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Design of a Microcontroller-Based Capacitor Switching System for a Power Distribution Network

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Abstract:- The recent development in digital technology, especially in digital switching systems using a microcontroller offers new and cheaper possibilities of improving the performance of electric power distribution networks. This research work involves the design of a microcontroller-based capacitor switching system that can automatically switch on and off capacitor banks in a power distribution network. The automated system switches on capacitor banks for voltage compensation when the distribution network voltage value drops below the ANSI C84.1 acceptable lower voltage limit. It also switches off the capacitor banks when the voltage values goes back within the standard limit, thus avoiding over-compensation of the line. The switching system consists of a 5VDC power supply unit, main controller unit (ATmega328P microcontroller), and voltage monitoring units that comprise main voltage sensor and phase voltage sensors. During the testing of this switching system, it was observed that the capacitor bank was automatically switched on for voltage compensation when the network phase voltage drops below the standard acceptable lower voltage limit, thus ensuring that the distributed phase voltage is always within the acceptable standard voltage limit. This system of improving the performance of power distribution network is highly recommended to electric power distribution providers since it is a cheaper and less complicated way of improving the power distribution network operation.

***Keywords**:- Distribution Network, Microcontroller, Voltage Drop, Capacitor Bank, Distribution Line.*

I. INTRODUCTION

The Electric power distribution system is becoming more complex due to the rapid and continuous increase in electricity demand [1], [2]. The performance of a distribution network can be measured or determined by the following key indicators [3];

i. Quality of power or voltage delivered.
ii. Reliability of the network.
iii. Availability of power on demand by consumers.
iv. Affordability of power.

Presently in Nigeria, the voltage value delivered to electricity consumers through the distribution network most times is low and often violates the standard acceptable voltage limit set by the American National Standard Institution (ANSI C84.1 - 90% $\leq$ V $\leq$ 106% of the nominal voltage value) [4], [5]. The Distribution network is the major link that provides power supply to the consumers from the high voltage transmission system [6], [7]. The load on the distribution network is not constant and it changes with time throughout the working period [8]. The voltage drop and power losses that occur in the distribution system mainly depend on the nature of the load in the system [9]. The voltage drop and power losses often occur on distribution system that is supplying power to industrial areas, due to the existence of more reactive power demand. To overcome these problems, reactive power or voltage compensation methods like the use of capacitor banks are employed to compensate for the shortfall of the reactive power needed in the system [10].

The distribution system supplies electric power to end-users through medium voltage (33KV and 11KV) or low voltage (415/220V) distribution systems. In electric power system, the losses which occur at the distribution level make up a major portion of the total losses in the system. Performance improvement of the distribution system leads to improvement in the efficiency of the power system. Most distribution networks are designed in a radial system because radial system construction is simple and more economical than ring and mesh systems [11]. The decrease in reactive power in the electrical system leads to poor voltage profile and increased power losses. To compensate for the reactive power growth in the distribution system, compensators like shunt capacitor banks are installed in the system, providing or generating the required amount of vars at the point of installation [12], [13], [14].

Presently in Nigeria, capacitor banks are permanently connected on the distribution line for voltage compensation but this method may lead to over-compensation of the network during off-peak loading period. This research provides a system whereby the capacitor banks are automatically switched on in the system to compensate for the voltage drop and automatically switched off, to avoid over-compensating the distribution line. The compensation from the capacitor will reduce the line current which is drawn by the load in the system thus resulting in voltage profile improvement, line loss reduction, better reliability, and stability of the distribution system [15], [16].

II. REVIEW OF RELATED WORKS

The major portion of occurrence of low voltage value in electric power system is the distribution system, which widens the gap between the demand and supply of the electricity. Electric power providers have a responsibility to ensure that the consumers are always supplied with the required/proper voltage value. However, consumers in the network, most especially those at the end of the feeders have been experiencing low voltage values and this is due to voltage drops or low voltage value in distribution system. Several authors presented works on ways of improving the voltage profile or quality of power in electric power systems generally and in the distribution aspect of the system precisely. The authors x-rayed the causes of poor voltage profile in the network, evaluated the effects on the performance of the network, and possible recommendations to minimize the causes of power losses and poor voltage profile.

U. Pallavi, T. Priyanka, and P. Jain [17] presented a paper that focuses on the design and implementation of voltage regulation and power factor correction using a microcontroller AT89C51. Switched shunt capacitors were used for reactive power compensation and to control the steady-state system voltages in the network. The authors based their design on the fact that using many, small distributed shunt capacitor banks located at distribution buses is more efficient and effective in terms of voltage compensation than a few large bulk shunt capacitor banks located at the sub-transmission or distribution bus.

J. Thirukkumaran, K.C. Naveen, S. Sindhu, R. Suparnna [18] produced voltage monitoring and power factor correction system using GSM. The authors developed an automated power factor corrector using shunt capacitor banks and this was achieved by measuring the power factor value and correcting using a microcontroller.

M. M. Than [19] produced a research work that involves the implementation of an automatic power factor correction system using solid-state switched capacitors and Arduino UNO microcontroller. The author explained the developed work and simulation aspect of power factor correction using the Arduino UNO microcontroller. This paper used C language software to program the microcontroller and implemented the design using Arduino UNO microcontroller.

V.A. Praveen, F. Sumaya, I.A. Sumalata, K.D. Badiger, S.S. Kandagal [20] developed an automatic power factor correction device that reads the power factor from both line voltage and current based on the delay in the arrival of the current signal to voltage signal from the AC mains. The authors used the microcontroller which calculated the compensation requirement and accordingly switched on different capacitor banks for compensation. The authors observed that the automatic power factor correction using capacitive load banks is very efficient as it reduces the cost by decreasing the power drawn from the supply.

P. C. Warule and G. U. Kharat [21] proposed an ARM Microcontroller Based SVC for Power Factor Correction System. This correction system as developed by the authors consists of a static VAR compensator that is made of capacitor bank in 4-binary sequential steps and a thyristor (SCR) or Traic controlled reactor of smallest step size.

Thus, in the reviewed research works, the authors presented various ways of improving the quality of power supplied to power consumers in the distribution network, but all those systems lack in providing a dynamic, flexible and robust system that improves the performance of distribution network and precisely the quality of power (voltage) supplied to power consumers and at the same time control the negative effect of over-compensation of the distribution line during the off-peak loading period. This developed system also improved on the operating principle of the existing works, in that before the developed work automatically switches on capacitor bank for voltage compensation process, the ATmega328 microcontroller initially verifies if the service transformer supplies real voltage value to the distribution line (that is, if the service transformer is energized), thus avoiding a case where the microcontroller sees virtual or false or unreal voltage value through the phase voltage sensors from the non-energized transformer as real voltage value below the standard acceptable lower voltage limit that needs compensation.

III. PROPOSED SYSTEM

The block diagram of the microcontroller-based capacitor switching system is shown in Figure 1.

The proposed system consists of a 5VDC power supply unit, main controller unit, and voltage monitoring units which comprise main voltage sensor and phase voltage sensors.

For simplicity, phase voltage from transformer low voltage side is monitored by voltage monitoring units in the research. From the block diagram, the phase voltage sensors monitoring values of phase voltages of each of the three phases continuously sample the phase voltages and sends analog signals proportional to the voltage values to the main controller unit through its inbuilt analog to digital converter input ports. The main controller unit compares the individual phase voltage values from the three phases with a reference voltage value to determine when to switch on the capacitor banks for compensation. But before that, the microcontroller must first confirm the presence of real/desired phase voltage

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value through the analog signal received from the main voltage sensor which signifies that the transformer is active or energized before the activation of the relays for capacitor switching process. Again, as the voltage value increases due to the compensation action of the capacitor or during the off-peak loading period, and goes back to a value within the ANSI C84.1 standard acceptable voltage limit, the main controller unit switches off the capacitor banks, in turn, to prevent the capacitor banks from over-compensating the distribution line.

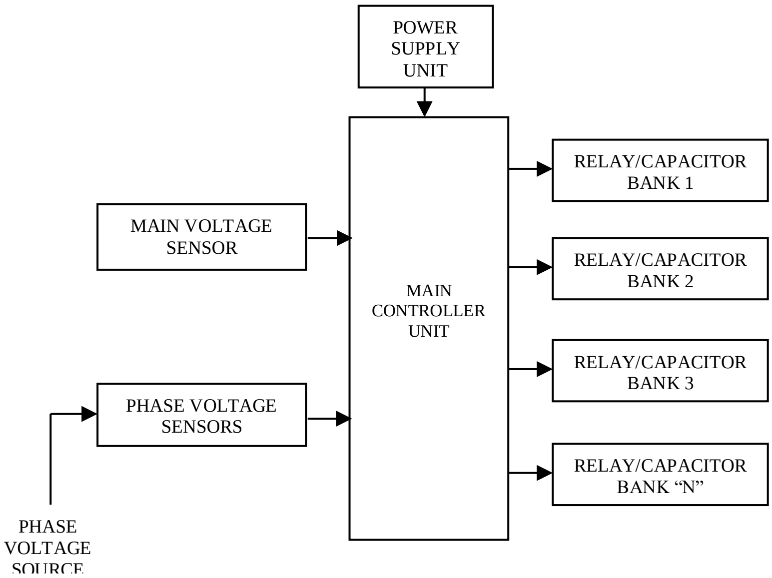

Fig. 1: Block diagram of microcontroller-based capacitor bank switching system

A. POWER SUPPLY UNIT

The power supply unit is an electronic circuit which supplies regulated 5V DC to the other components in the system. This circuit comprises 220/12V transformer, bridge rectifier, resistor, and a capacitor that forms the filter circuit and also voltage regulator (7805). It also has a 12VDC rechargeable battery backup. The circuit diagram for the power supply unit is shown in Figure 2.

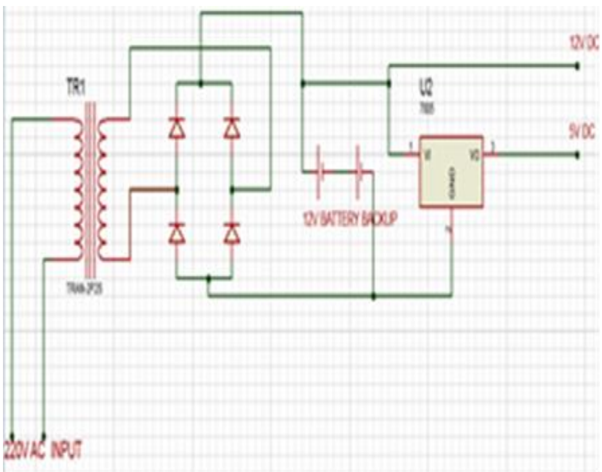

Fig. 2: Power supply circuit diagram

B. VOLTAGE MONITORING UNIT

The voltage monitoring unit is designed as a phase voltage sensor. In this system, we used the same type of circuit as voltage sensor, but are to be connected at different voltage source points and for different functions;

1. Main Voltage Sensor: Connected in a way that its input source is from the transformer secondary side (voltage source point before the low voltage fuse). This main voltage sensor always sends an analog signal to the main controller unit indicating the presence of real/active voltage value from the transformer (transformer active or energized).
2. Phase Voltage Sensor: Connected in such a way that its input source is from the point immediately after the low voltage fuse point. This is connected and used for monitoring the voltage values for each of the three phases.

These voltage sensors send analog signals proportional to the voltage value they monitor to the main controller unit through its inbuilt analog to digital converter input ports.

For simplicity, the loads at the three phases of the distribution lines are assumed to be balanced in the research. The voltage monitoring circuit is as shown in figure 4. It consists of a 415/12V Step-down transformer, a bridge rectifier, a filter circuit formed by the combination of resistance and capacitor. The output voltage of the rectifier and filter circuit serves as input to a voltage divider network of resistors R_1 and R_2 as shown in the signal conditioning circuit.

C. SIGNAL CONDITIONING IN A VOLTAGE SENSOR CIRCUIT

The circuit diagram for the voltage monitoring unit is designed as a voltage sensor that senses voltages and sends an analog signal indicating the voltage value to the controller. The analog signal realized after the bridge rectifier is 12V filtered DC voltage. This value is not suitable for the ADC of the microcontroller used in the system which tolerates a maximum of 5VDC. Thus, the need for a simple signal conditioning circuit as shown in figure 3 arises.

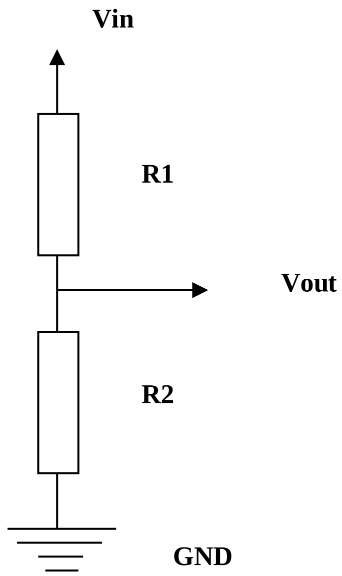

Fig. 3: Signal conditioning circuit (Voltage divider network)

Note;

- Vin is the output voltage of the voltage sensor circuitry.
- Vout is the conditioned signal.
- R1 and R2 are conditioning resistances.

In our design, we replaced the above circuitry with a variable resistor of 10kΩ.

From voltage division principle;

Vout = [(R2 x Vin) / (R1 +R2)] (1)

But R1+R2 =10kΩ since we are using a 10kΩ variable resistor.

Vin = 12VDC

Vout = 5VDC

We need to find the value of R2, which corresponds to the resistance the variable resistor will be tuned to give a maximum voltage of 5VDC.

R2 =50/12 = 4.1kΩ

Therefore it is either we use a 10kΩ variable resistor and tune it to get 4.1kΩ or we use two fixed resistors of 5.9kΩ and 4.1kΩ to condition the Vout to 5VDC, which is the maximum the microcontroller ADC can take.

Practically, the variable resistor should not be tuned to the maximum, and to be on the safe side, we used 4VDC and calibrated it to get exactly what we want.

We used a 10bit ADC.

The 4VDC will be divided into $4/2^{10} = 4/1024 = 0.00390625$V

This implies that every change in voltage of about 0.00390625V will be detected by the ADC.

So we mapped 4VDC to 12VDC (220VAC), thus calibrating the system to achieve what we are expecting.

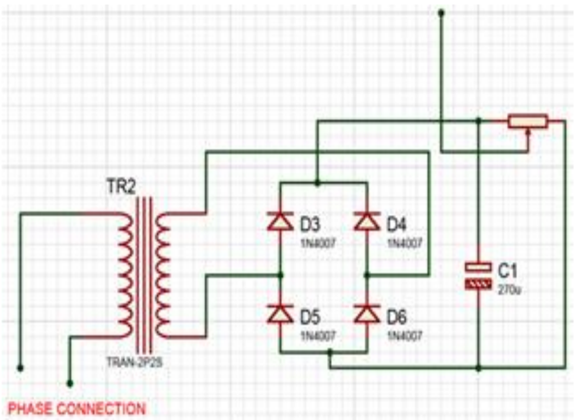

Fig. 4: voltage monitoring circuit diagram

D. MAIN CONTROLLER UNIT

The main controller unit used is the ATmega328P microcontroller. The controller must first confirm that the transformer is energized through the signal received from the main voltage sensor before the issue of switching the capacitor for voltage compensation. It compares signals from the three-phase voltage sensors (which is proportional to the voltage value on each of the phases) with a reference voltage value and then sends a control signal to the required relay to either switch on or switch off a capacitor bank depending on the voltage values received from the phase voltage sensors. The main controller (ATmega328 microcontroller) pin-out diagram is shown in Figure 5. As shown in the design, the microcontroller switches on the capacitor bank when the input voltage value received from the phase voltage sensors goes below the lower limit of the standard service voltage range stated by ANSI C84.1, which is 90% ≤ V ≤ 106% of the nominal voltage value.

The microcontroller sends a signal to the LCD which indicates the actual phase voltage value on the line. The instruction set for the ATmega328P microcontroller is written in C-language.

Fig. 5: The Pin-out of ATmega328P Microcontroller

E. LIQUID CRYSTAL DISPLAY (LCD)

The LCD shows the actual voltage values on the monitored lines. It displays phase voltage values before the switching call by the microcontroller and after the switching process.

These displayed data avail the maintenance team with prompt, quick information about the present performance status of the network and these facts assist them in their routine & maintenance checks which they carry out in regularly the network.

F. OPERATING PRINCIPLE OF MICROCONTROLLER-BASED CAPACITOR SWITCHING SYSTEM

The operating principle of the microcontroller-based capacitor switching system as designed has it that the phase voltage sensors for the three phases of the distribution line continuously monitor the phase voltage on each of the three phases of the network and sends analog signals which are proportional to the sensed voltage value to the microcontroller. The main voltage sensor continuously monitors the presence of real or desired voltage value from the service transformer and sends the analog signal which is proportional to the sensed voltage value to the microcontroller. The microcontroller

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(ATmega328P) receives analog signals from both the main voltage and phase voltage sensors. Initially, the microcontroller verifies the presence of real or desired voltage value from the service transformer through the signal it receives from the main voltage sensor. If it senses virtual or non-real or false voltage value, it sends a signal to GSM Module which automatically sends SMS once to Distribution System Operator (DSO) informing him that there is no voltage supply from that particular transformer (service transformer is not energized) notwithstanding that the transformer service feeder is energized and other transformers on that feeder might be energized too. But if the microcontroller senses a real or desired voltage value through the signal received from the main voltage sensor, It then compares the voltage values received from the three-phase voltage sensors with a reference voltage value and then sends a control signal to the required relay to either switch on or switch off the capacitor bank depending on the voltage value received from the phase voltage sensors. The system is designed in such a way that before the microcontroller sends a control signal to the relay for switching of the capacitor bank, it must first verify the presence of real or desired voltage value from the transformer that supplies the distribution line, if there is the presence of a real voltage value, then it signifies that the service transformer is energized. The microcontroller switches on the capacitor bank for voltage compensation when the voltage value received from the phase voltage sensors goes below the lower limit in the standard service voltage range as stated by ANSI C84.1 which is 90% $\leq$ V $\leq$ 106% of the nominal voltage value. By ANSI standard the acceptable phase voltage limit on the distribution line is between 216V and 254V.

The instruction set for the ATmega328P microcontroller is written in C language.

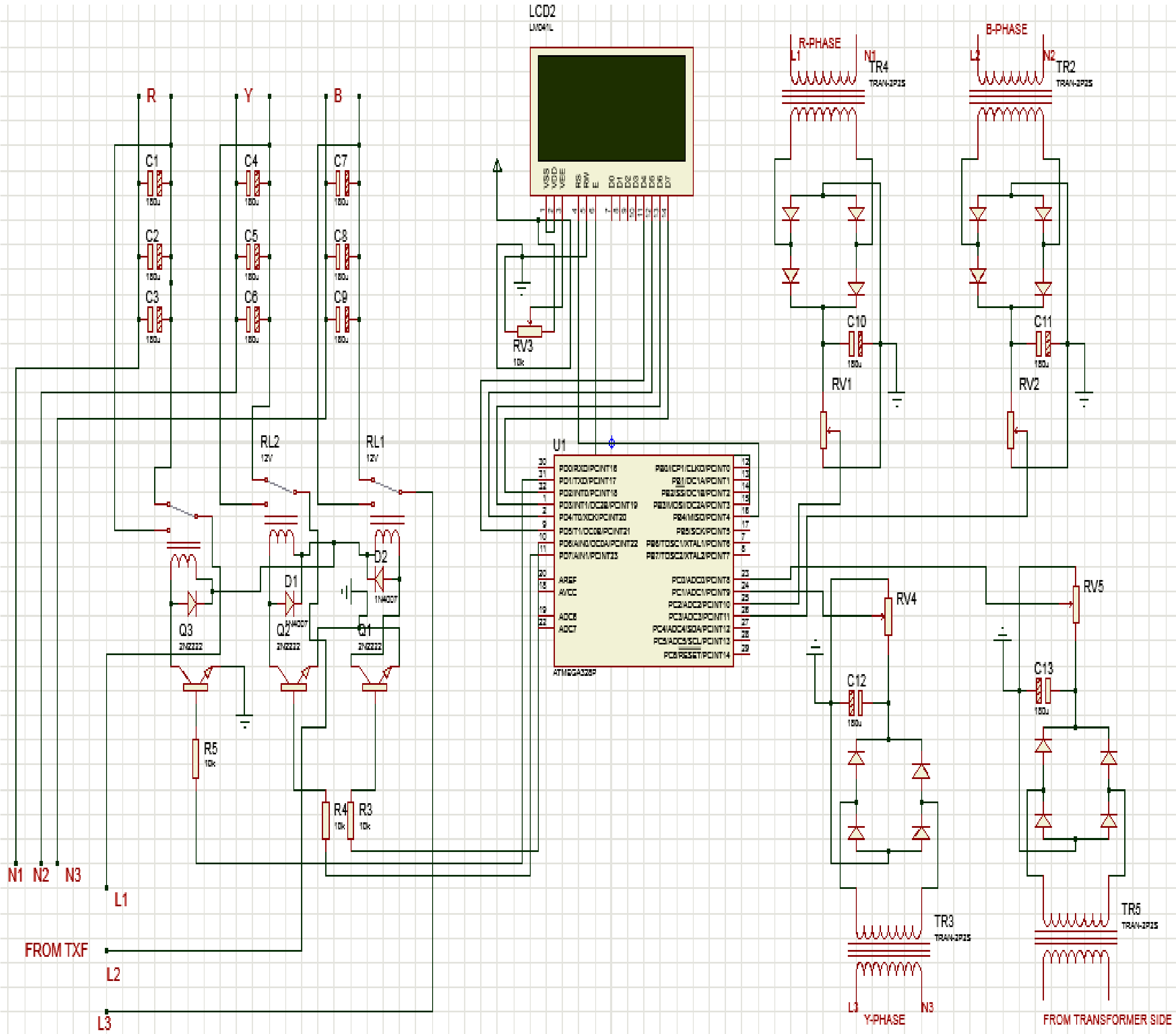

Fig. 6: Circuit diagram of microcontroller-based switching system

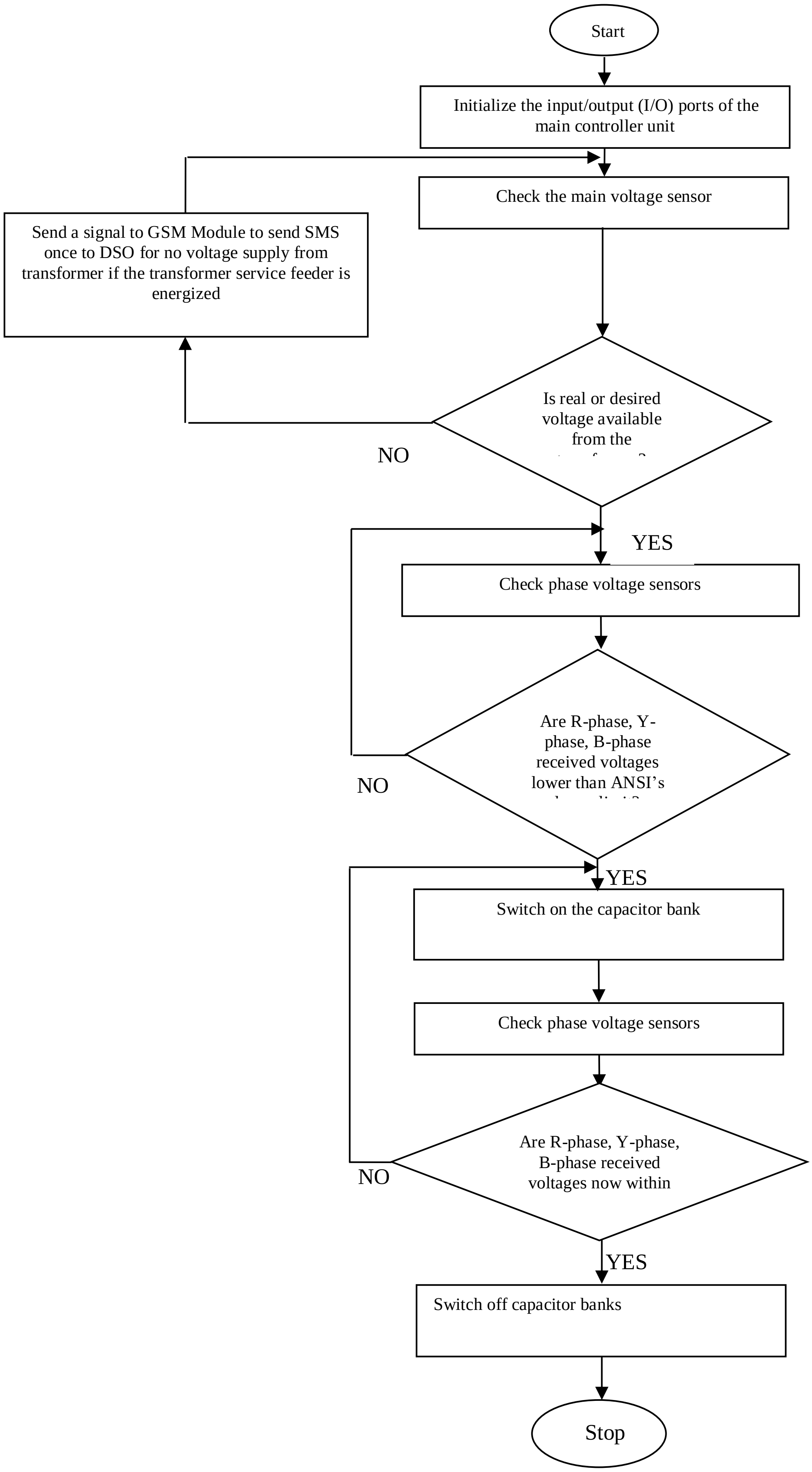

Fig. 7: Flow chat diagram of Microcontroller-based switching system

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IV. TESTING

For simplicity, the automated switching system was tested by injecting a voltage value of 220V from a voltage distribution board to the constructed work through red phase (Rph) voltage sensor of the device. The red phase sensor senses the 220V value and sends the analog signal to the ATmega328 microcontroller that controls the switching itself. The microcontroller compares the received signal with the reference voltage value. Since the injected 220V is within the ANSI standard phase voltage limit of 216 – 254V; the system did not see any need for voltage compensation, hence, the microcontroller did not send any signal to the relay for switching on of the capacitor bank. But when 190V was injected through the red phase voltage sensor, the microcontroller receives the analog voltage signal through its analog to digital converter ports, it then compares the received signal with the reference voltage value and due to the fact that sensed 190V is less than the minimum standard phase voltage value (216V), the microcontroller immediately responds by sending a closing signal to the open contact of the relay so as to switch on the capacitor bank for voltage compensation of the distribution line.

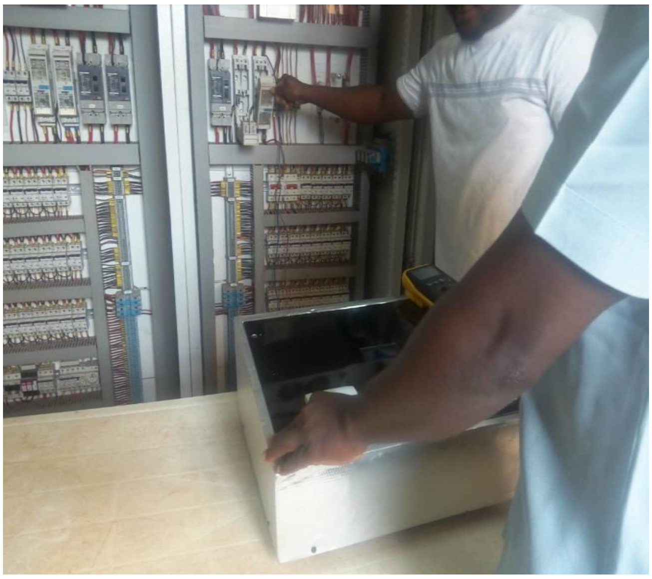

Fig. 8: Testing of the Switching System

V. CONCLUSION

This research work which involves the design of a microcontroller-based capacitor switching system would be very useful to electric power distribution providers when applied in the network, as it can automatically switch on or switch off capacitor banks anytime the service voltage (phase voltage) on the distribution line falls outside the ANSI C84.1 acceptable voltage limit ($90\% \leq V \leq 106\%$ of the nominal voltage value).

This system ensures that it only injects the amount of reactive power required to compensate the distribution lines, thus avoiding the consequence of overcompensating the lines.

This developed switching system can as well be used as an automated monitoring system that monitors the distribution transformer and automatically reports to the Distribution Station Operator when the transformer trips on fault notwithstanding that the transformer service feeder is still energized or active, thus improving the availability of transformer, and quality of power supplied to consumers.

The automated switching system also has it as a mode of operation that it must first verify if the voltage supplied by the service transformer is a virtual or non-real or false voltage value, which is also a value less than the ANSI C84.1 acceptable lower voltage limit, before deciding whether there would be voltage compensation process.

VI. RECOMMENDATION

It is recommended that electric power providers adopt this method of automatic line voltage compensation, as this automated switching system will assist in the following ways:

i. Mitigate voltage violations on the line and reduce losses associated with low voltage.
ii. The various voltage data displayed on the LCD avail the maintenance team with prompt, quick information about the present performance status of the network, and these facts assist them in their routine & regular maintenance checks in the network.
iii. Electric power consumers will ultimately benefit from this system as they will be able to consume power at acceptable voltages and relatively pay for the actual amount of power consumed, as losses would have been appreciably reduced.

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