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Electronic circuit with triac switch for a capacitor- start single-phase induction motor

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Electronic circuit with triac switch for a capacitor-start single-phase induction motor

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Abstract

An innovative electronic circuit for a capacitor-start single-phase induction motor was presented in this article. This new electronic circuit employs a traic-switch with a firing angle of about 90° to replace the conventional capacitor in order to start the motor by providing the required starting torque. The experimental results showed that such a new arrangement worked successfully under different operating conditions at laboratory scale as predicted in the theoretical analysis. The proposed circuit does not only replace the capacitor, but also believed to be most suitable for motors with variable power ratings. It is predicted that such a new scheme, with single-phase induction motor, may exhibit lower price in the market, thus consumers would enjoy buying cheaper and reliable appliances.

Keywords: Triac-switch; Single-phase induction motor; Firing angle

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الدارة الالكترونية مع مفتاح ترياك لمحرك حثي احادي الطور مع مواسع بدء الحركة

ملخص

تم في هذه الورقة تقديم دارة الكترونية للمحرك الحثي احادي الطور مع مواسع بدء الحركة، استخدمت الدارة الإلكترونية مع زاوية قدح مقدارها 90 درجةلابدال المواسع التقليدي وذلك لبدء حركة المحرك الحثي وتزويده بعزم الإنطلاق، واثبتت التجارب المخبرية نجاح عمل الدارة الالكترونية وتحت ظروف متعددة وتطابقت النتائج مع التحاليل النظرية وممكن ان تستخدم هذه الدارة لمحركات ذات قدرات مختلفة، واستخدام الدارة الالكترونية بدلا من المواسع يقلل من سعر المحركات الحثية احادية الطور.

1. Introduction

Single-phase motors are small motors with low power ratings of less than one horse-power. These motors are used in various domestic applications and office equipment as well as commercial and industrial sectors [1-5]. In Jordan, recent energy survey in the residential sector revealed that average dwelling uses a dozen or more of single-phase motors [6]. In fact, the number of single-phase motors today far exceeds the number of integral horsepower of all types of motors.

Recently, power electronics is getting more important, especially with electric machines, such as single-phase induction motors (SPIM), due to unique performance that can be achieved and relatively low costs. SPIM with only a main winding is able to produce a mechanical torque when its rotor rotates, but not at starting, i.e. at zero speed. Thus, such motors are provided with an auxiliary winding, with different configuration, on the stator in order to obtain the starting torque.

Single-phase motors are relatively simple in construction, however they are not always easy to analyze. Because of the high demand, the market is competitive and usually designer and engineers try hard to reduce costs by using tricks, e.g. starting method.

Single-phase induction motors can be classified in many ways, but the most important one is the starting method, which is referred to by a description of the employed method. In the market there are four commercial types. These are (i) resistance-start (slip-phase); (ii) shaded-pole; (iii) capacitor-run; and (iv) capacitor-start [7]. The latter, usually use large capacitors in order to develop the required high starting torque. But it should be remembered that large capacitor can be manufactured only as electrolytic capacitors, with relatively high losses of AC current [8], which prevent them from being permanently connected in series with auxiliary phase. Another drawback of an electrolytic capacitor is the excessive cost compared to the price of a conventional paper capacitor. Therefore, the motor is provided with two capacitors, the first, i.e. electrolytic capacitor, is used to start the motor and the other one, i.e. paper capacitor, is connected after

starting the motor. The capacitance of the paper capacitor is therefore significantly less than that of the start capacitor, which makes it possible to be permanently connected in series with the auxiliary winding. Capacitor-motors are single-phase induction motors that use a capacitor (or capacitance) in the auxiliary-winding circuit to cause a greater phase split between the currents in the main and auxiliary windings. But the size of utilized capacitor plays a major role in determining the terminal impedance of auxiliary winding. Unfortunately, this impedance changes dramatically from the starting to the running condition. This represents a crucial difficulty in designing and operating such type of electric-motors, especially when it comes to small sizes and capacity.

In the literature, only few researchers investigated various suggestions to improve the starting method of single-phase motors by using triac-switch in parallel with a capacitor. Muijadi and Zhao [1] has studied the effect of employing triac as a switch with a capacitor in order to reduce the capacitance value, consequently the size and cost of a single-phase motor would be less. Sundareswanan [4] investigated using a triac-switch in series with the main winding of a capacitor-run induction motor. His findings proved that such a new scheme could be used to improve motor's efficiency and hence its energy consumption reduced significantly. Rabinovici and Keller [9] presented a new electronic starter for the single-phase induction motors that replaces the starting capacitor as a phase shifting component for the current through the auxiliary winding circuit. Their study was limited to a single operating point, which is zero speed, and low rates of starting torque of only about 0.1 Nm. As can be seen this subject is very important to industry and researchers, therefore more attention should be given to study possible and promising new approaches to start single-phase motors without employing traditional capacitors. In this experimental work an innovative electronic circuit employs a traic switch with a firing angle of about 90° to replace the capacitor in order to start the motor by providing the required starting torque. The experimental set-up and theoretical analysis were presented.

Fig.1-a, shows the newly proposed design of the electronic circuit with a triac-switch to start the motor at a delay angle (α) of about 90°. The latter is usually determined as a function of the auxiliary winding resistance and inductance values, which is directly related to the applied load. The electronic circuit and auxiliary winding are disconnected when the speed switch is disconnected after the motor's speed reached the desired or setting value. Figs. 1-b & c, illustrates the vector diagrams of general and forward and backward components for two windings used in theoretical analysis, respectively.

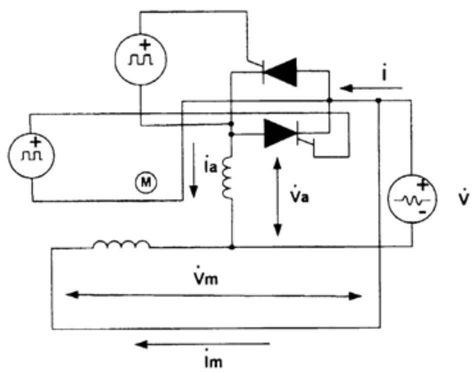

Fig. 1-a. Single–phase induction motor circuit with starting triac-switch

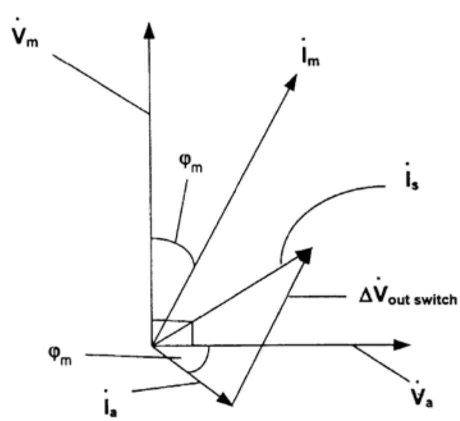

Fig. 1-b. General vector diagram of the proposed electronic-circuit

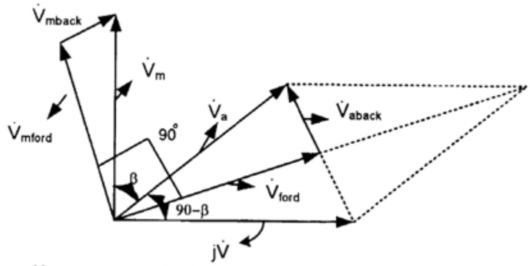

Fig.1-c. Vector diagram of forward and backward voltage for two windings

2. Background and Suggested Scheme

Capacitor motors are single-phase induction motors (SPIM) that use a capacitance in the auxiliary winding circuit to cause a greater phase split between the current in the main and auxiliary windings. The switch is disconnected after the speed reaches the desired value. In the arrangement shown in Fig. 2, the main phase (m) is connected to the supply line directly and the auxiliary winding (a) is connected to the supply line via a capacitance (C), with a chosen value that should initiate a circular magnetic field. Such value is basically determined at full load operation. In this case, both of winding coefficients are equal, i.e. Kwa = Kwm, where Kwa is the auxiliary winding coefficient and Kwm is the main winding coefficient. The electromagnetic torque (Tem) of a single phase induction motor is the sum of the two torques (forward component Tem1 and backward component Tem2 of the elliptical field) appeared in Fig. 2.

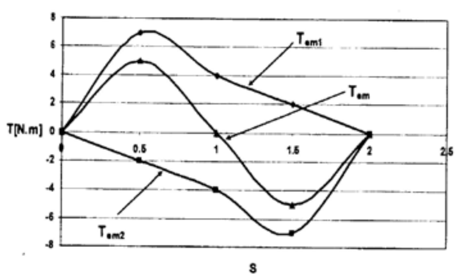

Fig.2. Typical Mechanical characteristics of a capacitor motor

When the rotor is at stand still and slip (s) is equal to unity, the forward (B1) and backward (B2) fields are weakened by the rotor currents to the same degree, and their peak flux densities are identical, then the two torques are equal in magnitude but opposite in direction, i.e. Tem1 = Tem2. Hence, the starting torque of a single-phase motor is zero and in order to start the motor, a special arrangement is needed, such as capacitor or suggested traic switch.

If a basic assumption is considered, as a general case shown in Fig. 3 a&b, in which auxiliary winding (a) has the same number of turns as that of the main winding $(W_a = W_m)$, then current, voltage and phase angle between them, as well as power in both phases turn out will have the same values, as seen in the following equations 1-4.

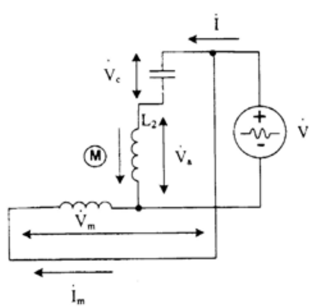

Fig.3-a. Basic circuit of SPIM with capacitor

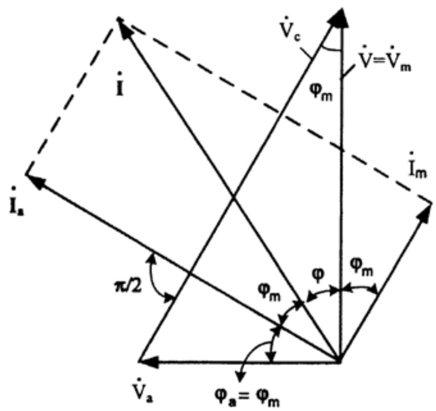

Fig.3-b. Vector diagram of SPIM with capacitor

$$\dot{V}_m = \dot{V}_a \quad (1)$$

$$\dot{I}_m = \dot{I}_a \quad (2)$$

$$\varphi_m = \varphi_a \quad (3)$$

$$\begin{aligned} P_m &= V_m \cdot I_m \cdot \cos(\varphi_m) \\ &= V_a \cdot I_a \cdot \cos(\varphi_a) = P_a \end{aligned} \quad (4)$$

Also, since a balanced two-phase supply produce a circular field and the phase currents and voltages are shifted in time-phase by $\frac{\pi}{2}$, thus, $\dot{I}_a = jI_m$ and $\dot{V}_a = jV_m$. But, it should be stressed that $\dot{V}_a$ can only be obtained with a two-phase supply. On the other hand, if the two windings energized from a single-phase supply, it will be impossible to adjust the value of capacitance so that the auxiliary phase voltage equals the main phase voltage $\dot{V}_a = jV_m$, which is essential for a circular field to be established. Thus, it is necessary to change the

number of turns of the auxiliary winding (Wa + ΔWa = Wm and Fa + ΔFa = (Wa . Ia + ΔWa . ΔIa) =Wm. Im = Fm = const where (Wa + ΔWa) / Wm = Nam is the turns ratio of a capacitor motor) to maintain the circular field. Hence, the phase (a) current and voltage are altered as follows:

$$\dot{I}_a = \frac{\dot{I}_m}{N_{am}} \quad (5)$$

$$\dot{V}_a = \dot{V}_m N_{am} \quad (6)$$

As a result it is important for designers and manufactures of single-phase motors to decide the number of turns of auxiliary winding Wa that will sustain the circular field, as described in the following equations 7&8:

$$\dot{V}_a + \dot{V}_c = \dot{V} \quad (7)$$

$$W_a = N_{am} \cdot W_m = W_m \tan(\varphi_m) \quad (8)$$

The capacitance value of a circular field, as shown in Fig. 3-a&b, is given by equation (9):

$$C = \frac{I_a \cdot \sin(\varphi_m)}{\omega \cdot V_a} \quad (9)$$

where $I_a = \frac{V_c}{X_c}$

For the proposed circuit, shown in Fig. 1-a, at $\alpha \approx 90^{\circ}$, the effective signal coefficient (γeff) equals the ratio of numbers of turns of main to auxiliary windings (Nma= Wm/Wa=1/Nam) multiplied by the signal coefficient (γ), (i.e. γeff =Nma γ), where γ is the ratio between phase voltage of auxiliary and main windings (γ =Va/Vm). There are three cases for the effective signal coefficient as follows:

1. $\gamma_{eff} = 1$, means a circular field is established.
2. $\gamma_{eff} \neq 1$, means an elliptical field is established.

3. $\gamma_{eff} = 0$, means a pulsated field, which is the worst case.

As can be seen case #1 is desired and the triac-switch with a firing angle of about 90° is deemed to facilitate starting the single-phase motor easily and smoothly. In the studied scheme, the value of sin of angle β, between the voltage ($\Delta \dot{V}out$) and voltage $\dot{V}_m$, will be equal to γeff – see Fig.1-c.

3. Equivalent circuit of SPIM with triac switch

The proposed starting system for a single-phase motor consists of a novel electronic circuit, which is composed of two anti-parallel thyristors, i.e. triac, and a firing circuit with a variable delay angle (α) of about 90° – see Fig. 1-a. This new system is connected in series with the auxiliary winding of the motor to replace the capacitor. Hence, vector diagrams of this newly proposed starting scheme are shown in Figs. 1 b&c. The forward and backward voltages, for both windings, could be determined from the following equations:

$$\dot{V}_{ford} = 0.5\left(\dot{V}_m + N_{ma}.j\dot{V}a\right) \qquad \textbf{(10)}$$

$$\dot{V}_{back} = 0.5\left(\dot{V}_m - N_{ma}.j\dot{V}a\right) \qquad \textbf{(11)}$$

Assuming that Nma = 1, then γeff = γ = sin(β), which leads the value of phase voltage of both windings identical, as illustrated in the following equations:

$$\dot{V}_a = \dot{V}_m = \dot{V} \qquad \textbf{(12)}$$

$$\dot{V}_{aford} = 0.5\left(\dot{V}_a - j\dot{V}_m\right) \qquad \textbf{(13)}$$

The absolute values of forward and backward components could be determined by the following equations:

$$\dot{V}_{aford} = \dot{V}_{mford} = \dot{V}_{ford} = \frac{\dot{V}\cos(90^o - \beta)}{2} = \dot{V}\sqrt{0.5(1+\sin(\beta))} \quad \textbf{(14)}$$

$$\dot{V}_{aback} = \dot{V}_{mback} = \dot{V}\ \frac{\sin(90^o - \beta)}{2} = \dot{V}\sqrt{0.5(1-\sin(\beta))} \quad \textbf{(15)}$$

The equivalent circuit of SPIM with traic-switch is shown in Fig.4-a&b. As can be seen, there are two circuits: one for forward and the other is the backward.

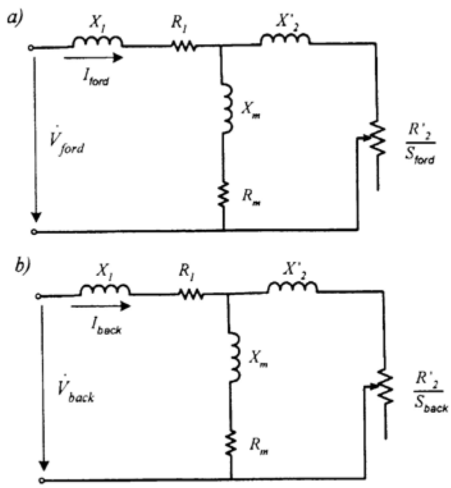

Fig. 4-a. General equivalent circuit of SPIM with triac switch

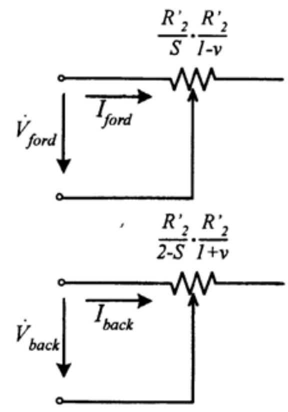

Fig. 4-b. Simple equivalent circuit of SPIM with triac switch

The variables, impedance and current, of the equivalent circuit of SPIM with triac, shown in Fig 4-a, could be determined for both components. The forward and backward impedance equal:

$$Z_{aford} = Z_{mford} = Z_{ford};$$

$$Z_{aback} = Z_{mback} = Z_{back}; \quad \textbf{(16)}$$

And the currents are:

$$\dot{I}_{ford} = \frac{\dot{V}}{Z}\sqrt{0.5(1+\sin(\beta))};$$

$$\dot{I}_{back} = \frac{\dot{V}}{Z}\sqrt{0.5(1-\sin(\beta))} \quad \textbf{(17)}$$

If the SPIM is considered as an ideal motor, then its main parameters, such as inductive resistance, of equivalent circuit are neglected except the rotor active resistance. The impedances of equivalent circuit, shown in Fig. 4-b, are found as

$$Z_{ford} = \frac{R_2'}{\left(1 - \dfrac{\omega_2}{\omega_1}\right)}$$

$$Z_{back} = \frac{R_2'}{\left(1 + \dfrac{\omega_2}{\omega_1}\right)} \qquad \textbf{(18)}$$

Substituting equations (18) in (17) will yield following equations:

$$\dot{I}_{ford} = \frac{\dot{V}}{R_2}\sqrt{0.5(1+\sin(\beta))}\left(1 - \frac{\omega_2}{\omega_1}\right) \qquad \textbf{(19)}$$

$$\dot{I}_{back} = \frac{\dot{V}}{R_2}\sqrt{0.5(1-\sin(\beta))}\left(1 + \frac{\omega_2}{\omega_1}\right) \qquad \textbf{(20)}$$

The Electromagnetic power of SPIM is given by equation (21):

$$\begin{aligned} P_{em} &= P_{emford} - P_{emback} \\ &= 2I_{ford}^2 \frac{R_2'}{\left(1-\dfrac{\omega_2}{\omega_1}\right)} - 2I_{back}^2 \frac{R_2'}{\left(1+\dfrac{\omega_2}{\omega_1}\right)} \\ &= 2V^2\left(\sin(\beta) - \frac{\omega_2}{\omega_1}\right) \end{aligned} \qquad \textbf{(21)}$$

Consequently, the electromagnetic torque is:

$$T_{em} = \frac{P_{em}}{\omega_1} = \left[\frac{2V^2}{(\omega_1 R_2')}\right]\left(\sin(\beta) - \frac{\omega_2}{\omega_1}\right) \qquad \textbf{(22)}$$

For a circular field ($\sin\beta = 1$) and the rotor is at stand still state, the base value of the electromagnetic torque of SPIM is given by the following equation:

$$T_m = \left[\frac{2V^2}{(\omega_1 R_2')}\right] \tag{23}$$

And the normalized values of the electromagnetic torque of SPIM is determined by dividing the requested value on the base value:

$$T = \frac{T_{em}}{T_m} = \sin(\beta) - \frac{\omega_2}{\omega_1} \tag{24}$$

And normalized angular frequency is found by dividing the requested angular frequency on the base angular frequency

$$n = \frac{\omega_2}{\omega 1} = \sin(\beta) - T \tag{25}$$

Based on the previous equations, the mechanical characteristic of SPIM with triac switch, at α of about 90°, are illustrated in Fig. 5. As can be seen from curves, the maximum value of Torque will be at the starting torque and equal to unity (i.e. the field is circular; Nma = 1 and γeff = 1) and the torque and slip are inversely related. While the relation between torque and the effective signal coefficient is proportional. Such results of the SPIM with triac-switch are in full agreement with those reported for other starting systems [10].

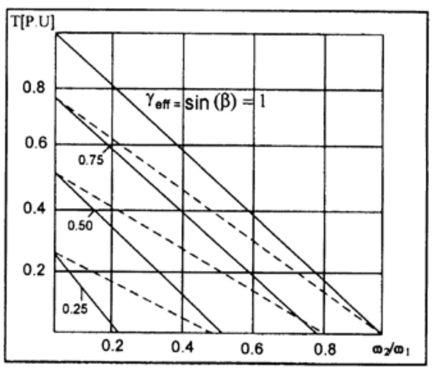

Fig.5. Mechanical characteristic of SPIM with triac at α = 90° (____Real Motor ----Ideal Motor)

4. Test Rig and Experimental Work

A single-phase motor, MS400-type, was selected randomly from the electric-machines laboratory in the Faculty of Engineering Technology with the following parameters [11]:

Parameter	**Designated value**
Input Power (W)	1000
Nominal Power (W)	750
Speed (rpm)	1430
No. of poles	4
Rated voltage (V)	220
Auxiliary winding resistance (Ω)	11.5
Main winding resistance (Ω)	3.5
Secondary resistance (Ω)	1.25
Leakage inductance reactance of auxiliary winding (Ω)	1.327
Leakage inductance reactance of main winding (Ω)	0.26
Magnetic inductance reactance (Ω)	65
Leakage inductance reactance of secondary winding (Ω)	4.2
Moment of inertia (Nm^2)	0.00348
Capacitance (μF)	30
Rated torque (Nm)	5.1
Max torque (Nm)	6.9

The load angle of the chosen SPIM (MS400) with triac-switch, at α=90°and Nam = 0.5, is calculated using equation (26):

$$\varphi = \tan^{-1}\left(\frac{X_{mot}}{R_{mot}}\right)$$

$$= \tan^{-1}\left(\frac{R_2'/(X_o \cdot S^2) + X_{sc}}{\frac{R_1 \cdot R_2'}{X_o^2 \cdot S^2} + \frac{R_2'}{S} + R_1}\right) \qquad \textbf{(26)}$$

Where: $X_o = X_1 + Xm + \frac{X_2^{'}}{\sigma_2}; \quad X_{sc} = X_1 \cdot \sigma_1 + \frac{X_2^{'} \cdot \sigma_1}{\sigma_2}$

$$\sigma_2 = 1 + \frac{X_2'}{X_m}; \quad \sigma_1 = 1 + \frac{X_1}{X_m\left(X_1 + X_2' + \frac{1}{\sigma_2}\right)}$$

The relationship between the calculated effective signal coefficient (γeff) of tested SPIM and load angle is shown in Fig.6 . It is clear that the maximum value of γeff would be at an angle of about 90°, which is in full agreement with the basic assumption that firing will occur at the same angle.

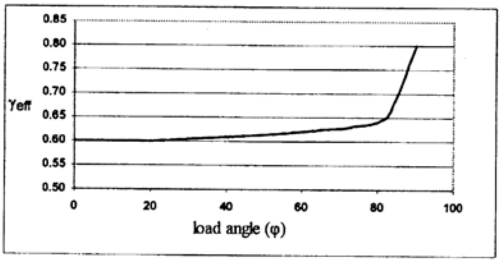

Fig.6. Effective coefficient of motor versus load angle

The control unit (for 1000 W pendulum machine, Model 67 10 610/67 10 611, made by ELWE Training Systems, Germany) has been designed to operate the pendulum machine driven by a 1000 W motor only [11]. This combination allows us to design and conduct various experiments aiming to test electrical machines in all four quadrants. The sequence for the operation of the automatic function as follows:

1. adjusting the start speed
2. Adjusting the stop speed
3. Setting the function selector on "start"
4. Switching on the motor of the tested machine (pressing push–button start)
5. Recording the speed and torque and all parameters of SPIM.

5. Discussion and Results

The experimentally obtained characteristic curves of the employed motor, with triac-switch instead of capacitor, are shown in Fig.7. It is obvious that the motor without capacitance or triac-switch has a zero starting torque, while the same motor with a triac-switch has a significant value of starting torque, which would facilitate easy start-up. In the non-linear section of load characteristics, at any speed the motor with triac-switch has higher values of torque compared with that without triac or capacitance. When reaching a critical speed, within the range between 1000 and 1200 rpm, the two cases behave identically. The difference between SPIM with triac-switch and conventional SPIM with capacitance is demonstrated in Fig.8. It can be seen that the two curves are close to each other, with slightly higher values of torque in the case of SPIM with triac-switch. Such results are in full agreement with what was predicted in the theoretical analysis. Thus, the hypothesis of starting a single phase motor by employing a triac-switch instead of traditional capacitor is proved theoretically and experimentally. It is anticipated that such a new starting method will benefit both of manufacturers and users of single phase motors through better performance and reduced costs.

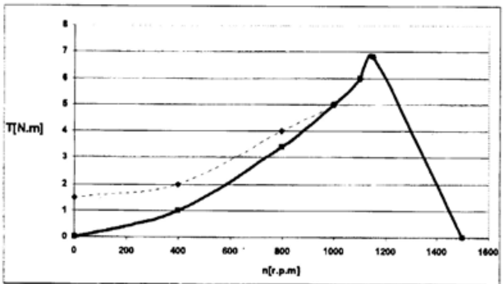

Fig.7. Loaded mechanical characteristics of motors (-- with-triac; ___without triac).

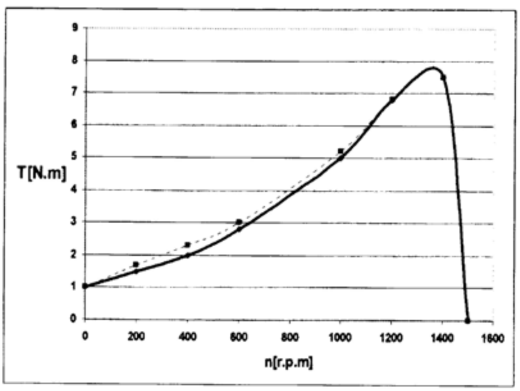

Fig.8. Loaded mechanical characteristics of motor(___with capacitor; --with triac).

5. CONCLUSION

In this paper theoretical analysis and different sets of experiments with the prim aim of testing a novel method to substitute for the traditional capacitor-start single-phase induction motor were presented. The obtained results showed that the electronic circuit with triac-switch is a feasible replacement for the capacitor-start single-phase induction motor system with $\alpha = 90°$. It was observed that the motor without capacitance or triac-switch has a zero starting torque, while the same motor with a triac-switch has a significant value of starting torque, which would facilitate easy start-up. Finally, the author is predicting that production of such a new starting method would be cheaper than the traditional capacitor-start for single-phase motors, and this circuit could work with different power ratings. Future work will concentrate on the dynamic analysis of triac-switch with single-phase motors and pertinent economic assessment.

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8. ABRIAVATIONS

a: auxiliary phase
B_1: forward field
B_2: backward field
c: capacitance
I_a: auxiliary current
F_a, F_m: Auxiliary and main magnetic forces
$I_s = I$ – source current
K_{wa}: auxiliary winding coefficient
K_{wm}: main winding coefficient
m: main phase
N_{am}: turns ratio
N_{ma} : ratio of number of turns of main to auxiliary windings
P: power
R: resistance
R_{mot}: resistance of motor equivalent circuit
S: slip of motor
SPIM: singl-phase induction motor
T: torque
T_{em}: electromagnetic torque
T_{em1}: forward electromagnetic torque
T_{em2}: backward electromagnetic torque
V_{out} : output voltage of triac switch
V_a, V_m: voltage of auxiliary and main windings
V_{afor}, V_{mfor}: forward voltage for auxiliary and main windings
V_{aback}, V_{mback}: backward voltages of auxiliary and main windings
W_a, W_m: number of turns for auxiliary and main windings
X: inductance resistance
X_{mot}: inductance resistance of motor equivalent circuit

Greek Letters:
α: delay angle
β: angle between main and auxiliary voltages
γ: signal coefficient
γ_{eff}: effective signal coefficient
φ: load angle
ω_2, ω_1 : angular speed of rotor and stator
ΔW_a, ΔW_m: change in the number of auxiliary and main windings
$\nu = \frac{\omega_2}{\omega_1}$: reflective frequency of rotor