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Protection of a Disturbed Electric Network using Solid State Protection Device

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***Abstract*— Relays are devices which, when supplied with appropriately scaled quantities, indicates an abnormal of fault condition on power system. Though electromechanical and semi conductor relays were installed and are still in used on system. Modern practice is to install digital (numerical) protection which uses microprocessors and the measured quantities are manipulated digitally. This paper presence the implementation of semiconductor relay for the enhancement of power system protection. The relay is to constantly monitor the parameters to be controlled and if it exceeds the percentage set range by the operational amplifier then with the help of the opto-coupler, it sends signal to the switching circuit to break the connection and isolate the faulty circuit. The bases of using the solid-state relay is because of its opto-coupler mechanism and minimal time delay which makes it optimal for power system protection. A 66kV power network was used to test the validity and reliability of the relay circuit. Results show better performance and system enhancement.**

***Index Terms*- opto-coupler, faults network, protection, power system, solid state relays**

I. Introduction

Power system protection is a branch of electrical power engineering that deals with the protection of electrical power systems from faults through the isolation of faulted parts from the rest of the electrical network [1]. Thus, protection schemes must be applied with an approach to clearing the system faults. The devices that are used to protect the power system from faults are called protective devices [2]. Protection scheme required for the protection of power system components against abnormal conditions such as faults or disturbances in an electric network essentially consists of protective relaying (e.g. solid state protective relay such as power transistors or thyristors) and circuit breaker. Protective relay functions as sensing devices, it senses the fault, and then determines its location and finally, sends tripping command to the circuit breaker. The circuit breaker after getting the command from the protective relay disconnects the faulted element [1]. The protective relay being the most important of any power system protection scheme should be properly designed to meet a reliable, efficient and fast operation [3].

The use of electromechanical relay (EMR) in protecting disturbed electric networks has been in use in power system engineering over years. However, the EMR are inexpensive, easy to use and allow the switching of load circuit controlled by low power, electrically isolated input signal [4]. One of the main disadvantages of an EMR is that it is a "mechanical device", that is, it has moving parts so the switching speeds (response time) due to physical movement of the metal contacts using a magnetic field is slow. Over a period of time these moving parts will wear out and fail, or that the contact resistance through the constant arcing and erosion may make the relay unstable and shortens its life span. Also, it is electrically noisy with the contacts suffering from contact bounce which may affect any electronic circuits to which it is connected [5].

However, as a result of these disadvantages, there is a need therefore, to device a more reliable means to overcome these disadvantages, hence the use of a solid state relay (SSR) which is a solid state contactless, pure electronic relay. The SSR being purely electronic devices has no moving parts within its design as the mechanical contacts have been replaced by power transistors, thyristors or triac. The electrical separation between the input control signal and the output load voltage is accomplished with the aid of an opto-coupler (a component that transfers electrical signals between two isolated circuits by using light) type light sensor.

Continuous rise in interconnection of loads/systems to the power system topology of most countries has resulted in higher demand of power which in most cases cannot be provided (or supplied) by generating stations (with several generating units in a single area network). To meet up with the demand, in most cases it leads to faults occurring on the power system network, such as: Over loading; Short circuit; and Over voltage and under voltage. It is as a result of these operational challenges encountered in the Nigeria Power System that has motivated this work to protect an electric network against faults using a solid state protective relays. The objective of this work is:

- To isolate a faulty section of electrical power system from the rest of the live system so that the portion can function satisfactorily without any severe damage due to fault current.
- To increase efficiency and reduce cost of protection by the use of SSR.
- To prevent damage to the system apparatus from hazards (like fire) with the help of SSR.
- To greatly improve on the transient state stability limit of the system.

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- To avoid permanent damage to the equipment and also to reduce possibility of developing simplest fault into more severe fault.

II. PROTECTION IN POWER SYSTEM NETWORK

Power system protection emerged at the beginning of the last century, with the application of the first electro-mechanical overcurrent relay. The majority of the protection principles currently employed in protection relays were developed within the first three decades of the last century, such as over current, directional, distance and differential protection. The development of modern science and technology, especially electronic and computer technology, promoted the development of relay technology, such as materials, components and the manufacturing process of the hardware structure of relay protection device. At the same time, great theoretical progress had been made in the relay protection software, algorithms, etc. [6].

The progress in modern technology stimulates the development in power system protection. In the last century from the emergence of protection to the end of the 1990s, the relay protection had gone through a number of development stages, migrating from mechanical to electro-mechanical, and subsequently to solid state semiconductor technologies. Today, solid state relays are replacing conventional relays in all areas of power system protection. However, many of the same relaying principles of protection are still playing a dominant role to date [7].

In order to attain the desired reliability, the power system network is divided into different protection zones [8]. The overall system protection is divided into: Generator protection; Transformer protection; Transmission line protection; Bus protection; and Feeder protection.

A. *Generator Protection*

A generator is subjected to electrical traces imposed on the insulation of the machine, mechanical forces acting on the various parts of the machine, and temperature rises. Even when properly used, a machine in its perfect running condition does not only maintain its specified rated performance for many years, but it does also repeatedly withstand certain excess of over load. Hence, preventive measures must be taken against overloads and abnormal conditions of the machine so that it can serve safely. Despite of sound, efficient design, construction, operation, and preventive means of protection, the risk of that fault cannot be completely eliminated from any machine [8]. The devices used in generator protection, ensure the fault, is rectified as quickly as possible.

An electrical generator can be subjected to either internal fault or external fault or both. The generators are normally connected to an electrical power system, hence any fault occurred in the power system should also be cleared from the generators as soon as possible otherwise it may create permanent damage in the generator. The number and variety of faults occur in generator are huge. Great care is to be taken in coordinating the systems used and the settings adopted, so that the sensitive, selective and discriminative generator protection scheme is achieved [9].

The various forms of protection applied to the generator can be categorized into two manners.
1. Protective relays to detect faults occurring outside the generator.
2. Protective relays to detect faults occurring inside the generator.

Other than protective relays, associated directly with the generator and its associated transformer, there are lightening arrestors, over speed safe guards, oil flow devices and temperature measuring devices for shaft bearing, stator winding, transformer winding and transformer oil etc. some of these protective arrangement are of non-trip type which only generate alarm during abnormalities. But the other protective schemes ultimately operate master tripping relay of the generator.

This should be noted that no protective relay can prevent fault, it only indicates and minimizes the duration of the fault to prevent high temperature rise in the generator otherwise there may be permanent damage. It is desirable to avoid any undue stresses in the generator, and for that it is usual practice to install surge capacitor or surge diverter or both to reduce the effects of lightening and other voltage surges on the machine.

B. *Transformer Protection and Transformer Fault*

There are different kinds of transformers such as two winding or three winding electrical power transformers, auto transformers etc. different transformers demand different scheme of transformer protection depending upon their importance, winding connections, earthing methods and mode of operation etc. It is a common practice to provide Buchholz relay protection to all 0.5MVA and above transformers. While for all small size distribution transformers, only high voltage fuses are used as main protective devices. For all larger rated and important distribution transformers, over current protection along with restricted earth fault protection is applied. Differential protection should be provided in the transformers rated above 5MVA [10].

Depending upon the normal service condition, nature of transformer faults, degree of sustained over load, scheme of tap changing, and many other factors, the suitable transformer protection schemes are chosen.

Although an electrical power transformer is a static device, but internal stresses arising from abnormal system conditions must be taken into consideration.

A transformer generally suffers from the following types of transformer fault: Over current due to overloads and external short circuits; Terminal faults; Winding faults; and incipient faults.

The above mentioned transformer faults causes mechanical and thermal stresses inside the transformer winding and its connecting terminals. Thermal stresses lead to overheating which ultimately affect the insulation system of the transformer. Deterioration of insulation leads to winding faults. Sometime failure of transformer cooling system, leads to overheating of transformer. So the transformer protection schemes are very much required. The short circuit current of an electrical transformer is normally limited by its reactance and for low reactance; the value of short circuit current may be excessively high. Whatever may be the faults, the transformer must be isolated instantly during fault otherwise major breakdown may occur in the electrical power system.

C. Busbar Protection / Busbar Differential Protection Scheme

In early days only conventional over current relays were used for busbar protection. But it is desired that fault in any feeder or transformer connected to the busbar should not disturb busbar system. In viewing of this time setting of busbar protection relays are made lengthy. So when faults occur on busbar, it takes much time to isolate the bus from the source which may cause much damage in the bus system [11].

In recent days, the second zone distance protection relays on incoming feeder with operating time of 0.3 to 0.5 seconds have been applied for busbar protection. But this scheme has also a disadvantage. The scheme of protection cannot discriminate the faulty section of the busbar.

Nowadays, electrical power system deals with huge amount of power. Hence any interruption in total bus system causes big loss to the company. So it becomes essential to isolate only faulty section of busbar during bus fault. Another drawback of the second zone distance protection scheme is that, sometime the clearing time is not short enough to ensure the system stability. To overcome the above mentioned difficulties, differential busbar protection scheme with an operating time less than 0.1sec, is commonly applied to many SHT bus systems.

The scheme of busbar protection, involves, kirchoff's current law, which states that total current entering an electrical node is exactly equal to total current leaving the node. Hence total current entering into a bus section is equal to total current leaving the bus section as shown in Figure 1.

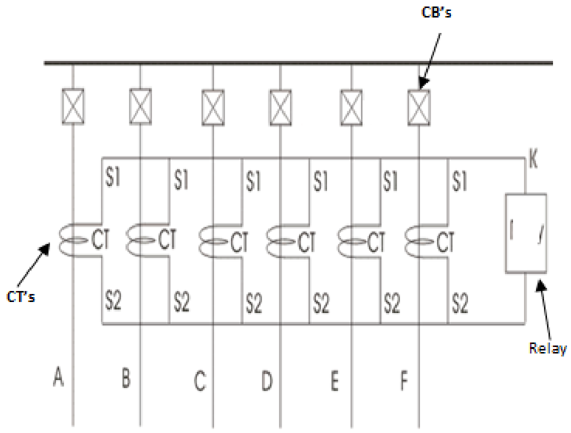

Fig. 1. Current Differential Protection indicating equal current entering and leaving the bus section.

Here, secondary of CTs are connected in parallel. That means, S1 terminals of all CTs connected together and form a bus wire. Similarly, S2 terminals of all CTs connected together to form another bus wire. A tripping relay is connected across these two bus wires.

D. Protection of Transmission Lines and Feeders

As the length of electrical power transmission line is generally long enough and it runs through open atmosphere, the probability of fault occurring in electrical power transmission line is much high than that of electrical power transformers and alternators. That is why a transmission line requires much more protective schemes than a transformer and an alternator [12].

Protection of transmission line should have some special features, such as:

- Tripping of circuit breaker closest to the fault point during fault.
- In case the circuit breaker closest is faulty, the next circuit breaker should trip as back up.
- The operating time of relay associated with protection of line should be as minimum as possible in order to prevent unnecessary tripping of circuit breakers association with other healthy parts of power system.

These requirements cause protection of transmission line much different from protection of transformer and other equipment of power systems [13]. There are three methods of protecting the transmission line: Time graded over current protection; Differential protection; and Distance protection.

E. Protective Relay

A relay can be operated with a small amount of power and can be used to control devices that draw much more power like circuit breakers and isolators. For example, the air conditioner in homes is controlled with the help of relays. An AC unit requires roughly 220VAC at around 30A, that comes out to be around 6600 Watts however the coil used to control the relay may only need a few watts to pull the contacts together. A relay is like a remote control switch and has many applications because of its long life, high accuracy, relative simplicity and proven high reliability [14]. These are very useful when controlling an requirement of huge amount of voltage or current with the use of a small electrical signal.

In the industry a wide variety of application require the use of relays. Electrical power systems can be protected against trouble and power blackouts using sophisticated relays. These can also be utilized in the control and regulation of power generation and distribution [15].

Initially the contact is normally open which means not connected. The coil generates a magnetic field when current (I) passes through it and closes the switch (i.e. top contact gets connected). A spring is used to again pull back the switch open, when power is removed from the coil. Figure 2 shows the basic circuit for relay operation [16].

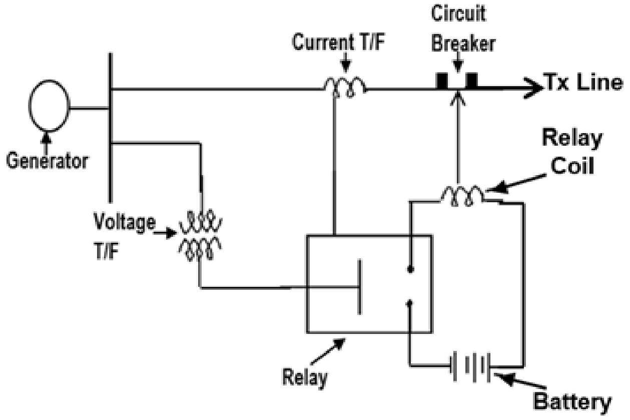

Fig. 2. Basic circuit for relay operation: It activates the opening and closing of contact for protection.

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The main part of the relay is the sensing unit which basically is an electrical coil. AC or DC current can be used to power the coil. When applied current/ voltage increases from the threshold value, the armature of the relay gets activated by the coil, which is used to close the open contacts. The switch mechanism is actuated by a magnetic force that is generated when power is supplied to the coil [17].

When coil is energized, it sends information to the circuit breaker that breaks the circuit till the fault clearance or isolates the faulty part. The relay compares the current or voltage from the transformer connected before the relay and send information to the circuit breaker. The coil opens when the circuit breaker disconnects the faulty part [18].

The basic functions performed by the relay are:

- On/Off Control- For example, in air conditioning control, relay is used to limit and control the compressor power which is a high power load.
- Limit Control - In this, relay is used to control a set of parameters and disconnect the device if the value of these parameters goes above or below the set value. For Example, in Motor Speed Control, motor gets disconnected if the desired speed increases or decreases beyond the limit.
- Logic Operation – In this, the relay is connected to desired point only if a particular logic is getting fulfilled. For example, in Test Equipment control, the instrument under test is connected to a number of testing points.

Relay can be broadly classified on the basis of construction and application. There are three types of relay based on construction which are Electromechanical, Static and Numerical [19].

1) The Electromechanical Relays consist of the following parts: Spring, Electromagnet, Moveable armature, Stationary contact and Moveable contact. The two contacts are kept separated with the help of a spring. When the electromagnet gets energized the two contacts are pulled together. With proper application, the integration between power circuits and control circuits can be done with the help of electromechanical relays. Advantages of Electromechanical relays are no requirement of heat sink, lower cost, availability of multiple poles and easy switching in both AC and DC. Figure 3 shows an electromechanical relay.

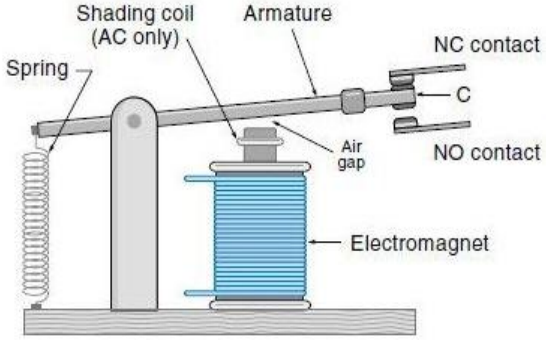

Fig. 3. Electromagnetic Relay helps the integration between power circuits and control circuits.

In Static Relay (Solid State Relays), the comparison or measurement of electrical quantities is performed by a static circuit which gives an output signal for the tripping of a circuit breaker. These are known as static as it does not have any moving part. In this type of relay analog electronic devices, instead of magnetic coil or mechanical components, are used to create the relay characteristics and the incoming current or voltage waveforms are monitored by analog circuits, not digitized. In this case, there is no effect of gravity or vibration or shock. Sometimes, these relays use microprocessor but cannot be called microprocessor relays as it lacks the attribute of digital/numeric relay. These relays use semiconductor devices like diodes, SCR, TRIAC, Power transistor etc. to conduct load current. Relatively low control circuit energy is required to perform switching of the output state from OFF to ON position since there is use of semiconductor devices. To protect the circuit under control for introduction of electrical noises, the static relays are often used. Static relays are highly reliable and have a long life. It does not have any moving parts or contact bounce and thus have a fast response [18]. The classification of SSR by the nature of the input circuit, is as follows [19].

a. Reed Relay coupled SSR application of control signal occurs on the coil of the reed relay. Thyristor switch is triggered when the appropriate circuitry is activated upon closing of reed switch as shown in Figure 4.

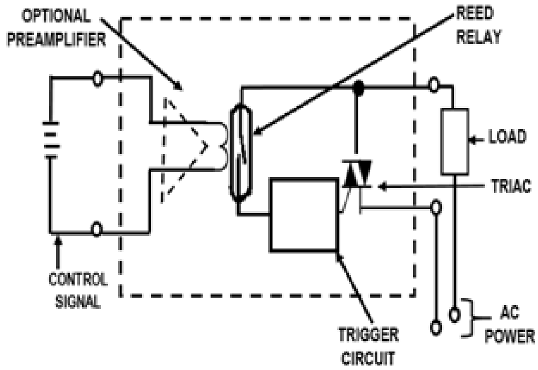

Fig. 4. Reed Relay SSR closes when the thyristor switch is triggered and the appropriate circuitry is activated.

b. Transformer coupled SSR has a low-power transformer primary consisting of the control signal. The thyristor switch is triggered by the secondary that is generated by the primary excitation as shown in Figure 5.

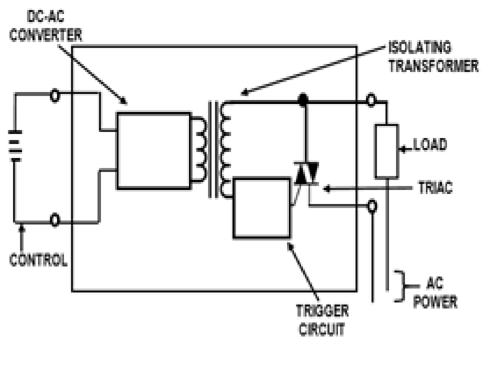

Fig. 5. Transformer Coupled SSR helps to trigger the thyristor switch by the secondary which is generated by primary excitation.

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c. In Photo Coupled SSR, a light or infrared source (generally LED) consist of the control signal. A photo- sensitive semi- conductor device (diode, transistor or thyristor) detects the radiation from that source and generates an output. This output triggers the TRIAC which is used to switch the load current. The electrical isolation is excellent as the input and output path are coupled only by a beam of light. The use of solid state protective relay type was adopted in this work due to its numerous advantages over other types of protective relays. These benefits are not limited to the following [20]:

- High degree of reliability
- Long operational life
- Zero-voltage turn-on, low electro- magnetic induction
- Shock and vibration resistant
- No contact bounce which leads to arcless switching
- Microprocessor compatible
- Fast response

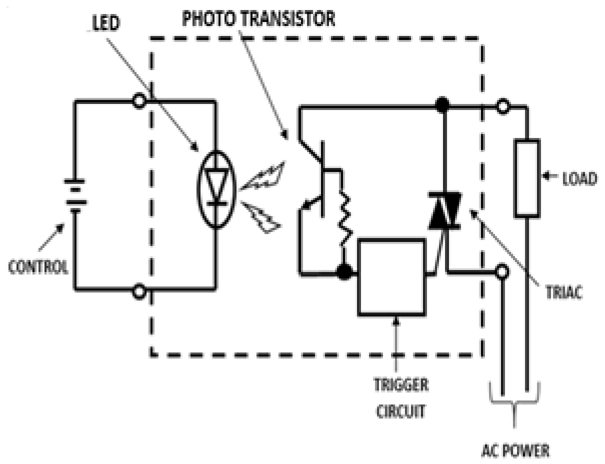

Fig. 6. Photo Coupled SSR output triggers the TRIAC which is used to swich the load current.

III. DESIGN AND MODELING METHOD

This project has five distinct units which include the power supply unit, the voltage sensing unit, the current sensing unit, the switching unit and the output unit as shown in Figure 7.

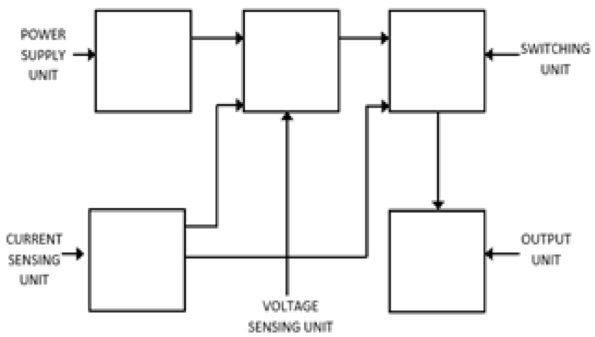

Fig. 7. Block Diagram of a solid state relay for protection indicating the five units.

The materials used to actualize this project include the following: DC power supply; Diodes; Capacitors; Resistors; Transistors; Solid State Relay; Operational Amplifier (LM324); NOT Gate; Light emitting diodes (LEDs); Voltage Regulator; Current Transformer; Lamp; Variable Resistors; and Plastic Casing.

A. The Power Supply Unit

This serves as input unit to the system because A.C mains enter the circuit through this point. In this unit, power is converted from A.C to D.C and filtered as shown in Figure 8.

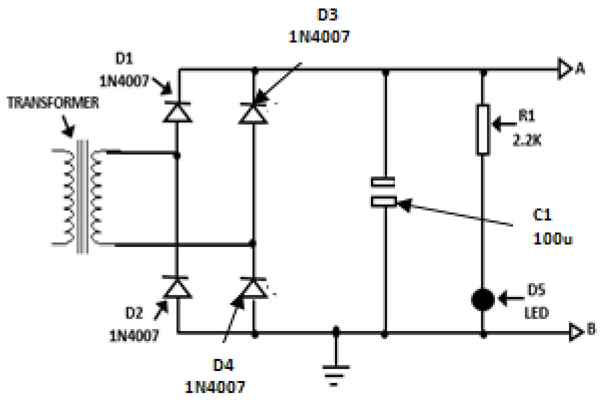

Fig. 8. Circuit Diagram of the Power Supply Unit which serves as input unit to convert AC power to DC power and filter.

The circuit diagram of the power supply consists of step-down transformer (T1), diodes (D1 to D4), capacitor (C1), Resistor (R1) and Light emitting diode (D5).

The operation of the power supply unit occurs in three stages; the transformer stage, rectifier stage and filter stage.

a. Transformer Stage:

This section consists of a Step-down transformer (240V/12V). The rating of the transformer was chosen because of the conversion of 240V to 12V AC which is the circuit requirement, then a voltage regulator is used during the voltage sensing stage to regulate and stabilize the voltage to 12v DC which is the circuit requirement; this is to make sure that the circuit is fully operational even when the mains voltage is below 200V AC. Resistors are used as current limiters for Light emitting diodes. The light emitting diodes serve as indicators for presence of the mains supply.

b. Rectifier Stage:

In rectifier section, diodes were configured in a full wave bridge rectifier so as to boast the circuit efficiency. The rectifier converts 12V AC voltage from the Supply from the transformer output to 12V pulsating DC. During circuit operation, diodes D1and D4 conducts and produce a positive half cycle, that is forward biased, while diodes D2 and D3 becomes reverse biased. In negative half cycle, diodes D2 and D3 conduct and becomes forward biased. But since load current is in the same direction in both half cycles, full wave rectifier appears across the output terminals.

c. Filter Stage:

An electrolytic capacitor is used to filter the pulsating D.C voltage that comes out from the rectifier section. During operation, the capacitor charges up (i.e store energy) during conduction of half cycle thereby opposing any changes in voltage. Hence, filter out voltage pulsations. A light emitting diode (LED) is attached immediately after the filtration

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capacitor, this is done with a current limiting resistor and this serves as a power indicator.

B. The Voltage Sensing Unit

The voltage sensing Unit consists of a voltage regulator (IC1), Comparator (IC2), resistor (R3, R4, R5, R6 and R7), NOT gate and a light emitting diode. This circuit operates by stabilizing the rectified voltages 12V dc with the help of voltage regulator. The resistors used to form the voltage dividers include (R3, R4, R6 and R7). The resistor R5, function as a limiting current resistor to the Not gate. The reduced voltages are compared through the inverting and the non-inverting inputs of the Comparators. During the process, when the voltage in the non-inverting input is greater than the inverting, input the output of the comparator (IC2) becomes “high” (logic 1). But in a situation where the voltage in the inverting inputs is greater or equal to the non-inverting inputs, the output will become “low” (logic 0), and the LED in series with the NOT gate will come on indicating that there is no output from the comparator.

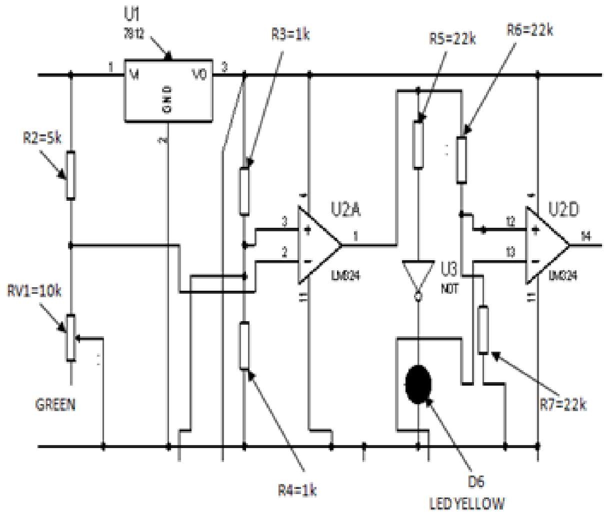

Fig. 9. Circuit Diagram of the Voltage Sensing Unit, operates by stabilizing the rectified voltages using voltage regulator.

C. The Current Sensing Unit

This part of the system is made up of a current transformer, rectification diodes, filtering capacitors, resistor and a Comparator (LM324N). The main function of this unit is to covert current to voltage. It monitors the current flowing through the conductor from the mains input to the output and then compares it with a pre-calibrated value (30A).

This unit monitors the current passing through the conductor to the output and coverts it into voltage, the AC voltage is then rectified with a full wave diode rectification using IN007. The direct current (DC) voltage is then divided using one fixed and one variable resistor, this is to make it possible to recalibrate the current sensor. The output from the voltage divider is then passed through the non-inverting input of a comparator that has a reference voltage set to 6V DC, when the non-inverting input of the comparator (LM 324N) is greater than the inverting input, the system will give an output of 12V DC which will enter a latching system which has a reset.

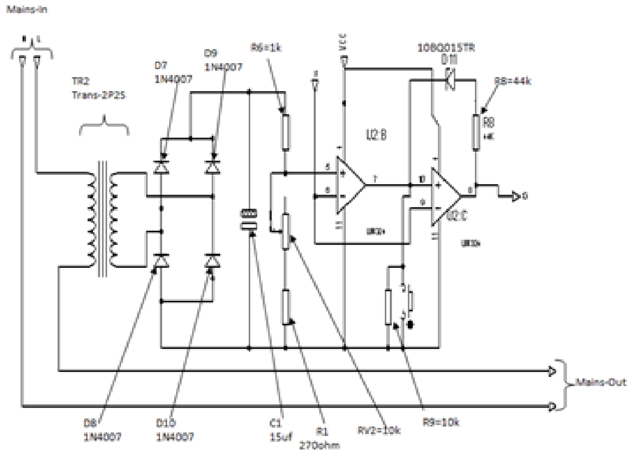

Fig. 10. Circuit Diagram of the Current Sensing Unit to convert current to voltage.

D. The Switching Unit

The switching unit is responsible for the making and breaking states of the relay. Transistors are used to drive the solid state relays in this unit. The unit consists of an NPN transistor (Q1), resistors, and the solid state relay. Transistor (Q1) conducts when its base senses voltage. This transistor is used to activate the collector current to the quantity required by the solid state relay.

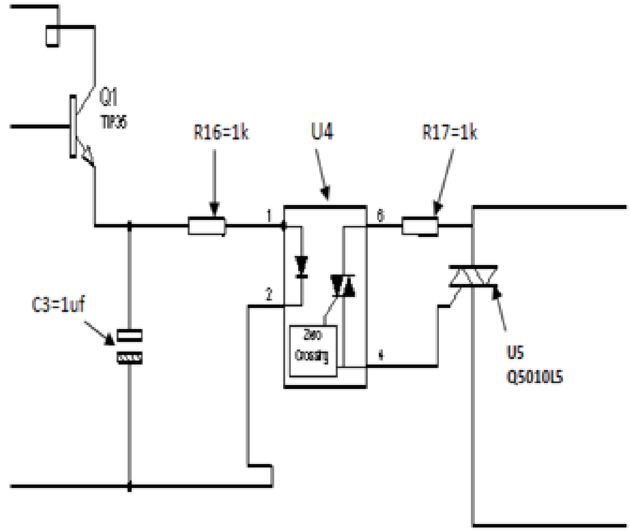

Fig. 11. Circuit Diagram of the Switching Circuit is responsible for the making and breaking states of the relay.

E. The Output Unit

This output unit can also be described as the load on a power system network. It consists of 200W lamp. This is used to show the behavior of the solid state relay to over voltage, under voltage, over current or short circuit faults.

IV. ANALYSIS OF DESIGN MODEL

The design modeling of components of these four selected sub – units: The power supply unit; switching unit; Voltage sensing unit; and Current sensing unit, are as shown in Figures 12, 14, 15 and 16.

A. Design Modeling of the Power Supply Unit

This power supply unit comprises of transformer, a bridge rectification unit, a filtering capacitor, resistor and a LED indicator.

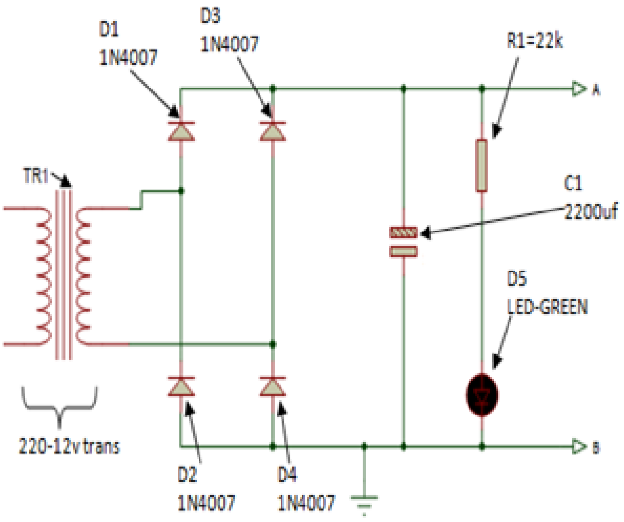

Fig. 12. The complete circuit diagram of the power supply unit used for modelling.

a. The transformer used in this project is a step down transformer, which steps down 220volt AC mains to 12-volt DC supply. The transformer operates on the principle of electromagnetic induction, where the voltage in the primary is completed in the secondary by time varying magnetic flux that pass through both windings through the core.
Using the specific transformer for this work, the value of K , is 0.0545 and the maximum primary voltage given as 311.13V. With subsequent calculation, the maximum secondary voltage is gotten as 16.97V.

b. The system was rectified using bridge rectification method with four diodes arrangement (or incorporating four diodes). The choice of IN4001 as rectifier diode was based on the fact that the maximum normal forward current of 500mA for the IN4001 while the maximum current of the transformer is 1.2A. Also, the pick inverse voltage (PIV) rating of IN4001 is 50V while the transformer can only present a pick inverse voltage of √2 x 24 across the two non – conducting diodes equals 33.94V which is the PIV of the transformer.

$$PIV = 2V_{max} \text{ (For full wave)} \quad (1)$$

$$PIV = 2 \times 16.97V = 33.94V$$

$$V_{rms} = 0.707 \times V_{max} \quad (2)$$

$$V_{rms} = 0.707 \times 16.97V = 12V$$

This unit converts AC voltage from the transformer secondary winding into pulse of unidirectional current, that is, it converts the sinusoidal voltage into pulsating DC signal.

c. A 4700µf capacitor is used, as a filter, to smooth the output voltage from the rectifier circuit to obtain the steady DC demanded by the electronic equipment's ripple voltage.

d. Analysis of the Power Supply Indicator

To ensure the presence of rectified power in the system, a green colour light emitting diode (LED) with forward voltage drop of 2V and forward current of 15mA was used as power supply indicator. The LED was protected with a current limiting resistor (R_s) equal to 500Ω.
With a multiplication factor of 1.5 to prolong the life span of the LED. Rs become 750Ω. Thus, a standard value of 1kΩ was used.

B. Design Modeling Of The Voltage Sensing Unit

The voltage sensing circuit uses 7812 regulators to stabilize the 12V DC from the filter circuit and also uses LM324 integrated circuit (IC) which has four operational amplifiers incorporated in it. The internal structure of this IC is as shown in Figure 13 with its pin arrangement.

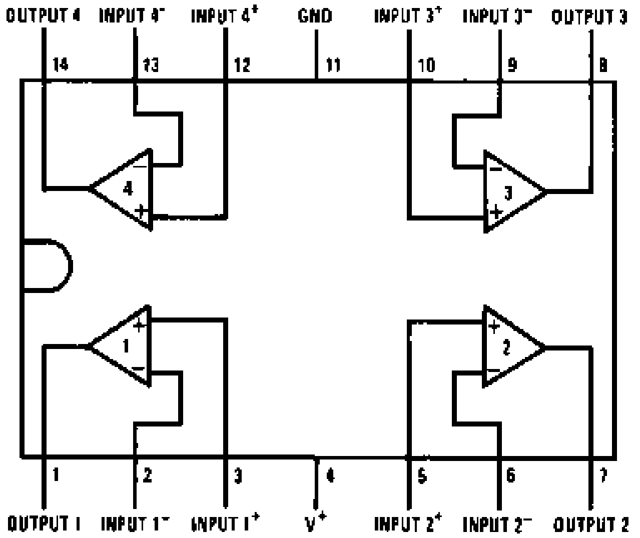

Fig. 13. Internal structure of LM324 IC is used to stabilize the 12V DC.

The operational amplifier, which was configured as a comparator compares voltage between two points.

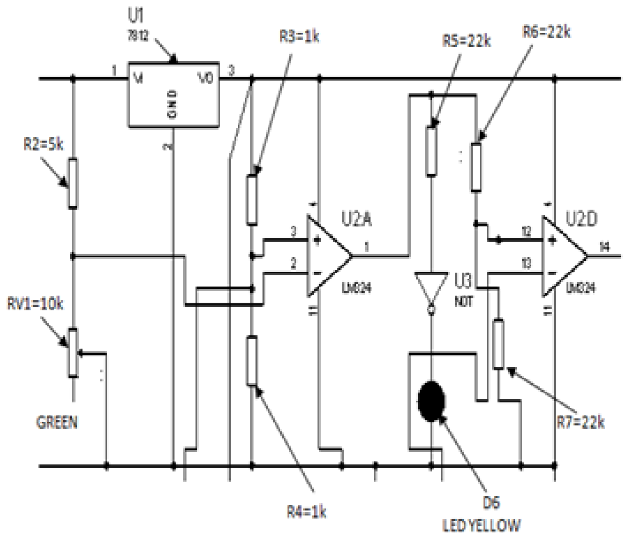

Fig. 14. The complete circuit diagram of the voltage sensing unit used for the modelling.

The circuit gives an output only when V_3 is greater than V_2 and also gives a no output when V_2 is greater than V_3. The 10kΩ variable resistor is used to vary the voltage between point 3 and point 2, as a variable resistor, any resistor with a

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wide range of variation can be used, so 10kΩ was used in the design.
Since V_{OUT} = 9.8V
Required voltage (needed) = 12V.
Hence, a positive voltage regulator of 12V is used (7812)

C. Design Modeling Of The Current Sensing Unit

The current sensing unit uses current transformer, LM324 integrated circuit also as a comparator. To obtain the current transformer, the primary winding of a voltage transformer is rewound using a single core of wire equivalent to the current carrying capacity of the load.

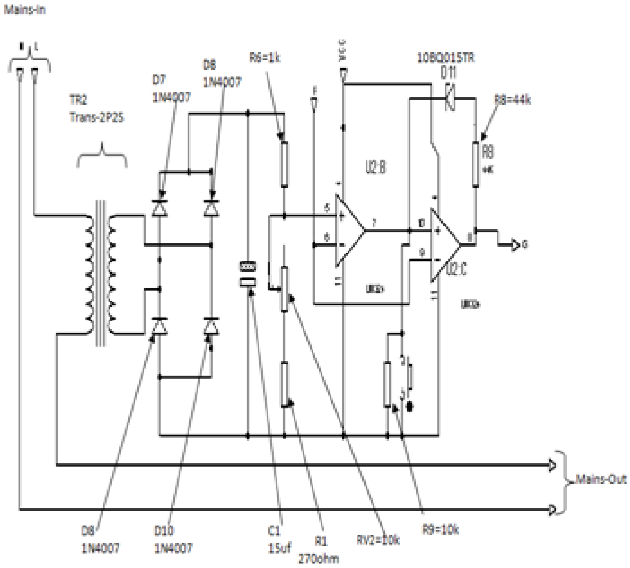

Fig. 15. The complete circuit diagram of the current sensing unit used for modelling.

For a 30A load, P = 6.6KW.
Hence, a 1:500 current transformer is made. The other parameters of the current sensing unit remain the same as that of a voltage sensing unit.

D. Design Modeling of the Switching Circuit

At the output of the comparator, we have the switching unit, the switching unit comprises of a transistor (2N2222A-H331) NPN and a resistor of base resistance 1KΩ. The transistor was configured as a switch which has specific characteristic of being triggered ON by base current of 10mA (From data sheet catalog).
Therefore, a standard value of 1KΩ resistor was used as the base resistor.

E. Design Modeling of the Switching Interphase

The switching inter phase uses a 3-32VDC (input), 24-380VAC (output) 400Ω solid state relay and the minimum collector current that can trigger this relay is 15mA gotten from the manufacturer data sheet for the switching unit, the collector current I_C is given by;

$$I_C = \frac{V_{CC}}{R_L} \qquad (3)$$

$$\Rightarrow I_C = \frac{12}{400} = 30mA$$

Where R_L is the relay resistance, the 30mA is sufficient to trigger the relay and as such 400Ω, 12V relay was chosen.

F. The Principle of Operation of the Complete Circuit Diagram

The circuit diagram has four operational amplifiers that are all configured as comparators. From the circuit, power is supplied to the V_{CC} (terminal 4) of the operational amplifier.
The first operational amplifier (voltage sensing unit) compares voltages between pins 3 and 2 of the operational amplifier. The non-inverting terminal pin 3 was set to a reference voltage of $6V_{DC}$, terminal 1 gives output only when pin 3 is higher than pin 2. The 10kΩ variable resistor is used to set voltage between pin 2 and pin 3, such that pin 3 is higher than pin 2. The output signal from the comparator biases the second operational amplifier through 2.2kΩ resistor which limits the flow of current to the second operational amplifier which is also configured to act as a comparator.
The second operational amplifier compares the voltage between pin 12 and pin 13. Pin 12 acts as the reference voltage, the operational amplifier gives output when pin 12 is greater than pin 13. The output through pin 14 sends signal to the base of the transistor 2N2222A-H331.
The 2N2222A-H331 transistor was configured as a switch, 1kΩ resistor was used as the base resistor R_b and this limits the base current and hence limits voltage drop at the output of the transistor, which switches ON the SSR, the switching inter phase in this case opens and closes based on the signal from the SSR. When the voltage at pin 2 is higher than that at pin 3, the output signal will be zero, then the NOT gate will trigger the LED (yellow) ON. This shows there is no output from the operational amplifier, which shows that there is over voltage and the SSR will cut off the load.
Furthermore, the current transformer takes in current (30A maximum) into its input (primary) from the supply (mains), and gives equivalent stepped down voltage (12V) at the output (secondary), the 12V AC is rectified using a full wave bridge rectifier and it's then filtered. The output of the filter circuit is fed into the third operational amplifier which also acts as a comparator (current sensing unit) compares voltages between pin 5 and pin 6 of the operational amplifier. The non-inverting terminal pin 6 was also set to a reference voltage of $6V_{DC}$, pin 7 gives output only when pin 5 is higher than pin 6. The 10kΩ variable resistor is used to set voltage between pin 5 and pin 6, such that pin 5 is higher than pin 6.
The output signal from the comparator biases the fourth operational amplifier which is also configured to act as a comparator which equally compares the voltage between pin 10 and pin 9 and gives output at pin 8 when pin 10 is higher than pin 9. The output signal is fed to the second operational amplifier which also compares the voltage from the current sensing unit and the reference voltage of the voltage sensing unit and gives output when the voltages are equal or the voltage from the current sensing unit is less.
The output signal from the second operational amplifier flows through the 1kΩ resistor to the 2N2222A-H331 transistor, which then switch ON and OFF the solid state relay, when there is over voltage, over current and/or short circuit, the switching inter phase is opened, hence the load is cut off by the solid state relay. However, when the fault is cleared, the switching inter phase is closed, hence the solid state relay triggers the load and it will start functioning normal again. The result was tested as shown in Figure 17.

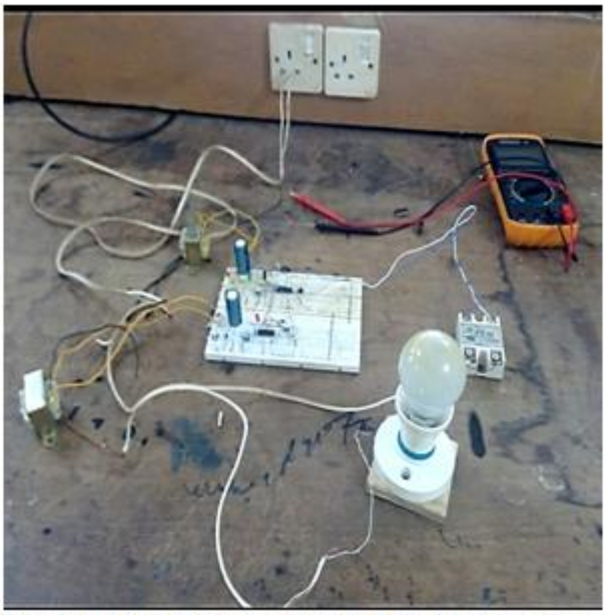

Fig. 16. The complete circuit diagram of the current sensing unit.

V. CONCLUSION AND RECOMMENDATION

The paper provides implementation of solid state protective relays with zero voltage switching for the protection of an electric network. Relay plays a pivotal role in modern power system protection to sense and isolate different types of fault in the power circuit. The selection of relays depends on power rating, voltage and current rating, effect of external factors etc. The designed and implementation of the protection of a disturbed electric network using a solid state protective relay is provided. Due to the use of semiconductor, arc less switching is possible with which the efficiency, reliability and life time of the protection unit increases.

With the protection of an electric network against over current, short circuit and/or under voltage using a solid state protective relay now unveiled, However, it is recommend that other approaches should be used to complement this approach. The protection of power system network is a necessary and inevitable process to ensure the security of the system since fault is inevitable.

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