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# Development of Generator Protection using Multifunction Numerical Relay in Laboratory

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**ABSTRACT**: A 3-phase synchronous generator is a vital component of power system and thus requires a dedicated protection system. To protect the generator against the adverse effects caused by abnormal or fault condition in power system or within the generator itself, it requires quick isolation from the system. In this paper, a laboratory setup has been developed to cater various protections applicable to scaled generator. In this work, a 3-phase circuit has been simulated including generator, measuring equipments (CTs & PTs), circuit breaker and variable load bank. A control circuit comprising of main relay and auxiliary relay has been developed for the protection of generator. A multifunction numerical relay (MiCom P341) is used to provide various protection features such as overload/overcurrent, over/under voltage, over/under frequency and restricted earth fault (REF) protection which are employed in actual field. The analog signal captured from the secondary of CTs and PTs are given as an input to relay which has an inbuilt high speed processing unit. As per the rating of generator, various parameter settings related to particular protection feature has been calculated by authors and given to the relay. The relay operates successfully and isolates the generator during all abnormal or fault conditions within the set time. The experimental results confirm the satisfactory operation of the developed laboratory prototype.

**KEYWORDS:** Laboratory Prototype, Generator Protection, Numerical Relay Settings, Various Fault/abnormal Conditions

## I. INTRODUCTION

A modern generating unit is a complex system comprising the generator stator winding, associated transformer, rotor with its field winding and excitation system, and prime mover with its associated auxiliaries. Faults of many kinds can occur within this system, for which different forms of electrical and mechanical protection are required. As generators are exposed to more harmful operating conditions than any other power system element, more sophisticated and innovative protection schemes are required. However, selection of protection functions that a particular generator needs and determining appropriate setting values require a thorough knowledge of the protected machine. Protection relay technology, over the last two decades, has evolved from single-function electromechanical relays to static relays and finally to multifunction digital/numerical relays which requires much less wiring and panel space. Multifunction numerical relays are capable of providing complete protection, including differential protection, stator & field winding to ground fault protection, out-of-step protection, over/under voltage and frequency protection, and loss-of-excitation protection, to generators of all sizes at low cost [1],[2].

Many researchers have done effort in the academic environment to demonstrate the concepts of protection for various equipments of power system. References [3], [4] illustrate a laboratory setup that focuses on design, modelling and testing of relay using high speed digital signal processing (DSP) boards. Redfern et al. [5] described relay testing using actual voltage and current data converted from the data files generated by power system simulation software. Lee *et al.* [6] presented operation of an instantaneous overcurrent relay and a reverse power relay using hardware and software strategy. Kabir [7] shows the performance of a single computer implementing an over-current protection in a laboratory experiment on a scaled down power system. Chen et al. [8] presented an intelligent embedded microprocessor based overcurrent protection scheme in laboratory environment. McLaren *et al*. [9] demonstrated a relay testing facility using Real Time Digital Simulator (RTDS). Oza *et al.* [10] has described a new power system protection laboratory based on senior design projects. Mehta and Oza [11] also presented laboratory simulation of generator protection using electromagnetic relays. Reference [12] described performed of the multifunction protection systems for generator. This paper also addresses the need for application of redundancy and backup protection when applying multifunction

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generator protection systems on large or important generators. Khan et al. [13] presented restricted earth fault protection with superconducting fault current limiter for 100% stator winding. Charles [14] demonstrated a new area of special protection and grounding needed for generator. Although, numbers of generator protection schemes have been proposed so far, there exists a lot of scope for further development especially in laboratory environment using digital relaying scheme.

This paper demonstrates a detailed study of various types of faults/abnormal conditions that occur in generators and the appropriate protection schemes with their fundamental concepts, including fault detection and clearance. Paper also includes the laboratory simulation, methodology and sample results of dynamic relay testing using a scaled model of prime mover-generator-load setups. Some of the abnormal conditions applied to the generator include: overload /overcurrent, internal faults (L-g fault), external faults, over/under excitation and low frequency operation [15], [16]. Actual current and voltage signals are given as an input to a multifunction numerical relay [17] which detect the said abnormal conditions and take appropriate action.

## II. EQUIPMENT RATINGS

The ratings of different equipments used in laboratory prototype of generator protection are mentioned below:

1) Synchronous Generator :
   - A) Synchronous Generator Armature :
     3- Phase, 50 Hz, 3 KVA, 415 V, 1500 rpm, Yn connected.
   - B) Synchronous Generator Field Excitation :
     220 V, DC excitation, 1.4 A.
2) DC Shunt Motor ( Prime Mover)
   10 HP, 220 V (DC), 19 A, 1500 rpm.
3) Rheostats ( for controlling various parameters)
   - A) One 18 Ω, 12 A rheostats in series with DC motor armature winding.
   - B) One 185 Ω, 2.3 A rheostat in series with DC motor field winding.
   - C) One 185 Ω, 2.3 A rheostat in series with DC field excitation of generator.
4) Instrument Transformers :
   - A) Current Transformers (CT):
     3 CTs in respective phases – burden: 15 VA, CT ratio of 10/5 A, class 1.0
     1 CT in neutral – Burden: 15 VA, CT ratio of 10/5 A, class 1.0
   - B) Potential Transformers (PT) :
     3 PTs each between phases to neutral –Burden: 50 VA, 220/110 V, class B.
5) Relay:
   - A) Numerical Relay:
     17 Watts, $V_x$= 110-250 V DC or 100-240 V AC, $I_n$=1 or 5 A, $V_n$=100-120 V AC, 50-60 Hz.
   - B) Auxiliary Relay:
     230 V AC, Contact capacity: 10 A, 3-NO and 3-NC contacts.
6) Circuit Breaker:
   A) L&T make, 220 V, Contactor with 6-NO and 2-NC contacts having 30 A capacity.

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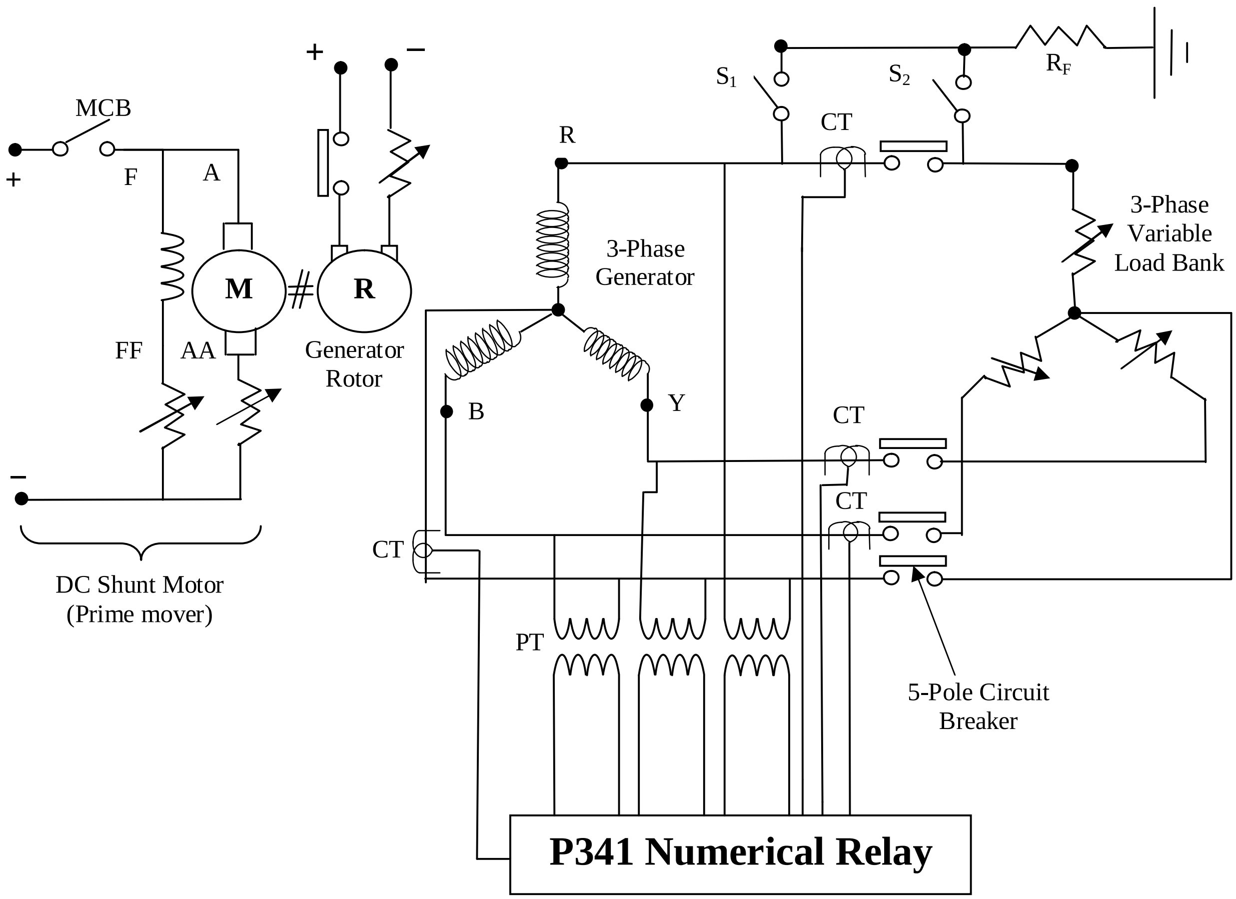
B) Two numbers switch $S_1$ and $S_2$ having capacity of 20 A.

## III. LABORATORY PROTOTYPE (HARDWARE SETUP)

### *3.1 Power Circuit*

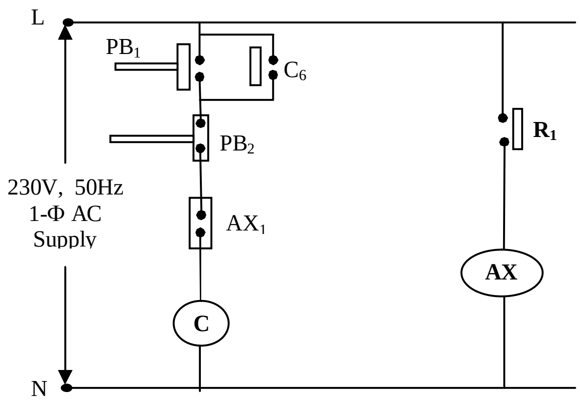



**CT** = Current Transformer, **PT** = Potential Transformer, **$S_1$ & $S_2$** = Fault Switches,
**$R_F$** = Fault Resistance, **MCB** = Miniature Circuit Breaker

Fig. 1 Schematic Diagram of Laboratory Setup

In actual field, steam turbine, hydro turbine, gas turbine etc. act as a prime mover to the generator; however in laboratory simulation, DC shunt motor is used as a prime mover. As shown in the Fig. 1, the 3-ϕ synchronous generator (unit to be protected) is mechanically coupled with a separately excited DC shunt motor (prime mover). The DC motor field and armature winding are excited by a 220 V DC supply through rheostat of appropriate ratings for its motoring action to generate desired mechanical power. The rotor winding of the generator is also excited by 220 V DC supply through separate rheostat. These series rheostats are required to control different parameters of generator such as voltage and speed/frequency. A 3-ϕ variable load bank is connected to the generator through contactor (circuit breaker). A set of CTs (10/5A) and PTs (220/110V) are connected in respective phases as shown in Fig.1. Secondary signals of CTs and PTs are given to numerical relay. Switches $S_1$ and $S_2$ are used to simulate internal and external fault conditions respectively. The contacts of 5-pole Circuit Breaker (CB) are connected in system to isolate generator during abnormal/faulty condition.

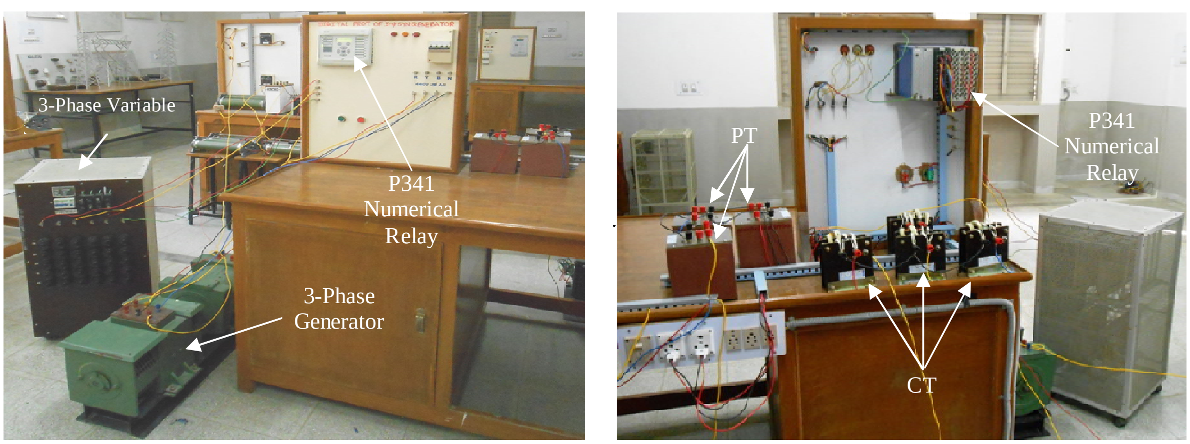
### *3.2 Control Circuit*




**PB$_1$/ PB$_2$**= ON/OFF Push Button, **R$_1$**= Main Relay Contact
**C**= Coil of Contactor (CB), **AX**= Auxiliary Relay

Fig. 2 Control Circuit of Laboratory Setup

Fig. 2 shows the control circuit implemented in the laboratory for real time protection of generator. The positions of all the contacts depicted in the control circuit are under the condition when generator runs at no load. Initially, the contactor coil (C) is energized manually using a push button (PB$_1$) which is normally in open condition. One of the contacts (C$_6$) of the contactor itself provides hold path for continuous energization of contactor. Also for manually de-energizing the contactor, a push button (PB$_2$) is provided in series with PB$_1$ and coil of contactor. Under any abnormal or fault condition in the system, numerical relay successfully detects it and closes its main contact R$_1$ to energize an auxiliary relay (AX) as shown in Fig. 2. As and when AX energizes, one of its contacts (AX$_1$), connected in series with coil of contactor opens. As a result the contactor is de-energized and thus all five contacts (as shown in Fig. 1) are opened to disconnect generator stator windings, neutral path and DC field excitation. Thus generator is isolated from faulty section or protected against any abnormal condition. Figure-3 shows photograph of front and rear view of the developed prototype in laboratory environment.




3(A) Front view of Laboratory Setup

3(B) Rear view of Laboratory Setup

Fig. 3 Hardware Setup in Laboratory

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## IV. SIMULATION RESULTS AND DISCUSSION

Different protective features available in the numerical relay have been simulated in the laboratory. Various protections along with their actual relay settings and relay operation are described below:

### A. Overload & Overcurrent Protection (50/51)

In actual field the overload situation in power system may arise due to excessive load on the system and/or overcurrent condition may arise due to occurrence of fault (i.e. insulation failure, etc.). Overload & overcurrent protection of relay operates when the value of current rises above the threshold setting as mentioned in the table -I. The overload condition has been simulated in laboratory by gradually increasing the load with the help of 3-phase load bank. An external high resistance L-g fault (R-g) has been simulated at reduced voltage (180V) by closing the switch $S_2$ connected through a rheostat of 18 Ω, 12 A. Table-I shows relay setting range and the results in terms of threshold setting and operation time for overload & overcurrent phenomenon applied to developed setup.

Table-I Relay setting for overload/overcurrent condition in generator protection

| Protection type | Characteristic | Setting Range | Step Size | Actual Setting | |
|---|---|---|---|---|---|
| Overload setting (I >) | DT (Definite Time) Characteristic | 0.08 to 4.0 In<br>In= Nominal Current | 0.01In | Pick up= 1A | Top= 3Sec |
| Overcurrent setting (I >) | DT (Definite Time) Characteristic | 0.08 to 4.0 In<br>In= Nominal Current | 0.01In | Pick up= 2A | Top= 1Sec |

### B. Overvoltage (59) & Undervoltage (27) Protection

*Overvoltage Protection (59)*

In real field overvoltage may occur due to sudden cut out of load, failure of Automatic Voltage Regulator (AVR), etc. Overvoltage protection of relay operates when the voltage magnitude rises above the threshold value set as mentioned in Table-II. In laboratory overvoltage condition is simulated by varying the field excitation of the generator. The rheostat connected in the field excitation system is varied and resistance value is decreased so more field current is allowed to flow, thus inducing higher emf in the stator than rated. This condition can also be simulated by suddenly disconnecting the load bank from generator.

*Under voltage Protection (27)*

Under voltage condition may arise due to sudden rise in load on the system, fault condition in nearby system failure of AVR system, etc. Under voltage protection of relay operates when voltage magnitude at generator terminals or at the load end goes below the threshold setting as mentioned in Table-II. Under voltage condition has been simulated in the laboratory by varying the rheostat connected in the field excitation system. The resistance of rheostat is increased, thus reducing field current of generator and inducing reduced voltage on generator terminals.

A set of PT (connected to the terminal of generator) will sense healthiness of generator terminal voltage as per the set value in relay. Actual voltage signals from the secondaries of all three phase PTs are given to relay for over & under voltage protection.

Table-II Relay setting for overvoltage and under voltage condition in generator protection

| Protection type | Characteristic | Setting Range | Step Size | Actual Setting | |
|---|---|---|---|---|---|
| Overvoltage setting (V >) | DT (Definite Time) Characteristic | 60-185 V | 1 V | Pick up= 120V (Phase Voltage) | Top= 5Sec |
| Under voltage setting (V <) | DT (Definite Time) Characteristic | 10 to 120 V | 1 V | Pick up= 50V (Phase Voltage) | Top= 5Sec |

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**C. Over frequency & Under frequency Protection**

*Over frequency Protection (81-O)*

Over frequency condition may arise due to excess generation than load demand or due to outage of large load. This condition can easily be corrected by reducing the power input to prime mover with the help of governing system. Over frequency protection of relay operates when the frequency of the system rises above the set value as mentioned in table-III. Relay measures the frequency of voltage signal given through PTs. In laboratory this condition is created by increasing the speed of DC motor (prime mover). This in turn is achieved by controlling the rheostats connected in series with field and armature winding of DC motor (field and armature control method of DC motor speed control). The speed is made to increase by reducing the current either through field or armature which in turn is achieved by increasing the resistance value of these two rheostats. Another method to simulate over frequency in isolated system is to cut out a heavy load from the system.

*Under frequency Protection (81-U):*

When the system is overloaded due to sudden fall of heavy load on generator, the generator delivers larger current and the frequency of the system drops. This condition can be overcome by either increasing the generation (increasing mechanical power input to the turbine) through governing system or by load shedding. Under frequency protection of relay operates when the frequency of the system goes below the set value as mentioned in Table-III. For laboratory simulation of this condition, the speed of DC motor (prime mover) is reduced by decreasing resistance of field and armature rheostat of DC motor. Another way of simulating this condition is by overloading the system.

Table-III Relay setting for over frequency and under frequency condition in generator protection

| Protection type | Characteristic | Setting Range | Step Size | Actual Setting | |
|---|---|---|---|---|---|
| Over frequency setting (F >) | DT (Definite Time) Characteristic | 45 to 65 Hz | 0.01Hz | Pick up=51.5 Hz | Top= 3 Sec |
| Under frequency setting (F <) | DT (Definite Time) Characteristic | 45 to 65 Hz | 0.01Hz | Pick up=48.5Hz | Top= 2 Sec |

**D. Restricted Earth Fault Protection (REF)**

The objective of restricted earth fault (REF) protection is to detect the earth fault in the specific zone starting from the generator neutral point to generator terminal. As shown in Fig. 4 all the CT secondaries are connected in differential fashion along with the Sensitive Earth Fault (SEF) unit of numerical relay connected across them.

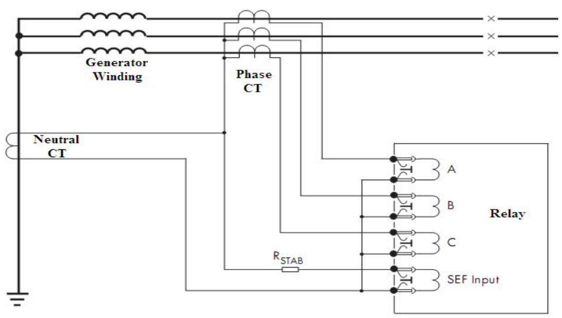


Fig. 4 CT connection for REF Protection of Generator

In normal operating conditions, the phasor sum of the currents in the lines is equal to the neutral current and thus minimum (almost zero) current flow through the relay coil. Thus relay remains stable under normal operating conditions. As and when an internal fault occurs due to failure of insulation of any phase winding, it results in current difference which operates the relay successfully. In laboratory, relay operation has been tested by manually creating an internal and external fault with the help of switches $S_1$ and $S_2$ respectively (Fig. 1). Under external fault condition, REF feature of relay remains stable. In the event of an internal fault simulated by closing switch $S_1$, the relay operates as per the setting given in Table-IV and isolate itself from the DC excitation system & also from the load system.

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Table-IV Relay setting for earth fault condition (REF) in generator protection

| Protection type | Characteristic | Setting Range | Step Size | Actual Setting | |
|---|---|---|---|---|---|
| SEF/REF Protection ($I_{ref} > I_s$) | DT (Definite Time Characteristic) | 0.005-0.1 $I_n$<br>$I_n$ = nominal current | 0.00025 $I_n$ | Pick up = 0.025A | Top= 0.1 Sec, (Class-A Protection) |

## V. CONCLUSION

A real time implementation of multifunctional digital relaying scheme in laboratory environment for scaled generator is presented in this paper. The 3-phase power circuit simulation and prototype implementation of various protection schemes applicable to generator has been carried out. The developed laboratory setup is capable of discriminating th normal and abnormal/faulty condition of generator. Restricted Earth Fault (REF) protection scheme is designed and implemented to detect all types of internal ground faults. All other abnormalities such as overload/overcurrent, under/over voltage phenomenon, low frequency have been detected by the prototype as per design criteria and relay setting. An average tripping time of the order of 0.1sec to 5sec is achieved for all kinds of internal & external faults and abnormalities. The experimental results confirm the satisfactory operation of the developed generator protection scheme with linear/non linear loads.

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