IMPLEMENTATION OF A SINGLE PHASING PROTECTIVE CIRCUIT FOR THREE PHASE INDUCTION MOTORS

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Analysis of the induction motor failures show, that a significant number of motors are damaged due to single phasing. At such conditions the current increases rapidly and the motor is subjected to burnouts and consequently to long downfalls in the corresponding industry. Normally all motors are protected against thermal overloading by bimetal relays, but they are not always capable to ensure protection at single phasing. A secure protection is needed to trip the motor off in any case of single phasing especially for high power motors. The problems related to the motor protection against single phasing are discussed in this paper and for ensuring of such protection an electronic circuit is proposed and described. The circuit reacts immediately whenever a motor line current gets zero. A signal from this circuit switches off the motor starter on failures of anyone of the three phases. In such way the motor burnouts and downfalls are prevented.

Keywords: induction motor, overloading, single phasing, protection

1 INTRODUCTION

The three phase induction motors (IM) are widely used in the industry. The long-term motor life depends upon the proper selection of their protection. Studies in many countries show that the main reasons for motor failures are: thermal over loading as a result of voltage or load variations, single phasing or rotor blockages. Thermal overloading and single phasing make up to 44% of malfunction causes [1]. Due to these reasons the motor current increases and if protection does not operate on time, the IM overheats and burns out, causing down falls in the particular industry. The down falls and IM repairs are very costly and for instance the losses are millions of pounds per year in the UK [1].

In the majority of the IM applications bimetal over load relays (OLR) are used for motor thermal protection. The OLR are not always effective to protect the motor against single phasing. When one of the stator winding remains without voltage supply the motor continues to operate as a single-phase device, drawing power from the remaining two phases. This mode of operation is called single phasing and could occur for example when one of the fuses connected in each motor line blows.

The objectives of this paper are to describe the reaction of the bimetal OLR in any case of single phasing and to propose an electronic circuit for effective motor protection in such cases.

2 THERMAL PROTECTION OF INDUCTION MOTORS

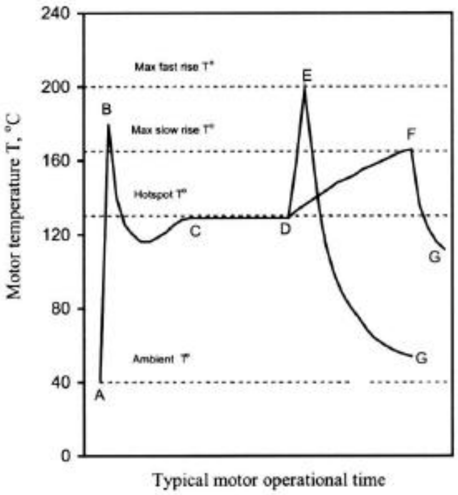
The most critical motor part in respect to thermal overloading is the winding insulation. Depending on the capabilities of the insulating materials to withstand long term operating temperatures the following classes are introduced, as shown in Table 1:

Table 1

Insulation Class	A	B	F	H
Long term (rated) operating temperature, °C	105	130	155	180
Allowable maximum slow rise temperature, °C	140	165	190	215
Allowable maximum fast rise temperature, °C	180	200	225	250

The long term operating (rated) temperature is the maximum allowable temperature in a spot of a coil, or so called hot-spot temperature. The hot-spot temperature is higher than the average temperature of the coil by up to10 degrees [1, 2].

The life expectancy of the insulation and of the motor depends mainly upon the hot-spot temperature. If the motor operates continuously at its rated temperature the life expectancy could be more than 10 years. If the same motor operates continuously at a temperature 10 °C higher than the rated, the life of the IM will be halved according to Montsinger rule. It follows that the ideal protection should trip the motor out whenever the hot spot temperature is overshot. However this is not worth in respect to the continuity of the industrial process involving induction motors. This process must continue uninterrupted as long as possible and nuisance switching off should be avoided. For short periods of time, like at startup, higher temperatures are allowed because they do not affect the aging of the motor insulation. IEC [3] accepted that the coil temperature, measured after tripping by the resistance method, could be higher than the long-term temperature, as shown in Table 1. Slow rise temperatures are typical for long but small overloading whereby the motor and the bimetal temperatures are equal and change in exactly the same way. For class B this temperature is 165 °C. Fast rise temperatures are due to large but short term overloading like short-circuit or single phasing currents, or sudden blockage of the rotor. In such cases the coil temperature increases adiabatically, the bimetal temperature is lower and differs significantly from that of the coil. Fast rise temperatures are very critical and if overshot they lead to immediate insulation damage like cracking, breakdowns, melting or burnouts. Fast rise temperature for class B materials is 200 °C. A typical thermal process is shown in Figure 1.



A – Startup of the motor;
B - Temperature pick at startup;
C - The hot spot temperature is established;
D - Fault occurs;
DE - Fast temperature rise due to short circuit or single phasing current;
E - OLR trips the motor off (T < 200°C);
DF - Slow temperature rise due to small overloading;
F - OLR trips the motor off (T < 165°C);
EG and FG - Cooling characteristics.

Figure 1. Typical temperature characteristics

This shows the importance of a correctly chosen and set up thermal protective device, which will keep the motor temperatures in the allowable limits.

Contemporary IM have very limited capabilities to withstand the thermal overloading because of the well known trend for maximum utilization of the materials and reduced costs of production. Due to this motor damages occur continuously.

The main reason for this is that protection against small but long term overloading cannot be achieved very easily. The OLR cannot reflect precisely the heating and cooling of the IM because they are very different bodies in respect to volume, construction and cooling surfaces. The bimetal thermal time-constant is smaller than that of the motor and the OLR heats and cools faster. The motor is a complex body comprising copper windings, ferromagnetic parts and insulation. The motor has variable thermal time-constant because the heating is accounted by different motor parts. In case of small but long overloading all motor parts (stator, rotor, windings, insulation) determine the temperature, its rise and the thermal time-constant. In case of sudden large but short term overloading the temperature, its rise and the thermal time-constant depend upon the winding copper only. The thermal time-constant in this case is smaller than that in the previous one. Between these two extreme cases there are many other related to other constants.

The action of an OLR is determined by the time-current characteristics, which show the tripping time versus overload current at cold and hot stages. The requirements to bimetal time-current characteristics are standardized [4] and shown in Table 2.

Table 2

Current ratio I/I_r 3-phase supply	Current ratio I/I_r Single phasing	Trip Time Cold OLR	Trip Time Hot OLR
1.05	-	>2 hours	-
1.2	1.32	-	< 2 hours
1.5	1.65	-	< 2 min
6.0	-	> 2 sec	
6.0	-	> 5 sec	

Here I is the operating motor current and
I_r is the rated motor current

As it is shown in Table 2, the trip current of the OLR at single phasing is higher than the current at normal supply. A current ratio of 1.32 is recommended instead of 1.2 and a ratio of 1.65 is replacing the ratio 1.5. This is due to the fact that at single phasing only two bimetals are heated by the current and they cannot produce the necessary mechanical force to activate the motor starter unless the trip current is increased.

Typical time-current characteristics are shown in Figure 2. Each time-current characteristic represents the average time of response for any overload current. Actually there is an area of dissipation around any characteristic, which represents the range of responses. The dissipation is due to manufacturing tolerances and material property inconsistencies [5]. The OLR time-current characteristics match the motor heat-damage curve, which shows the duration of any overload current not damaging the motor.

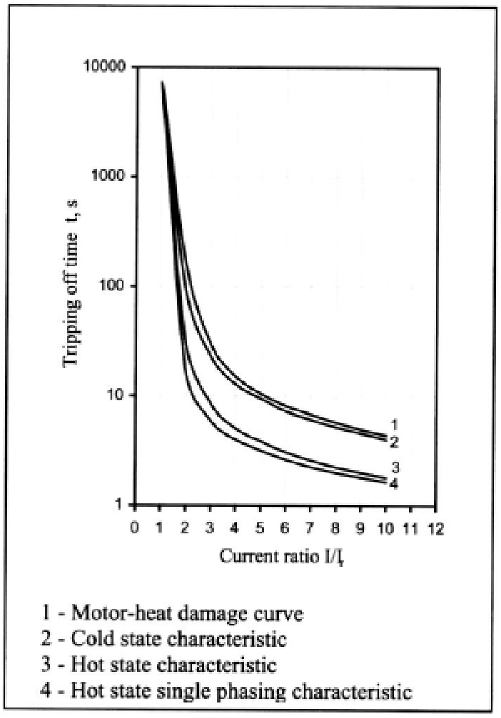


Figure 2. Bimetal time-current characteristics

The OLR time-current characteristic reflects the following overload conditions:

Case 1. The IM is overloaded with small currents in the range of $I = (1.05 \text{ to} 1.2)\ I_r$. This is due to small load or voltage variations. Under these conditions the motor could operate for a long time period and should be tripped out at a time of about 2 hours, whereby the aging of the insulation will not be affected. The action of the OLR in this case is not very precise, because of the nature of the time-current characteristic and the significant area of time-response dissipation. At the same overloading currents one and the same OLR could give very different time-responses.

Case 2. The IM is overloaded with currents in the range of $I = (1.2 \text{ to } 1.5)\ I_r$ due to light overloading. The tripping time for a current of $1.5I_r$ should be less than 2 minutes to avoid overheating and burnouts.

Case 3. The motor is overloaded with currents in the range of $I = (1.5 \text{ to } 6)\ I_r$ due to single phasing, periodical startups, impeded startups or motor reverses. The normal startup takes a few seconds whereby the current declines to its rated value. In case of impeded startup the OLR should trip the motor out after a time slightly longer than the normal startup time.

Typical current curves for different startups are shown in Figure 3.

When the motor starts on no-load the tripping time should be slightly longer than 2 seconds.

Starting period of a fully loaded motor is longer and the tripping should occurs after a period of 5 seconds.

At heavy-duty start the motor should be tripped after a time period longer than 15 seconds. These time intervals are selected to allow the motor to accelerate during the starting period.

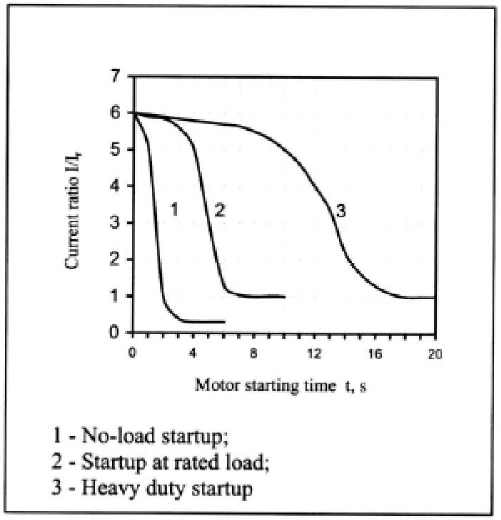


Figure 3. Current characteristics at different loads

3 MOTOR PERFORMANCE AT SINGLE PHASING

Single phasing could occur at startup or at running conditions, when the motor is fully loaded, under-loaded or overloaded. The stator windings could be star or delta connected. The reaction of the bimetal

OLR is described below assuming that it is set at the rated line motor current.

3.1 Single phasing at startup

At single phasing a motor cannot develop starting torque because a single-phase current produces a pulsating magnetic field. This field has two components rotating in opposite directions-forward and reversed. Both components produce equal torques acting in opposite directions and due to this the motor cannot start.

A. Star-connected motor (Figure 4)

The starting current I_{L3} of a star connected motor is 3-times less than the starting current of the same motor if it is delta connected. Usually $I_{L3} = (2 \text{ to } 2.66)\, I_r$.

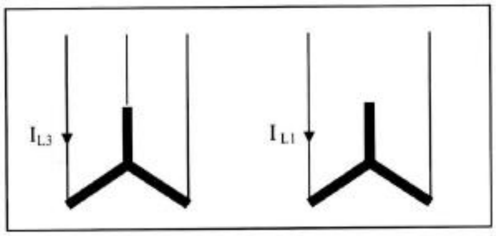


Figure 4. Star connected windings at normal supply and at single phasing

At single phasing one of the windings is without current. The line current equals the phase current and flows in the remaining two phases.

At normal supply the current is:

$$I_{L3} = \frac{V}{\sqrt{3}Z} \quad (1)$$

At single phasing the current is:

$$I_{L1} = \frac{V}{2Z} = \frac{\sqrt{3}}{2} I_{L3}, \qquad I_{L1} = \frac{\sqrt{3}}{2}(2 \text{ to } 2.66) I_r \quad (2)$$

Where: I_{L3} is the line current at normal supply;
I_{L1} is the line current at single phasing;
I_r is the rated current;
V is the line voltage;
Z is the phase impedance.

It follows that $I_{L1} < I_{L3}$ but still larger that the rated current and the OLR will trip the motor off the circuit.

B. Delta-connected motor (Figure 5)

The starting current at normal supply for delta-connected motors is $I_{L3} = (6 \text{ to } 8)\, I_r$.

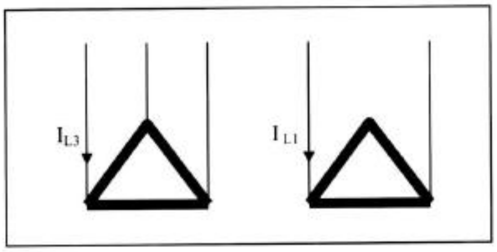


Figure 5. Delta connected windings at normal supply and at single phasing

At single phasing all windings carry currents. One winding carries 2/3 I_{L1} and the other two carry 1/3 I_{L1} of the line current I_{L1}.

At normal supply the phase current I_{ph} is:

$$I_{ph} = \frac{I_{L3}}{\sqrt{3}} = \frac{(6\,to\,8)I_r}{\sqrt{3}} = (3.46\,to\,4.62)I_r \quad (3)$$

At single phasing:

$$I_{L1} = \frac{3V}{2Z} = \frac{3I_{L3}}{2\sqrt{3}} = \frac{\sqrt{3}}{2} I_{L3} = (3\,to\,4)I_r \quad (4)$$

$$\frac{1}{3} I_{L1} = \frac{\sqrt{3}}{6} I_{L3} = (1.73\,to\,2.3)I_r \quad (5)$$

$$\frac{2}{3} I_{L1} = \frac{I_{L3}}{\sqrt{3}} = (3.46\,to\,4.62)I_r \quad (6)$$

It is clear again that the starting line current I_{L1} is smaller than the line current I_{L3}, as at the star connected motors. The maximum phase currents at single phasing and at normal supply are equal. At single phasing an OLR set at the rated current will prevent damages or burnouts of the motor.

3.2 Single phasing of a running motor

3.2.1 Motor at rated load

If single phasing occurs during the normal operation of a fully loaded motor the speed of the motor reduces and the current sharply increases (Figure 6) because the motor should deliver the same output power to the load. Figure 6 shows the line current as a function of the load at normal supply and at single phasing.

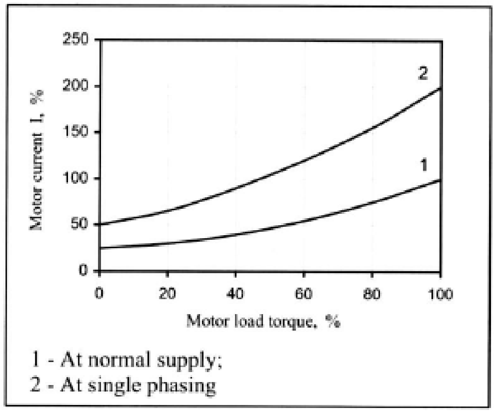


Figure 6. Current-load characteristics

The following relations are valid:

$$P_{out3} = \sqrt{3}VI_{L3}\cos\varphi_3\eta_3 = P_{out1} = VI_{L1}\cos\varphi_1\eta_1 \qquad (7)$$

$$I_{L1} = \sqrt{3}VI_{L3}\left(\frac{\cos\varphi_3\eta_3}{\cos\varphi_1\eta_1}\right) = \alpha\sqrt{3}I_{L3} \qquad (8)$$

Where: $P_{out1} = P_{out3}$ are the powers delivered to the load at single phasing or at normal supply and

$\alpha = \dfrac{\cos\varphi_3\ \eta_3}{\cos\varphi_1\ \eta_1}$ is a coefficient specifying the additional motor overloading due to different values of the power factors and the efficiencies at normal supply and at single phasing.

At normal supply and full load the small IM, having power up to 11kW, and medium power IM, having power up to 75kW, operate with power factors and efficiencies in the range of 0.75 to 0.9, depending upon the size and construction of the motor [2, 6]. Efficiency is essentially constant over a range from 50 to 125% of full load. Power factor is more affected by the under loading. At no-load conditions the power factor and the efficiency have very low values and fall below 0.2.

At single phasing both the power factor and the efficiency have 5 to 10% lower values at any load point, because of the increased magnetizing current and the action of the "reversed" magnetic field. The decrease is more significant at no-load conditions.

A. Star-connected motor

At single phasing the line current increases $\alpha\sqrt{3}$ times and the OLR will trip the motor out in a time prescribed by the standard.

B. Delta-connected motor

At normal supply the phase current is $I_{ph} = \dfrac{I_{L3}}{\sqrt{3}}$.

At single phasing the line current increases $\alpha\sqrt{3}$ times and

$$I_{L1} = \alpha\sqrt{3}I_{L3}$$

(9)

A current of

$$\frac{2}{3}I_{L1} = \alpha\frac{2}{\sqrt{3}}I_{L3} = 1.155\alpha I_{L3} = \alpha 2I_{ph}$$

(10)

flows in one of the windings and a current of $\frac{1}{3}I_{L1} = \alpha I_{ph}$ in the other two windings.

At single phasing the fully loaded motor will be tripped off the circuit in a time of t_1 seconds depending upon the current I_{L1} (eq.9). Since one of the windings is overloaded with a larger current of $2\alpha I_{ph}$ (eq.10) the motor should have been tripped off in a shorter time $t_2 < t_1$ to prevent possible burnouts. This possibility is due to the fact that the times t_1 and t_2 are close to each other and the trip time–current characteristic has a wide area of dispersion.

In general the delta-connected motors are not surely protected at single phasing and the burnouts are quite possible.

3.2.2 Single phasing of a under loaded motor

When the motor is under loaded, or operates at no load, the line current is reduced (Figure 6).

The possibilities of protection of a medium power motor are cleared in the following example, where a 120-A, 380-V, 3-phase squirrel cage induction motor is protected by a bimetal OLR set at the rated line current. The results of the calculated powers, line and phase current and trip times are given in Table 3.

Table 3

Load, %	25	50	75	100	125
I_{L3}, A	30	60	90	120	150
$I_{ph3} = I_{L3}/\sqrt{3}$, A	17.3	34.6	52	69.3	86.6
$S_{in3} = \sqrt{3}\, I_{L3}\, 380$, KVA	19.7	39.5	59.3	79	98.7
Power factor $\cos\varphi_3$	0.54	0.72	0.80	0.84	0.83
Efficiency η_3	0.77	0.86	0.89	0.88	0.83
$P_{out} = S_{in3}\cos\varphi_3\eta_3$ kW	8.2	24.5	42.2	58.4	68.4
Power factor	0.33	0.56	0.71	0.8	0.81

$\cos\varphi_1$					
Efficiency η_1	0.6	0.78	0.85	0.86	0.81
$S_{in1}=P_{out}/\cos\varphi_1\eta_1$, KVA	41.4	56.1	69.9	84.9	104
$I_{L1} = S_{in1} / 380$, A	109	147	184	223	274
$I_{ph1} = 2/3.\ I_{L1}$	73	98	123	149	183
$I_{L1}/120$	0.91	1.22	1.53	1.86	2.3
Trip off time t_1 due to I_{L1}, s	**400**	**65**	**18**	**11.5**	**8**
$I_{ph1}/69.3$	1.05	1.41	1.77	2.15	2.64
Trip off time t_2 due to I_{ph1}, s	**120**	**24**	**13**	**9**	**7**
Coefficient α	**2.1**	**1.42**	**1.18**	**1.08**	**1.05**

It is clear that when the motor is under loaded one of the windings is exposed to overheating and burnouts, because the time t_2 is significantly less than the time t_1 (see cases of 50% and 75% load). Single phasing protection is highly recommended.

When the motor is fully loaded or overloaded the trip times t_1 and t_2 are close to each other. They fall into one and the same area of dissipation of the trip-time-current characteristic and the protection is uncertain. Due to this it is better if the motor is supplied with a single phase protection.

The analysis of the motor performance and the fitting of the OLR time-current characteristics show that in many cases the OLR could not protect the motor against damages due to single phasing. Therefore it is better to provide a separate protection against it.

4 SINGLE PHASING PROTECTIVE CIRCUIT

Thermo bimetal relays are usually used to protect induction motors against over loading. Since this protection is not very reliable in cases of single phasing some other methods for single phasing protection are used. For example [7] three current relays (CR) could be connected in each motor line and when the current in one of the phases becomes zero the corresponding CR will open its contact and will interrupt the control circuit of the motor. The disadvantage of such protection is the need of shunting the CR contacts during the start-up. This protection cannot operate if the stator coils are delta connected and the circuit is interrupted somewhere inside the coils.

In other cases protective circuit with electronic elements is used [8]. It protects the motor in cases of overloading, short circuit currents and single phasing. The main disadvantage is that the number of electronic elements and electromagnetic relays is very large and due to this the whole protection is very unreliable and costly.

In this paper a protective circuit against single phasing is proposed and shown in Figure 7. Current transformers are connected in each one of the motor lines. They are simulated by the sources CT1, CT2 and CT3, producing voltage signals shifted at 120°. These voltages correspond to the current in each of the motor lines. The signals are rectified and filtered by sets of rectifiers and filters accordingly. Further the three filtered voltages are applied to a NAND circuit. If currents are present in the three motor lines, high-level signals (logical 1) are applied to all NAND inputs and its output is low-level signal (logical 0) [9, 10, 11]. Due to this the intermediate relay (IR) is not energized and through its normally closed contact (NCC) the operating voltage is applied to the coil of the motor starter. The motor operates in its normal conditions.

In case of single phasing, the voltage produced by one of the sources CT1, CT2 or CT3 is zero and one of the NAND inputs will be a low-level signal (logical 0).

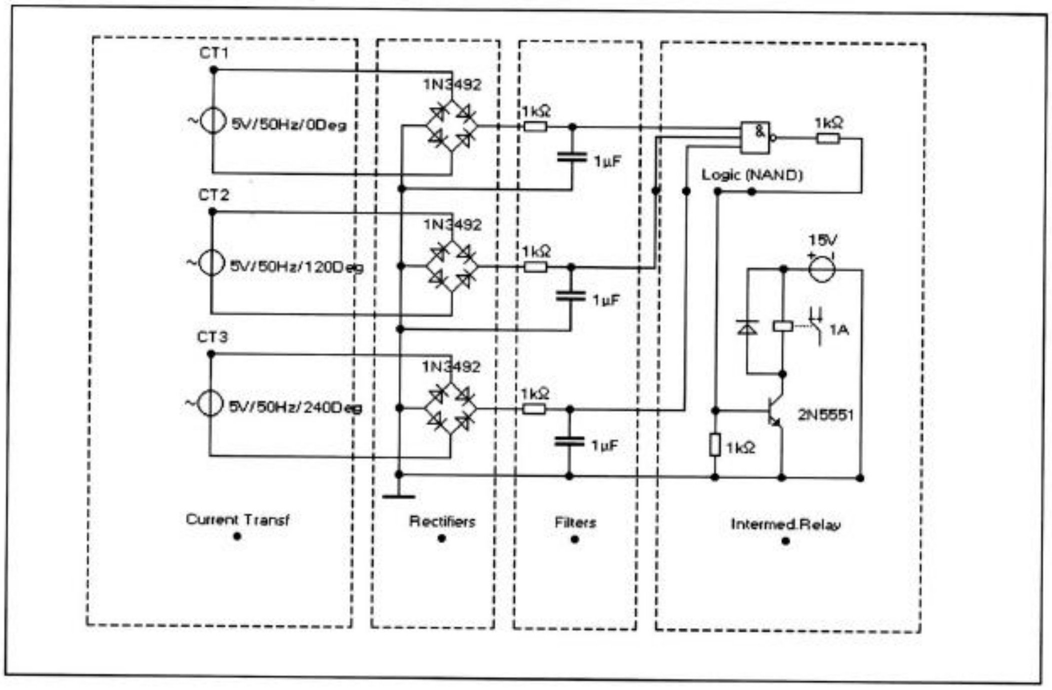


Figure 7. Circuit diagram of the single phasing protection

The NAND output becomes high-level signal (logical 1), the IR is energized and opens its NCC. The coil of the main starter is off and immediately switches the motor off. In addition to this a sound or a light signal could be produced to indicate the voltage failure in one of the phases.

Compared with any other existing system for single phasing protection, the described circuit has advantages in terms of its simplicity, low expenses and reliability. It can be implemented for a cost of 50$ to 100$ depending on the motor size, which is 2 to 3 times less than the cost of the existing solutions.

5 CONCLUSIONS

The induction motors are widely used in industry and they have to be properly protected against damages due to thermal overloading. Single phasing could lead to burnouts and costly fall downs. There are motor applications where the single phasing and the impossibility of the motor restart are dangerous for the driven mechanism. Due to this the motor should be tripped off, or at least a signal should be provided. To ensure protection against single phasing damages an electronic circuit is proposed and tested. The main components of this circuit are current transformers, sets of rectifiers and filters, a logical circuit and a low power intermediate relay. All these elements are market available, not very bulky and not very expensive. The protective circuit is suitable for any type and size of motors and could be activated at any case of single phasing and at any load conditions of the motor.

In case of single phasing the motor is immediately switched off the circuit. In addition to this a light or sound signal could also be produced to indicate the failure of one of the phases.

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