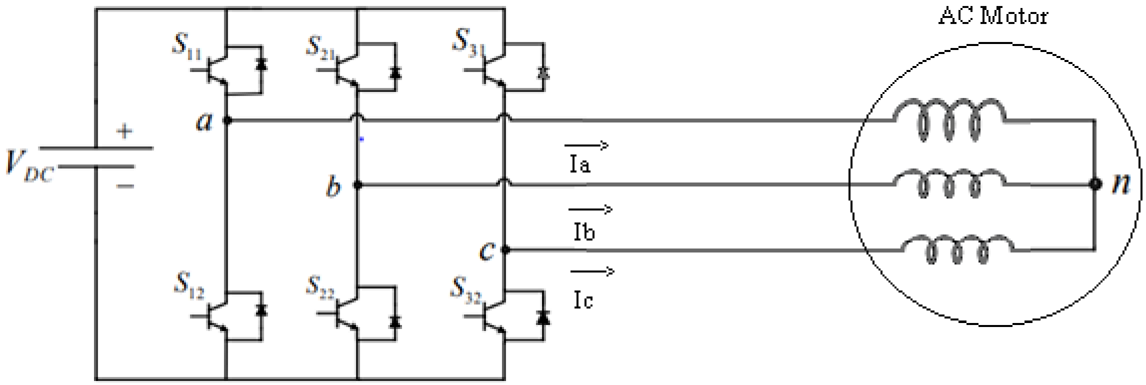


Fig (3.4): *Three-phase Full –Bridge Inverter*

Equation of inverter

$\mathrm{V(ab, ac, cb)(rms)} = 0.87\mathrm{vdc}$

$\mathrm{Vab(rms)} = 109.18\mathrm{V}$

$\mathrm{Vac(rms)} = 109.18\mathrm{V}$

$\mathrm{Vcb(rms)} = 109.18\mathrm{V}$

- Switching fairing

$$\rightarrow s_{11} + s_{12} = 1 \qquad \textbf{(3.1)}$$

$$\rightarrow s_{21} + s_{22} = 1 \qquad \textbf{(3.2)}$$

$$\rightarrow s_{31} + s_{31} = 1 \qquad \textbf{(3.3)}$$

Table (3.1): The switching states in a three-phase inverter

s_{11}	s_{12}	s_{31}	v_{ab}	v_{bc}	v_{ca}
0	0	0	0	0	0
0	0	1	0	$-v_{DC}$	v_{DC}
0	1	0	$-v_{DC}$	v_{DC}	0
0	1	1	$-v_{DC}$	0	$-v_{DC}$
1	0	0	v_{DC}	0	$-v_{DC}$
1	0	1	v_{DC}	$-v_{DC}$	0
1	1	0	0	v_{DC}	$-v_{DC}$
1	1	1	0	0	0

which when expanded gives the phase voltages in terms as:

$$v_{an} = \frac{1}{3}(2v_{ab} + v_{bc})$$

$$v_{bn} = \frac{1}{3}(2v_{bc} - v_{ab})$$

$$v_{an} = \frac{-1}{3}(2v_{bc} + v_{ab})$$

3.4.2 Six Step Voltage Source Inverter:

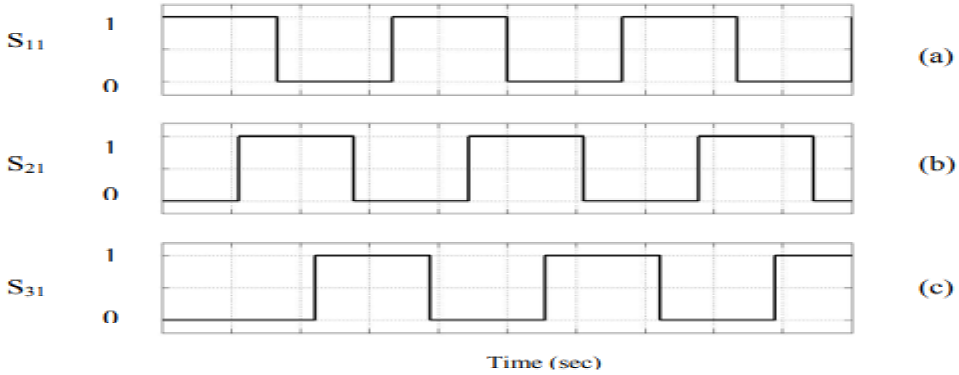


Fig (3.5): Generation of the switching signals for top devices (a) S_{11} (b) S_{21} (c)s_{31}

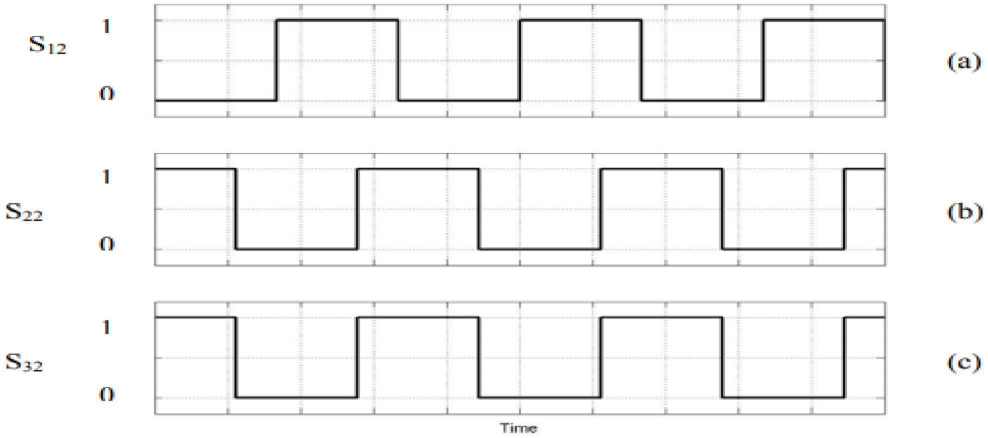


Fig (3.6): Generation of the switching signals for bottom devices (a) S_{12} (b)S_{22}(c) S_{32}

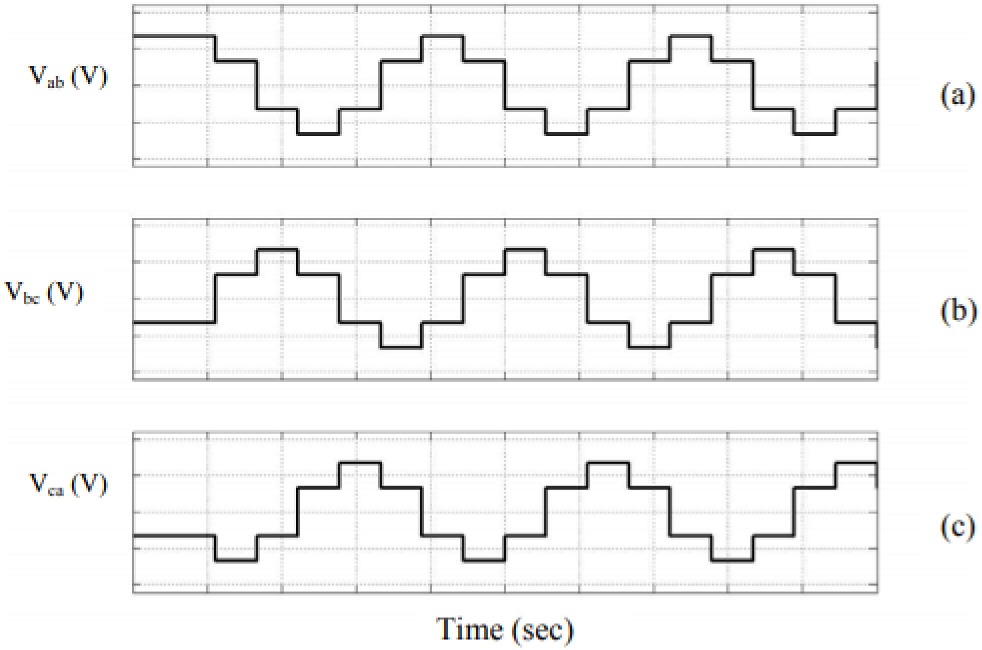


Fig (3.7): Line voltages (a)V_{ab} (b)v_{bc} (c) V_{ca}

3.5 Speed and position control

The servo motor is specialized for high-response, high-precision positioning. As a motor capable of accurate rotation angle and speed control, it can be used for a variety of equipment.

- Closed Loop Control

A rotation detector (encoder) is mounted on the motor and feeds the rotation position/speed of the motor shaft back to the driver. The driver calculates the error of the pulse signal or analog voltage (position command/speed command) from the controller and the feedback signal (current position/speed) and controls the motor rotation so the error becomes zero. The closed loop control method is achieved with a driver, motor and encoder, so the motor can carry out highly accurate positioning operations. An END signal is obtained that communicates the completion of the positioning operation.

3.5.1 Position Control Using a Pulse Signal

The controller inputs the pulse signal. The speed and stop position are then controlled according to the pulse number.

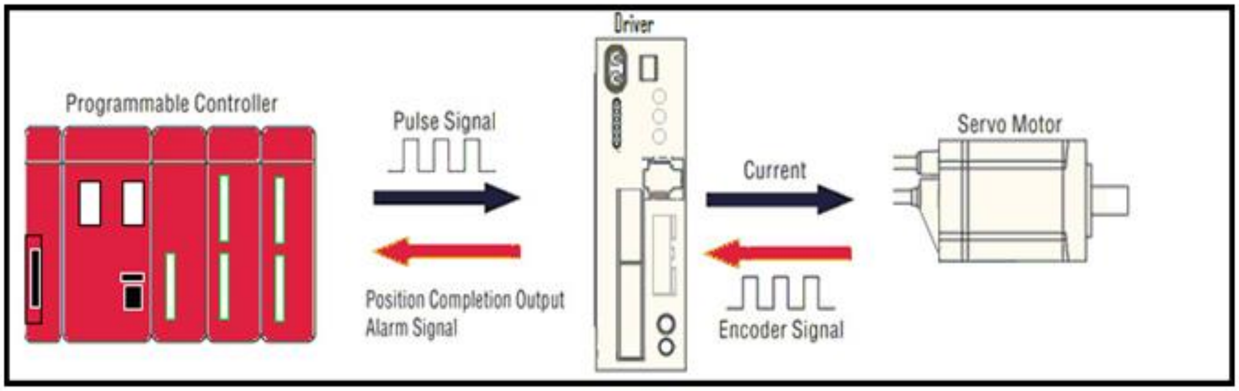


Fig (3.8): Position Control Using a Pulse Signal

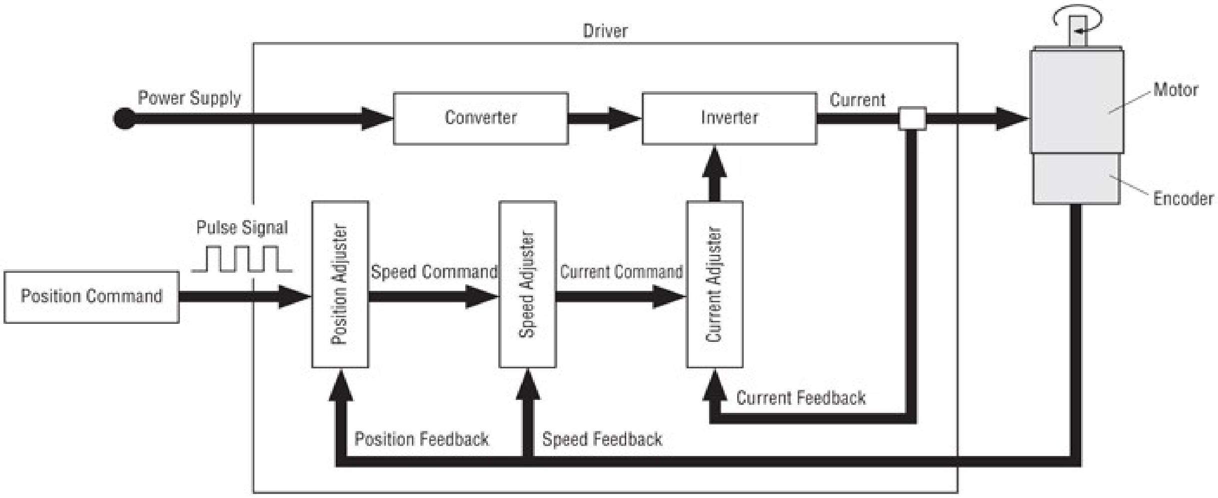


Fig (3.9): Position Control Diagram

3.5.2 Speed Control by Analog Voltage

-Analog Voltage from PLC sets the speed

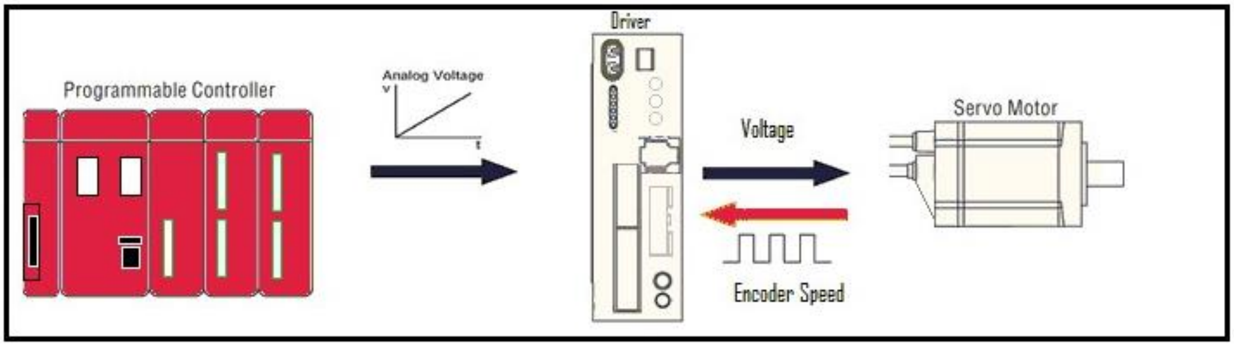


Fig (3.10): Speed Control by Analog Voltage

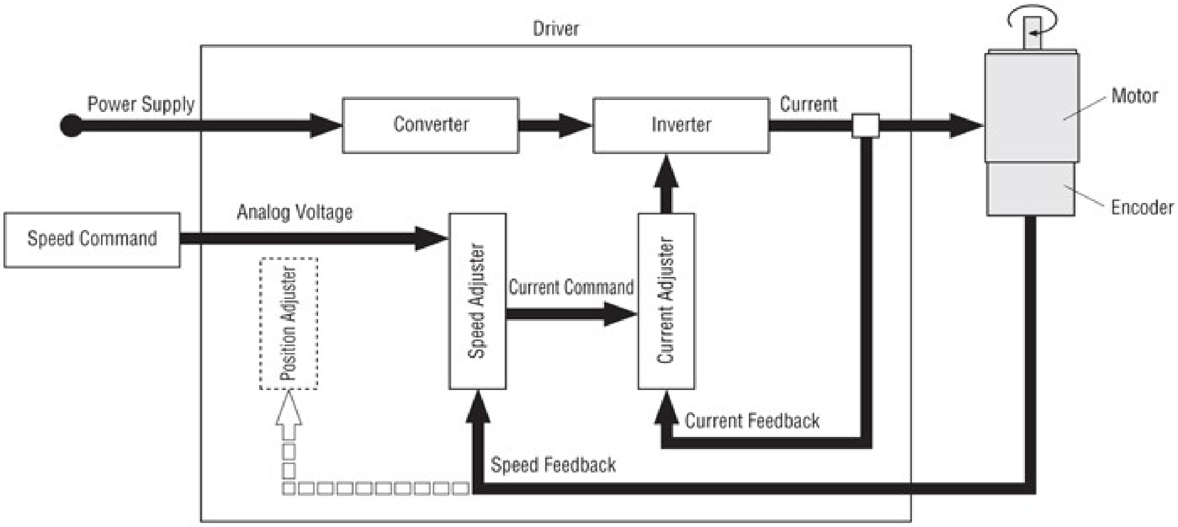


Fig (3.11) Speed Control Diagram

3.5.3 Torque Control by Analog Voltage

-Analog Voltage from the PLC limits the Torque

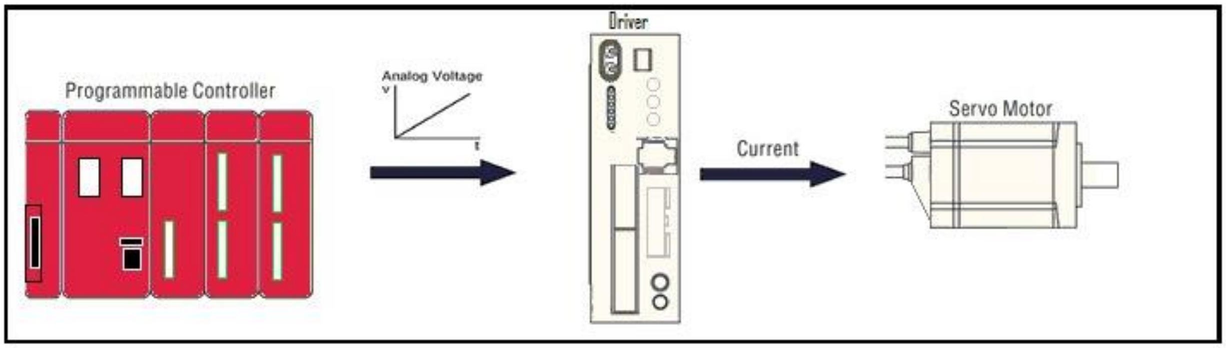


Fig (3.12): Torque Control by Analog Voltage

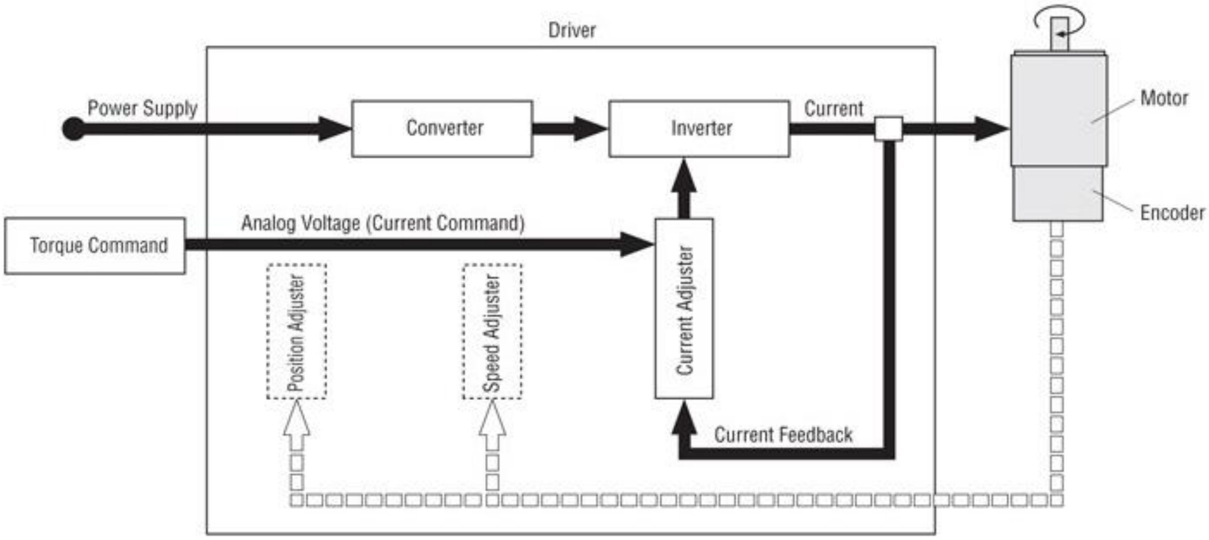


Fig (3.13): Torque Control Diagram

3.6 The project design using MATLAB

3.6.1 Design Converting the synchronous motor into a servo motor

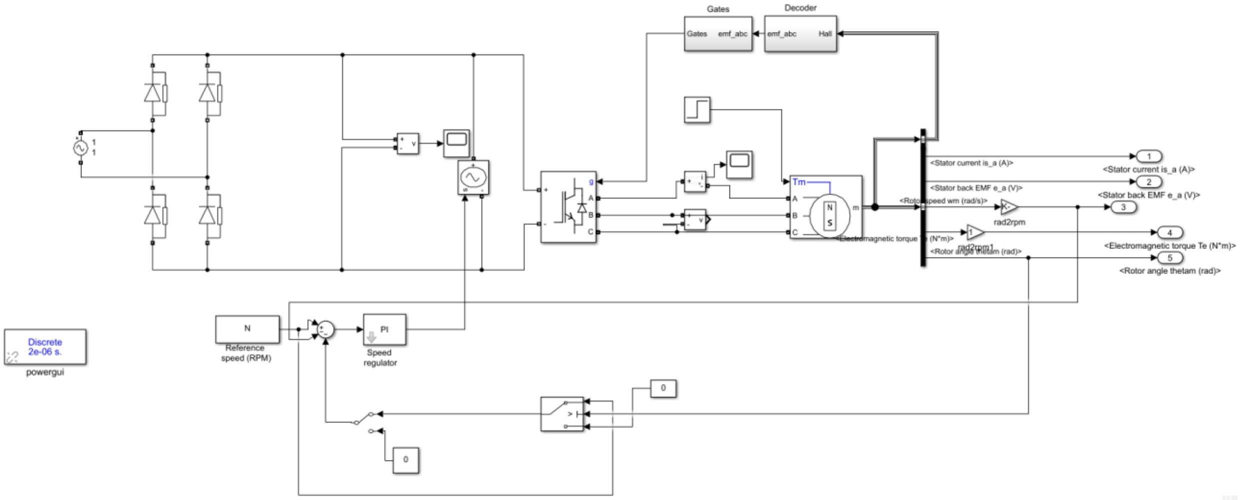


Fig (3.14): The project design using MATLAB

-The output result of speed control when the speed is set to 1500 rpm

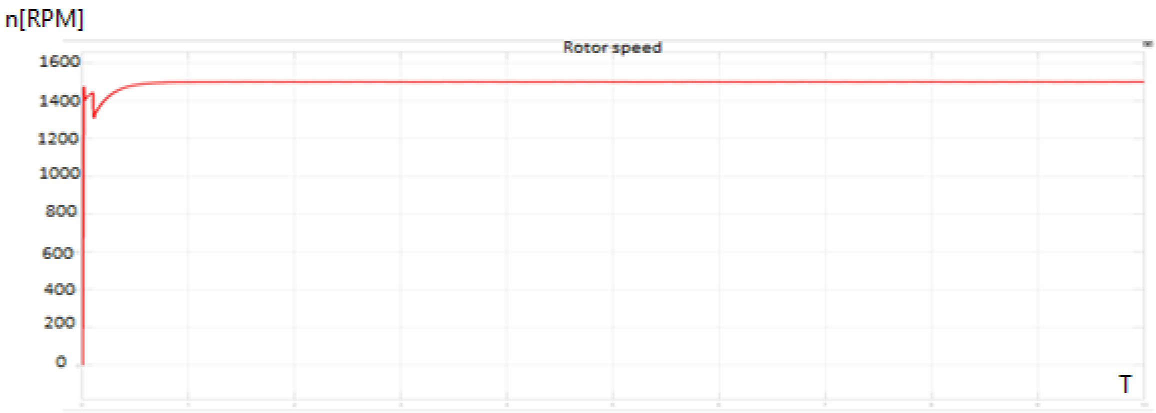


Fig (3.15): output result of speed control

The user specifies the required speed value for the motor using the plc controller.

Speed starts increasing until it reaches 1500 rpm and then stabilizes at the desired speed as the fig (3.15)

-The output result of position control when the theta is set to 45

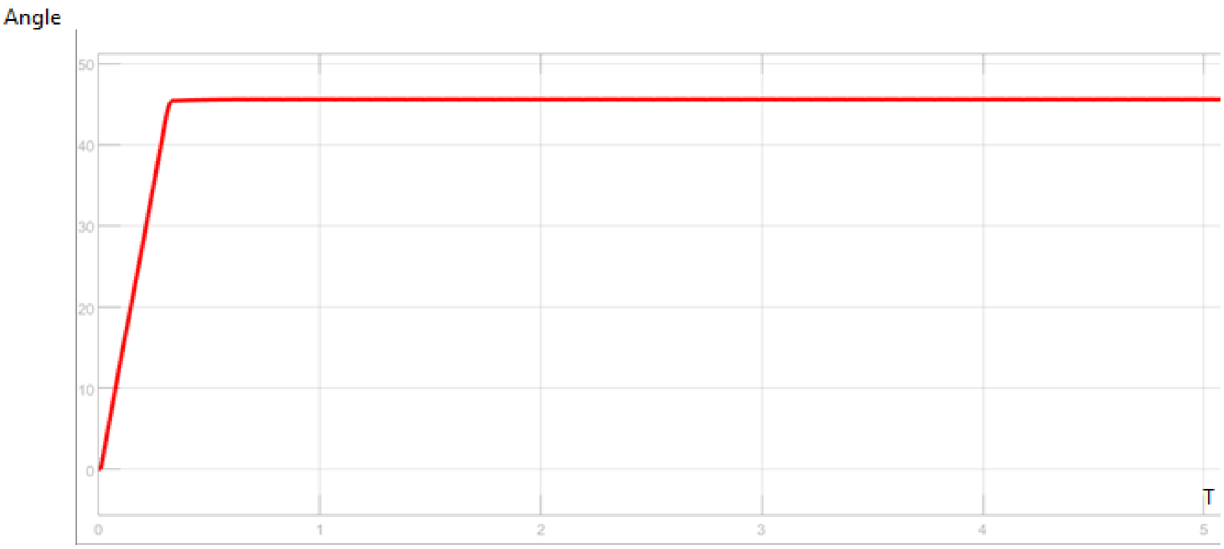


Fig (3.16): position control When the theta is set to 45°

The user specifies the angle value required for the motor using the plc controller.

The angle starts to increase until it reaches 45 degrees and then stabilizes at the desired angle, which means that the motor stops working.

-The output result of speed when position control When the theta is set to 45^{o}

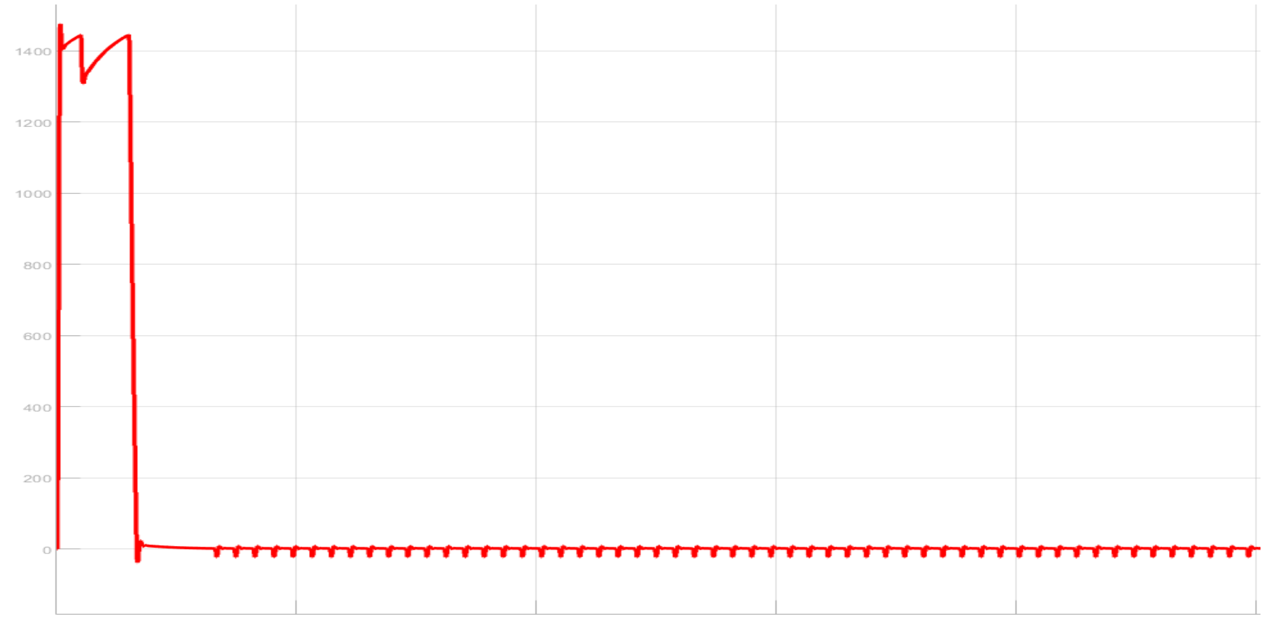


Fig (3.17): the speed when position control when the theta is set to 45^{o}

Speed curve, speed setting at 1500rpm, angle setting at 45 degrees

We notice that the speed increases until it reaches 1500 revolutions per minute and then stabilizes until the engine reaches a 45-degree angle, then the speed decreases until the speed reaches zero, which means the engine stops.

Chapter 4

Conceptual design

This project mainly consists of several sections connected to each other to effectively control the speed and direction of the motor, and these sections are:

- PLC controller (DVP14SS211T).
- Servo drive Panasonic (MBDDT2210).
- Servo motor Panasonic (MSMD042PIS).
- SCSI CN 50 pin servo motor drive.
- 24V DC power supply.

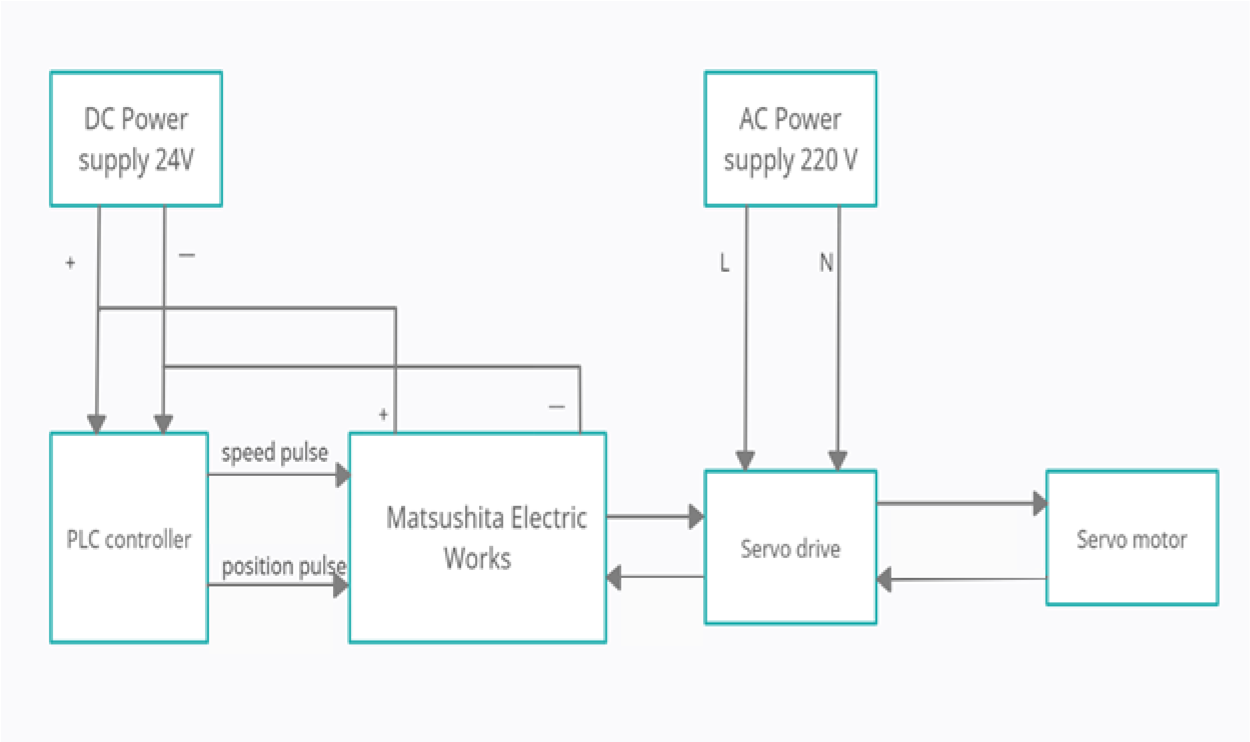


Fig (4.1): The interfacing between these sections is shown in the block diagram.

4.1 Components of the project.

1. Plc controller (DVP14SS211T).

It is responsible for sending the pulse to the driver and controlling the pulses.

The plc is controlled by computer and the connection between them is via DELTA PLC programming cable and is controlled by is soft 3.09 software

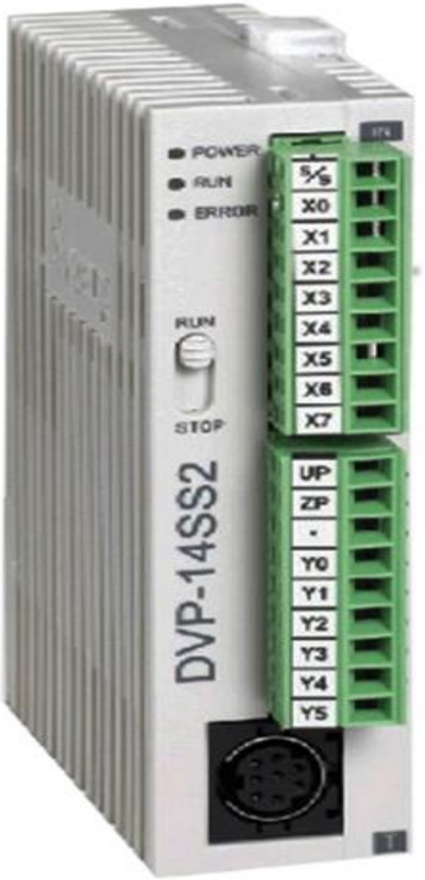


Fig (4.2): Plc model (DVP14SS211T) power input 24 v_{dc}.

2. SCSI CN 50 pin servo motor driver.

The goal of this electronic unit is to connect the control unit to the driver, where the connection to the control unit is made by connecting the wires connected to the output of the controller.

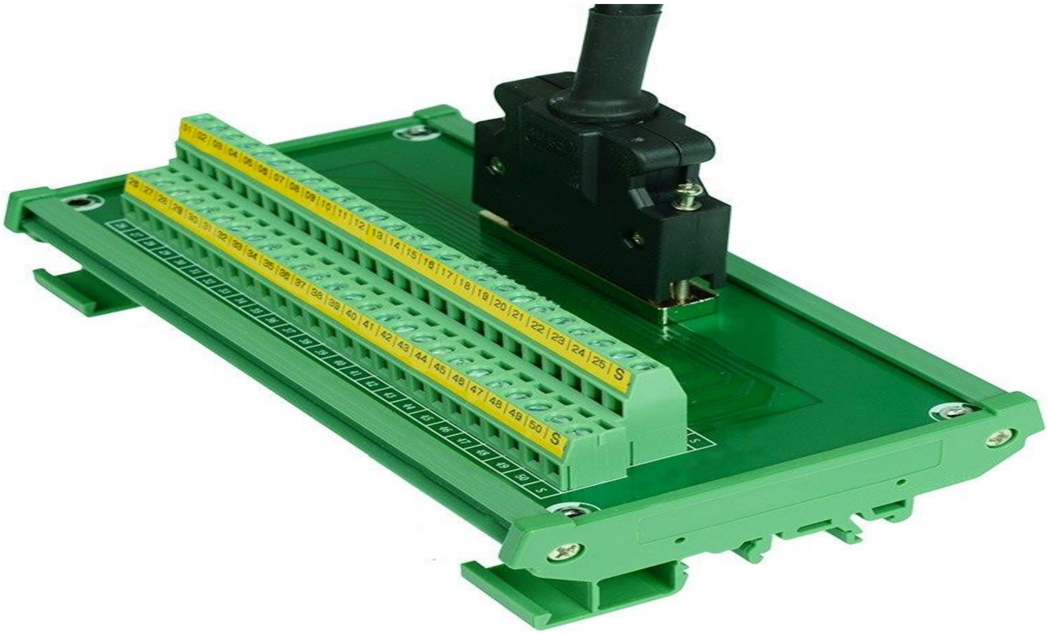


Fig (4.3): SCSI CN 50 pin servo motor drive pins.

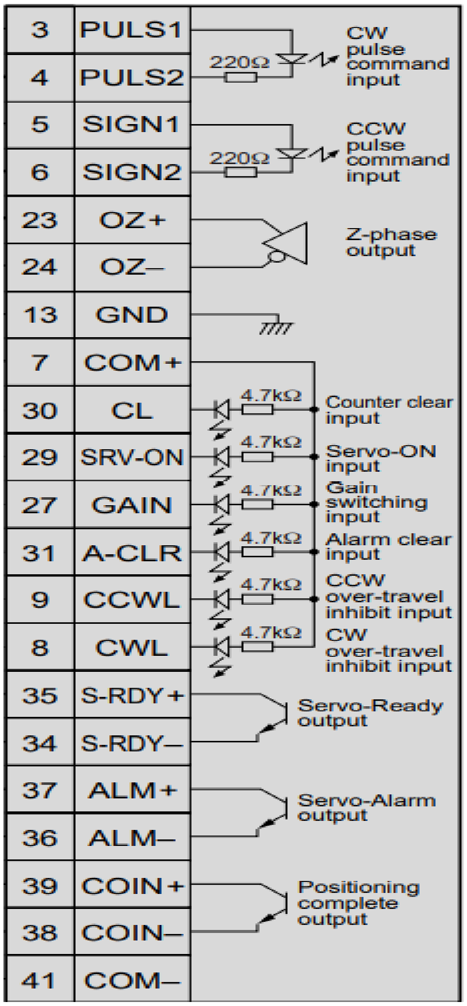


Fig (4.4): Internal connection of SCSI CN 50 pin servo motor drive pins.

3. Servo drive:

A servo drive receives a command signal from a control system, amplifies the signal, and transmits electric current to a servo motor in order to produce motion proportional to the command signal. Typically, the command signal represents a desired velocity, but can also represent a desired torque or position. A sensor attached to the servo motor reports the motor's actual status back to the servo drive. The servo drive then compares the actual motor status with the commanded motor status. It then alters the voltage, frequency or pulse width to the motor so as to correct for any deviation from the commanded status.

Where the RS232 part is connected to the computer and the Connect to CN X4 part is connected to the driver device , Where the driver device settings are made by PANATERM program and adjust the settings and input the parameters parameter.

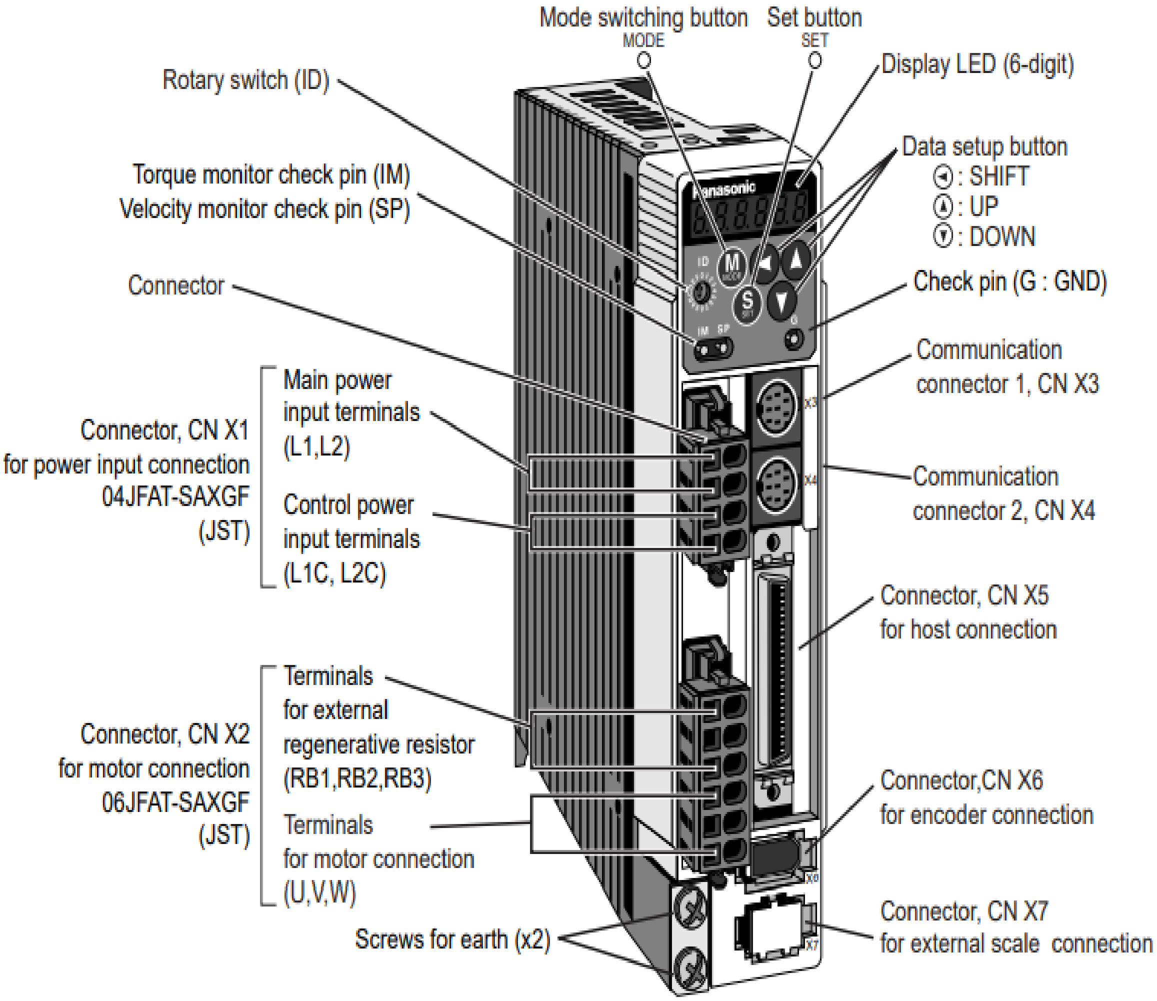


Fig (4.5): The servo driver used in the practical part MBDDT2210 single phase (200V, 200W, former B)

4. Servo motor:

The function of the servo motor is to receive a control signal that represents the desired output position of the servo shaft and its rotational speed and to apply power to its motor until its shaft turns to that position at the required speed.

The position sensor is used to find the position of rotation of the shaft, so that it knows the direction in which the motor should rotate to move the shaft to the desired position.

Fig (4.6): The servo motor used in the practical part.

4.2 Adjust parameter settings

Table (4.1): The parameter parameter for the driver can be set by the panaterm software or by the buttons on the driver.

Number	16bit parameter	Setting value
00	Axis address	1
01	LED display at power up	1
02	Control mode	3
03	Torque limit selection	3
04	Overtravel input inhibit	1
05	Internal/external speed switching	3
06	ZEROSPD input selection	2
07	Speed monitor (SP) selection	8
08	Torque monitor (IM) selection	12
09	TLC output selection	8
0A	ZSP output selection	8
0B	Absolute encoder set up	2
0C	Baud rate of RS232	2
0D	Baud rate of RS485	5
0E	Front panel lock set up	1
0F	For manufacturer use	0
10	1st position loop gain	63
11	1st velocity loop gain	35
12	1st velocity loop integration time constant	16
13	1st speed detection filter	0
14	1st torque filter time constant	65
15	Velocity feed forward	300
16	Feed forward filter time constant	50
17	For manufacturer use	0
18	2nd position loop gain	73
19	2nd velocity loop gain	35
1A	2nd velocity loop integration time constant	999
1B	2nd speed detection filter	0
1C	2nd torque filter time constant	65
1D	1st notch frequency	1500
1E	1st notch width selection	2
1F	For manufacturer use	0

Number	16bit parameter	Setting value
20	Inertia ratio	5
21	Real time auto tuning set up	0
22	Machine stiffness at auto tuning	4
23	Adaptive filter mode	1
24	Vibration suppression filter switching selection	0
25	Normal auto tuning motion set up	0
26	Software limit set up	10
27	Velocity observer	0
28	2nd notch frequency	1500
29	2nd notch width selection	2
2A	2nd notch depth selection	0
2B	1st vibration suppression frequency	0
2C	1st vibration suppression filter	0
2D	2nd vibration suppression frequency	0
2E	2nd vibration suppression filter	4
2F	Adaptive filter frequency	0
30	2nd gain action set up	1
31	1st control switching mode	10
32	1st control switching delay time	30
33	1st control switching level	50
34	1st control switching hysteresis	33
35	Position loop gain switching time	20
36	2nd control switching mode	0
37	2nd control switching delay time	0
38	2nd control switching level	0
39	2nd control switching hysteresis	0
3A	For manufacturer use	0
3B	For manufacturer use	0
3C	For manufacturer use	0
3D	JOG speed	300
3E	For manufacturer use	0
3F	For manufacturer use	0

Number	16bit parameter	Setting value
60	In-position range	24
61	Zero speed	50
62	At-speed	1000
63	In-position output set up	0
64	For manufacturer use	0
65	Under voltage error response at main power-off	1
66	Error response at over travel limit	0
67	Error response at main power-off	0
68	Error response action	0
69	Sequence at Servo-OFF	0
6A	Mech. brake delay at motor standstill	0
6B	Mech. brake delay at motor in motion	0
6C	External regenerative resistor set up	3
6D	Main power-off detection time	35
6E	Emergency stop torque set up	0
6F	For manufacturer use	0
70	Position deviation error level	25000
71	Analog input error level	0
72	Overload level	0
73	Over speed level	0
74	5th internal speed	0
75	6th internal speed	0
76	7th internal speed	0
77	8th internal speed	0
78	Numerator of external scale ratio	0
79	Multiplier of numerator of external scale ratio	0
7A	Denominator of external scale ratio	10000
7B	Hybrid deviation error level	100
7C	External scale direction	0
7D	For manufacturer use	0
7E	For manufacturer use	0
7F	For manufacturer use	0

Number	16bit parameter	Setting value
40	Command pulse input selection	0
41	Command pulse direction of rotation set up	0
42	Command pulse input mode	3
43	Command pulse inhibit input invalidation	1
44	Numerator of output pulse ratio	1500
45	Denominator of output pulse ratio	0
46	Pulse output logic inversion	0
47	Z-phase of external scale set up	821
48	1st numerator of command pulse ratio	0
49	2nd numerator of command pulse ratio	0
4A	Multiplier of numerator of command pulse ratio	0
4B	Denominator of command pulse ratio	400
4C	Smoothing filter	1
4D	FIR filter set up	0
4E	Counter clear input	2
4F	For manufacturer use	0
50	Velocity command input gain	500
51	Velocity command input logic inversion	1
52	Velocity command offset	0
53	1st internal speed	0
54	2nd internal speed	0
55	3rd internal speed	0
56	4th internal speed	-2000
57	Velocity command filter	300
58	Acceleration time	0
59	Deceleration time	0
5A	S-shaped accel. /decal. time	0
5B	Torque command selection	0
5C	Torque command input gain	50
5D	Torque command input inversion	0
5E	1st torque limit	300
5F	2nd torque limit	300

The circuit diagram of the SCSI CN 50 pin, plc and pushbutton connection is shown.

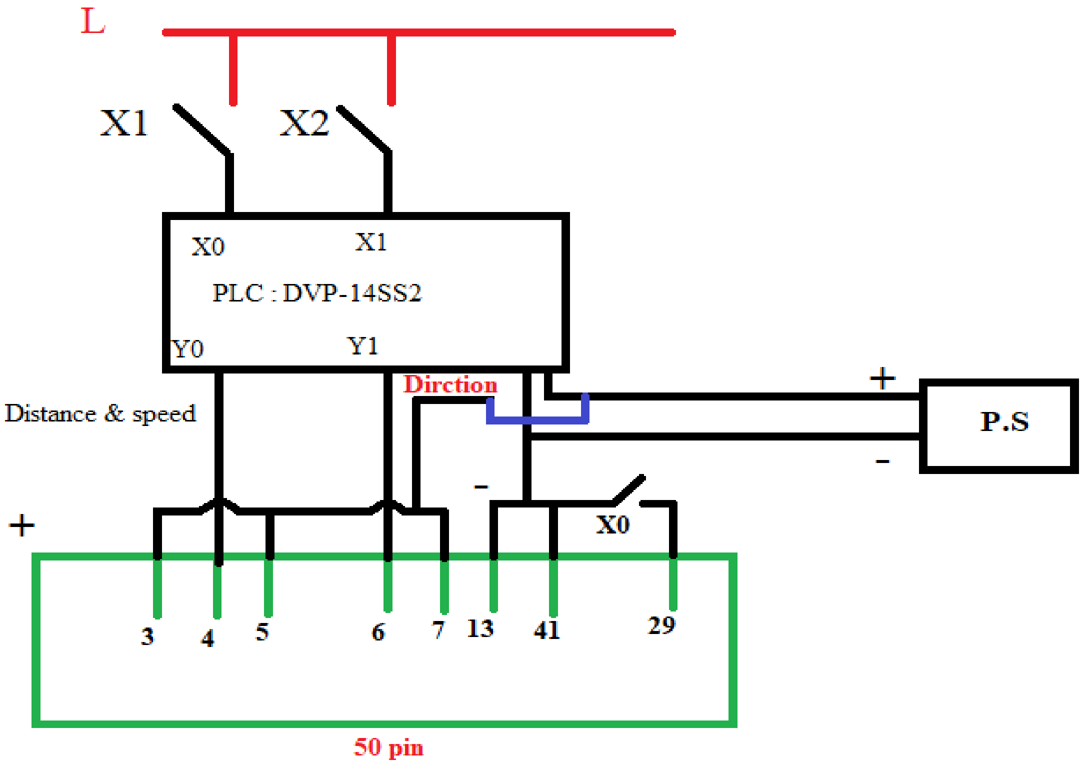


Fig (4.7): internal connection between plc and SCSI 50 pin and three pushbuttons.

Table (4.2): Three control buttons are used to operate the servo motor and determine the direction as shown in the following table:

Pushbutton number	Pushbutton name	Type of button	Color button	Function of the button
Pushbutton 1	X0	Toggle switch	Green	Servo on
Pushbutton 2	X1	Toggle switch	Red	Direction
Pushbutton 3	X2	Pushbutton switch	Green	Start

The circuit diagram of the SCSI CN50 pin, plc, pushbutton and power supply connection is shown.

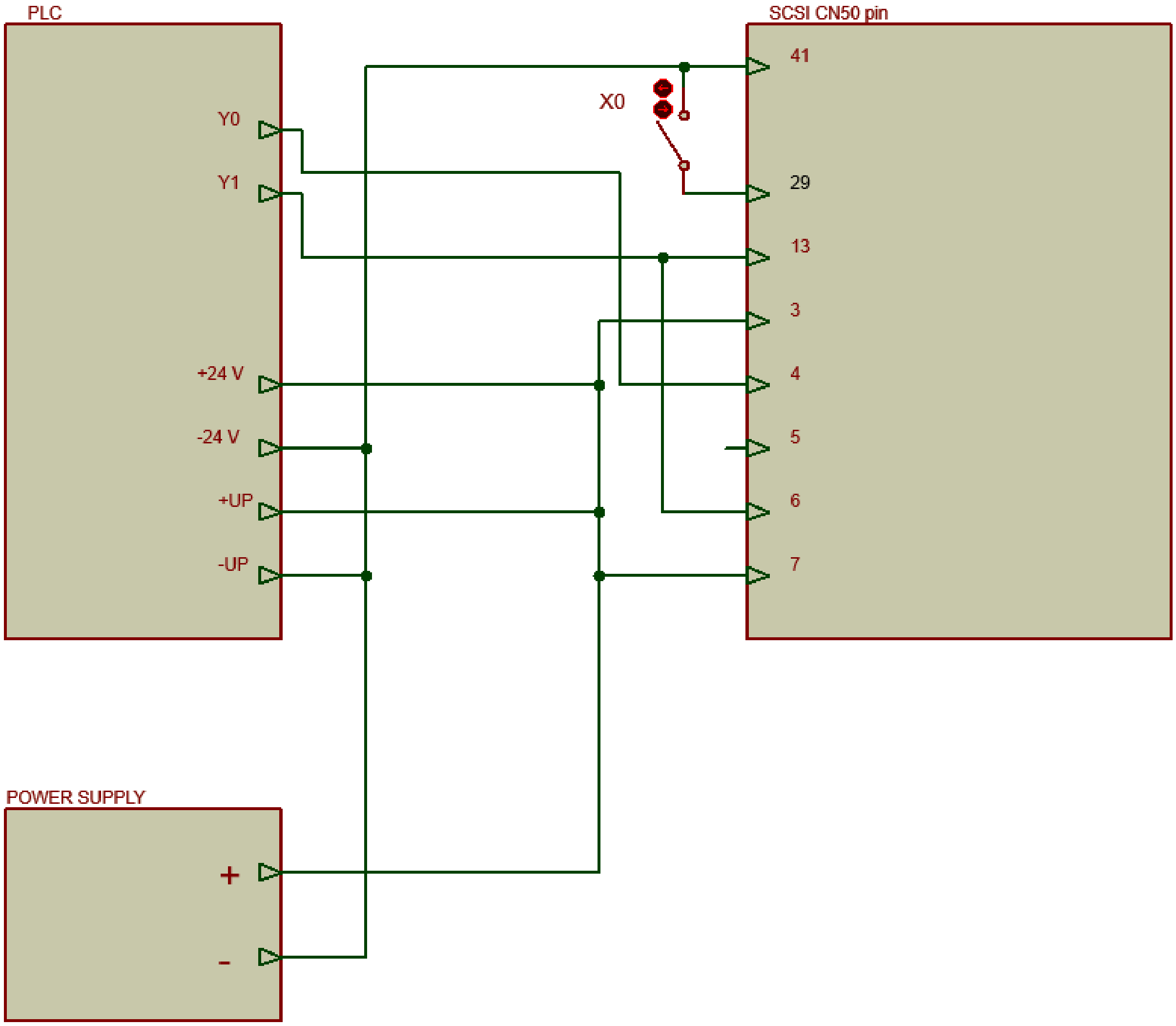


Fig (4.8): internal connection between plc and SCSI 50 pin and power supply.

Finally, I have the following practical connection

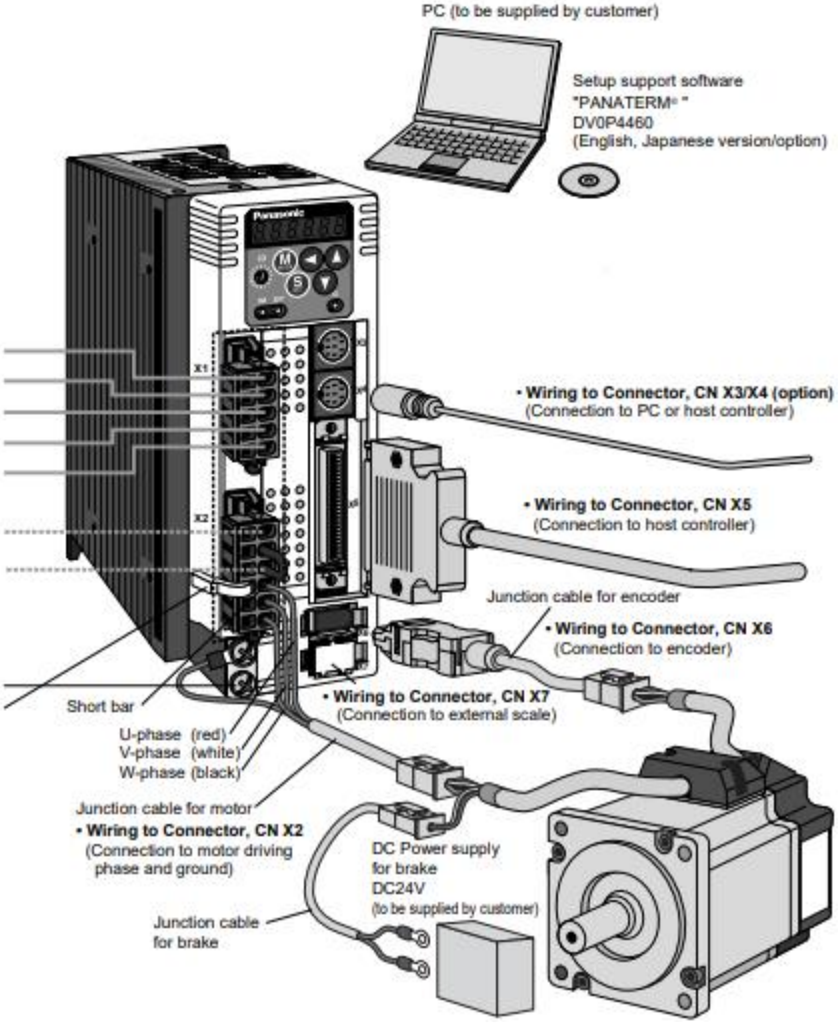


Fig (4.9): Connect the Hardware Part

Chapter 5

Hardware results

5.1 Explain the method of controlling the project in practical terms

5.1.1 **How to set a motor speed by using PLC**

After adjusting the driver settings, the speed was calibrated according to the number of pulses, so that at 1 rpm equal to 6.667 pulses, an internal equation was set in the programming as shown in the following figure:

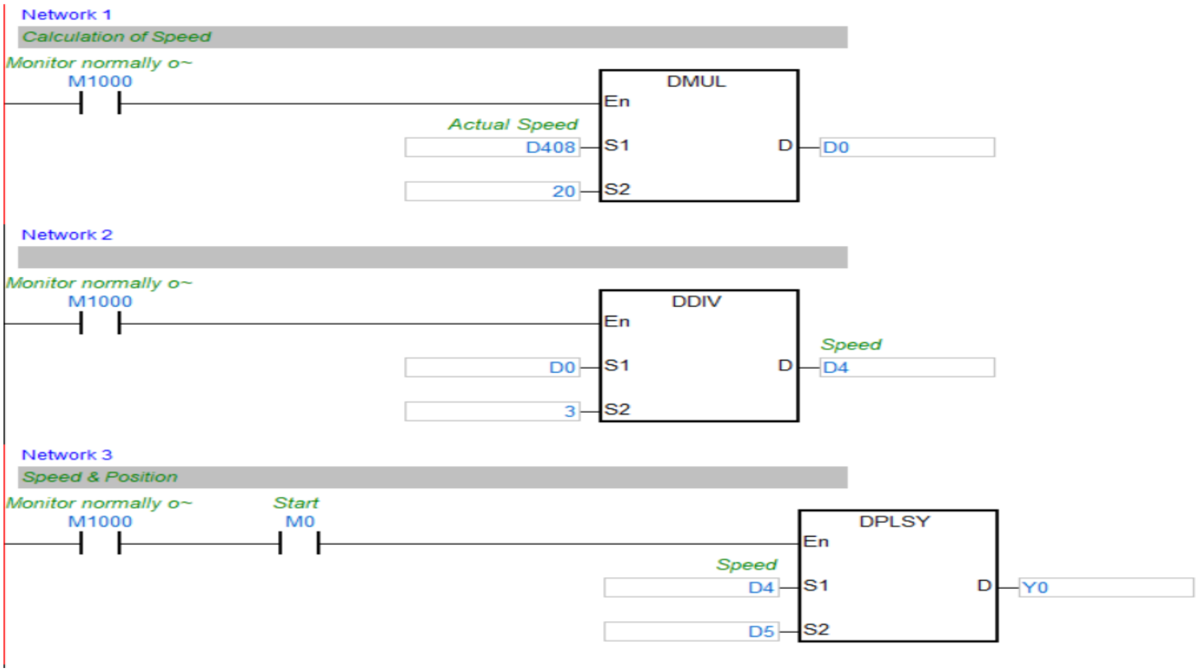


Fig (5.1): Plc programing speed control.

The equation used to set the speed

$$n = \frac{20}{3} * speed$$

n : number of pluses.

The speed at 1 rpm :

$$n = \frac{20}{3} * 1RPM$$

$$n \ = 6.667 pluses.$$

5.1.2 How to set a motor position by using PLC

After adjusting the driver settings, the position was calibrated according to the number of pulses, so that for every 400 pulses the motor completes a full cycle, an internal equation was set in the programming as shown in the following figure:

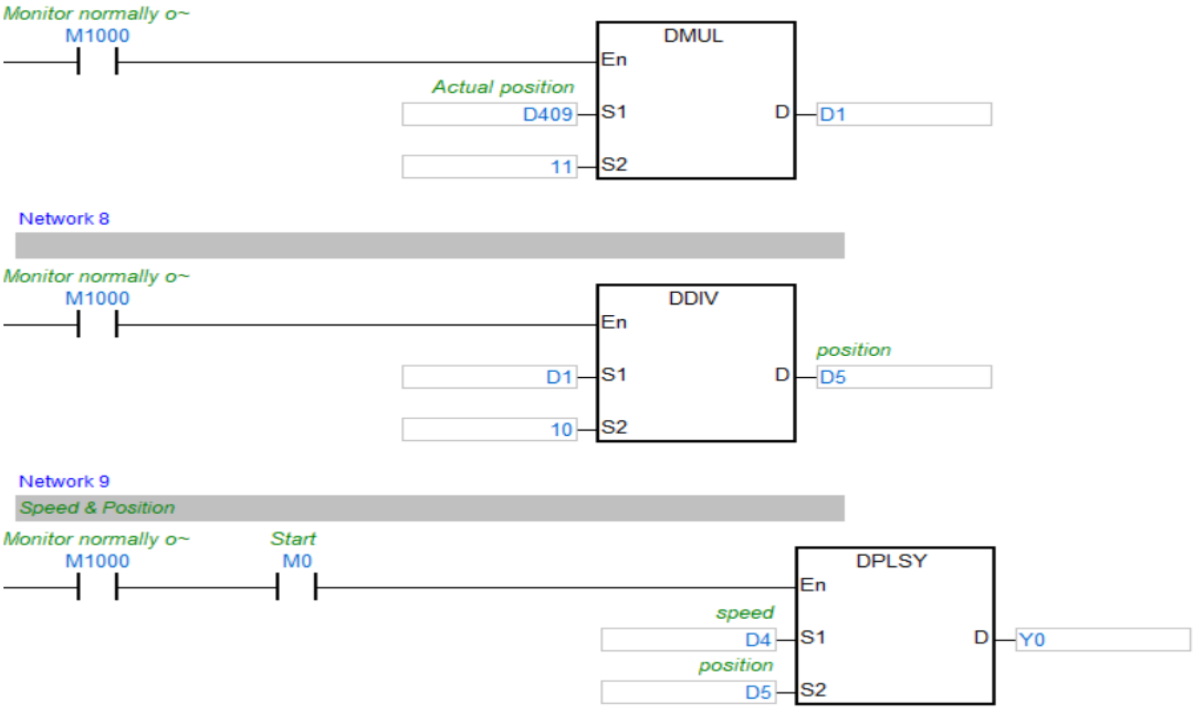


Fig (5.2): Plc programing position control.

The equation used to set the position:

400 pulses = 1 turn

$$n = \frac{400}{360} * degree$$

n : number of pluses.

The motor completes a full cycle

1 turn =400 pluses

$$n = \frac{400}{360} * 360$$

$$n \ = 400\, pluses.$$

5.1.3 How to start work of by using PLC

Three Push Button were used to control the principle of operation of the system, start the motor set the required direction.

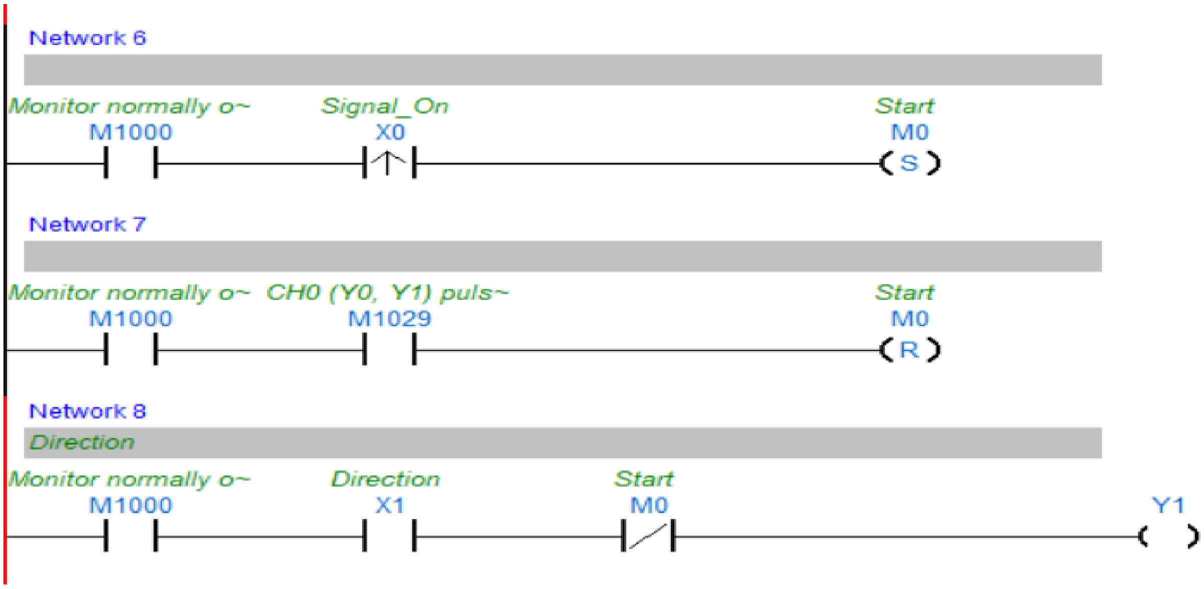


Fig (5.3): Plc programing Pushbutton control.

5.2 The load

The DC motor load has been added so that the motor forms a load on the shaft to the servo motor, by which a load is created against the torque of the servo motor, and when the load torque of the servo motor is increased, the speed of the servo motor decreases and the closed control loop corrects the error ($\Delta w = 0$), where The control system works to maintain the motor speed by increasing the motor torque until it reaches a steady state for the system $Tm = T_L$, the following shows the parameters for the load (DC motor):

Globe motors	
Date code	HA0035
Rated Voltage	DC 24V
Reduction Ratio	1:401
No-Load Speed	100 RPM
No-Load Current	0.15 A
Rated Torque	15 Kg.cm
Rated Current	0.6 A
D Shaped Output Shaft Size	6*14mm (0.24" x 0.55") (D*L)
Gearbox Size	37 x 30.5mm (1.46" x 1.2") (D*L)
Motor Size	36.2 x 33.3mm (1.43" x 1.31") (D*L)
Mounting Hole Size	M3 (not included)

Fig (5.4): Connecting the load with the servo motor.

The following table (5.1) shows the results of adding the load and changing the torque to the motor:

Speed Servo motor (rpm)	**Tm=TL (N.m)**
50	13
150	17
300	22
700	123
800	215
1000	300→(Full load)

The protection system for the servo motor works through the driver as it works to disconnect the motor when overloading after a certain period of time, by detecting the risk of an increase in the current drawn from the nominal current of the servo motor.

Chapter 6

Conclusion

- The servo motor can be used in many industrial automation applications such as (CNC Machine, cutting machine) that works with high precision by moving the motor at different angles and speeds.

- A simple educational model was designed showing the principle of operation and control of the servo motor using some industrial parts, where a PLC and driver were used to calibrate the required angle and speed.

- The closed-loop control unit was provided by an encoder sensor that works on reading the speed and torque and transmitting these data to the driver for processing as it was mentioned in the project.

- A simulation of the system was built using MATLAP and showed curves explain the behavior of the motor when adjusting the speed and angle of the servo motor.

- We were able to show the mechanical properties of the motor without load and at different speeds, as the motor was running at different speeds with a torque equal to the nominal torque of the motor ($Tm = Tn$), and when the motor was started with a load at different speeds, The control system works to stabilize the required speed by generating torque as it is proportional to the increase in the load torque ($Tm=T_L$) by increasing the armature current.

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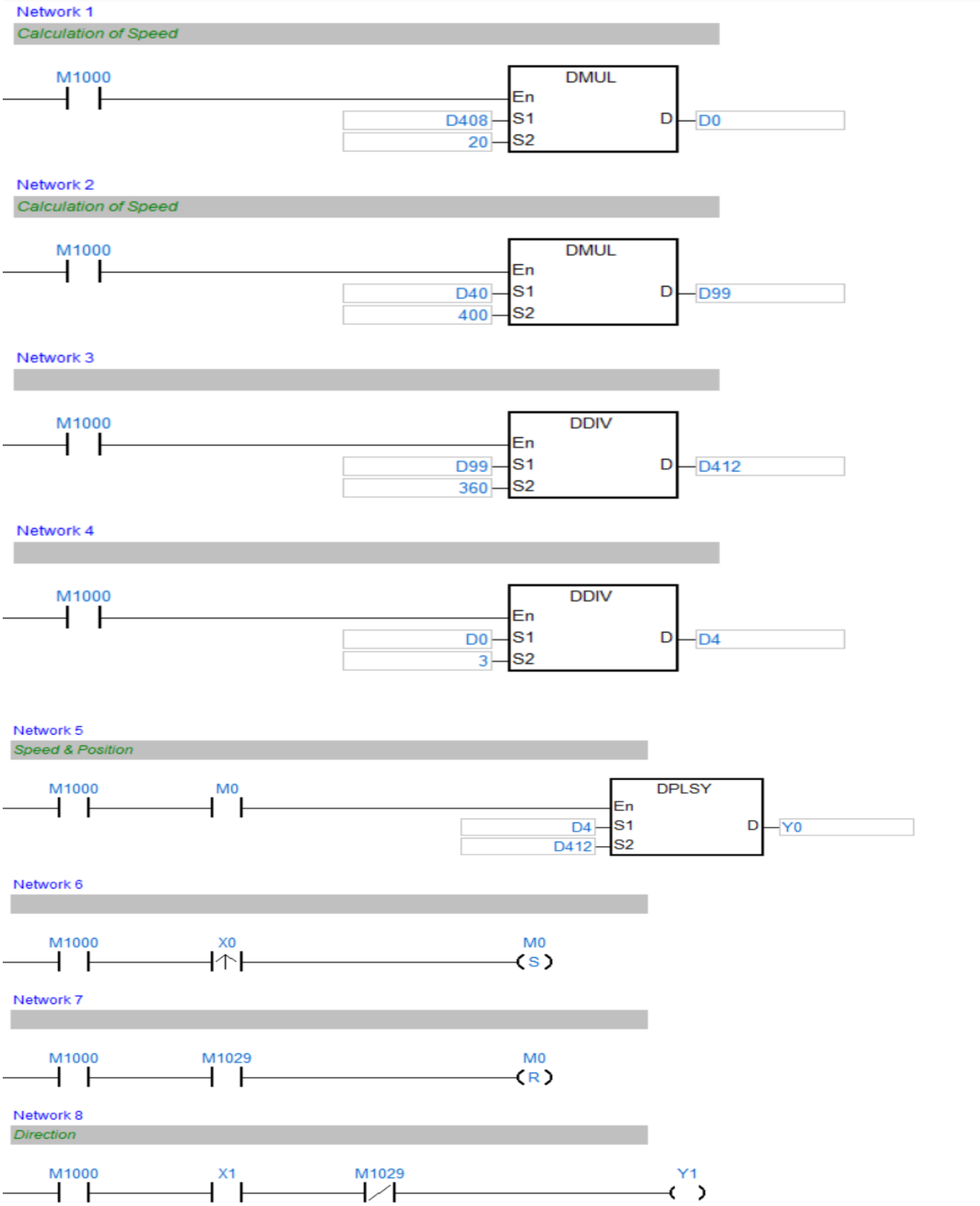
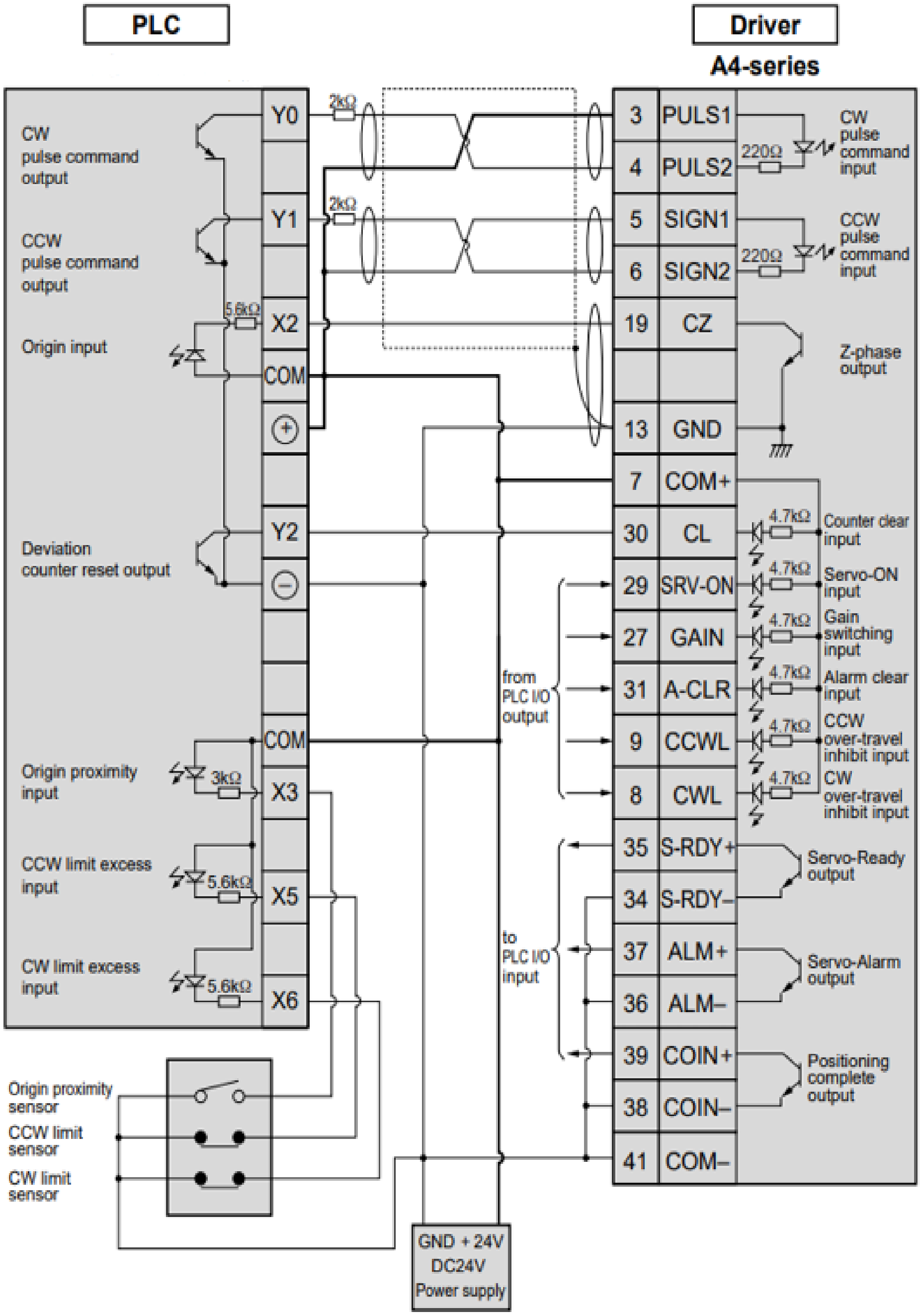
Appendix(A)

Programming the project using the PLC

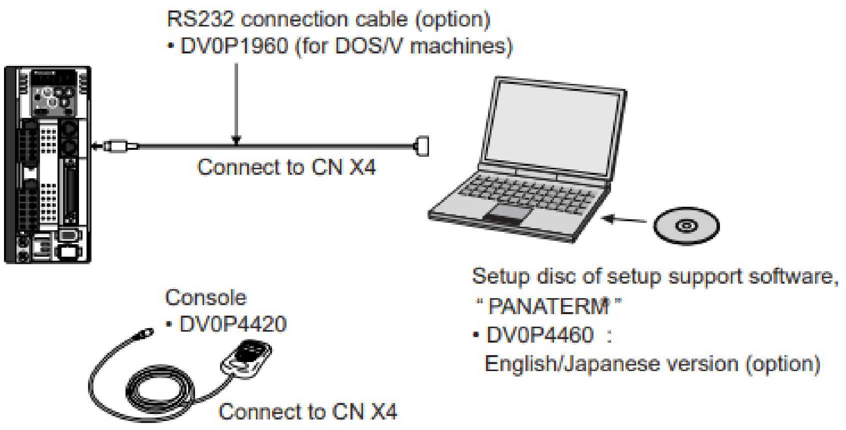


Appendix(B)

Servo drive Panasonic (MBDDT2210) datasheet



How to Connect



<Remarks>

- Connect the console connector to the connector, CN X4 of the driver securely.
- Do not pull the cable to insert/unplug.

Setup of Parameter and Mode

Composition and List of Parameters

Group	Parameter No. (Pr□□)	Outline
Functional selection	00 to 0F	You can select a control mode, designate I/O signals and set up a baud rate.
Adjustment	10 to 1F, 27 to 2E	You can set up servo gains (1st and 2nd) of position, velocity, integration, etc, and time constants of various filters.
	20 to 26, 2F	Parameters related to Real Time Auto-Gain Tuning. You can set up a mode and select a mechanical stiffness.
	30 to 3F	You can set up parameters related to gain switching(1st ←→ 2nd)
Position (Step) Control	40 to 4F	You can set up an input form, directional selection of command pulses, dividing of encoder output pulse and set up a division multiplier ratio of command pulse.
Velocity Control, Torque Control	50 to 5A, 74 to 77	You can set up an input gain of command pulse, reverse polarity and adjust offset. You can also set up internal speeds (1 to 8th speed), acceleration/deceleration time.
	5B to 5F	You can set an input gain, reverse polarity and set up a torque limit of torque command.
Sequence	60 to 6F	You can set up detecting conditions of output signals, such as positioning-complete and zero-speed. You can also set up a deceleration/stop action at main power-off, at alarm output and at servo-off, and clear condition of the deviation counter.
	70 to 73	You can set up actions of protective functions.
Full-Closed Control	78 to 7F	You can set up dividing of external scale.

For details, refer to "Parameter Setup" of each control mode.

- **In this document, following symbols represent each mode.**

Symbol	Control mode	Setup value of Pr02
P	Position control	0
S	Velocity control	1
T	Torque control	2
F	Full-Closed control	6

Symbol	Control mode	Setup value of Pr02
P/S	Position (1st)/Velocity (2nd) control	3*
P/T	Position (1st)/Torque (2nd) control	4*
S/T	Velocity (1st)/Torque (2nd) control	5*

* When you select the combination mode of 3, 4 or 5, you can select either 1st or 2nd with control mode switching input (C-MODE).

When C-MODE is open : 1st mode selection
When C-Mode is closed : 2nd mode selection
Do not enter the command 10ms before/after the switching.

Parameters for Functional Selection

Parameter No. (Pr□□)	Set up of parameter	Range	Default	Unit	Related Control Mode
00 *1	Address of axis	0 to 15	1	–	all
01 *1	Initial display of LED	0 to 17	1	–	all
02 *1	Setup of control mode	0 to 6	1	–	all
03	Selection of torque limit	0 to 3	1	–	P, S, F
04 *1	Setup of over-travel inhibit input	0 to 2	1	–	all
05	Switching of Internal/External speed setup	0 to 3	0	–	S
06	Selection of ZEROSPD input	0 to 2	0	–	S, T
07	Selection of speed monitor (SP)	0 to 9	3	–	all
08	Selection of torque monitor (IM)	0 to 12	0	–	all
09	Selection of TLO output	0 to 8	0	–	all
0A	Selection of ZSP output	0 to 8	1	–	all
0B *1	Setup of absolute encoder	0 to 2	1	–	all
0C *1	Baud rate setup of RS232	0 to 5	2	–	all
0D *1	Baud rate setup of RS485	0 to 5	2	–	all
0E *1	Setup of front panel lock	0 to 1	0	–	all
0F	(For manufacturer's use)	–	–	–	–

- For parameters with suffix of "*1", change will be validated after the reset of the control power.

Parameters for Adjustment of Time Constant for Gains and Filters

Parameter No. (Pr□□)	Set up of parameter	Range	Default		Unit	Related Control Mode
			A to C-frame	D to F-frame		
10	1st gain of position loop	0 to 3000	<63>	<32>	1/s	P, F
11	1st gain of velocity loop	1 to 3500	<35>	<18>	Hz	all
12	1st time constant of velocity loop integration	1 to 1000	<16>	<31>	ms	all
13	1st filter of velocity detection	0 to 5	<0>		–	all
14	1st time constant of torque filter	0 to 2500	<65>	<126>	0.01ms	all
15	Velocity feed forward	–2000 to 2000	<300>		0.1%	P, F
16	Time constant of feed forward filter	0 to 6400	<50>		0.01ms	P, F
17	(For manufacturer's use)	–	–		–	–
18	2nd gain of position loop	0 to 3000	<73>	<38>	1/s	P, F
19	2nd gain of velocity loop	1 to 3500	<35>	<18>	Hz	all
1A	2nd Time constant of velocity loop integration	1 to 1000	<1000>		ms	all
1B	2nd filter of velocity detection	0 to 5	<0>		–	all
1C	2nd torque filter time constant	0 to 2500	<65>	<126>	0.01ms	all
1D	1st notch frequency	100 to 1500	1500		Hz	all
1E	Selection of 1st notch width	0 to 4	2		–	all
1F	(For manufacturer's use)	–	–		–	–
27	Setup of instantaneous velocity observer	0 to 1	<0>		–	P, S
28	2nd notch frequency	100 to 1500	1500		Hz	all
29	Selection of 2nd notch width	0 to 4	2		–	all
2A	Selection of 2nd notch depth	0 to 99	0		–	all
2B	1st damping frequency	0 to 2000	0		0.1Hz	P, F
2C	Setup of 1st damping filter	–200 to 2000	0		–	P, F
2D	2nd damping frequency	0 to 2000	0		0.1Hz	P, F
2E	Setup of 2nd damping filter	–200 to 2000	0		–	P, F

- For parameters which default values are parenthesized by "< >", default value varies automatically by the real-time auto-gain tuning function. Set up Pr21 (Setup of Real-time auto-gain tuning mode) to 0 (invalid) when you want to adjust manually.

Parameters for Auto-Gain Tuning

Parameter No. (Pr□□)	Set up of parameter	Range	Default		Unit	Related Control Mode
			A to C-frame	D to F-frame		
20	Inertia ratio	0 to 10000	<250>		%	All
21	Setup of real-time auto-gain tuning mode	0 to 7	1		–	All
22	Mechanical stiffness at real-time auto-gain tuning	0 to 15	4	1	–	All
23	Setup of adaptive filter mode	0 to 2	1		–	P, S, F
24	Selection of damping filter switching	0 to 2	0		–	P, F
25	Setup of action at normal mode auto-gain tuning	0 to 7	0		–	All
26	Setup of software limit	0 to 1000	10		0.1rev	P, F
2F *3	Adaptive filter frequency	0 to 64	0		–	P, S, F

*3 this parameter will be automatically set up when the adaptive filter is validated (Pr23, "Setup of adaptive filter mode" is "1", and you cannot set this up at your discretion. Set up Pr23, "Setup of adaptive filter mode" to "0" (invalid) to clear this parameter.

Parameters for Adjustment (2nd Gain Switching Function)

Parameter No. (Pr□□)	Set up of parameter	Range	Default	Unit	Related Control Mode
30	Setup of 2nd gain	0 to 1	<1>	–	All
31	1st mode of control switching	0 to 10	<0>	–	All
32	1st delay time of control switching	0 to 10000	<30>	166μS	All
33	1st level of control switching	0 to 20000	<50>	–	All
34	1st hysteresis of control switching	0 to 20000	<33>	–	All
35	Time for position gain switching	0 to 10000	<20>	(1+setup value) x 166μs	P, F
36	2nd mode of control switching	0 to 5	<0>	–	S, T
37	2nd delay time of control switching	0 to 10000	0	166μS	S, T
38	2nd level of control switching	0 to 20000	0	–	S, T
39	2nd hysteresis of control switching	0 to 20000	0	–	S, T
3A	(For manufacturer's use)	–	–	–	–
3B	(For manufacturer's use)	–	–	–	–
3C	(For manufacturer's use)	–	–	–	–
3D	Setup of JOG speed	0 to 500	300	r/min	All
3E	(For manufacturer's use)	–	–	–	–
3F	(For manufacturer's use)	–	–	–	–

- For parameters which default values are parenthesized by "< >", default value varies automatically by the real-time auto-gain tuning function. Set up Pr21 (Setup of Real-time auto-gain tuning mode) to 0 (invalid) when you want to adjust manually.

Parameters for Position Control

Parameter No. (Pr□□)	Set up of parameter	Range	Default	Unit	Related Control Mode
40*1	Selection of command pulse input	0 to 1	0	–	P, F
41*1	setup of rotational direction of command pulse	0 to 1	0	–	P, F
42*1	setup of command pulse input mode	0 to 3	1	–	P, F
43	Canceling of command pulse prohibition input	0 to 1	1	–	P, F
44*1	Numerator of pulse output division	1 to 32767	2500	–	all
45*1	Denominator of pulse output division	0 to 32767	0	–	all
46*1	Logic reversal of pulse output	0 to 3	0	–	all
47*1	Setup of Z-phase of external scale	0 to 32767	0	–	F
48	1st numerator of electronic gear	0 to 10000	0	–	P, F
49	2nd numerator of electronic gear	0 to 10000	0	–	P, F
4A	Multiplier for numerator of electronic gear	0 to 17	0	–	P, F
4B	Denominator of electronic gear	1 to 10000	10000	–	P, F
4C	Setup of smoothing filter for primary delay	0 to 7	1	–	P, F
4D*1	Setup of FIR smoothing	0 to 31	0	–	P, F
4E	Counter clear input mode	0 to 2	1	–	P, F
4F	(For manufacturer's use)	–	–	–	–

- For parameters with suffix of "*1", change will be validated after the reset of the control power.

Parameters for Velocity/Torque control

Parameter No. (Pr□□)	Set up of parameter	Range	Default	Unit	Related Control Mode
50	Input gain of speed command	10 to 2000	500	(r/min)/V	S, T
51	Input reversal of speed command	0 to 1	1	–	S
52	Offset of speed command	–2047 to 2047	0	0.3mV	S, T
53	1st speed of speed setup	–20000 to 20000	0	r/min	S
54	2nd speed of speed setup	–20000 to 20000	0	r/min	S
55	3rd speed of speed setup	–20000 to 20000	0	r/min	S
56	4th speed of speed setup	–20000 to 20000	0	r/min	S, T
74	5th speed of speed setup	–20000 to 20000	0	r/min	S
75	6th speed of speed setup	–20000 to 20000	0	r/min	S
76	7th speed of speed setup	–20000 to 20000	0	r/min	S
77	8th speed of speed setup	–20000 to 20000	0	r/min	S
57	Setup of speed command filter	0 to 6400	0	0.01ms	S, T
58	Setup of acceleration time	0 to 5000	0	2ms/(1000r/min)	S
59	Setup of deceleration time	0 to 5000	0	2ms/(1000r/min)	S
5A	Setup of sigmoid acceleration/deceleration time	0 to 500	0	2ms	S
5B	Selection of torque command	0 to 1	0	–	T
5C	Input gain of torque command	10 to 100	30	0.1V/rated torque	T
5D	Input reversal of torque command	0 to 1	0	–	T
5E	Setup of 1st torque limit	0 to 500	<500>*2	%	all
5F	Setup of 2nd torque limit	0 to 500	<500>*2	%	P, S, F

*2 Defaults of Pr5E and Pr5F vary depending on the combination of the driver and the motor.
Refer to P.57, "Setup of Torque Limit".

Parameters for Sequence

Parameter No. (Pr□□)	Set up of parameter	Range	Default	Unit	Related Control Mode
60	In-position (positioning complete) range	0 to 32767	131	Pulse	P, F
61	Zero speed	10 to 20000	50	r/min	all
62	At-speed (arrived speed)	10 to 20000	1000	r/min	S, T
63	Setup of in-position output	0 to 3	0	–	P, F
64	(For manufacturer's use)	–	–	–	–
65	Selection of LV-trip at main power off	0 to 1	1	–	all
66*1	Sequence at run-prohibition	0 to 2	0	–	all
67	Sequence at main power off	0 to 9	0	–	all
68	Sequence at alarm	0 to 3	0	–	all
69	Sequence at servo-off	0 to 9	0	–	all
6A	Setup of mechanical brake action at stall	0 to 100	0	2ms	all
6B	Setup of mechanical brake action in motion	0 to 100	0	2ms	all
6C*1	Selection of external regenerative resister	0 to 3	A, B-frame : 3, C,D,E-frame : 0	–	all
6D*1	Detection time of main power shut-off	35 to 1000	35	2ms	all
6E	Setup to torque at emergency stop	0 to 500	0	%	all
6F	(For manufacturer's use)	–	–	–	–
70	Excess setup of positional deviation	0 to 32767	25000	256Pulse	P, F
71	Excess setup of analog input	0 to 100	0	0.1V	S, T
72	Setup of over-load level	0 to 500	0	%	all
73	Setup of over-speed level	0 to 20000	0	r/min	all

Parameters for Full-Closed Control

Parameter No. (Pr□□)	Set up of parameter	Range	Default	Unit	Related Control Mode
78*1	Numerator of external scale division	0 to 32767	0	–	F
79*1	Numerator multiplier of external scale division	0 to 17	0	–	F
7A*1	Denominator of external scale division	1 to 32767	10000	–	F
7B*1	Excess setup of hybrid deviation	1 to 10000	100	16X external scale pulses	F
7C*1	Reversal of direction of external scale	0 to 1	0	–	F
7D	(For manufacturer's use)	–	–	–	–
7E	(For manufacturer's use)	–	–	–	–
7F	(For manufacturer's use)	–	–	–	–

- For parameters with suffix of "*1", change will be validated after the reset of the control power.