Automatic Overload and Single Phase Protection of Three-Phase Motors

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***Abstract*—This paper contributes for the analysis and the suggested protection against single phasing of three-phase induction motors. Practice is showing that significant number of three-phase motors is damaged due to single phasing. At such conditions the current increases considerably and the motor is subjected to burnout. Accordingly, this may cause long production interruptions in the relevant industries. Generally all motors are protected against thermal overloading by bimetal relays, but they are not always capable to ensure protection at single phasing. As a result of the current research, a reliable electronic protection is proposed that can trip-off any three-phase motor in a case of single phasing. Such protection is especially valuable when applied to high power motors. The suggested protection is designed to react instantly whenever anyone of the motor line currents becomes zero. A signal from the protecting circuit switches-off the motor starter in case of failures of anyone of the three phases.**

Keywords—three phse motor; single phasing; electronic protection;

I. INTRODUCTION

Long-term three-phase motor operation depends upon the proper selection of its protection. 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 the three-phase motor lines "blows" and disconnects one of the stator windings. Surveys in many industries show that the main reasons for three-phase motor failures are the thermal overloading as a result of voltage or load variations, rotor blockages or single phasing. Thermal overloading and single phasing cause up to 44% of malfunction cases [1].

Due to the phenomenon of the single phasing, the current of the motor increases considerably. If the protection does not operate instantly, the motor overheats and its operation fails, causing downfalls in the particular industry.

In the majority of the applications bimetal over load relays (ORL) are used for the motor protection. These relays are not always effective to protect the three-phase motor against single phasing. The objectives of this research are to describe the reaction of the bimetal OLR in cases of single phasing and to propose an automatic electronic single phasing protection.

II. THERMAL AND OVERLOAD RELAYS PROTECTION OF THREE PHASE 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 [2], as shown in Table 1:

TABLE I

Insulation Class	A	B	F	H
Long term operating temperature, [^{o}C]	105	130	155	180
Allowable maximum slow rise temperature, [^{o}C]	140	165	190	215
Allowable maximum fast rise temperature, [^{o}C]	180	200	225	250

The long term operating (rated) temperature is the maximum allowable temperature in 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 three-phase 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^{o}C higher than the rated, its life will be halved according to Montsinger rule [2], [3]. It follows that the ideal protection should trip out the motor whenever the hot spot temperature is exceeded. 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 switching-off should be avoided.

For short periods of time, like at startup, higher temperatures are allowed since they do not affect the aging of the motor insulation. It is accepted that the coil temperature, measured after startup by the resistance method, could be higher than the long-term temperature [3], [4] as shown in Table I. 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 and the bimetal temperature differs significantly from that of the coil. Fast rise temperatures are very critical and if exceeded 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.

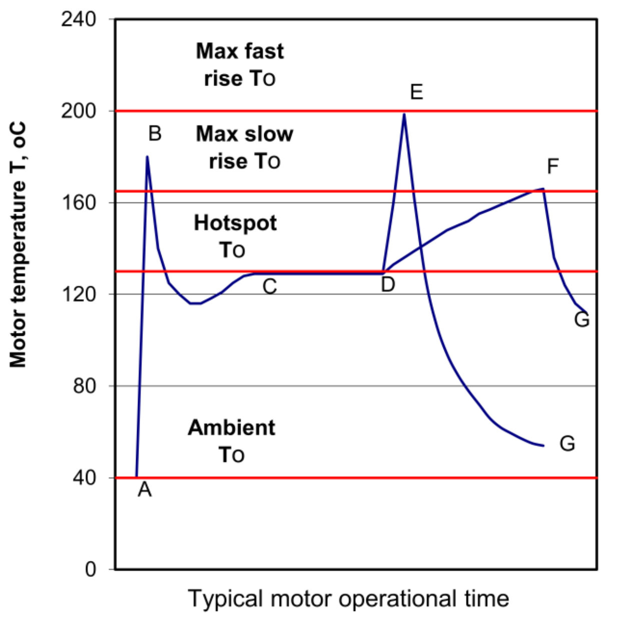

Fig. 1. *Typical Temperature Characteristics*

The description of the elements of the temperature characteristics is as follows:

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- Cooling characteristics.

FG- Cooling characteristics.

The elements of the temperature characteristics show the importance of a correctly chosen and set up thermal protective device, which will keep the motor temperatures in the allowable limits. The existing three-phase motors 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 these facts, motor damages occur frequently.

The main reason for these motor failures is that the protection against small, but long term overloading cannot be achieved very easy. The OLR cannot reflect precisely the heating and cooling of the induction motors since they are with 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 three-phase motor is a complex device containing of copper windings, ferromagnetic parts and insulation. The motor has variable thermal time-constant since the heating depends on the different motor parts [5]. 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 situation. Between these two extreme cases there are many other set of circumstances related to other constants.

Typical experimental time-current characteristics are shown in Figure 2. Each characteristic represents the average time of response for any overload current. The OLR time-current characteristics match the motor heat-damage curve, which shows the duration of any overload current not damaging the motor.

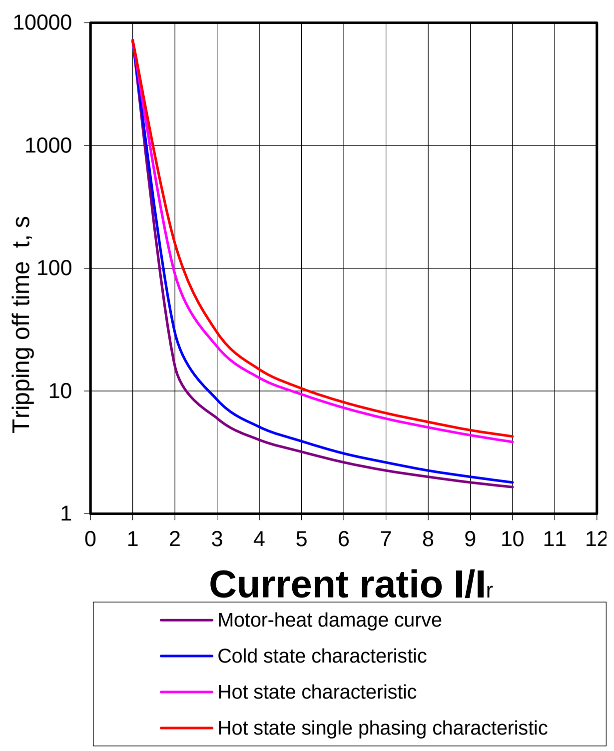

Fig. 2. *Bimetal Time-Current Characteristics*

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

<u>Case 1:</u> The three-phase motor is overloaded with small currents in the range of I = (1.05 to1.2) I_R, where I_R is the rated current of the motor. 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.

<u>Case 2:</u> The three-phase motor is overloaded with currents in the range of I = (1.2 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.

<u>Case 3:</u> The three-phase motor is overloaded with currents in the range of I = (1.5 to 6) I_R due to single phasing, periodical startups, impeded startups or motor reverses. The normal startup takes a few seconds after which the current declines to its rated value and the motor is not tripped out. In case of impeded startup the OLR should trip out the motor 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.

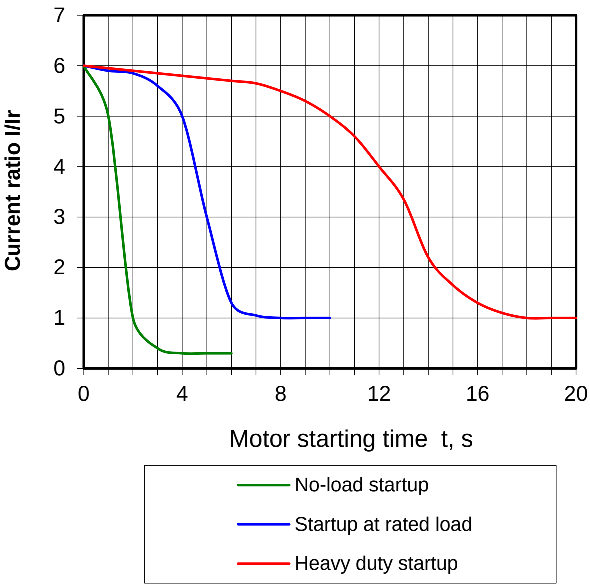

Fig. 3. *Current Characteristics at Different Loads*

III. 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 over load relay (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, since a single-phase current produces a pulsating magnetic field with two components rotating in opposite directions - forward and reversed. Both components produce equal torques acting in opposite directions and due to this fact the motor cannot start. This phenomenon can be examined for the two possible motor connections:

A. Star-connected motor

The starting current I_{L3} of a star connected motor is three times smaller, compared to the starting current of the same motor if it is delta connected. The starting current of a star-connected motor at single phasing usually is I_{L3} = (2 to 2.66) I_R.

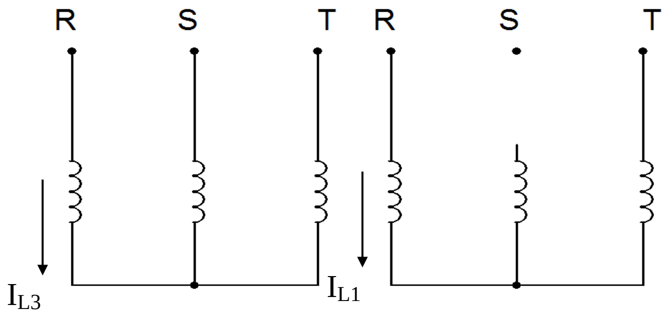

Fig. 4. *Star Connected Windings at Normal Supply and at Single Phasing*

At single phasing, there is no current through one of the windings. The line current equals the phase current and flows in the remaining two phases [6], [7].

At normal supply the current is:

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

While, at single phasing the current is increased to:

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

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 it is still larger that the rated current I_R and the OLR will trip-off the motor the circuit.

B. Delta-connected motor

The starting current at normal supply for delta-connected motors is I_{L3} = (6 to 8) I_R.

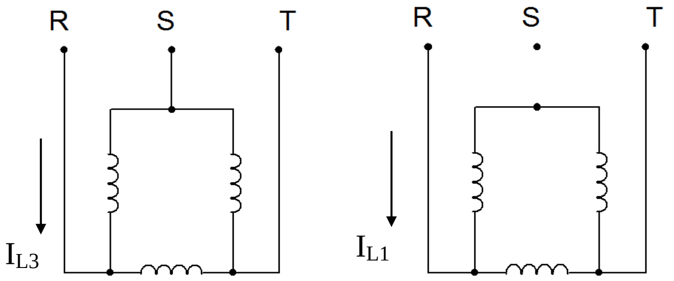

Fig. 5. *Delta Connected Windings at Normal Supply and at Single Phasing*

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

$$I_{PH} = \frac{I_{L3}}{\sqrt{3}} = \frac{(6\,to\,8)I_R}{\sqrt{3}} = (3.46\,to\,4.62)I_R \qquad (3)$$

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

At single phasing:

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

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

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

It is clear again that the starting line current I_{L1} is smaller than the line current I_{L3}, or $I_{L1} < I_{L3}$, like at the star-connected motors. At the same time, the maximum phase currents at single phasing and at normal supply are equal. At single phasing bimetal over load relays (ORL) 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, since the motor should deliver the same output power to the load.

The following relations are valid:

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

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

where: P_{out1} = P_{out3} are the powers delivered to the load at single phasing or at normal supply;

$\alpha = \frac{\cos\varphi_3\,\eta_3}{\cos\varphi_1\,\eta_1}$ 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.

The line current as a function of the load at normal supply and at single phasing are presented at Fig. 6.

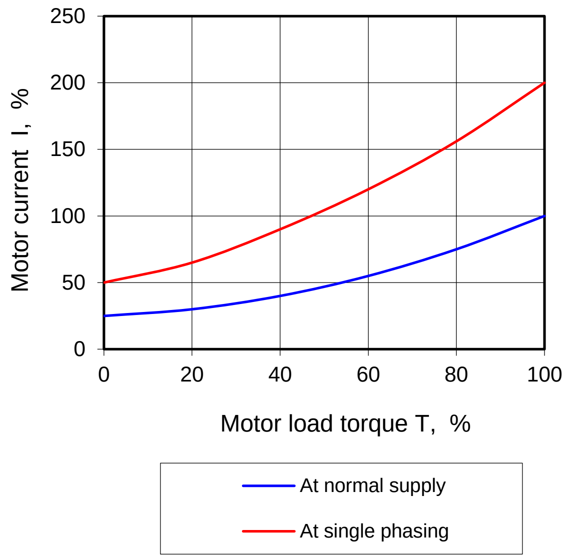

Fig.6. *Current-Load Characteristics*

At normal supply and full load a small three-phase induction motor, having power up to 11kW, and medium power motor, 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 [8], [9]. The efficiency is more or less 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. In this case, the OLR will trip-out the motor in a time prescribed by the standard.

B. Delta-connected motor

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

In case of single phasing the line current increases $\alpha\sqrt{3}$ times and it becomes equal to $I_{L1} = \alpha\sqrt{3}\, I_{L3}$. A current of $2/3 I_{L1} = \alpha 2/\sqrt{3} I_{L3} = 1.155\alpha I_{L3} = \alpha 2 I_{PH}$ flows in one of the windings, while a current of

$1/3 I_{L1} = \alpha I_{PH}$ in the other two windings.

At single phasing the fully loaded motor will trip-off the circuit after a time of t_1 seconds that depends on the current I_{L1}.

Since one of the windings is overloaded with a larger current of $2\alpha I_{PH}$, the motor should have been tripped-off in a shorter time $t_2 < t_1$ to prevent possible burnouts. However, the values of the times t_1 and t_2 are close to each other and therefore the trip-off time–current characteristic has a wide area of dispersion. Nevertheless, the delta-connected motors usually are not protected for single phasing and the motor burnouts are quite possible.

3.2.2 Single phasing of a under loaded motor

When a three-phase motor is under-loaded, or operates at no load, the line current is considerably reduced, as seen at Figure 6.

The possibilities of protection of a medium power motor are clarified at the following example, where a 120-A, 380-V, three-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 II.

TABLE II RESULTS FOR THE CASE OF PROTECTION OF A MEDIUM POWER THREE-PHASE MOTOR BY A BIMETAL ORL

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 $\cos\varphi_1$	0.33	0.56	0.71	0.8	0.81
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
$I_{PH1} = 2/3.\, I_{L1}$, A	73	98	123	149	183
$I_{L1}/120$, A	0.91	1.22	1.53	1.96	2.3
Trip off time t_1 due to I_{L1}, s	**400**	**65**	**18**	**11.5**	**8**
$I_{ph1}/69.3$, A	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 obvious that when the motor is under-loaded, one of the windings is exposed to overheating and burnouts, since the time t_2 is significantly less than the time t_1 (comparing the cases of 50% and 75% load). Apparently, in these circumstances, a single phasing protection is highly recommended.

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

The analysis of the motor performance and 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 strongly recommended to provide an independent automatic protection that would prevent the single phasing and the damaging consequences of it.

IV. Single Phasing Protection Circuit

The suggested in this research simple protection circuit, preventing the damaging consequences of a single phasing is presented in Fig. 7.

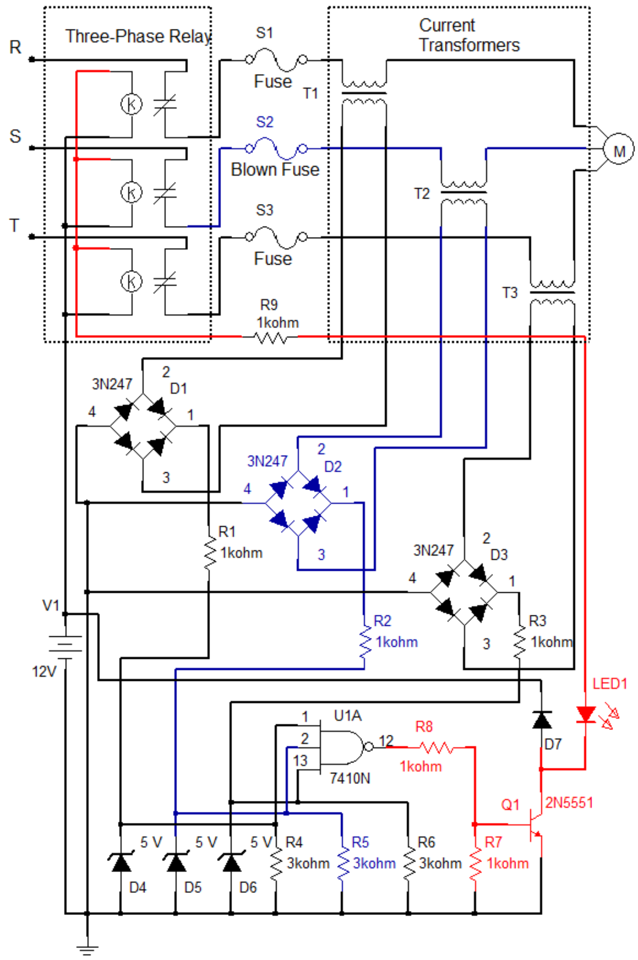

Fig. 7. *Single Phasing Protection*

The operation of the circuit at Fig.7 is demonstrating a typical protection from single phasing. The three-phase inductive motor is connected to the supply line terminals *R*, *S* and *T* via the normally closed contacts of a three-phase relay, a set of three fuses and the primary coils of three current transformers *T1, T2* and *T3*. The voltages at the secondary windings of these transformers are rectified by three independent bridge rectifiers *D1*, *D2* and *D3*. The three rectified voltages are applied to three independent voltage stabilizers employing the Zener diodes *D4*, *D5* and *D6*. The purpose is the output voltages of each one of the stabilizers to be equal to 5V that corresponds to logical levels of 1. These output voltages are applied to a tree-input NAND gate [10], [11].

At normal operation of the three-phase motor, all current transformers produce secondary voltages that are further rectified and stabilized. All the inputs of the NAND gate are equal to logical 1 and its output is logical 0. The transistor *Q1*, operating as an electronic switch is in “off” state and the low power intermediate three-phase relay coil is not energized. Since the relay is with normally closed contacts, it is providing supply current to all of the phases of the three-phase motor.

In case of a “blown” fuse *S2,* as shown in Fig.7, a single phasing occurs, the outputs of the second transformer *T2* and accordingly of the second bridge rectifier *D2* become 0V. Then one of the inputs to the NAND gate (in this case the input applied terminal 2), becomes logical 0. As a result the NAND output becomes logical 1 and via the transistor *Q1*, the three-phase relay is energized and disconnects instantly the three-phase motor supply, in this way protecting it from the damaging effects of a single phasing. A light-emitting diode *LED1* is indicating the tripping-off of the three-phase motor due to the failure of one of the phases and the developed condition of single phasing. The diode *D7* protects the transistor *Q1* during the switching processes.

V. CONCLUSIONS

The tree-phase induction motors are widely used in the industry and they have to be properly protected to prevent damages due to thermal overloading and single phasing. There are motor applications where the single phasing and the impossibility of motor restart are unsafe for the driven mechanism. Due to these circumstances the motor should be tripped-off.

To ensure motor protection and preventing damages due to single phasing, a simple electronic circuit is proposed and tested. The operation of the suggested circuit was initially simulated with the aid of the software package “Multisim”. Further a prototype was built and tested successfully in laboratory conditions. Its simplicity and easy implementation can be very useful for industry [7], [12], [13]. The protective circuit is suitable for any type and size of three-phase motors and is completely reliable for any case of single phasing. If a single phasing occurs, the motor is instantly switched-off from the circuit. In addition, a light or sound signal could also be produced to indicate the failure of one of the phases.

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