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Evaluation of Voltage/Frequency and Voltage Source Inverter Control Strategies for Single-Phase Induction Motors Using MATLAB Simulation

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Abstract—**There is a growing interest in studying the single-phase induction motor due to its wide use in many applications, the most important of which are domestic and industrial. A simulation model is built by implementing and running the model using MATLAB to identify the system behavior of the induction motor. To study and analyze the system behavior in different cases, it is proposed to implement and run the model in two ways: the first without control techniques and the second using control techniques. Tests are conducted according to a methodology based on scenarios that include all expected cases that can be assumed to suit real-time operation. To evaluate control strategies, the clear effect between their use and non-use must be demonstrated through clear measurement criteria to include response speed and performance improvement. In induction motor tests, the focus is on electrical and mechanical quantities and the transient and steady state of the system, including a 220-volt supply voltage and a 50 Hz frequency. The initial test case refers to using the model to simulate three cases: the first without load, the second with a constant load of one newton meter, and the third operating the motor as a pump by changing the load according to the pumping quantity and linked to the motor output. After conducting these tests, the different simulation results can be indicated in terms of the change in electrical and mechanical quantities over time during the proposed operating period. The results showed the high starting current that may affect the motor, and the response time for the motor to operate at the rated speed can be considered. Therefore, this requires the use of techniques to improve performance and provide response speed with a gradual increase in the starting current to protect the motor from high starting current. Voltage and frequency control techniques, as well as voltage-to-frequency ratio and another technique representing the voltage source inverter, were used. The results indicate a clear improvement through the stability of the motor by operating with a short response time compared to other cases and the specified rotational speed and specified torque, which shows a relatively high-efficiency performance.**

Keywords—Open Loop System; Single Phase Induction Motor (1ph-IM); Starting Torque; Voltage Controller; Frequency Controller; Voltage/Frequency Controller(V/F); Voltage Source Inverter (VSI).

I. INTRODUCTION

Induction motors, so named because they operate by mutual induction between the field formed in the stationary part and the field formed by the coils of the rotor. They also have another name, which is called non-harmonic, because the speed of rotation of the rotor is not equal to the rotating field in the stationary part. This type of motor is widely used in domestic and industrial applications for two reasons: the first is its low manufacturing cost compared to other motors, and the second is its ease of operation and maintenance [1]-[3]. These motors are of two types: single-phase and three-phase. Induction motors, like other motors, consist of two parts: the stator and the rotor. The stator is cylindrical in shape, hollow, made up of a group of magnetic iron plates that are insulated from each other, and it contains long openings called channels in which the coils are placed. The rotating part in the induction motor consists of the axis of rotation, the lip, and rests on the two side covers, and insulated magnetic iron plates are pressed on it to form a cylindrical shape that contains channels around its outer perimeter in which the coils are placed. The rotor coils are either copper rod shorted at both ends and are called the shorted rotor motor. There is another type in which aluminum is cast inside the ducts and is called the squirrel cage motor. Another type has slipped rings and the rotor is made by placing coils of insulated copper wires in the ducts and connecting their ends to slip rings. The initial torque in an induction motor is generated by the passage of an electric current in the stator coils, which creates a rotating magnetic field in the air gap. The field cuts the rotor coils, generating an induced electromotive force, which in turn causes a current to pass through the rotor coils. Thus, a mechanical force is generated that affects the rotor and makes it rotate with a torque in the direction of the rotating magnetic field [4]-[6].

The starting torque in a single-phase induction motor is zero because it contains a single electrical circuit and the magnetic field changes according to the change in electrical current, so there is no mechanical force to rotate the motor. Therefore, the field must be displaced to create an initial self-torque by generating a new phase from the original phase that differs from it by a certain angle through the phase splitting process. Phase splitting is done using auxiliary coils placed in the rotor with the main coils and occupying a third of the channels and connected in parallel with the main coils. When the motor is connected to the source, two different fields are created due to the difference in the resistance of the main and auxiliary coils as a result of the difference in the current passing through the auxiliary and main coils. Then the initial torque is obtained and the motor rotates at an increasing speed. When the motor reaches 75% of the rated speed, the auxiliary coils are disconnected by a centrifugal switch or a magnetic or thermal complement [7]-[9].

This method has high starting current, low starting torque, low power factor and low efficiency and is suitable for home use such as refrigerators and water coolers. The second method is to connect the capacitor in series with the auxiliary coils (starting the movement) and connect the capacitor in parallel with the main coils (operating). The capacitor provides the starting coil current to the operating coil current at an angle, which creates an initial torque due to the difference in the fields generated in both the operating coil and the starting coil. These motors are characterized by high initial torque, high efficiency, and an average power factor. Voltage control is one of the methods of controlling the speed or starting of a single-phase induction motor where the voltage is proportional to the torque and the frequency is proportional to the speed. To maintain the magnetic flux and to maintain stability it is preferable to use voltage/frequency control [10]-[12].

In [13], the single-phase induction motor was described as an adjustable speed motor. The voltage/current technology and its relationship with speed were studied. The study indicated the importance of using the inverter and considering it as the best option. In [14], the single-phase induction motor was described through a conventional operating condition using a normal capacitor as an initial test condition. Then, another operating condition was adopted by adopting the electronic system with a single-phase inverter controller and using the capacitor system. The operation included changing the capacitance of the capacitor connected in series with the auxiliary coil to provide better performance for the induction motor. In [15], a description of a single-phase induction motor operating with voltage control technology and constant torque operation was presented to address the problem of improving the motor efficiency. The study [16] provided an evaluation of the use of variable speed control techniques for the single-phase induction motor in addition to the working principle of these techniques. In [17], voltage/frequency technology was used to control the speed of a single-phase induction motor with different operating conditions in order to save energy with better efficiency. The researchers relied on a DC source, an inverter, and voltage/frequency control technology. The researchers reached the possibility of improving the performance of the induction motor. By reviewing these studies and other sources of current research that dealt with different cases about the induction motor, the researchers found that there is a need to build a simulation model that is simple, appropriately effective, inexpensive, reliable, and efficient to enable its use in modern and future applications. Referring to the aim of the study, it is to evaluate and improve the performance and efficiency of the single-phase induction motor using the proposed control techniques, address the problem of high starting current, and provide safe operation of the electric motor.

This study contributes to building a suitable simulation model to conduct some preliminary tests for the proposed system cases. The study includes methods of implementing and operating the system under no load, constant load and variable load conditions, in addition to other methods including the presence of controllers and others without controllers. A suitable analysis of the system behavior can be developed according to the methods used and proposed to simulate the system and determine the reasons for the change in the system behavior for all the proposed cases. From the system results and after analyzing the system behavior, the effectiveness of the system and the proposed control methods can be verified. Improvements in motor performance, reduction of starting current and effectiveness of different control methods. This paper proposes simulation models for SPIM control using variable voltage, variable frequency, V/F control and VSI method to control the capacitor-driven CR-SPIM to improve the motor characteristics by reducing the impact of starting and its problem on motor operation.

II. METHODOLOGY

A. Single-Phase Induction Motors

Single-phase induction motor are a special case of three-phase motors. They do not differ from them in appearance, composition, or working principle. Although the characteristics and performance of 1ph-IM are considered low compared to those of three-phase motors, they have found wide spread use in daily uses for home and office purposes as well as military and medical applications because of its operation at low power, availability of a single-phase source, and its low price [18]-[20].

1ph-IM consists of two parts, the stator contains the main windings and the rotor is a squirrel cage type which supplies the current generated by electromagnetic induction. The magnetic field produced in the stator is pulsating, not circular, and this makes the rotor vibrate, not rotate, when it starts. In SPIM, the starting mechanism is necessary to enable them to start moving itself. These motors suffer from the problem of high losses and noise due to the high pulse torque, and the other problem is their low efficiency when working [21]-[23]. The problems of SPIM drive are overcome are addressed by adding an auxiliary winding in the stator, where the two windings are spaced apart from each other at an angle of 90 degree and connected together in parallel with the supply source. The most common type of SPIM is the capacitor-run CR-SPIM, where a capacitor is added in series with the auxiliary winding to increase starting torque and motor efficiency. After the motor reaches 75% of its rated speed, the centrifugal switch disconnects the starting capacitor from the circuit [24]-[27].

Constant V/f control is a technique for motor speed control, this method is widely used in industrial applications due to its simple and inexpensive, such as pumps and fans, where the load torque is proportional to square of operating frequency. With V/f technique, when the input voltage decreased the frequency also decreased linearly. In three-phase induction motors can be applied V/f speed control easily. But in SPIM, the speed-control using V/f constant for only the main winding can result the motor current is increasing and a drop in torque of motor at low frequency. By varying the voltage and frequency, and keeping the ratio between them constant, the developed torque can be kept constant through the speed range [28]-[30].

Voltage Source Inverter (VSI) is used to transfer real power come a DC power source to an AC load. DC source voltage is constant nearly and amplitude of AC output voltage is controlled by adapted to a suitable control strategy. VSI's are used widely applications such as electronic frequency changer circuits and adjustable speed drives for AC motor, also becoming grid connection for renewable energy sources, where variable voltage DC power source converted to an AC system with a nearly constant voltage. VSI's are divided into three types (single-phase half-bridge inverter, single-phase full bridge inverter and three phase voltage source transformer) [31]-[35].

The equivalent model of asymmetric SPIM can be shown in Fig. 1, the main and auxiliary windings based on the double revolving field theory (DRFT). The impedance equations (1), (2), (3), and (4) are represented as follow: [36]-[38].

$$R_f = \frac{X_m^2 R_2/S}{(R_2/S)^2 + (X_2 + X_m)^2} \tag{1}$$

$$X_f = \frac{X_m\left[(R_2/S)^2 + X_2(X_2 + X_m)\right]}{(R_2/S)^2 + (X_2 + X_m)^2} \tag{2}$$

$$R_b = \frac{X_m^2 R_2/(2-S)}{(R_2/(2-S))^2 + (X_2 + X_m)^2} \tag{3}$$

$$X_b = \frac{X_m\left[(R_2/(2-S))^2 + X_2(X_2 + X_m)\right]}{(R_2/(2-S))^2 + (X_2 + X_m)^2} \tag{4}$$

where, (R_f, X_f) Resistance and reactance of forward impedances, (R_m, X_m) main winding resistance and leakage reactance, (R_b, X_b) resistance and reactance of backward impedances, (R_2, X_2) resistance and reactance of rotor, (a_s) turn ratio between main and auxiliary winding. Eq. (5) and (6) represent the average electromagnetic developed torque (T_{av}) and peak amplitude of pulsating torque (T_{puls}) respectively.

$$T_{av} = \frac{1}{\omega_1}\begin{bmatrix} {I_m}^2 + a_s^2 I_a^2)(R_f - R_b) \\ +2a_s(I_m I_a sin\varphi)(R_f - R_b) \end{bmatrix} \tag{5}$$

$$T_{puls} = \frac{1}{\omega_1}\begin{Bmatrix} \left[{I_m}^4 + (a_s I_a)^4 + 2(a_s I_m I_a)^2\cos(2\varphi)\right] \\ * \left[\left(R_f - R_b\right)^2 + \left(X_f - X_b\right)^2\right] \end{Bmatrix}^{1/2} \tag{6}$$

Where, (φ) is phase angle difference between main and auxiliary winding, (I_m, I_a) are main and auxiliary winding current and (ω) is angular synchronous speed.

In induction motors, the torque is created by the interaction of the magnetic fields of stator and rotor. If the voltage constant and the frequency are increased, this leads to a decrease in flux, which causes the motor to weaken. While maintaining the voltage value and reducing the frequency, then magnetic saturation occurs because the magnetic flux is large causing failure of motor. Because of this, both voltage and frequency must be changed in a fixed ratio. This is known as constant v/f controller of an induction motor [39]-[42].

VSI's receive DC voltage at input side and convert it to AC voltage and frequency may be constant or variable depending on application. Fig. 2 Shows the circuit diagram for single phase bridge VSI. In this circuit used four switches (in 2 legs) to generate the A.C waveform at the output. Any semiconductor switch like MOSFET, IGBT, or BJT can be used; load current is in the same phase with output voltage therefor four switches are adequate for resistive load. The main objective behind adopting control strategies is to generate good quality controllable AC voltage and to minimize the harmonic distortion, the filtering requirements and switching loses [43]-[46].

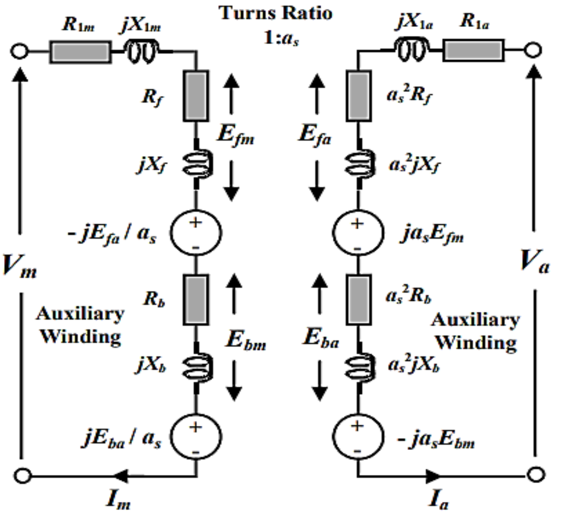


Fig. 1. The equivalent model of symmetric 1ph-IM

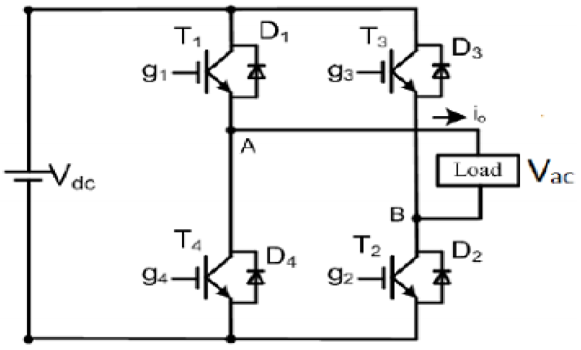


Fig. 2. Full Bridge Inverter

B. *starting a single-phase induction motor*

To study electrical machines and develop a methodology through which those interested in this field of studies can identify, this requires providing basic concepts that include the types of these machines, their parts, methods of operation, how they are powered by energy sources, in addition to the principle of operation, the advantages and disadvantages of each type, appropriate applications, and many other concepts. Electric motors are classified into direct current machines and alternating current machines. There are also two main forms of alternating current machines, according to the number of phases, including single-phase and three-phase. Motors that operate on alternating current are single-phase induction motors, which require a single-phase power source when they are to be operated. They are often available in homes, so this type is most commonly used in household applications such as water pumps, fans, water and air coolers, refrigerators, etc. [47]-[52].

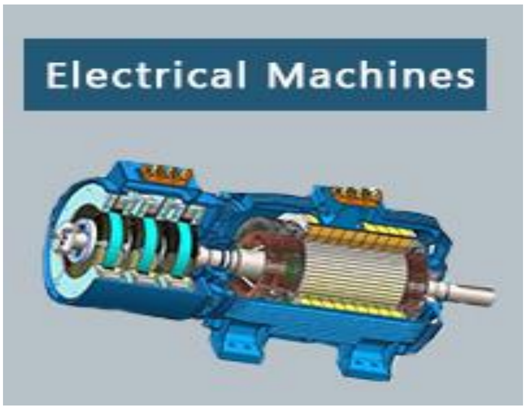
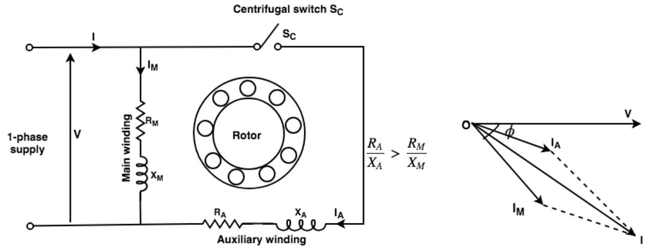


Fig. 3. Longitudinal section showing the electrical machine parts

There are five methods one of which is used in starting a single-phase induction motor and the motor is named according to those methods and they include shaded pole motor, split phase motor, capacitor starting motor, capacitor starting motor, permanent split capacitor motor (PSC). Resistance starter motor is another name for split phase induction motor, it consists of two parts, stator and rotor. The rotor is single cage type, and the stator has two windings, the first is the primary winding which has low resistance and high inductive reactance and the second is the auxiliary winding. There is a 90-degree displacement between them in the space.

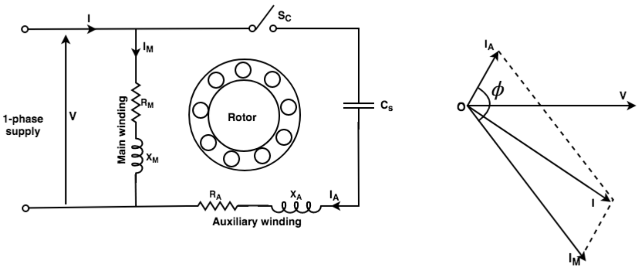


(a) Circuit diagram (b) Phasor diagram

Fig. 4. 1ph-IM type one (Split-phase induction motor)

The characteristics of this type of motor (resistance induction motor or split phase motor) can be described as having a high starting current that reaches several times the load current, which is about seven or eight times the full load current. While the initial torque is one and a half times the full load torque and reaches the maximum torque at a value of two and a half times the full load torque when the motor rotates at a speed of about 75% of the rotating speed of the rotor. These motors are inexpensive and easy to start, suitable for washing machine motor, air conditioner fan, blender, grinder, pumps, typewriters, etc.

The second type of induction motors is the capacitor motor, and all three types contain a capacitor with the auxiliary and main stator coils. It is used to produce the phase difference required to generate torque as a result of producing the difference in the core between the two fields resulting from the current passing through the stator coils of the motor. It produces a starting torque estimated at three times or more and may reach four and a half times the full load torque, proportional to the value of the capacitor with a small resistance for the auxiliary motor coils. The increase in the capacitor causes an increase in the cost compared to the first type.



(a) circuit diagram (b) Phasor diagram

Fig. 5. 1ph-IM type two (Capacitor start motor)

This type is used in applications that require continuous and repeated operation at high loads, such as pumps and compressors for refrigerators and air conditioners.

There is also a third type of single core induction motor called a double capacitor motor using two capacitors Cs and CR, the two capacitors are connected in parallel.

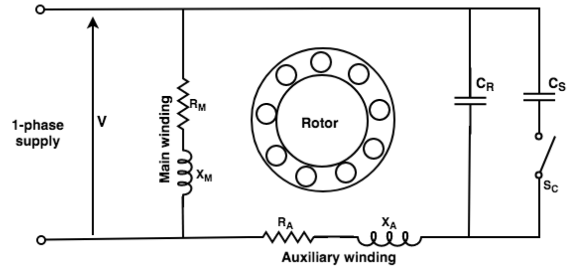


Fig. 6. 1ph-IM type three (Two-value capacitor motor)

The dual value capacitor motor is used for high inertia type loads which require frequent start-ups such as refrigeration, pumping equipment and air compressors.

There is another type is called Permanent Split Capacitor Motor (PSC) which is also one of the single-phase induction motors. Capacitor C is connected to the starting coil in series and permanently at starting and operating conditions.

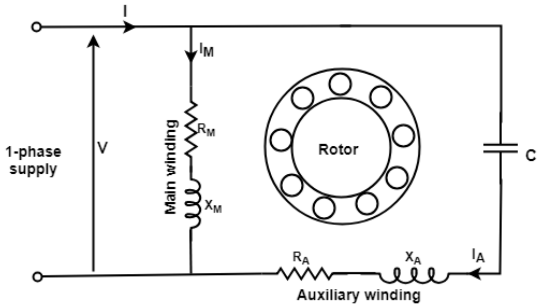


Fig. 7. 1ph-IM type fourth (Permanent-split capacitor motor)

The capacitor emitter is characterized by not needing a centrifugal switch, high efficiency, high power factor and high torque. While it is expensive when using oil-filled paper capacitors, which are larger in size and more expensive. It is characterized by low initial torque compared to full load torque. It can be used in fans, air conditioners and refrigerator compressors.

Among the single-phase induction motors there is a class called the shaded pole motor, a simple, self-starting type with poles protruding on either side, a copper ring and a single-turn coil (the shade coil).

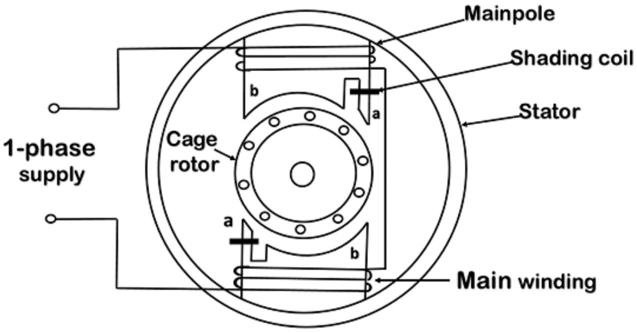


Fig. 8. 1ph-IM type fifth (Shaded-pole motor with two stator poles.)

This type is used in applications that require low starting torque such as small appliances like dryers, exhaust fans and table fans.

The principle of operation of a single-phase induction motor depends on producing a rotating field from the effect of an alternating current passing through the stator coils, which creates a magnetic field around the first coil and a magnetic field around the second coil, and because there is a difference angle between the two coils of 90 degrees in space. Therefore, the result will be the production of a rotating magnetic field with a constant value ϕ_m and irregular, which results in the creation of an irregular torque to operate the motor at the starting torque [53]-[57].

$$\varphi_A = \varphi_m \sin \omega t \qquad (7)$$

$$\varphi_B = \varphi_m (\sin \omega t + 90^o) \qquad (8)$$

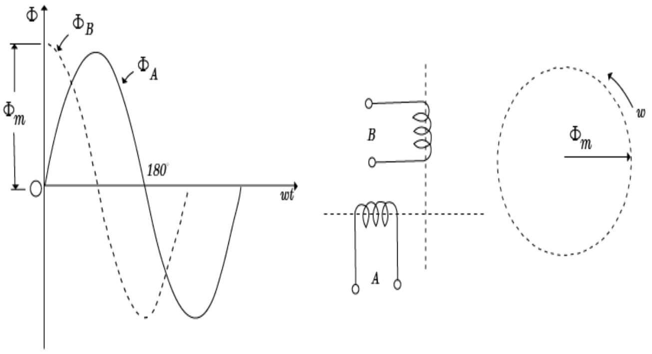


Fig. 9. Production of the uniform magnetic field

To know the behavior of a single-phase induction motor operating system, the operating principle must be known. To know the operating principle, the components of the system must be known, as it consists of a fixed part, which contains main and auxiliary coils that are connected to the power source and generate a rotating magnetic field as a result of the passage of an electric current in the motor coils, which is an electrical energy that is considered the energy entering the motor. As there is a fixed member, there is a rotating member responsible for the mechanical movement coming out of the motor as an output energy. The single-phase induction motor needs auxiliary means to start it, as it cannot start itself. Certain methodologies can be used to make the required difference by following one of the theories, including the double rotating field theory, and there is another theory that can be used, which is the cross-field theory. The first is the double rotating field theory, which states that a single phase can create a magnetic field, and it can be analyzed into two pulsating magnetic fields of equal magnitude and opposite direction. The resultant torque of a single-phase induction motor can be represented mathematically by the relationship between the magnetic field generated by the auxiliary coils of the stator and the main coils as a result of the motor being fed from an alternating source and an electric current flowing in the stator coils.

III. SIMULATION MODEL AND RESULTS FOR SINGLE PHASE INDUCTION MOTOR

In this section there are two parts, the first part is Simulation Model for single phase induction. Second part is Simulation Results for single phase induction as show in the following bellow:

A. *Simulation Model for Single Phase Induction Motor*

In this part there are two states, first using open loop system without controller and second states by using open loop system with controller as show in the following bellow:

- *Open Loop* System *Of Single-Phase Induction Motor Without Controller*

First test, simulation Model of 1ph-IM without control at no-Load when Tm=0 N.m. Single phase induction motor types Work is underway to build a simulation model and operate it using MATLAB to identify the characteristics and features of each type and choose the best by conducting tests. The simulation includes different test cases, including first operating the motor at the specified voltage and in the no-load condition to identify the specified speed of the single-phase induction motor. The test can be conducted using the simulation model at no-load without controller in Fig. 10 to Fig. 12.

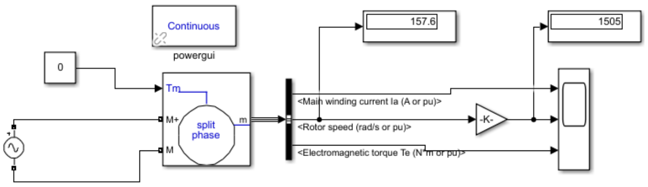


Fig. 10. Simulation Model of 1ph-IM type one (Split-phase induction motor) without control at No Load when Tm=0 N.m

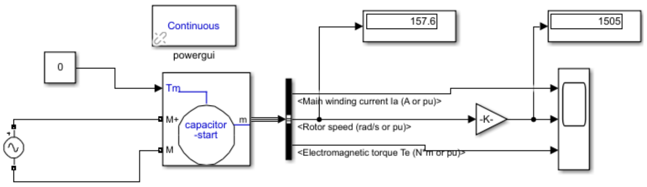


Fig. 11. Simulation Model of 1ph-IM type two (Capacitor start induction motor) without control at No Load when Tm=0 N.m

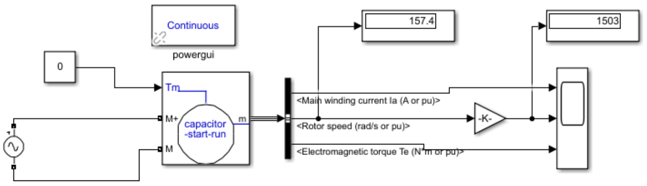


Fig. 12. Simulation Model of 1ph-IM type three (Capacitor start run induction motor) without control At No Load when Tm=0 N.m

Single phase induction motors have parameters as follow, Main winding stator (2.02Ω, 7.04e-3H), Main winding rotor

(4.12Ω, 5.6e-3H), main winding mutual inductance (0.1772H), auxiliary winding stator (7.14Ω, 8.5e-3H), nominal Power=186.5(VA), voltage source =220V, freq.=50 Hz, inertia=0.0146 aux/main, pole pairs=2 and turn ratio=1.18.

Second test, simulation Model of 1ph-IM without control at constant Load when Tm=1 N.m. The test can be conducted using the simulation model in Fig. 13 to Fig. 15.

Third test, at load without controller this case has been proposed to know the behavior of the system under load which operating within a specific application, which represents 1ph-IM such as water or fuel pump. The test can be conducted using the simulation model in Fig. 16 to Fig. 18.

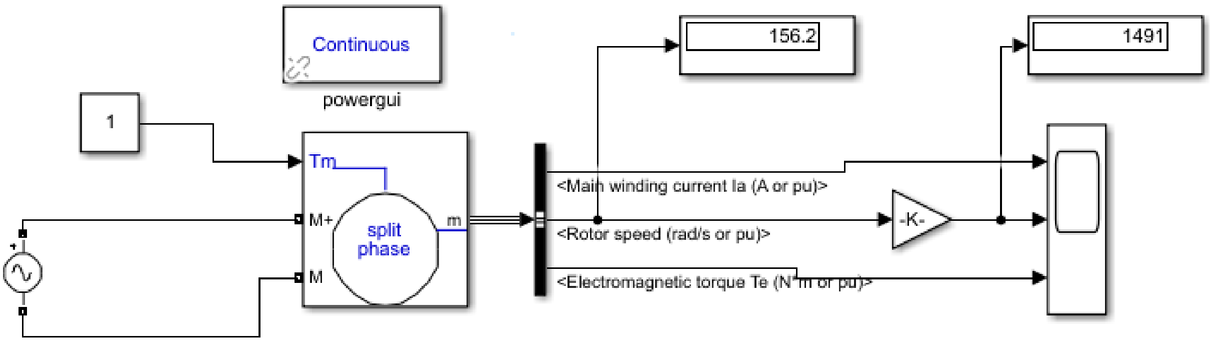


Fig. 13. Simulation Model of 1ph-IM type one (Split-phase induction motor) without control at constant Load when Tm=1 N.m

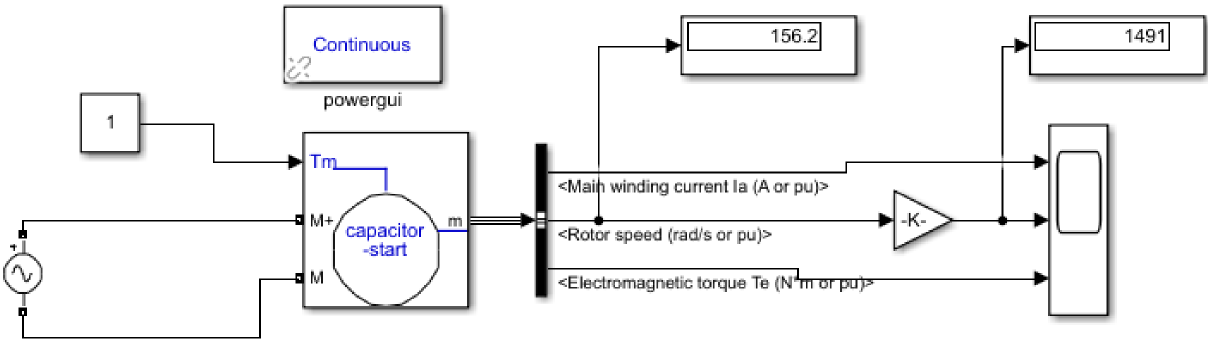


Fig. 14. Simulation Model of 1ph-IM type two (Capacitor start induction motor) without control at constant Load when Tm=1 N.m

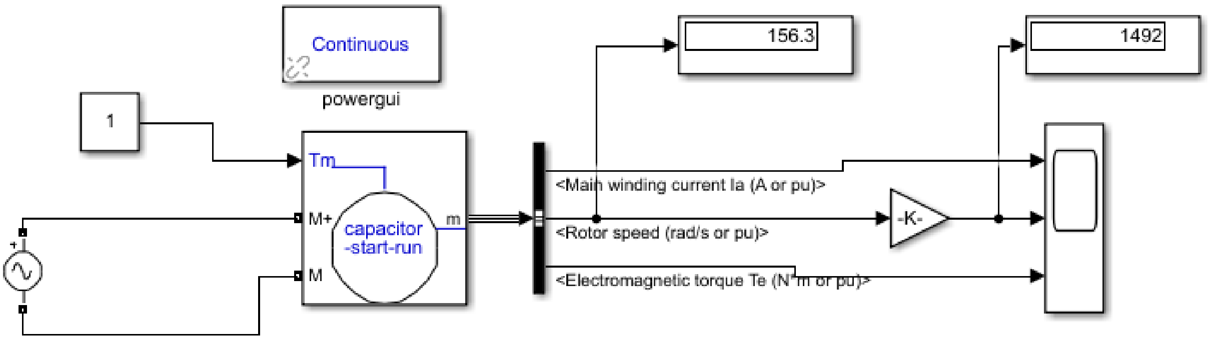


Fig. 15. Simulation Model of 1ph-IM type three (Capacitor start run induction motor) without control at constant Load when Tm=1 N.m

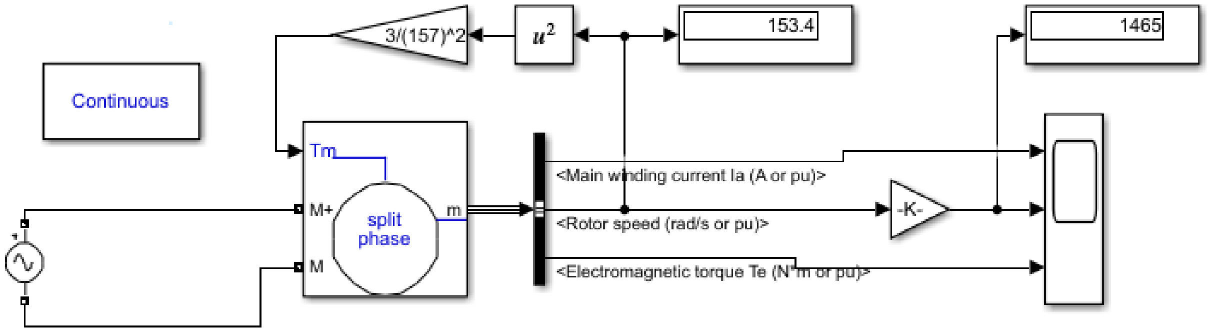


Fig. 16. Simulation Model of 1ph-IM type one (Split-phase induction motor) without control at pump Load when Tm=3 N.m

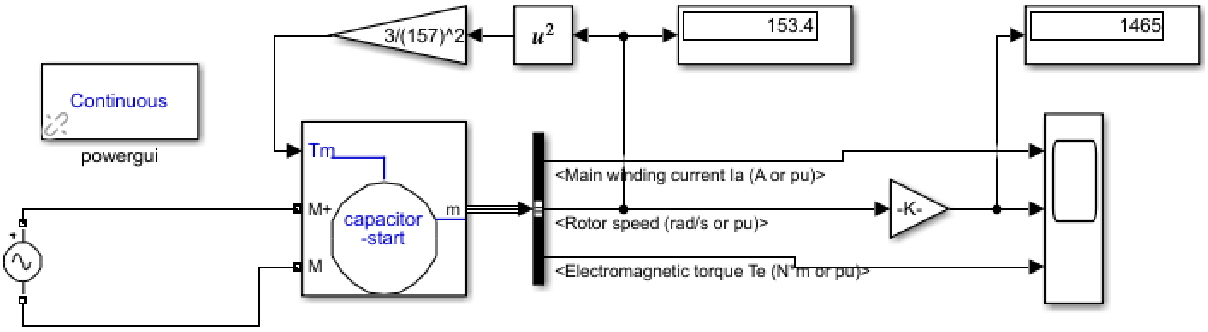


Fig. 17. Simulation Model of 1ph-IM type two (Capacitor start induction motor) without control at pump Load when Tm=3 N.m

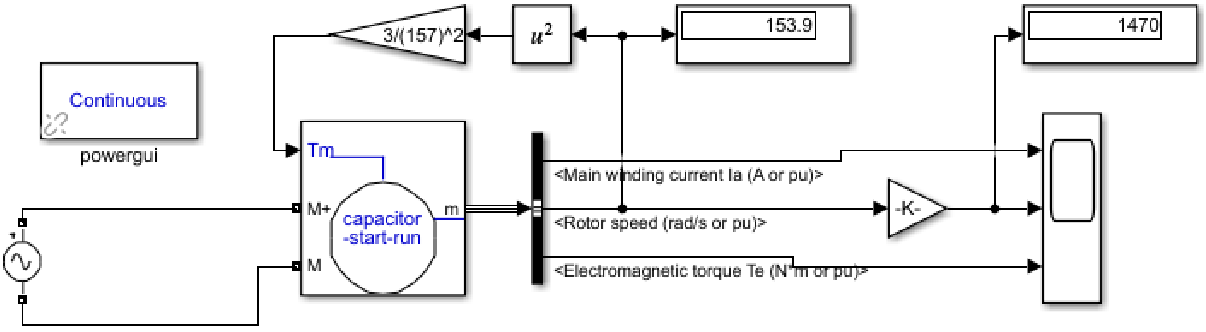


Fig. 18. Simulation Model of 1ph-IM type three (Capacitor start run induction motor) without control at pump Load when Tm=3 N.m

- *Open Loop System of Single-Phase Induction Motor with Controller*

If induction motor is to be operated for any application, the relationships between torque and speed are chosen, For example, if the torque is 3 Newton meters and the speed is 157, the relationship is written (3/(157)^2) multiplied by the square of the speed to obtain the specified torque at the specified speed. Fourth test with controller test include at load with controlling by the voltage, at load with controlling by frequency and at load with controlling by voltage / frequency (V/F) ratio.

Controlling by the voltage, controlling the speed to obtain the specified value requires providing the specified voltage. This type of supply source does not have a tolerance for change, so it requires changing the type of model which is shown in Fig. 19.

Controlling the speed of the induction motor using voltage control technology by specifying the current. Therefore, the type of application and the amount of variable load must be specified, which requires specifying the specified values for the control process, such as using the motor as a pump, in which the torque is 3 Newtons multiplied by the square of the specified rotational speed divided by the square of the actual rotational speed. Therefore, when the two speeds are equal, it operates with the specified torque, rotates at the specified speed, and draws the specified current.

Controlling by frequency, a model with the possibility of changing the frequency must be determined by constructing the signal that represents the voltage and frequency, with the ability to control the frequency, the simulation model can be shown in Fig. 20.

Controlling by voltage/frequency, (V/F) ratio, in this case a model was proposed that simulates the process of controlling the ratio of voltage over frequency. A model must be determined with the possibility of changing the frequency by constructing the signal that represents voltage and frequency with the permission to control frequency and voltage in order to improve the characteristics of the motor and its operation. The simulation model can be shown in Fig. 21.

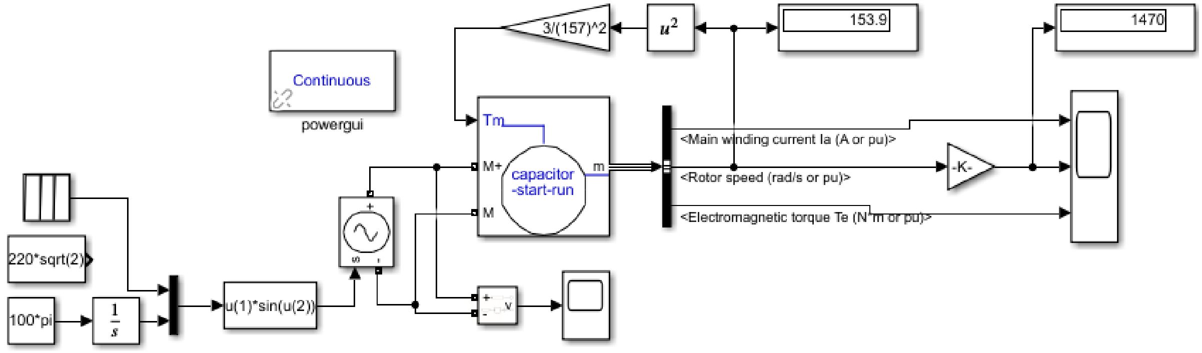


Fig. 19. Simulation Model of 1ph-IM type three (Capacitor start run induction motor) with voltage control at pump Load when Tm=3 N.m

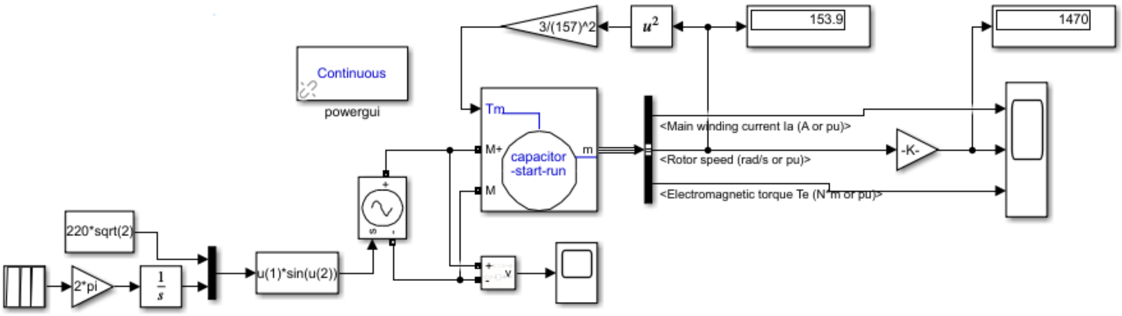


Fig. 20. Simulation Model of 1ph-IM type three (Capacitor start run I.M) with frequency control at pump Load when Tm=3 N.m

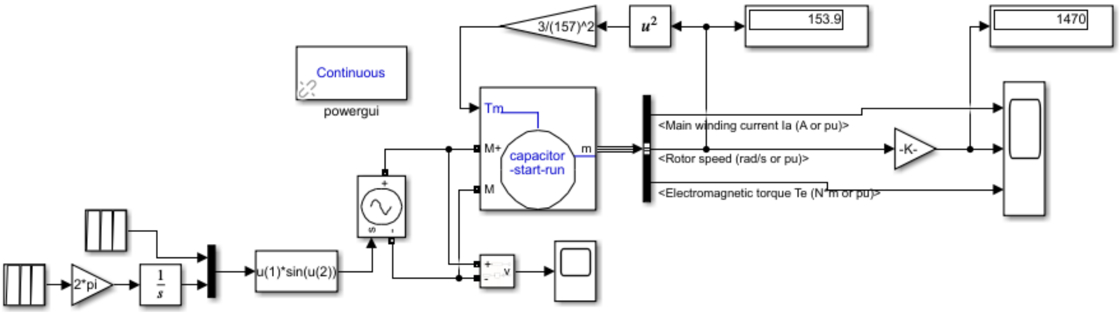


Fig. 21. Simulation Model of 1ph-IM type three (Capacitor start run I.M) with voltage /frequency control at pump Load when Tm=3 N.m

- *Open Loop System of Single-Phase Induction Motor by Using Voltage/Frequency Controller of VSI-SPIM*

Single phase Induction motor react as a pump with Voltage/frequency controller of VSI-SPIM, this section presents open loop for Voltage/Frequency Controller of VSI-single phase induction motor. Fig. 22 represented simulation model of V/F controller of VSI-SPIM.

B. Simulation Results for single phase induction motor

There are three sections in this part include, simulation result of 1ph-IM without control at no Load when Tm=0 N.m, simulation result of 1ph-IM without control at constant Load when Tm=1 N.m and simulation result of 1ph-IM without control at constant Load when Tm=3 N.m,

- *Simulation Results of 1ph-IM without Control at No Load When Tm=0 N.M*

In this part, the simulation results without control at No Load when Tm=0 N.m by using the models in Fig. 10 to Fig. 12. The results of this test case can be seen as shown in the Fig. 23 to Fig. 25, it shows three quantities: the first is an electrical quantity representing the current of the induction motor for an operating period of one second, divided into two periods. The first represents an oscillating period of the starting current, estimated at about 49, 42 and 42 amperes, with a time duration of 0.3, 0.1 and 0.1 while the second period starts at 0.4, 0.2 and 0.15, records an oscillating current estimated at about 7, 6 and 6 amperes for three models respectively. The simulation results indicate that the estimated change between the transient and steady state current is about seven times. The second and third quantities represent speed and torque, which are mechanical quantities. The speed begins to increase gradually until it reaches the value at which it stabilizes with the stabilization of the current quantity, and remains constant at 1505, 1505 and 1503 rpm respectively. It is also possible to point out the change in the amount of torque during the operating period for this case. The torque begins to change from zero and gradually increases in proportion to the increase in speed and decrease in current, and it stops at the time period. In which both the current and torque stabilize at an amount estimated at about 10 N.m.

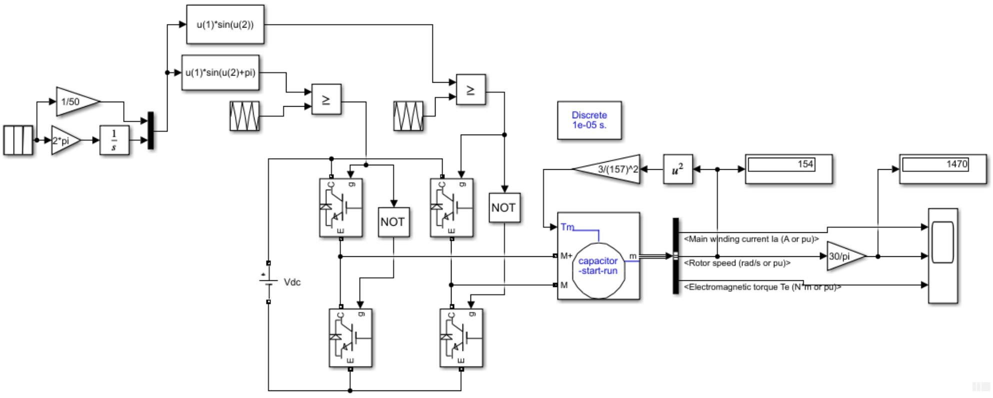


Fig. 22. Simulation Model of 1ph-IM type three (Capacitor start run induction motor) with voltage/frequency controller of VSI-SPIM at pump Load when Tm=3 N.m

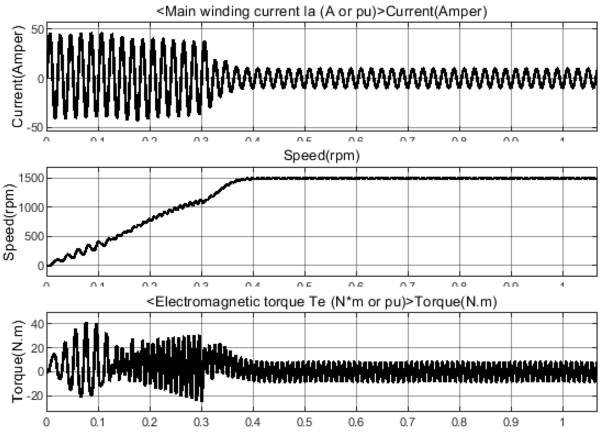


Fig. 23. Simulation result of 1ph-IM type one (Split-phase induction motor) without control at No Load when Tm=0 N.m

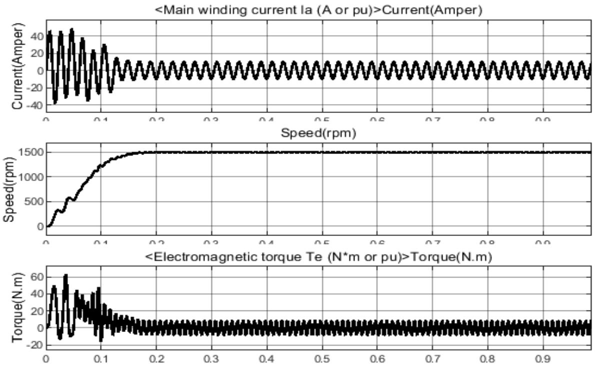


Fig. 24. Simulation result of 1ph-IM type two (Capacitor start induction motor) without control at No Load when Tm=0 N.m

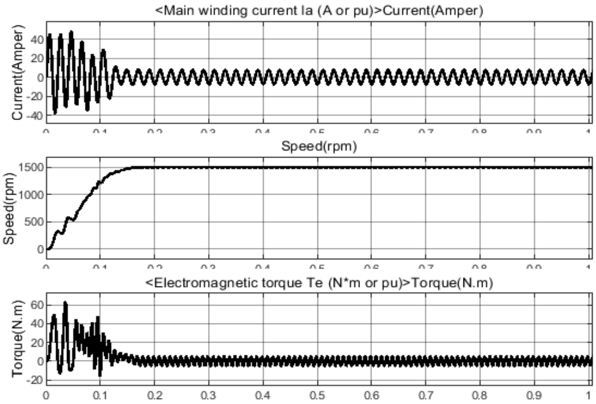


Fig. 25. Simulation result of 1ph-IM type three (Capacitor start run induction motor) without control at No Load when Tm=0 N.m

- *Simulation Results of 1ph-IM without Control at Constant Load when Tm=1 N.M*

In this part, the simulation results for the models of 1ph-IM without control at constant Load when Tm=1 N.m by using the models in Fig. 13 to Fig. 15. The results of this test case can be seen as shown in the Fig. 26 to Fig. 28, it shows two quantities: the first is an electrical quantity representing the current of the induction motor for an operating period of one second, divided into two periods. The first represents an oscillating period of the starting current, estimated at about 49, 49 and 42 amperes, with time duration of 0.35, 0.1 and 0.05 while the second period starts at 0.45, 0.15 and 0.12 and records an oscillating current estimated at about 7, 7 and 6 amperes for three models respectively. The simulation results indicate that the estimated change between the transient and steady state current is about seven times. The second and third quantities represent speed and torque, which are mechanical quantities. The speed begins to increase gradually until it reaches the value at which it stabilizes with the stabilization of the current quantity, and remains constant at 1491, 1491 and 1492 rpm respectively. It is also possible to point out the change in the amount of torque during the operating period for this case. The torque begins to change from zero and gradually increases in proportion to the increase in speed and decrease in current, and it stops at the time period in which both the current and torque stabilize at an amount estimated at about 10 N.m.

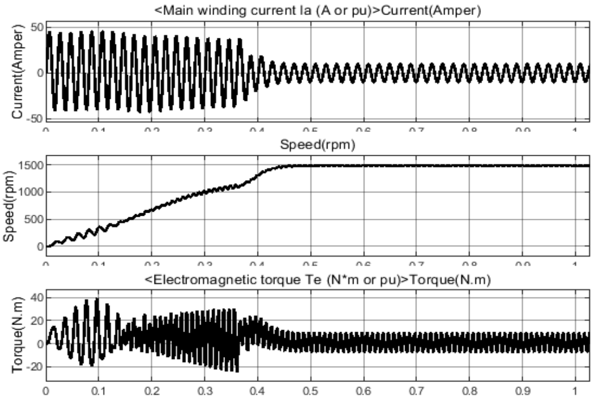


Fig. 26. Simulation result of 1ph-IM type one (Split-phase induction motor) without control at constant Load when Tm=1 N.m

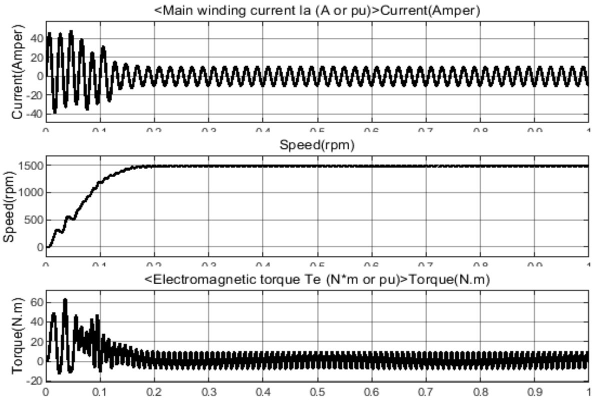


Fig. 27. Simulation result of 1ph-IM type two (capacitor start induction motor) without control at constant Load when Tm=1 N.m.

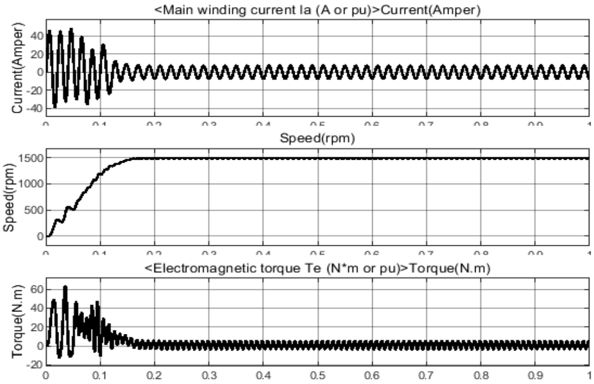


Fig. 28. Simulation result of 1ph-IM type three (capacitor start run induction motor) without control at constant Load when Tm=1 N.m

- *Simulation Results of 1ph-IM without Control at Pump Load when Tm=3 N.M*

In this part, the simulation results for the model of 1ph-IM without control at pump Load when Tm=3 N.m by using the models in Fig. 16 to Fig. 18. The results of this test case can be seen as shown in the Fig. 29 to Fig. 31.

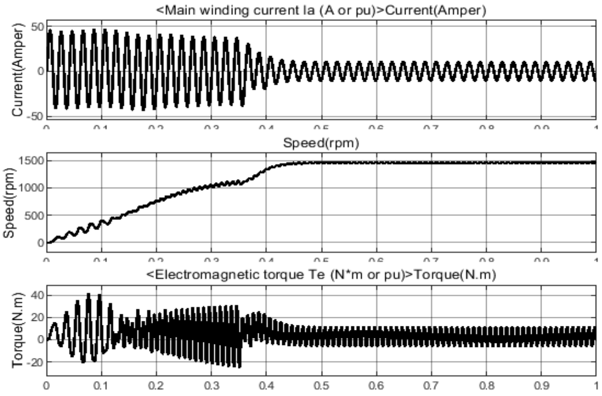


Fig. 29. Simulation result of 1ph-IM type one (Split-phase induction motor) without control at pump Load when Tm=3 N.m

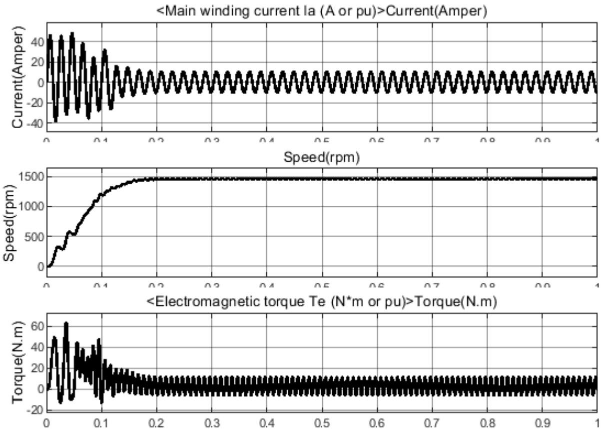


Fig. 30. Simulation result of 1ph-IM type two (capacitor start induction motor) without control at pump Load when Tm=3 N.m

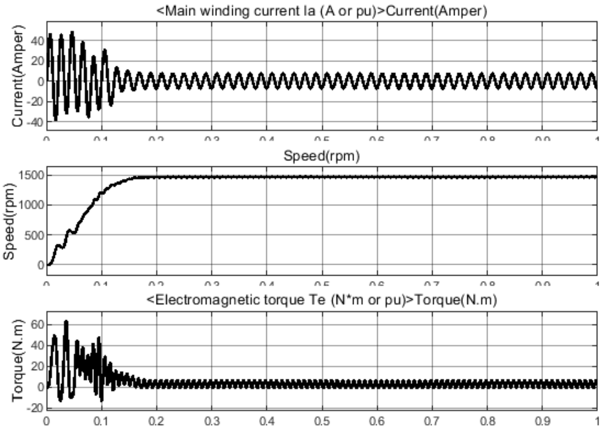


Fig. 31. Simulation result of 1ph-IM type three (capacitor start run induction motor) without control at pump Load when Tm=3 N.m

- *Simulation Results of 1ph-IM with Voltage Control at Pump Load when Tm=3 N.M*

In this part, the simulation results for the model of 1ph-IM with voltage control at pump Load when Tm=3 N.m by using the model in Fig. 19. The results of this test case can be seen as shown in the Fig. 32 to Fig. 34.

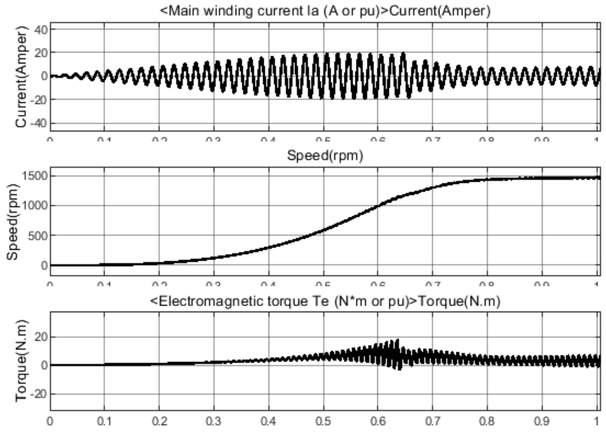


Fig. 32. 1ph-IM with voltage control at stability in 1sec

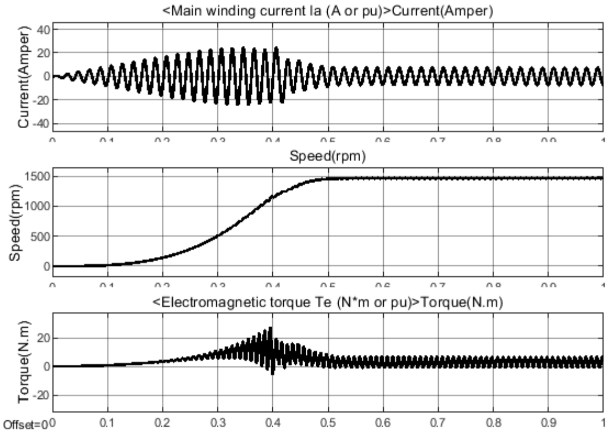
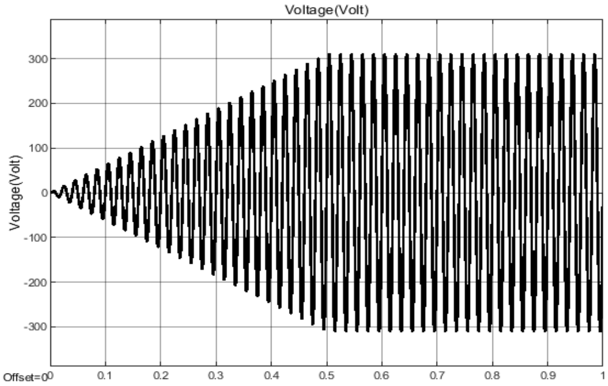
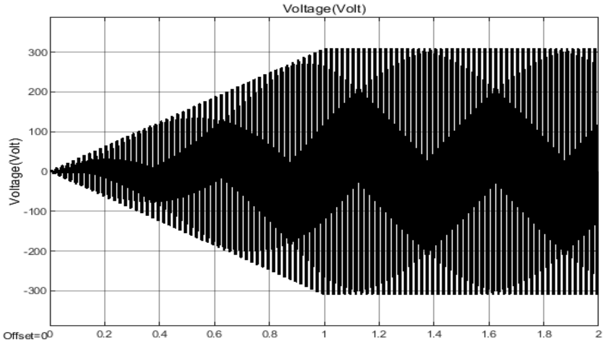


Fig. 33. 1ph-IM with voltage control at stability in 0.5 sec



(a) at 0.5 sec



(b) at 1 sec

Fig. 34. Voltage stability for 1ph-IM in 0.5 sec and 1 sec

- *Simulation Results of 1ph-IM with Frequency Control at Pump Load when Tm=3 N.M*

In this part, the simulation results for the model of 1ph-IM with frequency control at pump Load when Tm=3 N.m by using the model in Fig. 20. The results of this test case can be seen as shown in the Fig. 35 and Fig. 36.

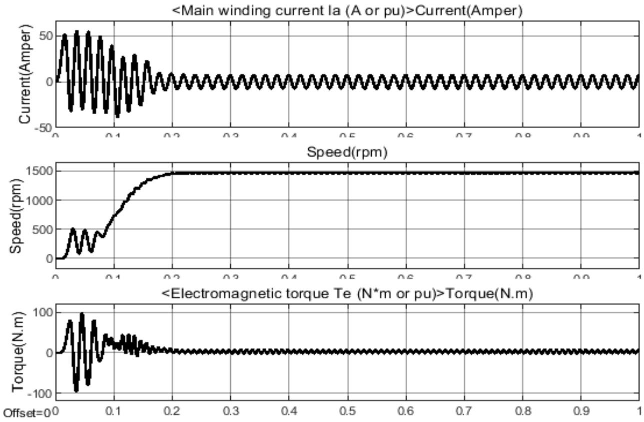


Fig. 35. 1ph-IM with frequency control (Current, speed and torque)

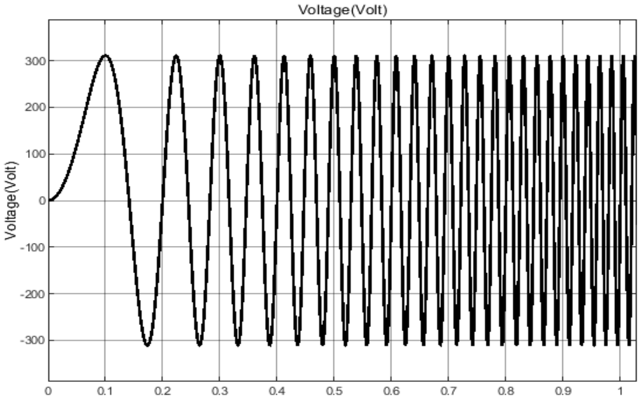


Fig. 36. 1ph-IM with frequency control (Voltage)

- *Simulation Results of 1ph-IM with Voltage/Frequency Control at Pump Load*

In this part, the simulation results for the model of 1ph-IM with voltage/ frequency control at pump Load when Tm=3 N.m by using the model in Fig. 21. The results of this test case can be seen as shown in the Fig. 37 and Fig. 38.

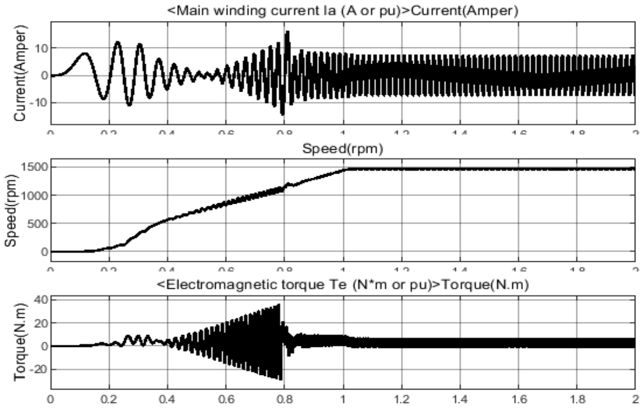


Fig. 37. 1ph-IM with Voltage/ frequency control (current, speed and torque)

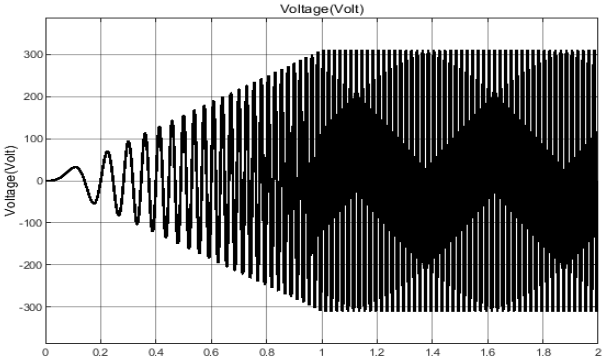


Fig. 38. 1ph-IM with Voltage /frequency control (Voltage)

- *Simulation Results of 1ph-IM Type Three (Capacitor Start Run Induction Motor) with Voltage/Frequency Controller of VSI-SPIM at Pump Load*

In this part, the simulation results for the model 1ph-IM type three (Capacitor start run induction motor) with voltage/frequency controller of VSI-SPIM at pump Load by using the model in Fig. 22. The results of this test case can be seen as shown in the Fig. 39.

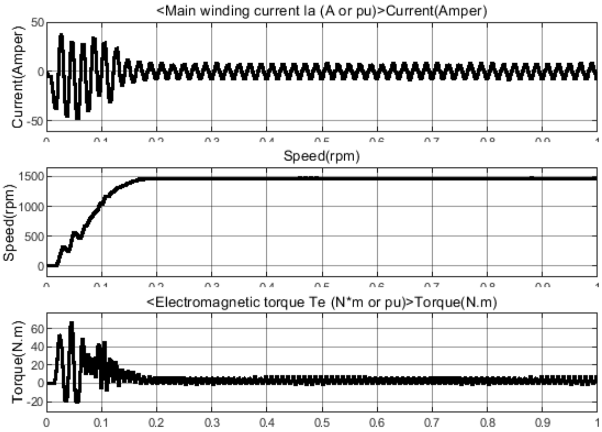


Fig. 39. 1ph-IM with Voltage /frequency control of VSI-SPIM at pump Load

The simulation results can be displayed in Table I to Table IV, including the table containing the results of the first test case. Results of the single-phase induction motor operating conditions including electrical and mechanical quantities and time periods of the system's transient and steady state (test condition, transient time, steady state time, rotational speed, initial torque, steady-state torque, starting current, steady-state current):

TABLE I. CHARACTERISTICS OF SINGLE-PHASE INDUCTION MOTOR RUNNING CONDITION WITHOUT LOAD

Test Condition	No Load (Split-phase I.M)	No Load (Capacitor start I.M)	No Load (Capacitor start run I.M)
Transient Time	0.3 sec	0.1sec	0.1sec
Steady State Time	0.4sec	0.2sec	0.15sec
Rotational Speed	1505rpm	1505rpm	1503rpm
Initial Torque	0-40N.m	0-62N.m	0-62N.m
Steady State Torque	10N.m	10N.m	10N.m
Starting Current	49Amper	42Amper	42Amper
Steady State Current	7Amper	6Amper	6Amper

TABLE II. Characteristics of Single-Phase Induction Motor Running Condition with Load

Test Condition	At (Tm=1) Load (Split-phase I.M)	At Load (Capacitor start I.M)	At Load (Capacitor start run I.M)
Transient Time	0.35 sec	0.1sec	0.05sec
Steady State Time	0.45sec	0.2sec	0.12sec
Rotational Speed	1491rpm	1491rpm	1492rpm
Initial Torque	0-40N.m	0-62N.m	0-62N.m
Steady State Torque	10N.m	10N.m	10N.m
Starting Current	49Amper	49Amper	42Amper
Steady State Current	7Amper	7Amper	6Amper

TABLE III. Characteristics of Single-Phase Induction Motor Running Condition with Pump Load

Test Condition	Pump Load (Split-phase I.M)	Pump Load (Capacitor start I.M)	Pump Load (Capacitor start run I.M)
Transient Time	0.35 sec	0.1sec	0.1sec
Steady State Time	0.4sec	0.2sec	0.15sec
Rotational Speed	1465rpm	1465rpm	1470rpm
Initial Torque	0-40N.m	0-62N.m	0-62N.m
Steady State Torque	10N.m	10N.m	10N.m
Starting Current	49Amper	42Amper	42Amper
Steady State Current	7Amper	6Amper	6Amper

TABLE IV. Characteristics of Single-Phase Induction Motor Running Condition with Pump Load

Test Condition	Pump Load - voltage control	Pump Load - frequency control	Pump Load - voltage /frequency control	Pump Load - voltage /frequency control of VSI-SPIM
Transient Time	0.65 sec	0.075sec	0.05sec	0.1sec
Steady State Time	0.75sec	0.2sec	0.12sec	0.15sec
Rotational Speed	1470rpm	1470rpm	1470rpm	1470rpm
Initial Torque	0-20N.m	0-100N.m	0-62N.m	0-67N.m
Steady State Torque	10N.m	10N.m	10N.m	10N.m
Starting Current	20Amper	52Amper	48Amper	40Amper
Steady State Current	3Amper	7Amper	6Amper	6Amper

IV. CONCLUSIONS

The simulation results indicate that the starting current can be reduced and the stability of the motor can be improved, in addition to the performance under load conditions can be improved with the shortest time to reach steady state when using the voltage/frequency (V/F) control method compared to other single-phase induction motor (SPIM) control methods. Therefore, it is preferable to control the voltage/frequency ratio (V/F) as it is found to be the most effective in reducing the starting torque and reducing the effects of high starting currents, thus ensuring smooth motor operation. The problem of high starting current was mitigated by using the voltage and frequency control methods, which showed a significant reduction in the current peaks during starting. This will help to clarify the practical significance, potential impact, and potential for the use of this technology in real-world applications. The proposed control methods can be effectively implemented in specific practical applications, such as water pumps, air conditioning units, or other systems that use SPIMs. While the simulation results are promising, further experimental validation using real-world devices is needed to confirm the effectiveness of the proposed control methods under different operating conditions. These control methods are suitable for applications involving SPIMs, especially when reducing starting currents and improving performance is critical. This study demonstrates that the proposed control methods significantly improve the performance and reliability of SPIMs, providing a viable solution for a range of industrial and consumer applications where efficient motor operation is essential.

REFERENCES

[1] A. H. Ahmed, A. S. Yahya, and A. J. Ali, “Speed Control for Linear Induction Motor Based on Intelligent PI-Fuzzy Logic,” *Journal of Robotics and Control (JRC)*, vol. 5, no. 5, pp. 1470-1478, 2024.

[2] C. S. Kumar, S. Ravikrishna, P. Rajasekar, and M. Venkatesan, “Prognostic Real Time Analysis of Induction Motor,” *International Journal of Robotics and Control Systems*, vol. 4, no. 1, pp. 139-150, 2024.

[3] S. W. Shneen and A. L. Shuraiji, “Simulation model for pulse width modulation-voltage source inverter of three-phase induction motor,” *International Journal of Power Electronics and Drive Systems*, vol. 14, no. 2, pp. 719-726, 2023.

[4] V. K. Awaar *et al*., “Speed Control of Induction Motor using Digital Signal Processor TMS320F28027F,” in *E3S Web of Conferences*, vol. 391, p. 01178, 2023.

[5] H. V. Coutinho, J. A. Toledo, L. A. Silva, and T. A. Maia, “Design and implementation of a low-cost and low-power converter to drive a single-phase motor,” *Machines*, vol. 11, no. 7, p. 673, 2023.

[6] A. A. Mutlag, M. K. Abd, and S. W. Shneen, “Power Management and Voltage Regulation in DC Microgrid with Solar Panels and Battery Storage System,” *Journal of Robotics and Control (JRC)*, vol. 5, no. 2, pp. 397-407, 2024.

[7] J. Kanuch, P. Girovsky, J. Zilkova, and M. Pastor, “Design and Measurement of a Frequency Converter with SPWM Modulation of Output Voltage for a Two-Phase Induction Motor,” *Elektronika ir Elektrotechnika*, vol. 29, no. 3, pp. 11-18, 2023.

[8] A. A. Mutlag, M. K. Abd, and S. W. Shneen, “Voltage Regulation and Power Management of DC Microgrid with Photovoltaic/Battery Storage System Using Flatness Control Method,” *Journal of Robotics and Control (JRC)*, vol. 5, no. 6, pp. 1664-1672, 2024.

[9] U. C. Nwaneto, S. A. Seif Kashani, and A. M. Knight, "Modeling Lyapunov Control-Based Selective Harmonic Compensated Single-Phase Inverter in the Dynamic Phasor Domain," in *IEEE Open Journal of Industry Applications*, vol. 4, pp. 346-365, 2023.

[10] Z. B. Abdullah, H. S. Dakheel, and S. W. Shneen, “Simulation model of using ANN and PID controller for 2Ph-HSM by matlab,” in *AIP Conference Proceedings*, vol. 3002, no. 1, 2024.

[11] N. Khosravi *et al.*, “A novel control approach to improve the stability of hybrid AC/DC microgrids,” *Applied Energy*, vol. 344, p. 121261, 2023.

[12] S. -C. Choi, J. -H. Kim, Y. -D. Yoon, C. -O. Hong, C. -H. Park, and J. -H. Cho, "V/F Control Method for Pulsating Torque Reduction in a Single Phase Induction Motor," *2023 IEEE International Symposium on Sensorless Control for Electrical Drives (SLED)*, pp. 1-6, 2023.

[13] A. S. Ba-thunya, R. Khopkar, Kexin Wei, and H. A. Toliyat, "Single phase induction motor drives-a literature survey," *IEMDC 2001. IEEE International Electric Machines and Drives Conference (Cat. No.01EX485)*, pp. 911-916, 2001.

[14] T. A. Lettenmaier, D. W. Novotny, and T. A. Lipo, "Single-phase induction motor with an electronically controlled capacitor," in *IEEE Transactions on Industry Applications*, vol. 27, no. 1, pp. 38-43, Jan.-Feb. 1991.

[15] C. Mademlis, I. Kioskeridis, and T. Theodoulidis, "Optimization of single-phase induction Motors-part I: maximum energy efficiency control," in *IEEE Transactions on Energy Conversion*, vol. 20, no. 1, pp. 187-195, March 2005.

[16] M. Jannati *et al*., “A review on variable speed control techniques for efficient control of single-phase induction motors: evolution, classification, comparison,” *Renewable and Sustainable Energy Reviews*, vol. 75, pp. 1306-1319, 2017.

[17] G. S. Ilango and N. Rajasekar, “An improved energy saving v/f control technique for solar powered single-phase induction motor,” *Energy conversion and Management*, vol. 50, no. 12, pp. 2913-2918, 2009.

[18] M. Vidlák, L. Gorel, and P. Makyš, “A sensorless stable V/f control of SPMSM based on constant power factor control with a novel MTPA tracking,” *Transportation Research Procedia*, vol. 74, pp. 799-806, 2023.

[19] S. W. Shneen, A. L. Shuraiji, and K. R. Hameed, “Simulation model of proportional integral controller-PWM DC-DC power converter for DC motor using matlab,” *Indones. J. Electr. Eng. Comput. Sci*, vol. 29, pp. 725-734, 2023.

[20] E. Nandhini and A. Sivaprakasam, “A New Closed Loop Constant v/f Control of Induction Motor with Torque Control Based on DPWM,” *International Journal of Electrical and Electronics Research*, vol. 11, no. 2, pp. 523-528, 2023.

[21] S. Laha, J. Dhali, and P. K. Gayen, "Comparative Performance between V/F and Rotor Flux-Oriented Controls of Induction Motor Drive," *2023 IEEE Devices for Integrated Circuit (DevIC)*, pp. 1-6, 2023.

[22] J. C. Travieso-Torres, M. A. Duarte-Mermoud, M. Díaz, C. Contreras-Jara, and F. Hernández, “Closed-loop adaptive high-starting torque scalar control scheme for induction motor variable speed drives,” *Energies*, vol. 15, no. 10, p. 3489, 2022.

[23] M. Vidlak, S. Agarlita, and I. Boldea, "MTPA Control Strategy for ALA Rotor SynRM Based on Reactive and Apparent Power Calculation under Sensorless V/f Control with Stabilization," *2023 International Conference on Electrical Drives and Power Electronics (EDPE)*, pp. 1-6, 2023.

[24] M. Saloumi, A. A. A. Ismail, and M. S. Suleiman, "Modified Diode Clamped Inverter-Based Single Phase Induction Motor Closed-Loop V/f Control," *2023 Advances in Science and Engineering Technology International Conferences (ASET)*, pp. 1-6, 2023.

[25] Z. B. Abdullah, S. W. Shneen, and H. S. Dakheel, “Simulation model of PID controller for DC servo motor at variable and constant speed by using MATLAB,” *Journal of Robotics and Control (JRC)*, vol. 4, no. 1, pp. 54-59, 2023.

[26] M. A. Mossa, H. Khouidmi, and A. Ma’arif, “Robust flux and speed state observer design for sensorless control of a double star induction motor,” *Journal of Robotics and Control (JRC)*, vol. 3, no. 4, pp. 464-475, 2022.

[27] M. A. Mossa, H. Echeikh, and A. Ma’arif, “Dynamic Performance Analysis of a Five-Phase PMSM Drive Using Model Reference Adaptive System and Enhanced Sliding Mode Observer,” *Journal of Robotics and Control (JRC)*, vol. 3, no. 3, pp. 289-308, 2022.

[28] L. H. Pratomo, A. F. Wibisono, and S. Riyadi, “Design and Implementation of Double Loop Control Strategy in TPFW Voltage and Current Regulated Inverter for Photovoltaic Application,” *Journal of Robotics and Control (JRC)*, vol. 3, no. 2, pp. 196-204, 2022.

[29] I. Suwarno, Y. Finayani, R. Rahim, J. Alhamid, and A. R. Al-Obaidi, “Controllability and Observability Analysis of DC Motor System and a Design of FLC-Based Speed Control Algorithm,” *Journal of Robotics and Control (JRC)*, vol. 3, no. 2, pp. 227-235, 2022.

[30] D. H. Shaker, S. W. Shneen, F. N. Abdullah, and G. A. Aziz, “Simulation Model of Single-Phase AC-AC Converter by Using MATLAB,” *Journal of Robotics and Control (JRC)*, vol. 3, no. 5, pp. 656-665, 2022.

[31] Z. Anthony, E. Erhaneli, Y. Warmi, Z. Zulkarnaini, A. Anugrah, and S. Bandri, “A new windings design for improving single-phase induction motor performance,” *International Journal of Electrical and Computer Engineering*, vol. 12, no. 6, p. 5789, 2022.

[32] M. Pepliński, D. Adamczak, and P. Gnaciński, “Single-phase induction motor under voltage fluctuations,” *Scientific Journal of Gdynia Maritime University*, no. 123, pp. 40-49, 2022.

[33] I. D. Chasiotis, Y. L. Karnavas, and F. Scuiller, “Effect of rotor bars shape on the single-phase induction motors performance: An analysis toward their efficiency improvement,” *Energies*, vol. 15, no. 3, p. 717, 2022.

[34] M. Dawood and A. M. Ali, “Effect of Changing Running Capacitor on Performance of a Single–Phase Induction Motor,” *Kerbala Journal for Engineering Sciences*, vol. 2, no. 2, pp. 96-107, 2022.

[35] M. A. Esmaeel and N. M. H. Hassan, “Analysis and comparison of single-phase induction motor operation from single-and two-phase power sources using MATLAB simulation results,” *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 13, no. 3, pp. 1380-1389, 2022.

[36] Y. Zahraoui, M. Akherraz, C. Fahassa, and S. Elbadaoui, “Induction Motor DTC Performance Improvement by Reducing Flux and Torque Ripples in Low Speed,” *Journal of Robotics and Control (JRC)*, vol. 3, no. 1, pp. 93-100, 2022.

[37] S. V. Umredkar, A. Junghare, and M. Renge, “Operation of symmetrical and asymmetrical two-phase induction motor by using 3-leg voltage source inverter,” *Trends in Renewable Energy*, vol. 4, no. 3, pp. 64-76, 2018.

[38] M. A. Awdaa, A. A. Obed, and S. J. Yaqoob, “A Comparative Study between V/F and IFOC Control for Three-Phase Induction Motor Drives,” in *IOP Conference Series: Materials Science and Engineering*, vol. 1105, no. 1, p. 012006, 2021.

[39] S. W. Shneen, F. N. Abdullah, and D. H. Shaker, “Simulation model of single phase PWM inverter by using MATLAB/Simulink,” *International Journal of Power Electronics and Drive Systems*, vol. 12, no. 1, p. 212, 2021.

[40] R. R. Gomes, L. F. Pugliese, W. W. Silva, C. V. Sousa, G. M. Rezende, and F. F. Rodor, “Speed Control with Indirect Field Orientation for Low Power Three-Phase Induction Machine with Squirrel Cage Rotor,” *Machines*, vol. 9, no. 12, p. 320, 2021.

[41] H. Maghfiroh, I. Iftadi, and A. Sujono, “Speed control of induction motor using LQG,” *Journal of Robotics and Control (JRC)*, vol. 2, no. 6, pp. 565-570, 2021.

[42] O. K. Dahham and A. M. Ali, “Performance assessment of a multi-speed single-phase capacitor motor using a hybrid analytical–FEM methodology,” in *IOP Conference Series: Materials Science and Engineering*, vol. 1090, no. 1, p. 012056, 2021.

[43] B. A. Saputra, E. P. Hidayat, and A. Z. Arfianto, “Internet of things-based steam pump motor protection due to voltage unbalance,” *Journal of Robotics and Control (JRC)*, vol. 1, no. 2, pp. 64-69, 2020.

[44] S. W. Shneen, H. S. Dakheel, and Z. B. Abdulla, “Design and implementation of variable and constant load for induction motor,” *International Journal of Power Electronics and Drive Systems*, vol. 11, no. 2, p. 762, 2020.

[45] U. Sharma and B. Singh, “Robust design methodology for single phase induction motor ceiling fan,” *IET Electric Power Applications*, vol. 14, no. 10, pp. 1846-1855, 2020.

[46] S. W. Shneen, M. A. A. Hussein, J. A. Kadhum, and S. M. Ali, “Application of LFAC {16 2/3Hz} for electrical power transmission system: a comparative simulation study,” *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, vol. 17, no. 2, pp. 1055-1064, 2019.

[47] G. A. Olarinoye, J. Yusuf, and B. Jimoh, “Improvement of Torque Production in Single-Phase Induction Motors,” *Nigerian Journal of Technological Development*, vol. 14, no. 2, pp. 39-45, 2017.

[48] S. W. Shneen, “Advanced optimal for power-electronic systems for the grid integration of energy sources,” *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 1, no. 3, pp. 543-555, 2016.

[49] N. Pimkumwong, A. Onkrong, and T. Sapaklom, “Modeling and simulation of direct torque control induction motor drives via constant volt/hertz technique,” *Procedia Engineering*, vol. 31, pp. 1211-1216, 2012.

[50] F. N. Abdullah, G. A. Aziz, and S. W. Shneen, “Simulation model of servo motor by using matlab,” *Journal of Robotics and Control (JRC)*, vol. 3, no. 2, pp. 176-179, 2022.

[51] L. H. Abood, “Optimal modified PID controller for automatic voltage regulation system,” in *AIP Conference Proceedings*, vol. 2415, no. 1, 2022.

[52] N. K. Bachache and J. Wen, “Particle swarm optimize fuzzy logic memberships of AC-drive,” in *Advances in Swarm Intelligence: Third International Conference, ICSI 2012, Shenzhen, China, June 17-20, 2012 Proceedings, Part I 3*, pp. 460-469, 2012.

[53] N. N. Kadhim, L. H. Abood, and Y. Abd Mohammed, “Design an Optimal Fractional Order PID Controller for Speed Control of Electric Vehicle,” *Journal Européen des Systèmes Automatisés*, vol. 56, no. 5, pp. 735-741, 2023.

[54] N. K. Bachache and J. Wen, “Multi objective swarm optimization design fuzzy controller to adjust speed of AC motor drive,” in *Advances in Swarm Intelligence: 4th International Conference, ICSI 2013, Harbin, China, June 12-15, 2013, Proceedings, Part I 4*, pp. 522-529, 2013.

[55] L. H. Abood, B. K. Oleiwi, and E. H. Ali, “Optimal backstepping controller for controlling DC motor speed,” *Bulletin of Electrical Engineering and Informatics*, vol. 11, no. 5, pp. 2564-2572, 2022.

[56] S. W. Shneen, H. S. Dakheel, and Z. B. Abdullah, “Design and Implementation of No Load, Constant and Variable Load for DC Servo Motor. *Journal of Robotics and Control (JRC)*, vol. 4, no. 3, pp. 323-329, 2023.

[57] S. O. Aldaikh *et al*., “Study of Starting Modes of Single-Phase Induction Motors When Changing the Parameters of the Stator Windings, Phase-Shifting Capacitor and Supply Voltage,” *Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska*, vol. 14, no. 2, pp. 34-41, 2024.