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Improving the starting torque and overall efficiency of split single phase induction motor

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ABSTRACT

Single-phase split induction motors consist of an auxiliary coil, a main winding and a centrifugal switch that separates the auxiliary coil. The starting torque of this motor is not large, and a resistance has to be added with the additional coil to increase the starting torque. Also, a mechanical centrifugal switch is used to disconnect the auxiliary coil. The motor also has another drawback that it has a constant speed. The aim of this research is to replace the added resistance with a current transformer that has a predetermined resistance and connected in series with the auxiliary coil such that it results in a maximum starting torque. In addition, it sends a signal to a control circuit that disconnect/connect the auxiliary coil through an electronic switch connected in series with the auxiliary coil. The connection/disconnection of the switch depends on the motor current not the motor speed to overcome the problem of switch false triggering due to motor overloading. The new technique increases the overall efficiency of the motor. MATLAB is used to simulate the system and verify the mathematical model.

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NOMENCLATURE

V_m, V_a	: Main and auxiliary voltage (V)
X_m	: Magnetizing reactance (Ω)
R_{1m}, R_{1a}	: Main and auxiliary winding resistance of stator (Ω)
X_{1m}, X_{1a}	: Main and auxiliary winding leakage reactance of stator (Ω)
R_r, X_r	: Rotor resistance and rotor leakage reactance (Ω).
Rr', $X_{r'}$	: Referred rotor resistance and referred rotor leakage reactance (Ω)
R_{Lv}, R_{HV}	: Resistance low/ high voltage side of current transformer
X_{LV}, X_{HV}	: Leakage reactance low/ high voltage side of current transformer
Z_{1m}, Z_{1a}	: Leakage impedance of the main winding and auxiliary winding (Ω)
Z_f,Z_b	: The forward and backward impedances (Ω)
N_m, Na	: The effective numbers of turns for main and auxiliary winding (turns)
a	: The turns ratio of the auxiliary and main winding
A	: Ignition angle
B	: Expansion angle
jaE_{fm}, $-jaE_{bm}$	: The internal voltages induced in the auxiliary winding by the revolving flues Φ_{fm} and Φ_{bm} of the main winding

jE_{fa}/a, $-jE_{ba}/a$: The internal voltages induced in the main winding by the revolving flues Φ_{fa} and Φ_{ba} of the auxiliary winding

1. INTRODUCTION

Single-phase induction motors consist of operating coils and auxiliary coils. In some types of these motors, auxiliary coils are disconnected after 75% of the motor rated speed, and it is done mechanically using a centrifugal switch. When single-phase induction motors are used in places that are subjected to ignition, it is preferable to replace the centrifugal switch with an electronic switch (a triode for alternating current (TRIAC)). In literature, the centrifugal switch is replaced with an electronic switch. The electronic switch is activated using a control circuit [1]. The electronic switch in the split phase induction motor (SPIM) has an ignition angle of 90 degrees from the electronic circuit and there is no connection between the voltage and current of the SPIM in the control circuit. Split single-phase induction motor was operated as a two-phase induction motor by designing a circuit uses a cyclo-converter or matrix converter that gives voltage and current perpendicular to each other by 90° [2]. The soft starting torque of the single-phase induction motor was obtained by using the scheme called with starting current control (WSCC) with pulse-width-modulated (PWM) AC Chopper. This method controls the voltage supplied to the motor not only on the main or auxiliary coils only but on both coils. Therefore, it is difficult to study which one causes an improvement in the starting torque of the motor [3].

The operation of the single-phase induction motor of different types has been studied from a single-phase source or from a two-phase source and a comparison was made between them during continuous operation or at start-up [4]. The TRIAC can be ignited using a current transformer. And the current transformer measures the current through the motor. When motor starts, the starting current is high, and therefore a high current is induces in the secondary of the current transformer that is sufficient to trigger the TRIAC. When the motor speed reaches 75% of its rated value, the motor current decreases, and therefore the current in the secondary is not sufficient to ignite the TRIAC. Although this method is easy to implement and simple, it has some disadvantages, such as when the current increases due to load reduction, it induces in the secondary coil values that may be sufficient enough to operate the TRIAC. Secondly, because the current transformer is placed in series with the operating coils or with the main feed line, the internal resistance of the current transformer causes a decrease in the starting torque of the motor. The third disadvantage is that the ignition angles for the TRIAC are not specified, and therefore the starting voltage and current cannot be controlled. And the fourth is that the TRIAC ignition depends only on the current transformer located in the main coil [5]–[7].

This paper studies the replacement of the centrifugal switch with an electronic switch (a TRIAC). The electronic switch is ignited through a control circuit that determines the ignition angles based on three inputs, namely: i) the zero points of the applied voltage, ii) the current passing through the auxiliary coil, and iii) the induced voltage in the auxiliary coil after disconnection. The advantages of this circuit are: first, the presence of the current Transformer in series with the auxiliary coil increases the starting torque of the motor. Secondly, the induced voltage in the auxiliary coil after the separation determines the speed of the motor and therefore the TRIAC cannot be ignited due to an error signal from the control circuit. The presence of a circuit to determine the zero point of the voltage source called (zero crossing detector) enables the control circuit to gradually change the ignition angle of the electronic switch and thus control the voltage and current of the auxiliary coil.

2. METHOD

Figure 1 shows a split single-phase induction motor with a control circuit for an electronic switch ignition as an alternative to a centrifugal switch. As shown in the figure, a step-up transformer is placed in series with the auxiliary windings and not with the main winding. The step-up transformer output is a voltage corresponding to the auxiliary coil current connected to the control circuit. A step-down transformer is also placed in parallel with the auxiliary coil to measure the applied voltage and the induced voltage while the electronic switch is connected and disconnected. The output voltage of the step-down transformer is connected to the control circuit as shown in the Figure 1. According to the signal of the step-down transformer and the step-up transformer, the base condition of the motor is determined whether it is starting, running with load or running without a load. The zero setting circuit detects the zero crossing point of the supply voltage and thus helps the control circuit to adjust the ignition angles of the electronic switch [8]–[11].

2.1. Analysis of split phase induction motor with electronic switch

To analyze the split phase induction motor with an electronic switch, the equivalent circuit in [12]–[14] is used after adding a current transformer in the auxiliary winding circuit, the equivalent circuit is modified (Z_{at}) as shown in the Figure 2(a) and (b).

$$Z_{at} = (R_{at} + jX_{at}) \quad (1)$$

where Z_{at} is total impedance of auxiliary winding and current transformer, R_{at} is total resistance of auxiliary winding R_{a1} and current transformer R_{eqt}, and X_{at} is total leakage reactance of auxiliary winding X_{a1} and current transformer X_{eqt}.

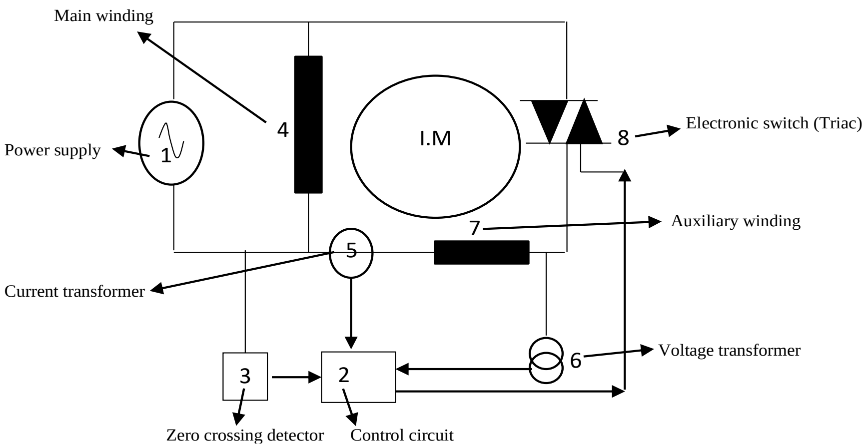

Figure 1. The single-phase induction motor operates with electronic switch

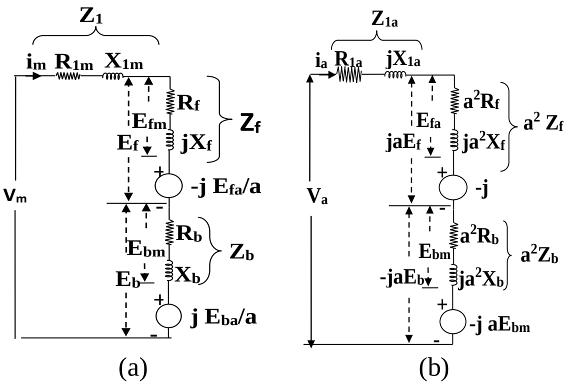

Figure 2. The equivalent circuit of spilt-phase induction motor (a) equivalent circuit of auxiliary winding and (b) equivalent circuit of main winding

The starting torque of the split phase induction motor can be increased by applying a resistance that is added in the circuit of the auxiliary coils with (2) [15]–[18].

$$R_{add} = \left(\frac{X_{at}}{X_m}\right)(R_m + |Z_m|) \quad (2)$$

Since the inductive current transformer has much less reactance than the electrical resistance, i.e., $X_{eqT} < R_{eqt}$, and therefore the inductive reactance has no effect on the starting torque. As for the electrical resistance, it has an effect, and so the current transformer is chosen so that its equivalent resistance is equal to the value of the added resistance, as in (3).

$$R_{eqt} = R_{add} = \left(\frac{X_{at}}{X_m}\right)(R_m + |Z_m|) \quad (3)$$

After adding the total impedance of the current transformer to the auxiliary winding of an induction motor (Z_{at}), the current of the auxiliary winding and the main winding can be calculated as (4) and (5).

$$\mathrm{V}_m = \mathrm{I}_m(Z_{1m} + Z_f + Z_b) - j(\frac{E_{fa}}{a}) + j(\frac{E_{ba}}{a}) \tag{4}$$

$$\mathrm{V}_a = \mathrm{I}_a(Z_{at} + a^2 Z_f + a^2 Z_b) + jaE_{fm} - jaE_{bm} \tag{5}$$

where Z_{1m}, Z_f and Z_b are the impedance of SPIM. The values of both the real and imaginary parts of Z_f and Z_b are given as:

$$\mathrm{Z}_f = \frac{[j\frac{X_m}{2}(j\frac{X'_r}{2}+\frac{R'_r}{2s})]}{[\frac{R_r}{2s}+j(\frac{X_m}{2}+\frac{X'_r}{2})]} = R_f + jX_{f,}\ \mathrm{Z}_b = \frac{[j\frac{X_m}{2}(j\frac{X'_r}{2}+\frac{R'_r}{2(2-s)})]}{[\frac{R'_r}{2(2-s)}+j(\frac{X_m}{2}+\frac{X'_r}{2})]} = R_b + jX_b$$

$$\mathrm{Z}_{1m} = R_{1m} + jX_{1m}, \qquad \mathrm{Z}_{1a} = R_{1a} + jX_{1a}$$

The air gap power is (6).

$$P_{gf} - P_{gb} = (|I_m|^2 + |a\mathrm{I}_a|^2)(R_f + R_b) + 2\mathrm{a}|I_a||I_m|(R_f + R_b)\, sin(\theta_a - \theta_m) \tag{6}$$

The torque developed by the machine is (7).

$$T = T_f - T_b = \frac{P_{gf}-P_{gb}}{\omega_{syn}} \tag{7}$$

Because of the presence of the inductive reactance in the auxiliary coil, although it is not large, it causes the current of the electronic switch not to reach zero when the voltage reaches zero. With this electronic switch it is not possible to ignite a period of time called β, the extinction angle and it can be calculated from the equation of auxiliary current during all operating periods, which is the steady state and the unstable state [15]–[18].

$$i\,(\omega t) = Vm/|Z_{at}|\ \ \sin(\omega t - \varphi) - Vm/|Z_{at}|\ \ \sin(\alpha - \varphi)e^{-(-\frac{\omega t-\alpha}{\omega \tau})} \tag{8}$$

when $\omega t=\beta$ at this moment, the value of the current is zero e.g., $i(\omega t)=0$.

$$\frac{Vm}{|Z_{at}|}\sin(\beta - \varphi) = \frac{Vm}{|Z_{at}|}\sin(\alpha - \varphi)\, e^{-(\frac{\beta-\alpha}{\omega\tau})} \tag{9}$$

The value of β can be calculated by looking at the motor data and the value of ignition angle (α) where different values of β are assumed and when the right of the equation becomes equal to the left of the equation it is the desired value of β. The voltage applied to the auxiliary coils can also be controlled by controlling the ignition angle (10).

$$\mathrm{V}_{or.m.s} = \frac{Vm}{\pi}\sqrt{[\,\beta - \alpha + \frac{\sin 2\alpha}{2} - \frac{\sin 2\beta}{2}]} \tag{10}$$

3. RESULTS AND DISCUSSION

3.1. Theoretical results

The following results are obtained using the motor and current transformer data given in:

- A split phase I.M data: 220 V, 60 Hz, P=4, X_{1m}=2.0 Ω, R_{1m}=1.5 Ω, X_{1a}=2.0 Ω, R_{1a}=1.5 Ω, R_r'=1.5 Ω, X_r'=1.5 Ω and X_m=48 Ω
- Current transformer and step-down transformer data: a=13/220, R_{Lv}=2.6 Ω, X_{LV}=0.76 R_{HV}=460 Ω, X_{HV}=221, Z_{eqtLV}=4.24+j1.545

Figure 3(a) is based on (4)-(5). The figure shows three signals taken from the auxiliary coil and their relationship to the motor speed while ignoring the influence of the control circuit on the motor operation. In the figure, the (I_a) line represents the voltage corresponding to the auxiliary current produced by the current transformer and used here to measure the current (I_a). It is noted that the value of the current is almost constant, and after 80% of the motor speed, the value of the auxiliary coil current decreases. The (V_c) line represents the voltage applied to the auxiliary coil when connecting the electronic switch and its value is constant under 80% of the motor speed and then increases as the motor speed increases. The (V_d) line represents the voltage induced by the auxiliary coil when disconnecting the electronic switch and this induced voltage starts from zero and gradually increases as the speed of the motor increases up to 80% of the speed, after that the induced voltage decreases as the speed increases to become the inverse relationship.

Figure 3(b) shows three input signals from the auxiliary coil circuit after connecting to the control circuit and their relationship to the motor speed. From the figure, the voltage applied to the auxiliary coil has a fixed value, which is represented by the (V_c) line, while the current rises to its highest value as the motor speed increases, which is represented by the (I_a) line. The voltage and current of the auxiliary coil drop to zero after the electronic switch is disconnected at 80% of the motor speed, then the induced voltage appears, which is represented by the (V_d) line. This induced voltage can be used to measure the motor speed as shown. The voltage generated on the terminals of the auxiliary coil after disconnecting the electronic switch decreases with increasing speed [19]–[25].

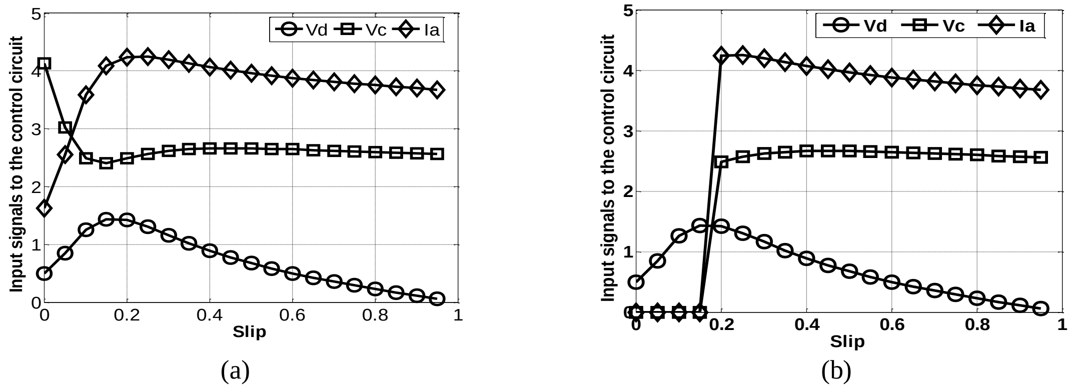

Figure 3. Three input signals from the auxiliary coil to the control circuit: (a) before connecting to the control circuit and (b) after connecting to the control circuit

Figure 4 Shows the relationship between the current of the main coil and the speed, which is the I_m curve, as well as the relationship between the current of the auxiliary coil and the speed in the case of the presence of a series-current transformer in the auxiliary coil, which is (I_{a1}) curve. As well as in the absence of the current transformer in the circuit of the auxiliary coil, which is (I_{a2}) curve. The results show that the presence of the current transformer in the auxiliary coil circuit reduces the current of the auxiliary.

Figure 5 Shows the relationship between motor torque and speed when the current transformer is connected to the auxiliary coil (T_1) and when the current transformer is not connected to the auxiliary coil (T) of the motor, which is shown by the (T_1) and (T) curves, respectively. The figure shows that the starting torque of the motor is large during the presence of the current transformer, due to the internal resistance of the transformer, which was selected to obtain the maximum possible starting torque of the motor.

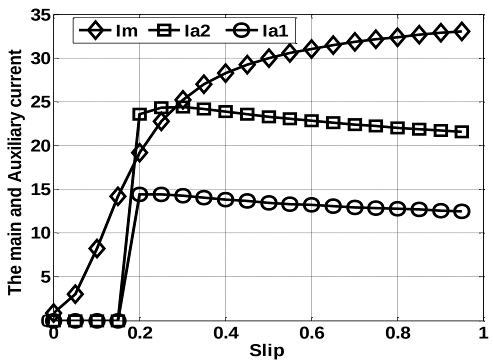

Figure 4. The current slip curves of SPIM

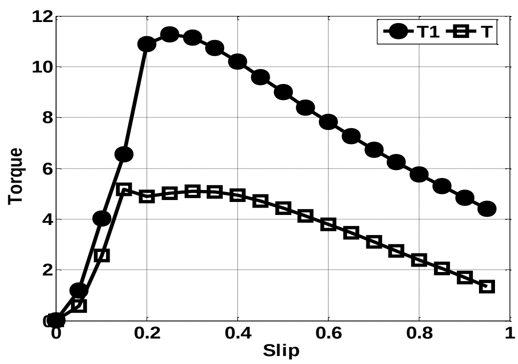

Figure 5. Torque slip curve of SPIM

3.2. Simulation results

The simulation of a spilt phase induction motor using the same data is used in steady-state analysis utilizing the MATLAB/Simulink software to simulate the system, the model block diagram is shown in Figure 6. Figure 7 Shows the right and left sides of (8) when angle β changes. The curves intersection point represents the value of β at which the current of the auxiliary coil is zero. From the figure, the value of the β angle is 190°, which is the same value from the MATLAB simulations shown in the next figure.

Figure 8 Shows the voltage and current of the auxiliary coil at an ignition angle of 90° (the possible range to change the ignition angle is from zero to 180°). The ignition angle from zero to 90° causes the motor to rotate in one direction and from 90° to 180° to rotate in the other direction. The angle of expansion is consistent with an extinction angle of 190°, as it was calculated from (7) and shown in Figure 7.

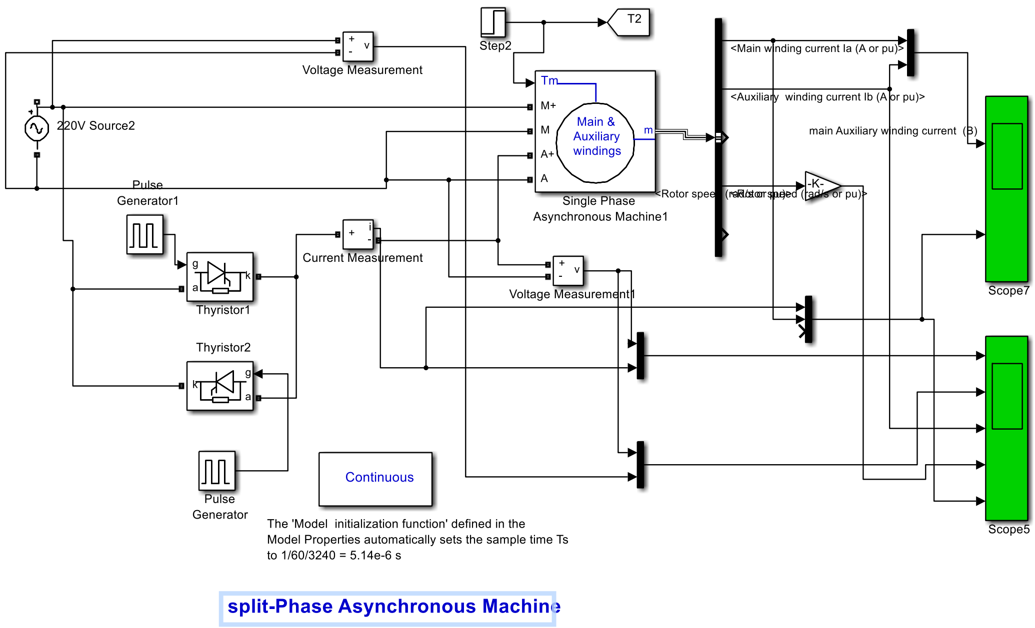

Figure 6. Simulink simulation model for spilt phase induction motor

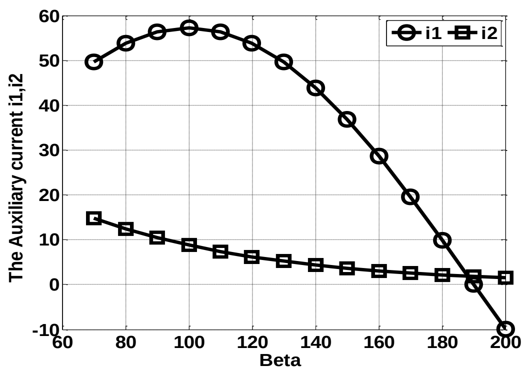

Figure 7. β Extinction angle

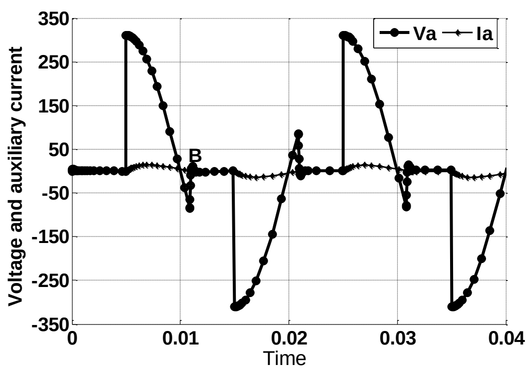

Figure 8. Auxiliary voltage and current at α=90

Figure 9 Shows the current flowing through the main winding and the auxiliary winding when the motor is started (s=1). From the figure, the maximum value of the current of the main coil is 45 A and R.M.S is 31 A, which is the same value as in the results shown in Figure 4. Also, the current of the auxiliary coil has a maximum value of 15 A and its R.M.S is 10 amps which is less than the calculated value. The ignition angle in this case was 90 degrees. In Figure 10, the motor speed is shown over time as the direction was reversed when the ignition angle was changed from 90° to 180°.

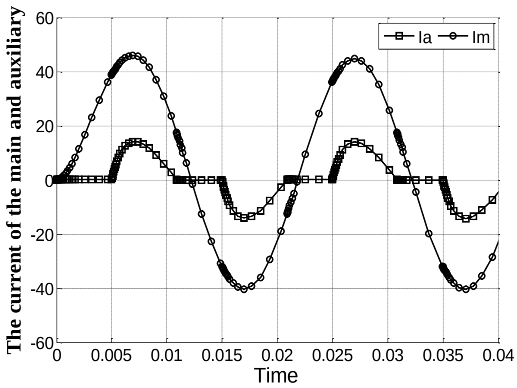

Figure 9. The main and auxiliary current of SPIM

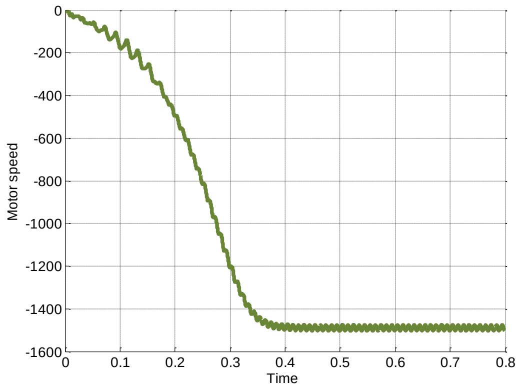

Figure 10. Speed of SPIM

3.3. Flow chart of induction motor control circuit

Figure 11 shows the flow chart of how the control circuit works so that the voltage and current applied to the auxiliary coil are read and compared with specific reference values from Figure 3(b) at 80% of the motor speed. Through this comparison, the disconnection and connection of the electronic switch is determined and the motor is kept running. After the motor is started and the electronic switch is disconnected, the induced voltage is measured at the terminals of the auxiliary coil and compared with the reference value. Through this comparison, the state of the motor is determined. If it is operating with a high load or without a load, and based on this, the electronic switch is ignited or not to keep the motor running.

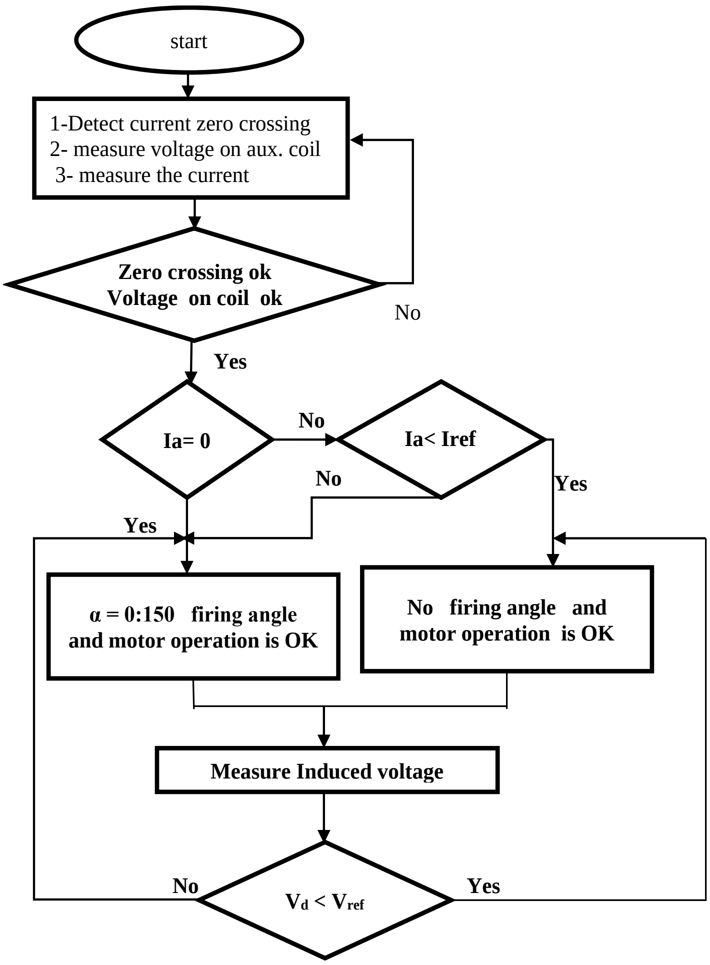

Figure 11. Flow chart of induction motor control circuit

4. CONCLUSION

The results show that the use of a current transformer to measure the current in the auxiliary coil reduces the current of the auxiliary coil and increases the torque of the motor. Also, there is no need for a centrifugal switch on new motors with control circuits, so it is very easy to disconnect the auxiliary current using an electronic switch control circuit. After the electronic switch is disconnected, a voltage is induced in the auxiliary coil. This induced voltage is inversely proportional to the speed of the motor. The higher the motor speed, the less the voltage generated. The lower the motor speed due to the load, the greater the voltage. When the speed drops too low due to the motor loading, the control circuit re-ignite the electronic switch and thus the control speed increases again and thus measuring this voltage keeps the motor running with different loads. It is also possible to change the ignition angle when the motor starts to move, and thus the speed can be gradually increase and the direction can be changed by changing the ignition angle. The circuit can perform many functions such as increasing the starting torque, controlling speed, changing direction and keeping the motor working with an increase in loading, also, there are no measuring devices connected at the main coil that can cause a reduction in voltage or a decrease in the current of the main coil.

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