A PROPOSED DISCRIMINATOR FOR MOTOR PROTECTION DURING STARTING

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Abstract

In this paper, development of a phase-angle variations detection relay for motor protection during starting is presented. The relay provides an early discrimination between the locked rotor (LR) and prolonged starting conditions. It is based on detection whether the phase-angle between voltage and current is varying at start. This detection is accomplished by successive measuring of the phase angle and comparing the values at two equidistant points within equal intervals. Length of the interval is correlated to the starting time and comparator resolution. An analysis, to show how the starting phase-angle is affected by the variations of parameters and supply voltage, is given. Concept of the design is described. A prototype of the proposed relay is built using digital integrated circuits, having equidistant points shifted by (N-2)/F, where N is the divisor of a decade counter which ranges from 4 to 100 and F is the supply frequency. Response time test results, conducted on the prototype, is shown to corroborate the proposed concept.

Key Words

Motor starting protection, digital relays, detection of phase angle variations..

I. INTRODUCTION

Recent reviews of the motor potential troubles and the required protection under various applications and loading considerations have been reported [1,2]. The

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protection applied to a particular motor depends on its size and the nature of the load to which it is connected. However, it has been recommended that all motors should be provided with protection against unbalanced supply voltage and overload[3].

Large motors have traditionally been protected against LR current and overheating by time overcurrent (oc) relays. The practical method of setting the relay has been to find a relay time-current curve which fits between the thermal limit curve of the motor and the time-current starting curve of the motor under load [3].

When the starting time is significantly less than the permissible LR time, discrimination between the LR and normal starting conditions can be accomplished on the time basis and full speed is reached before the relay can operate [4]. However, when the starting time is prolonged enough to approach or exceed the permissible LR time, discrimination is lost and the relay can operate to trip off the motor before it reaches full speed. This could occur even though the relay time-current curve is above that of the motor starting current curve [5].

A speed-sensing switch (mechanical or electronic) whose contacts are in series with those of a locked-rotor oc relay contacts has been applied to provide successful start and LR protection [6].However, this has the disadvantage of requiring direct access to the rotating parts which may not be feasible or economical.

An impedance relay has been employed as an alternative mean to the speed-switch, without an access to the rotor, by monitoring voltage, current and phase angle [7]. However, its applications procedure has been criticized [8]. This is mainly because it requires accurate predetermination of the parameters which may not be fulfilled and calculated settings must be verified by test trials. A failure to accelerate, when motor-torque and load-torque curves are crossed preventing attaining full speed particularly for large motors, still need to be provided by an effective way of protection as pointed out in references. [2,6].

State-of-the art motor protection trip units are multifunction microprocessor based. These have been addressed in two different forms. The first is based on the detection of unbalance by analyzing the instantaneous power [9]. However, this form is not sensitive to overloads, and can not discriminate between LR and prolonged starting conditions. The second is programmed with a thermal model of the motor to provide continuous thermal protection [10-12]. This form allows the motor to run with a temporary overload, which is useful (service factor). Nevertheless, temperature monitoring is an indirect and relatively slow method to detect LR condition.

In this paper, the development of a relay which provides an early discrimination between the LR and prolonged starting, as well as detection of failure to reach full running speed conditions is presented. The relay concept is based on the detection of variations in the phase angle between the positive sequence voltage and current of the motor during starting . In this detection, the phase angle is measured over a continuous time interval, converted into a binary number and stored. It is then compared with the corresponding value after n cycles of supply frequency; whether the motor is locked or not can be decided according to this comparison. Relay application using this concept will not require accurate determination of the motor parameters. A prototype is built in which $n = N - 2$ where N is the divisor of a binary counter. The number n can be controlled, at will, from 2 to 98 to suite motors of different starting time. An analysis to show the variations of the starting phase-angle as well as the basic concept of the proposed relay and circuit description of the prototype are given in the subsequent sections.

II. THE RELAY CONCEPT

The relay concept is based on the feature that the maximum value (below 90^{o}) of the phase- angle θ, between the voltage and current, occurs when the motor is locked. Further, while the motor is accelerating the angle θ decreases towards its value at full speed. Upon detection whether θ is varying or not the motor is running or locked, can be decided. The variations may be very small, particularly early in the acceleration cycle, as shown by the analysis given in section 3. Therefore, the proposed relay relies mainly on a direct digital high precision θ-variation detector, which forms the heart of the relay.

A block diagram of the relay representing various units and their interconnections is shown in Fig. 1. In this figure the positive sequence voltage signal V_1 is extracted from the 3-phase voltages V_a,V_b and V_c using a voltage positive sequence filter VPSF. The positive sequence current signal i_1 is derived from two-phase currents (for delta connected or isolated neutral motors) i_a and i_c via a current positive sequence filter CPSF. The zero-crossings positive square pulses S_v of V_1 and S_i of i_1 are obtained with zero-crossing detectors ZCD. *A bistable B is set by S_v and reset by S_i. The Q output of B will be* a train of pulses of frequency f_s, where f_s is the supply frequency. Each of these pulses is of width equal to θ of the relevant cycle number elapsed from the start. This train of pulses is termed hereinafter as θ train of pulses.

The θ train of pulses is divided by N and decoded to two-parallel form via a divider/decoder D/D. Output of the D/D will be two train of pulses θ_i and θ_{i+n} each of frequency of 1/T. Where T is the time interval between each two successive pulses in a train. θ_{i+n} appears a number n of cycles (of frequency fs) after θ_i. Where i and i+n designate the first and the last picked up pulses from the θ train of pulses during the interval T. A reset pulse r is also provided by the D/D which is ended before the θ_i pulse is generated. On the receipt of r, a zero is inserted into the ripple up counters UC1 and UC2 and at each application of a pulse to CU1 or UC2 the contents of the relevant counter increase by one.

Each of θ_i and θ_{i+n} pulses is then converted into a binary number. θ_i enables AND gate G_1 and releases a high frequency f_{clk} signal for a period of "t_i" corresponding to θ_i, where f_{clk} is obtained from high frequency pulse generator HFPG. At the end of the t_i period, UC1 will contain a quantity given by $f_{clk} * t_i$. This quantity is, temporarily, stored into a latch L_1. Similarly θ_{i+n} enables G_2 and releases f_{clk} signal for a period of t_{i+n} allowing a quantity of $f_{clk} * t_{i+n}$ to be inserted into UC2 and then latched into L_2. At the end of the period t_{i+n} a pulse transferring pulse P_t is generated via a monstable M. This P_t instructs the latches L_1 and L_2 to release their contents to a magnitude comparator C. If these two quantities are equal, a level "1" signal will appear at the output of C indicating no variations in θ have been detected. This level "1" enables a 3-input AND gate G_3 allowing the P_t pulse to appear at the input and output of G_4 as an LR trip pulse if both outputs of the level detector L_D and delay D_1 are at level "1". If these two quantities are not equal a level "0" signal will appear at the output of C indicating that variations of θ have taken place. This level "0" blocks G_3 preventing transmission of the tripping pulse.

III. RELAY PERFORMANCE DURING START

During normal start, the θ train of pulses will be of successively reduced width as shown in the timing diagram of fig. 2. Therefore, the quantity corresponding to $\theta_i +_n$ will be less than that of θ_i. Thus a level "0" signal will appear at the output of C. This will block G_3 and prevent tripping even though I_1 is higher than the nominal motor current I_N. Where I_1 is a dc signal obtained by rectifying and smoothing i_1.

After the elapse of the nominal starting time t_s a steady condition can be established at which $\theta_i = \theta_i +_n$ and again, a level "1" will appear at the output of C. This condition could lead to issuing a false LR tripping pulse if I_1 remains higher than I_N and G_4 is enabled as with the case of running at less than full speed. This is prevented via a delay D_1 which blocks G_4 just before the elapse of t_s. D_1 is made equal to $k_1 t_s$ where k_1 is adjustable, and can be adjusted from 10% to 90%. If the above condition is persisted after a delay D_2 AND gate G5 is enabled via D_2 and INVERTER I to provide a not reaching full speed trip signal. D2 is made equal to k_2 t_s ,where k_2 is adjustable and can be set from 110% to 120%. Where D_1 and D_2 are measured from the starting instant. This instant is marked by a pulse derived from I_1 using a window comparator wc. The time, t, which must be elapsed from the start before any change of θ can be detected, for a certain sensitivity of the detector, depends on the phase angle-time relationship during start.

IV. STARTING PHASE ANGLE-TIME RELATIONSHIPS

To establish a phase angle-time (θ-t) relationship during start, a resort is made to the interaction of the motor equivalent circuit and dynamics. With reference to the equivalent circuit given in appendix A, θ can be directly expressed in terms of stator resistance R_S, reactance X_S, rotor resistance R_r, reactance X_r, slip s and magnetizing reactance X_m as,

$$\theta = \tan^{-1}\big[(x_s + z_{rm}\sin\theta_{rm})/(R_s + z_{rm}\cos\theta_{rm}) \tag{1}$$

where,

$$Z_{rm} = (X_m.Z_r)/(X_m + Z_r) \tag{2}$$

$$Z_r = \sqrt{(R_r/s)^2 + X_r^2} \tag{3}$$

$$\theta_{rm} = \pi/2 + \tan^{-1}(SX_r/R_r) - \tan^{-1}\big[(X_m + X_r)S/R_r \tag{4}$$

The rotor parameters R_r and X_r may be expressed by a linear function of S as reported in [13] as,

$$R_r = (R_{r1} - R_{ro})S + R_{ro} \tag{5}$$

$$X_r = (X_{ri} - X_{ro})S + X_{ro} \tag{6}$$

where R_{r1} and X_{r1} are rotor resistance and reactance at S = 1, R_{ro} and X_{ro} are the corresponding values at S = 0.

The differential equation describing the motor dynamics can be given in its simplified form as;

$$J\frac{d\omega}{dt} = Ta \tag{7}$$

where J: is the total moment of inertia of the motor and load.

Ta is the acceleration torque, and ω is the rotor angular speed, as $\omega = \omega (1\text{-}s)_S$.

The value of T_a depends on the motor and load torques and can be expressed, generally, as a nonlinear function of ω [12]. If T_a is, conveniently considered of constant value during the starting time t_S, solution of eqn. 7 will be,

$$\omega = (T_a/J)\,t \tag{8}$$

Hence, S can be expressed as a linear function of t as,

$$S = (1\text{-}Kt) \tag{9}$$

Where $K = (Ta/J\omega_S)$ is a constant and can be determined in terms of rated slip S_o and t_S as,

$$k = (1\text{-}S_O)/t_S \tag{10}$$

$$S=1-(1-S_o)t/t_s \quad (11)$$

Consider two large field power plant motors of 6000 and 4500 HP of parameters given in appendix B, as quoted from references [12] and [13] respectively. Substituting with these parameters into eqns 1, through 6 and 11, for different values of t, the corresponding values of s and θ can be computed. The computed values of θ are plotted against t, for the two motors at 100% and 80% of the rated terminal voltages, as shown in Fig. 3. The initial rate of change of θ is about 0.63 and 0.28 deg/s. at 100% and 80% voltage, for the case of 4500 HP motor as shown in Fig.3 by curves a and b, respectively. Similar, for the 6000 HP motor the initial rate of change is about 0.064 and 0.036 deg/s, as given by curves c and d, respectively. It can be seen that the initial change of θ decreases as the motor size increases and/or the applied voltage decreases. Hence, if a θ-variation detector is designed to cover a wide range of different size motors, the detector resolution should be decided upon considering the start of the largest motor rating under reduced voltage. If a resolution of 0.05 degree is adopted, comparison intervals should be at least 0.079, 0.178, 0.781 and 1.388 s for the above cases a,b,c and d respectively.

V. DETECTOR CIRCUIT DESCRIPTION

The implemented prototype circuit of the θ-variations detector is shown in Fig.5. This circuit is fed by the signals $V_1(t)$ and i(t) provided through the VPSF and CPSF respectively. The VPSF circuit has been designed based on the principle of frequency-compensated fixed phase shift proposed by Byars [14]. This circuit is shown in Fig. 4, in which A_1 to A_5 are op amps 741 arranged to provide a stable phase shift, of $V_1(t)$, that does not vary significantly as the frequency deviates by about 8%. The CPSF circuit is similar to that of Fig. 4. except that op. amp. A_5 can be removed if no zero sequence component of motor current exist. Should a considerable harmonic distortion exist on the mains, a low pass filter should be added at the output of each of the VPSF and CPSF circuits. With reference to Fig. 5 the positive halves of the signals $V_1(t)$ and $i_1(t)$ are converted into two-trains of positive square pulses via comparators LM 339. The front edges of these two train of pulses are used to set and reset, respectively, a NAND gate bistable (using 7400) to produce the θ-train of pulses. This is divided by N and decoded into two parallel train of pulses θ_i and θ_{i+n} using two cascaded 4017 decade counters. Divisors N_1 and N_2 of the first and second 4017, respectively, can be controlled, individually at will from 2 through 10. Hence, an overall divisor $N = N_1N_2$ can be controlled from 4 through 100.

Using 7411, the θ_i train of pulses is obtained by ANDing , the θ train with Ql_1 and Qo_2, where Ql_1 is the Q_1 output of the first 4017 and Qo_2 is the Q_0 output of the second 4017. It is also used to provide the reset pulses. However the θ_{i+n} is obtained by ANDing the θ train with the outputs $Q_{(N1-1)}$ and $Q_{(N2-1)}$. The pulse duration of each of the outputs Q_1, $Q_{\{N1-1)}$, Q_{o2}, and $Q_{(N2-1)}$ is shortened through a monstable 74121 (to be less than 360^{o}). That is to avoid producing a false output during possible overlapping between the falling edges of the Qs output and the rising edges of the input θ pulses.

Both θ_i and θ_{i+n} pulses are converted into binary numbers by ANDing them with a HFPG signal through AND gate 7408. The HFPG signal is obtained using dual 4-input NAND gate Schemitt trigger, 7413, with external capacitor of 10 nf and variable resistor of 500 ohm. With these components an adjustable range of frequency from 100 KHZ to 1 MHZ can be obtained. A binary counter of maximum counting capacity equivalent to 90^{o} is used for each of the θ_i and θ_{i+n} converted trains. A 12-bit counter 4040 with a clock pulse frequency of 819 KHZ yields a resolution of measuring the angle of about 0.022 of a degree for a supply frequency of 50 HZ. Three 7485 are used to compare the contents of both counters which are latched into three 74116. Since the errors are additive, then the resolution at the comparison stage will be of about 0.044 of a degree.

Applications with this resolution to the 6000 HP motor (of section 4) will reveal periods of about 0.688 and 1.222 s, under 100% and 80% voltage, respectively, from the start before the detector can sense any variations in θ. Each of these periods represents, only, about 1.75% of the corresponding starting time. Nearly twice these periods (which is less than 5%) will be obtained for a resolution of about 0.1 degrees.

VI. RESPONSE TEST

The prototype of the proposed detector was tested by connecting its input sequence filters to the terminals of a 3.6 KW, 380 volts laboratory induction motor, via transactors and voltage transformers. The input counter/decoder was set to divide by 10. The applied voltage was reduced to about 70% of the rated, and so, the starting time was extended from 0.25 S (nominal) to about 0.5 S. The oscilloscope traces of the corresponding motor current, θ-train of pulses and the comparator output are given in Fig. 6. The appearance of the low-level intervals in the comparator output indicates that the motor is starting. Upon reaching a steady running speed, the compactor output remains high, which causes a tripping pulse to be generated as shown by the traces of Fig. 7. This generated pulse is not allowed to be transmitted since the current has dropped to the normal value.

The locked rotor condition was imposed on the motor at reduced applied voltage for safe operation. From the instant of switching the motor on a steady θ -train of pulses, was obtained. This causes a trip pulse to be transmitted every 10 cycles as shown by the traces of Fig. 8.

VII. CONCLUSION

The development and design of a phase-angle change based relay, for motor starting protection using digital integrated circuits has been presented. The relay action is based on detection of the changes in the phase angle during starting. Setting of the relay can be controlled at will to suite different size motors. It has been demonstrated that discrimination between prolonged starting and locked rotor can be achieved without the need for an access to the rotating parts or accurate predetermination of the parameters. Moreover, the proposed relay can provide detection of the failure to reach full running speed condition. Therefore, the developed relay can be used to protect motors which are subjected to abnormal starting conditions as with those driving high-inertia loads. The proposed phase-angle change concept can also be integrated with a microprocessor multifunction based relay to provide additional feature for motor protection.

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APPENDIX A

The traditional positive sequence equivalent circuit of the induction motor is shown in Fig A.

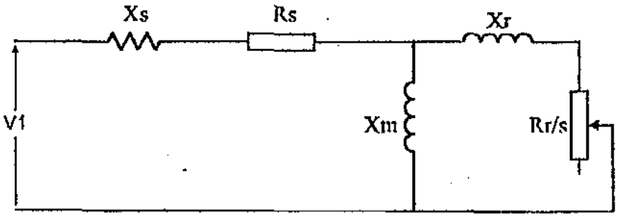


Fig. A Induction motor positive sequence equivalent circuit

APPENDIX B

The parameters of two actual power plant motors, of 6000 and 4500 HP, and of total inertias of 695000 and 2402001b-ft^2 respectively, are listed in the table given below as,

Motor HP	Rs	Xs	Xm	Running		Locked		S_0	Seconds	
				R_r	X_r	R_r	X_r		t_s at V=100%	t_s at V=80%
6000	0.0026	0.026	4.853	0.01	0.0977	0.026	0.0899	0.0126	39.1	70
4500	0.005	0.078	5.01	0.0044	0.0806	0.0166	0.0625	0.0044	22.3	49.4

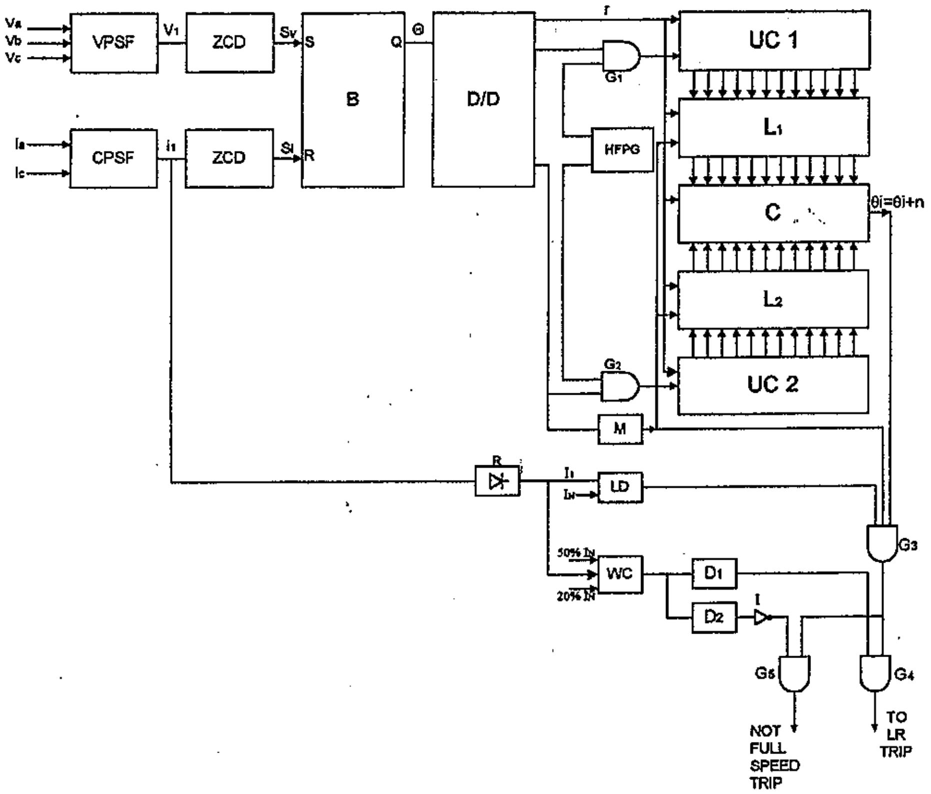


Fig.1 Block Diagram of The Proposed Relay

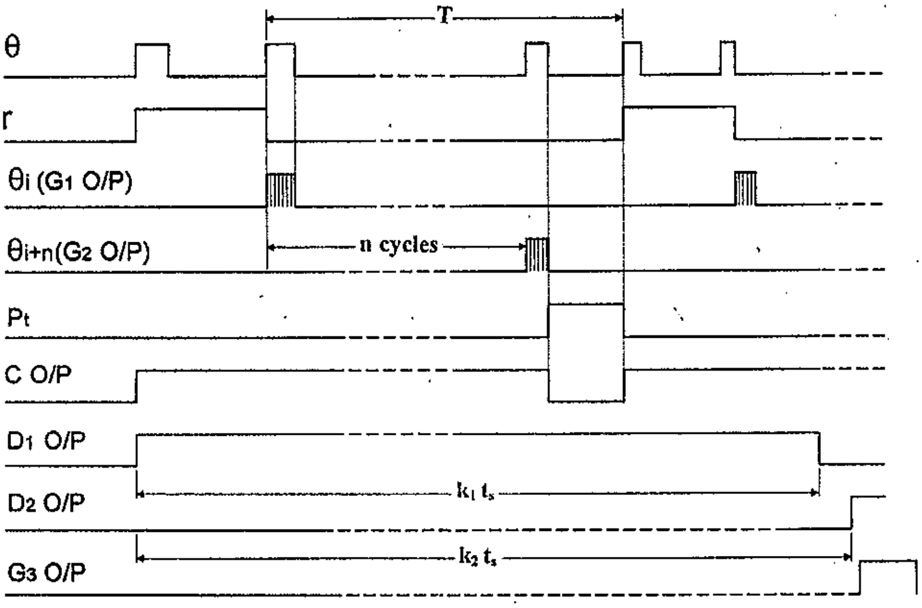


Fig. 2 Timing diagram of the θ-variation detection for a starting condition

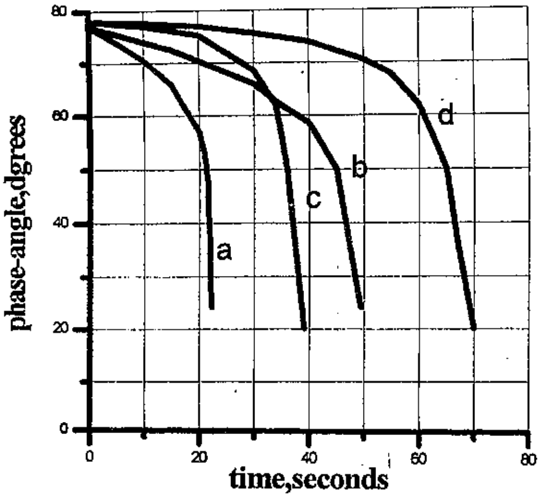
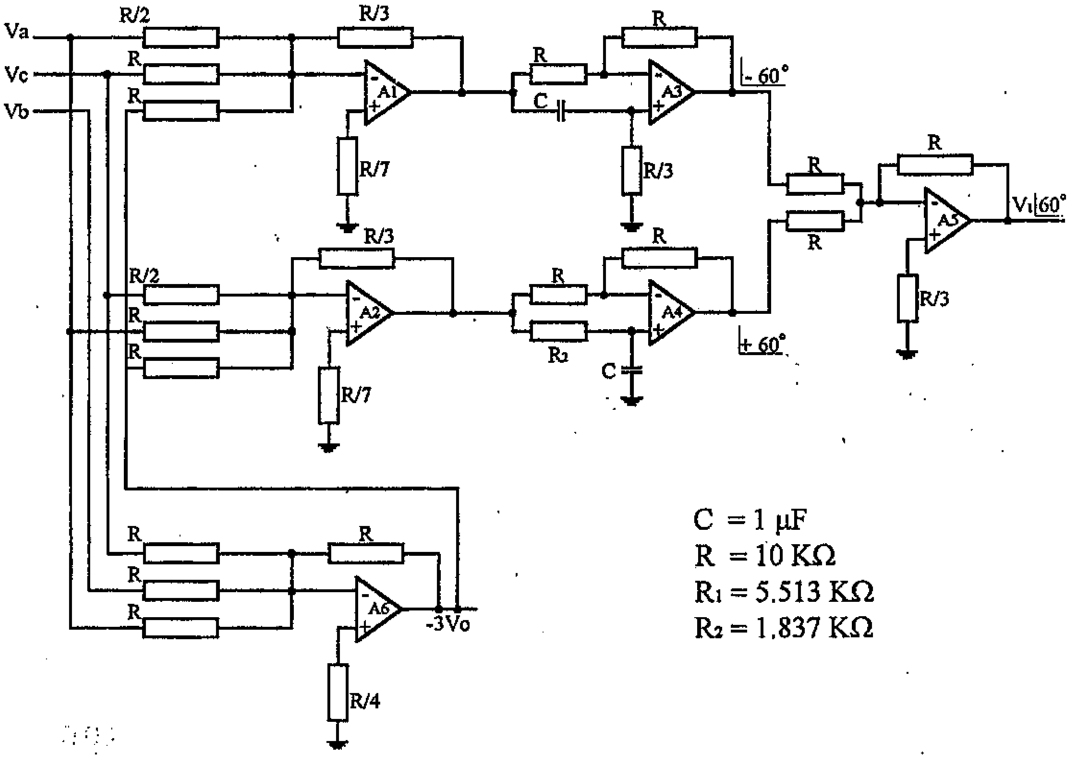


Fig. 3 Start phase-angle-time curves
a) 4500 HP motor at 100% voltage
b) 4500 HP motor at 80% voltage
c) 6000 HP motor at 100% voltage
d) 6000 HP motor at 80% voltage



$C = 1\ \mu F$
$R = 10\ K\Omega$
$R_1 = 5.513\ K\Omega$
$R_2 = 1.837\ K\Omega$

Fig. 4 Positive sequence voltage detector

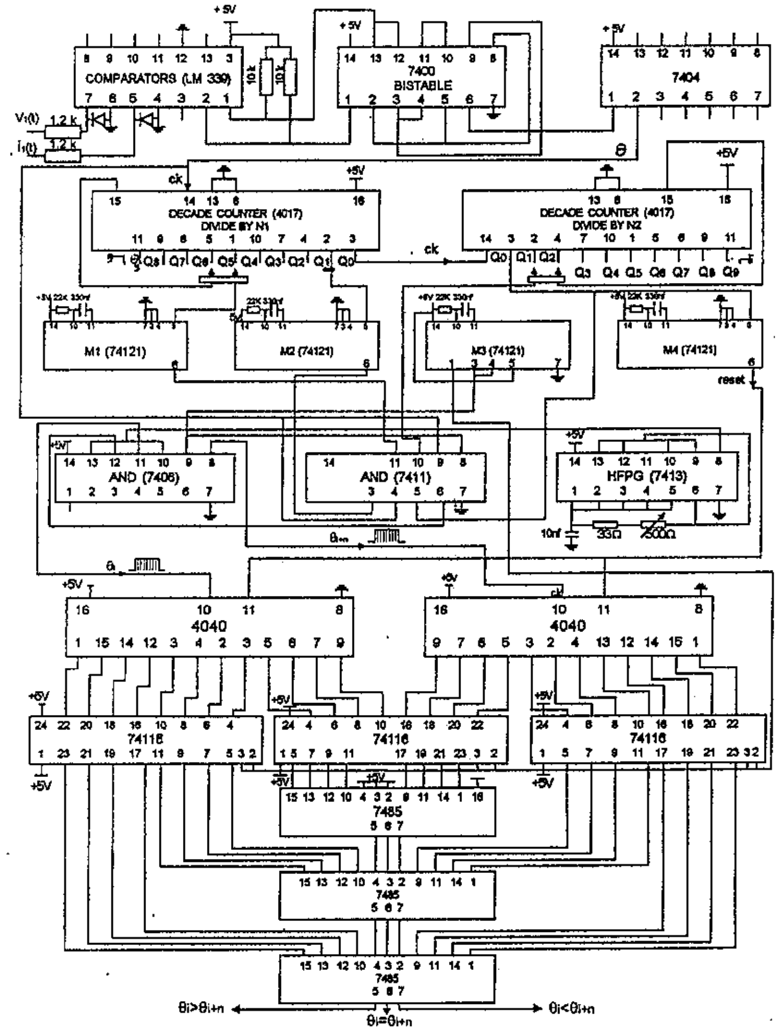


Fig. 5 Circuit Diagram of The θ-Variation Detection Prototype

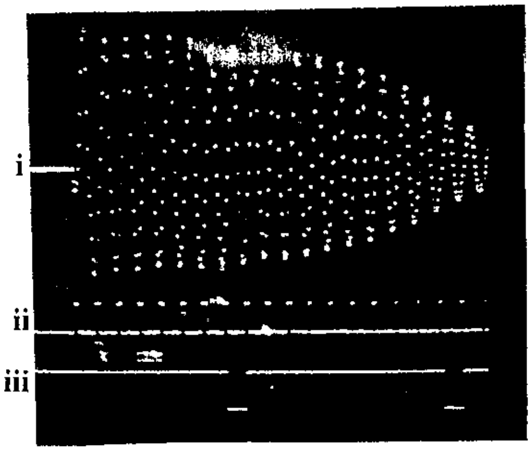


Fig. 6 Starting condition

i) motor current
ii) θ- train of pulses
iii) comparator output

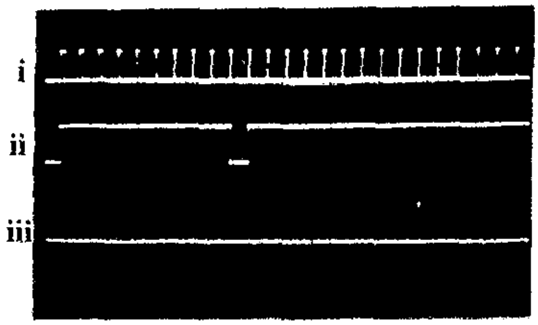


Fig. 7 End of starting period
i) θ- train of pulses
ii) comparator output
iii) Generated tripping pulse

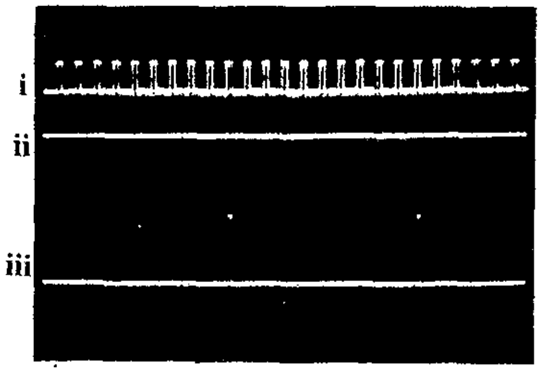


Fig. 8 Locked rotor condition
i) θ- train of pulses
ii) comparator output
iii) tripping pulses

عنوان البحث:**مميز مقترح لحماية المحرك خلال البدء**

باللغة الإنجليزية:**”A proposed Discriminator for Motor Protection during starting “**

ملخص البحث

فى هذا البحث تم استحداث متمم لحماية المحرك أثناء بدء الحركة. حيث يقوم المتمم بالتمييز بين حالة الدوران الممتدة و حالة العضو الدوار الموقوف دون الاستعانة بإشارة من العضو الدوار. و تعتمد فكرة التمييز هذه على اكتشاف التغيير فى زاوية الوجه بين الجهد و التيار أثناء البدء. حيث تبلغ الزاوية قيمتها العظمى و التى تقترب من الـ ٩٠ درجة عندما يكون العضو الدوار موقوف و تقل هذه الزاوية تدريجيا حتى قيمتها الصغرى عند السرعة الكاملة للعضو الدوار. و يتم اكتشاف التغيير فى الزاوية عن طريق القياس المتتابع للزاوية و المقارنة بين قيمتين عند نقطتين متباعدتين بفترة ثابتة فى دورة متكررة. و يعتمد زمن هذه الدورة المتكررة على زمن بدء المحرك ودقة المقارنة. كما تم تقدبم تحليل نظرى لبيان كيفية تغيير زاوية ا لوجه بين الجهد والتيار خلال فترة البدء عند جهد منبع مختلف لمحركات ذات مقنن مختلف. كما تم استعراض فكرة تصميم المتمم. و قد تم بناء نموذج معملى للمتمم باستخدام الدوائر المجمعة الرقمية. و فى هذا النموذج تم جعل الفترة بين النقطتين المتباعدتين قابلة للضبط و تساوى: (ن-٢)/ت حيث ن هى قاسم عداد رقمى عشرى و تتراوح ما بين ٤-١٠٠ , ت هو تردد المنبع. و قد أوضحت النتائج المعملية أن استجابة هذا النموذج تعزز الفكرة المقترحة.