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DESIGN AND DEVELOPMENT OF AN AUTOMATIC THREE-PHASE SEQUENCE REVERSAL DETECTION AND CORRECTION FOR INDUSTRIAL EQUIPMENT STRUCTURE

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ABSTRACT

The occurrence of incorrect phase sequence in a three-phase power system has continued to be a major challenge to many organizations in Nigeria especially in industrial sector where equipment powered by three-phase supply predominates. This phenomenon which is otherwise known as phase reversal often arises when the order in which the three phases are positioned is inadvertently altered, perhaps consequent upon electric power restoration by utility supply or during maintenance on motor-driven machinery. Lack of protection against such phase-reversal on three-phase systems and other-phase rotation sensitive equipment results in severe disruption and huge damage to such equipment and personnel alike. A number of means have been adopted to mitigate this problem. However, the main drawback of some of the existing designs was their inability to automatically correct the phase reversal and ensure that supply to equipment was not disrupted. The designed and constructed device detects and automatically corrects phase reversal with the use of electrical circuit involving electromagnetic contactor incorporating timer relay at the heart of the controller. In addition, it also incorporates under/over-voltage and phase failure protection. This is to ensure that connected loads operate within their manufacturers' specified voltage limits and also are protected against any damage that could result in the event of a phase loss.

Keywords: Phase-sequence, Phase-reversal, Under-voltage, Protection, Phase-loss, automatic

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1. INTRODUCTION

Phase reversal in a three-phase system causes connected three-phase motors and other rotating equipment to run in the reverse direction. In many cases, this can lead to exceedingly huge damage to equipment and machinery as well as injury to personnel; especially in situations where the motor is coupled to cutting equipment or conveyor belts. Also, unintended reversal of direction can cause gear teeth to shear, chains to break and the impeller of submersible pumps to unscrew off the end of the motor shaft; causing injury to operators and great economic loss. A 3-phase monitoring system with a phase reversal protection is therefore inevitable where three-phase motors and other rotation sensitive three-phase equipment may be reversed phase connected at any time; especially on equipment transporting people, such as escalators or elevators. [1, 2]

Three-phase motors and such rotation sensitive equipment find application in areas such as mining, pumping, elevator, crane, generator, irrigation and so on. A three-phase alternating current supply consists of three phases with the same amplitude and a phase shift of displaced 120 degrees from each other as shown in Figure 2.1 and are generally represented as L_1, L_2 and L_3. Also, the voltage or current waves of these phases attain their respective peak values periodically one after the other in a particular order. [3]. This order in which each phase of a three-phase supply reaches its maximum value is what is referred to as Phase rotation or Phase Sequence [4, 5].

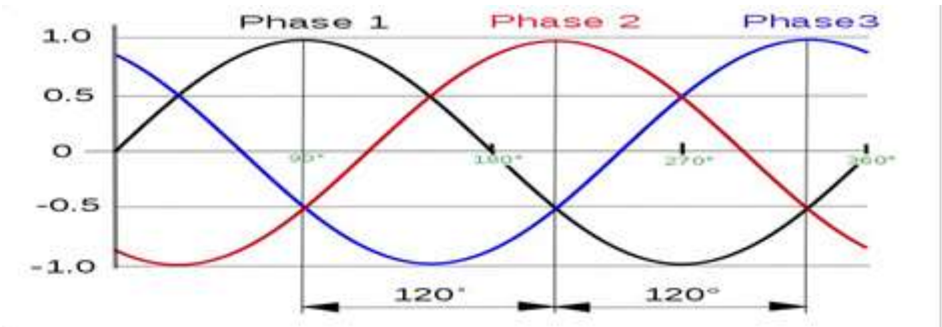

Figure 2.1: Three-Phase Alternating Current Waveform

For a 3-phase system, there are only two possible phase sequences, 1-2-3 and 3-2-1 corresponding to the two possible directions of alternator rotation; clockwise and anticlockwise as presented in Figures 2.2 and 2.3.[6].

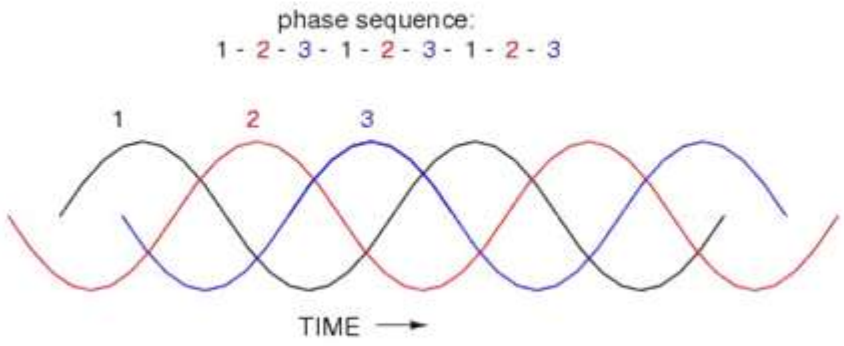

Figure 2.2: Clockwise rotation phase sequence: 1-2-3.

A 1-2-3 phase sequence means that first L1, then L2 and finally the L3 phase reaches its maximum value.

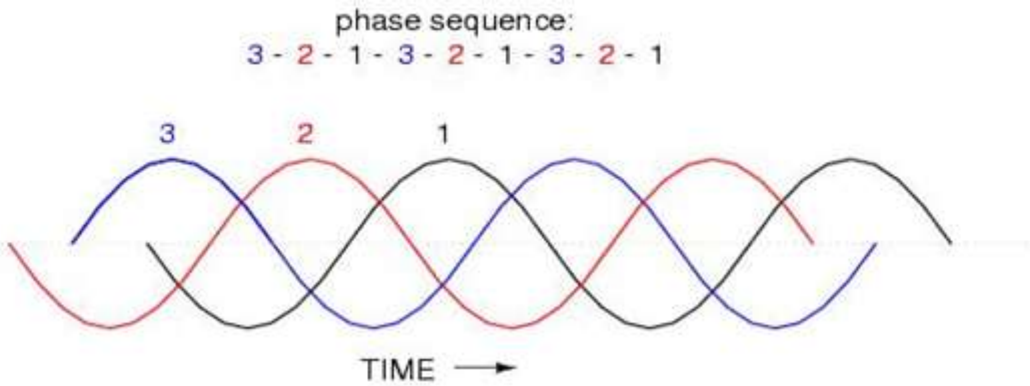

Figure. 2.3: Anticlockwise rotation phase sequence: 3-2-1.

However, in some cases, letters such as R, Y and B or A, B and C are used to represent the three phases; the two-phase sequences are respectively RYB or ABC and YRB or ACB. The phase sequence identification is purely a convention. There is actually no fixed standard as to which way the phases rotate (clockwise or anticlockwise). Wiring regulations only demand that the phase rotation of the supply is maintained throughout the installation [7]

2. PHASE REVERSAL (INCORRECT PHASE SEQUENCE)

Phase reversal occurs when any two phases of a three-phase supply are interchanged from the normal sequence. In most cases, it could be as a result of indeliberate error made during equipment installation such as when maintenance is performed on motor-driven machinery, modifications are made to the power distribution system, or when power restoration results in a different phase sequence other than it was before the power outage. This condition is destructive to rotation sensitive equipment such as elevators, screw and scroll compressors, centrifugal pumps, and conveyors as it causes them to run in the opposite direction. In many cases, this can cause serious damage to equipment and machinery; and injury to personnel if for instance; the motor is coupled to cutting equipment or belt conveyors. However, the voltage and current magnitudes are unaffected and will be the same whatever the sequence is.

The phase sequence of a three-phase supply can be reversed by interchanging the connection of any two phases of the three-phase supply.

2.2. Unbalanced Voltage

Any deviation in voltage and current waveforms from perfect sinusoidal in terms of magnitude or phase shift is termed as unbalance. Meanwhile, under unbalance voltage condition, the performance of three-phase motor is affected that leads to the supply of unstable negative currents [8].

According to [9], some common results of unbalance voltage includes drop in motor efficiency and early motor failure due to excess heat.Voltage imbalance on supply network are due to generation faults, unmatched impedance on transformer banks, or large single-phase loads on the three-phase network. Voltage imbalances in the customer installation on the other hand usually result from single-phase loads not evenly distributed across the 3-phase system. Single-phase-loads are often connected in such a manner that one-phase conductor carries significantly more current than the other two and the line-to-line voltages are affected.

2.3. Undervoltage

Under voltage is described by IEEE 1159 as the decrease in average voltage of a three-phase power system typically to 90% of nominal, at the power frequency for a period of time greater than 1minute. It can also be defined as a voltage which is below the optimum, operational or rated value of the system or a drop-in supply voltage below a definite value. It is usually caused by undersized or overloaded utility and facility transformer. Its damaging effects include equipment malfunction, premature failure, overheating due to high fault current and shut down; especially for motors [10].

2.4. Overvoltage

Overvoltage occurs when the supply voltage rises above the rated voltage of the connected equipment or load. Technically speaking, an overvoltage condition exists when the voltage exceeds the nominal voltage by 10% for more than 1minute [11]. It can cause excessive current to flow as well as create excessive voltage stresses. In both cases, the electrical insulation system of equipment can be degraded, reducing life of the equipment or causing damage to the equipment that results to cost increment [12].

2.5. Phase Loss (Phase Failure)

A phase failure occurs when one phase of a three-phase supply is open circuited. It is also referred to as single-phasing when a three-phase motor is running on two phases due to the loss of voltage on one phase. More current will flow through the other two lines and heat is generated in the stator winding. A phase loss that is not quickly detected and rectified can result in equipment failure or motor burnout.

3. SYSTEM DESIGN

The design involves monitoring of a three-phase supply network with a view to detecting irregularities in phase sequence in a 3-phase power network. It also incorporates a switching system that will connect the consumer installation when supply is confirmed suitable for use, and will disconnect it in the event of any of these anomalies. The system design block diagram, circuit connections as well as detailed description of mode of operation of the entire system are spelt out.

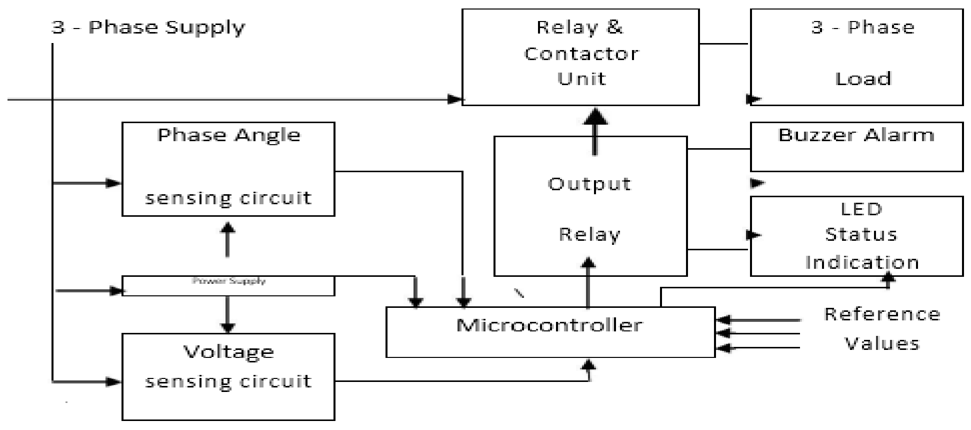

Figure 3.1: Block Diagram of an automatic phase reversal correction system, inco

3.1. Design Specifications

It is important to determine the specifications of the components needed in order to avoid system failure. This is obtainable using appropriate design calculations and analysis for the purpose of determining the rating(s) of the component or device.

The present work aims at designing for the control of a 5.5-kW three-phase squirrel-cage electric motor operating at 0.8 power factor lagging on a 400-Volt, 50-Hz supply.

In order to determine the size of the contactor to be used, the motor's full load current, **Im** is obtain thus:

$$P = \frac{\sqrt{3} \times V \times I_m \times \eta \times cos\theta}{1000}$$ **Equ 3.1**

where

nominal power (in kW)

V: is the voltage between phases

Im: rated current (in Amps)

η: per-unit efficiency

cosϕ: power factor.

From above,

$$\mathbf{Im} = \frac{P \times 1000}{V \times \eta \times cos\theta}$$ **Equ 3.2**

The system is designed for the control of a 5.5-kW three-phase squirrel-cage electric motor Operating at 0.8 power factor lagging on a 400-Volt, 50-Hz supply.

Assuming a premium efficiency class IE3, the motor efficiency is given as 89.6%.

Substituting all known parameters into Equation 3.2 gives

$$\text{Motor current } \mathbf{Im} = \frac{5.5 \times 1000}{\sqrt{3} \times 400 \times 0.896 \times 0.8}$$

$$= \mathbf{11.09A}$$

Based on the above motor current, a 12-A (AC-3) contactor will suffice. To choose a higher capacity would be extravagantly uneconomical, and bad engineering practice as the motor will not necessarily be operated at full rated nominal power.

To determine the size of the protective device, the nominal current would have to be calculated and the value obtained used to size the protective device. Table 3.2 below provides a summary of the power consumption of individual control component, obtained directly from their respective data sheets as well as the total load of entire control circuitry, calculated at an operating voltage of 220VAC.

For a single-phase circuit:

$$S = IV \qquad \text{Equ 3.3}$$

Where S = Apparent Power

I = Current

V = Voltage

Table 3.2: Control Components Power Consumption

Item	Description	Manufacturer/Part No.	Qty.	Nominal Power (VA)	Nominal current (mA)	Calculated Total nominal current (mA)
1	REVERSING CONTACTOR	Schneider LC2D12 M7	1	7	31.82	31.82
2	TIME DELAY RELAY	Omron H3DR – A	1	1.8	8.18	8.18
3	14-PIN (4PDT) RELAY	Schneider RXM4AB2P2	2	1.2	5.46	10.92
4	8-PIN (DPDT) RELAY	Carlo Gavazzi RCP8002230VAC	1	2.5	11.40	11.40
5	PILOT LIGHT Green Colour Red Colour	 XB7EV03MP XB7EV04MP	 1 2	 - -	 20.00 20.00	 20.00 40.00
6	ILLUMINATED BUZZER	Xider AD16-22SM	1	-	20.00	20.00
						142.32

3.2. System Description

The heart of the system is the three-phase supply monitoring relay which constantly monitors the incoming supply for phase sequence, phase failure, overvoltage and under-voltage. The microcontroller-based multifunction monitoring relay which integrates both voltage and phase-angle sensing circuits is self-powered, using the controlled supply for its power supply. The control voltage for the system is derived from one of the three phases. The monitoring relay, upon detection of a phase reversal, automatically signals a reversing contactor to correct the phase sequence; thereby guaranteeing continuity of supply. When the fault is corrected, the monitor will automatically reset and signal the reversing contactor to revert to original sequence. Moreover, upon detection of a phase angle displacement, following a phase failure; it cuts out supply to the contactor coil, thereby de-energizing the connected load(s) to avert a single-phasing condition as shown in fig. 3.4

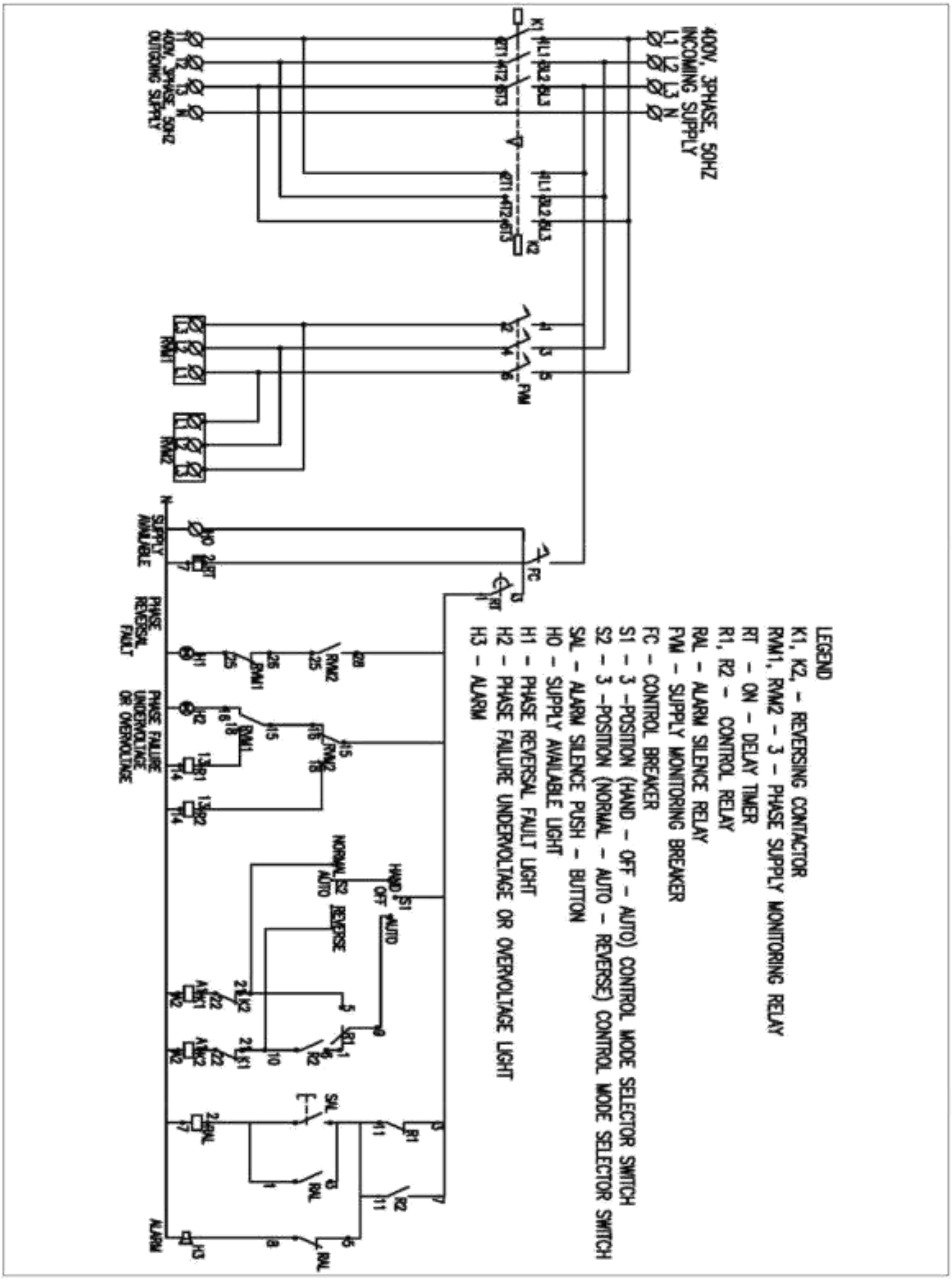

Figure 3.2 Schematic diagram of an automatic 3-phase sequence reversal and correction

The monitoring relay also monitors the voltage magnitude of the supply to ensure this does not exceed or fall below the predetermined threshold settings; and upon detection of an under or over-voltage condition, deactivates the contactor, which in turn, cuts out the three-phase supply to the connected loads. Reconnection is automatic when supply is confirmed suitable for use. An adjustable trip delay on crossing thresholds of between 380Volts and 415Volts prevents nuisance tripping.

Indicator lights mounted on the panel fascia signal when any abnormality conditions is detected and remain lit until fault condition is removed. An audible alarm is also activated when any of these conditions occurs. An alarm-mute button silences the alarm when depressed.

A 1.5-mm^2 single-core flexible control cable was used in the wiring. For a load current of 142.32mA, a 1-A rated protective device of appropriate tripping characteristics is sufficient. However, this is not always easy to come by on the market as it is not in regular demand. Moreover, as stated earlier, the protection device is intended to protect the control wiring and not the control devices. A single-pole 6-amp miniature circuit breaker was therefore chosen. This satisfies the requirement of Equation 3.2 above. The 6amps nominal rating of the breaker is greater than the 142.32mA load current but less than the current carrying capacity of the 1.5-mm^2 single-core flexible control cable.

3.3. Mode of Operation

When a three-phase supply is applied to the incoming supply terminals L1, L2, L3 and N; the supply monitoring breaker FVM and control breaker FC closed, terminals L1, L2 and L3 respectively on supply monitoring relays RVM1 and RVM2are energized (the three-phase connections were swapped on RVM2). Indicator light H_0 is illuminated to signal presence of supply and at the same time, timing relay RT is energized. When the set delay time has elapsed, timed contact RT/1-3 is actuated, activating the main control circuit.

If the rotational direction of phases is correct and all 3 phases are present at switch-on; instantaneously, RVM1 is energized but RVM2 is not. The make contact RVM2/25-28 maintains its open rest position while the break contact RVM1/25-26 opens; this way, the supply is cut out to the "Phase Reversal Fault" light, H1.At the same time, changeover contact RVM1/15-18 is actuated allowing the coil of control relay R1 to be energized via the series connected changeover contact RVM2/15-16 which also remains in its close rest position. Simultaneously, changeover contact R1/9-5 closes while break contact R1/11-3 opens. Because RVM2 is not energized, the changeover contact RVM2/15-18 also remains in its open rest position. Control relay R2 is not energized as supply is already disrupted via RVM2/15-18. Make contacts R2/10-6 and R2/11-7 respectively remain in their open rest positions. With the opening of the break contact R1/11-3, and R2/11-7 remaining in its open rest position; supply is cut out to the illuminated buzzer alarm H3.

3.4. Automatic Operation:

With the two control mode selector switches S1 and S2 in "Auto" position and the changeover contact R1/9-5 actuated, contactor K1 is energized via the series connected auxiliary break contact K2/21-22. The contactor's main contacts K1/1L1-2T1, K1/3L2-4T2 and K1/5L3-6T3 close, causing the three-phase power to be supplied to the outgoing supply terminals T1, T2 and T3.Theauxiliary break contact K1/21-22 also opens, cutting out supply to contactor K2to ensure that contactor K2 cannot be energized inadvertently while contactor K1 is closed.

In the event of an incorrect phase sequence; instantaneously, RVM2 is energized while RVM1 is not. The make contact RVM2/25-28 becomes actuated and switches on the

"Phase Reversal Fault" light H1 via the series connected break contact RVM1/25-26which remains in its close rest position. Also, changeover contact RVM2/15-18 is actuated, energizing control relay R2 while breaking the control line to control relay R1. At the same time, make contacts R2/10-6 and R2/11-7 are actuated. Since RVM1 is not energized, changeover and make contacts R1/9-5 and R1/11-3 remain in their respective close and open rest positions.

With the closing of the make contact R2/11-7, and the break contact R1/11-3remaining in its open rest position; the illuminated buzzer alarm H3 is activated via the break contact RAL/8-5, signaling an audible alarm and a visual continuous and flashing light. When the Alarm silence push button SAL is depressed, alarm silence relay SAL is energized. The break contact RAL/8-5 opens to disrupt supply to the illuminated buzzer H3. When the push-button is released, the alarm silence relay RAL maintains itself via the make contact RAL/1-3 which is now closed. The alarm goes off when there is a power outage and will not come on again unless the phase reversal has been corrected; when RVM1 is now energized and RVM2 is not, the scenario that is described above is repeated.

Since supply has been cut out to control relay R1 through the opening of the changeover contact RVM2/15-16 and all contacts on control relay R1 have remained in their respective rest positions; make contact R2/10-6, which was closed when RVM2 was energized, energizes the coil of contactor K2 via the series-connected changeover contact R1/9-1 and auxiliary break contact K1/21-22. The contactor closes, reversing the incorrect sequence on the supply. The auxiliary break contact K2/21-22 also opens to ensure that contactor K1 cannot be energized inadvertently while contactor K2 is closed; a safety measure to prevent two different phase sequences conflicting.

In the event of failure of one or more of the phases at switch-on, both RVM1 and RVM2 will not be energized. If one was already energized when this fault occurs, the two will still de-energize instantaneously. In either case, the relays' output contacts will remain in their respective normal rest positions. On the one hand, the series-connected changeover contacts RVM1/15-16and RVM2/15-16 allow current to flow to the indicator light H2, signaling a "Phase Failure" fault while on the other hand, prevent control relays R1 and R2 from being energized. Therefore, break contact R1/11-3 remaining in its open rest position activates, via the break contact RAL/8-5, the illuminated buzzer alarm H3 which signals an audible alarm and a visual continuous and flashing light. The alarm is silenced when the Alarm silence push button SAL is depressed. Operation is the same as described above. The "Phase Failure" light remains lit until fault is cleared. Also, while changeover contact R1/9-5, remaining in its original open position, prevents activation of contactor K1, the make contact R2/10-6 also cuts out supply to the coil of contactor K2. This way, supply output is inhibited upon detection of a phase failure fault irrespective of the phase rotation of the supply.

Upon detection of an undervoltage or overvoltage (that is, a voltage that exceeds or falls below the predetermined threshold settings), RVM1 and RVM2 are de-energized after a time delay set between 0.1second and 10seconds. Fault signaling and other operations are as already described for phase failure fault.

4. CONCLUSION

This paper presents the design and construction of a prototype of an electrical system that offers protection against phase reversal, phase failure, undervoltage and overvoltage faults in a three - phase electrical system. It constantly monitors the 3-phase supply to the installation and upon detection of a phase reversal, it automatically signals a contactor in reverse mode connection to effect correction of the incorrect sequence. In the event of an under-voltage or overvoltage condition, it cuts out supply to connected loads after a set delay time has elapsed. Moreover, upon detection of a loss of phase, it instantly disrupts supply to connected load(s).

An audible alarm is activated when any of the fault conditions is detected. An alarm-mute button silences the alarm when depressed. A fault indicator light signals occurrence of any of these unhealthy conditions and remains lit until fault condition is removed.

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