

Integrated Model for Anti-Motoring and Abnormal Frequency Protections in Large Generators

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Abstract: Large grid connected synchronous generators are required to be protected from several abnormal operating conditions that are both major and minor in nature. The generating units as such require multiple protection devices to provide comprehensive protection against these fault conditions. Amongst these protection functions, the Anti-motoring (ANSI Code-32) and Abnormal Frequency (ANSI Code-81) protections are discussed in this paper. The concepts and possible control strategy for implementation of these protection functions as a part of integrated multifunction generator protection relay have been outlined and modelled using Matlab Simulink software. The power system used for simulation was modelled using a separately excited large synchronous generating system connected to a 132 KV, 50 HZ transmission network through a high voltage breaker. The operation and performance of both of the protection functions have been analysed by simulating time varying output of prime mover and variable loads on the power system.

Keywords: Anti-motoring protection, Generator protection, Reverse Power, Overfrequency,

I. INTRODUCTION

Synchronous Generators are considered to be the most essential and dynamic components in large integrated power systems. When compared to protection of other power system components, a synchronous generator requires maximum number of protection from several abnormal operating conditions. Usually, a faulted power system component can be cleared by isolating all the electrical sources connected to it. However, Synchronous generator is a system with AC electrical (power system), DC electrical (field circuit) and mechanical (turbine-prime mover & generator inertia) sources of energy. A thorough understanding of the interactions amongst these sources of energy is essential to protect a synchronous generator.

Protection of a generator employs micro-processor based multifunction digital relays that use Digital Signal Processing methods. They offer several generator protection functions in one single device. It is common industrial practice to have redundant multifunction generator protection relays such as Main and Backup for protection of large AC generators so that ample protection functions remain intact even when any one unit is out of service. In these large generating units, redundancy is usually ensured by use of separate sets of CT and VT cores of instrument transformers, separate multifunction numerical relays, separate lockout relays (86), individual DC control supplies and separate breaker trip coils. It is also a common practice to have Main and Backup multifunction protection relays from different manufacturers or those that use different algorithms.

In this paper, anti-motoring and abnormal frequency protections of grid connected synchronous generator have been discussed, modeled and the response of these protective functions have been analyzed for various fault scenarios occurring in both the power system and its prime mover.

1.1 Motoring Operation

A generator is driven as a synchronous motor by the power system to which it is connected when the mechanical power input to its shaft from the turbine is lost ^[1]. While the generator excitation system is active, the generating unit tends to drive its prime mover at synchronous speed. Motoring mode of operation has destructive effect on the prime mover but the coupled generator would not be affected ^[6]. A Protection device/function that monitors the power flowing into the synchronous machine can sense this condition. Magnitude of motoring power drawn by the machine depends on the type of prime mover which in turn decides the sensitivity requirements of the anti-motoring function.

1.2 Abnormal Frequency Operation

Operation at other than normal frequency occurs as a consequence of unfavourable/ faulty conditions that exist within the power system to which the unit is synchronized and is attributable largely to the mismatches between generation and power demand. Over frequency operation of a generator occurs when generation far exceeds load demand. Over frequency can occur after the loss of a large load block or a major power exporting tie lines. On the contrary, under frequency operation can occur as a consequence of insufficient generation due to the failure of a large generating unit or loss of a major power importing tie line [2].

II. CONCEPTS OF ANTI-MOTORING PROTECTION

Motoring conditions can occur due to operator’s mistake during synchronization with machine speed slower than the power system; circuit breaker failure to open during unit shutdown; or due to a mechanical breakdown [4]. Both electrical and mechanical anti-motoring protection systems are usually implemented in majority of the power plants. Electrical anti-motoring protection is implemented by a directional sensing reverse power relay that senses reversal of the power flowing out of the generator terminals. Motoring power requirements at of any generation unit is a function of windage and frictional losses of the prime mover and rotor in association with the power losses in the generator. The anti-motoring protection operates to isolate the generator and prime mover from the power system [3]. Typical motoring power requirements for different types of generating units are as follows [4]:

Steam turbines	
a) Condensing types	1% - 3%
b) Noncondensing type	3 + %
Hydraulic Turbines	
a) Impulse type	0.2% - 2+%
b) Reaction type	+/- 25%
Diesel engines	+/- 25%
Gas turbines	50+ %

Various detection means are provided as part of the generator and its control, but supplementary reverse power protection device/function (ANSI 32) is recommended. Sensitive numerical relays with sensitivities down to 1 mA would be necessary when a generating unit is operating on part load [5]. Selection of CT and PT instrument transformers along with their interconnecting cables need special attention in such cases. Theoretically, an anti-motoring device, whether monitoring for secondary watts or current, compute power requirements of the generating unit as:

$$P = I * E \cos\theta \tag{1}$$

$$= I_r * E \tag{2}$$

Where E and I refer to line to line quantities and θ is the power factor angle.

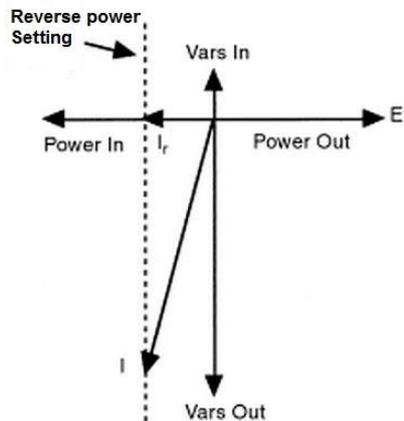


Fig. 1 Reverse power measurement principle

A directional element is used in anti-motoring protection function which serves the purpose of detecting the abnormal direction of power flowing into the generator terminals. Directional elements are particularly useful when the system has several sources, which in our case is the generating unit and the transmission grid network. The directional change in power flow is sensed by measurement of phase displacement between current and voltage.

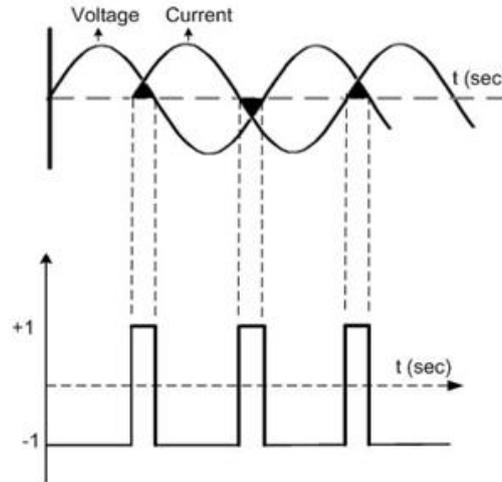


Fig. 2 Phase displacement between current and voltage during fault

The protective function detects flow of power beyond a threshold and in a given direction. Often, some installations also employ a ‘Low Forward Power’ protection in conjunction with reverse power which actually detects power flow out of generator terminals when the magnitude is below a minimum threshold. Multifunction numerical relays deployed for protection of a generating unit generally have two reverse power elements with different time delays. One element is implemented in sequential trip logic and the second one for motoring protection.

2.1 Sequential Trip Logic

Control systems of prime movers employ sequential trip logic which first initiates a turbine trip by way of restricting the supply of working fluid. Operation of circuit breakers later on is deliberately delayed until reversal of power flow is detected by the anti-motoring function as shown in Fig. 3.

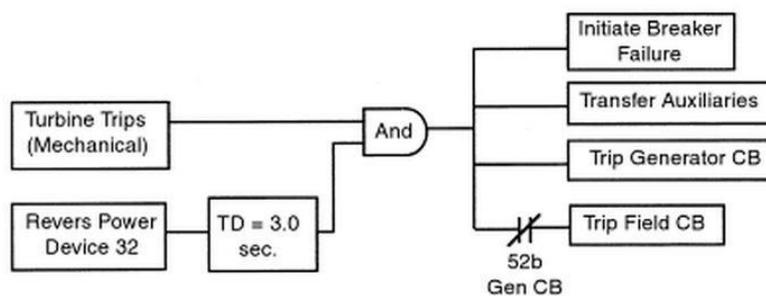


Fig. 3 Sequential trip logic^[3]

The energy intake of the turbine has to be brought down to a very low ‘No load’ value in order to avoid over speeding when the circuit breaker is opened. Sequential logic ensures the same by looking for appropriate feedback of the steam valves or Guide vane positions depending on whether the turbine is a steam turbine or a hydraulic one. Suitable interlocks are provided as part of the logics to confirm generator breaker trip before opening the field circuit breaker. In case of only one reverse power element, the anti-motoring protection is delayed to match with timings of the requirements of the sequential trip logic^[3].

2.2 Anti-Motoring Trip Logic

Sequential logic mentioned above can prevent over speeding of the unit. However, failure of this logic might result in motoring conditions which are to be prevented by dedicated anti-motoring scheme such as a separate anti-motoring device/function. This backup element is time coordinated with the sequential logic. The backup element is interlocked only by generator breaker closed feedback (52a contact). Care should be taken to provide sufficient time delay to the backup protection scheme so as to allow the generating unit to prevail during power system transients. At the same time, this delay shall not be more than the max. permitted motoring time^[3].

III. CONCEPTS OF ABNORMAL FREQUENCY PROTECTION

Under frequency operation of a synchronous generating unit is more of a concern than an over frequency operation. Appropriate timely governor action can promptly control an over frequency condition by reduction of power input to the prime mover. The generator load handling capacity is improved by increased speeds that prevail during over frequency incidents. On the contrary, excessive loading in the power system is the root cause of an under frequency event which is beyond the control of the generating stations. In an under frequency incident, generator loading capabilities are reduced by the reduction in ventilation of the unit due to reduced shaft speed. Under frequency conditions prevail in an over loaded system resulting in all grid connected generators exceeding their name plate rating. They would need more ventilation, but due to reduction in shaft speed, the ventilation capability of the generator deteriorates. Automatic Voltage Regulators of excitation systems resort to field forcing to sustain system voltage which would further over load field and stator circuits of the generator^[3].

3.1 Over Frequency Protection

Over frequency conditions occur when full or partial load shedding is carried out on a generating unit. Over frequency conditions does not impose any threat to the generating unit and normal governor control action could bring the unit back to rated synchronous speed without the need to trip the generator. Generators are designed with inbuilt over speed detectors. Over frequency element is used as additional protection with separately settable alarm and trip thresholds.

3.2 Under Frequency Protection

Generators may operate with under frequency conditions for a prolonged period as a result of insufficient load shedding or due to insufficient generation availability. Either case results in overloading of connected generating units. Gas and steam based generators are particularly at risk to damage from under frequency operation^[12]. At reduced frequencies, the prime movers are more vulnerable than the generator themselves due to probable mechanical resonance in the turbine blade structures. If the shaft speed coincides with natural frequency of the blades, resonance will occur thereby increasing the vibration levels several fold. Turbine blade structure can crack on account of cumulative damage accumulated due to excessive vibrations. Steam turbines are more adversely affected by abnormal frequency operation than the generators they drive. Operation near mechanical resonance will cause increased blade vibration and cumulative fatigue failure. Hydro turbines are not affected by under frequency operation, however over frequency which is actually over speeding is a concern that can result in typically 130 to 150% overspeed owing to huge mass and high kinetic energy of the water in the water conductor system. Excitation system performance in a self-excited generator deteriorates with under frequency conditions since underfrequency reduces the exciter output voltage and thereby reducing the generator terminal voltage.

Primary protection against underfrequency operation and over loading conditions is systematic load shedding. The under frequency function (device 81U) is used as a backup protection. Load shedding schemes are designed to trip designated distribution substation feeders to cater to maximum possible overload conditions^[7]. Permanent and temporary speed droop characteristics of the turbine governor determines the effective operating frequency in both overloaded and under loaded conditions of the generator^[3]. Underfrequency load shedding is used for those situations in which a portion of the interconnected systems becomes islanded and there is an imbalance between the generation and load. The underfrequency load shedding program is normally provided to restore the balance in an island with more load than generation. It is essential that generating units “hang on” as long as possible and do not unnecessarily trip while the underfrequency load shedding is in progress. Therefore, generation tripping relays must be set to coordinate with the underfrequency load shedding program. Underfrequency load shedding and generator tripping are normally addressed as a regional criteria^[2].

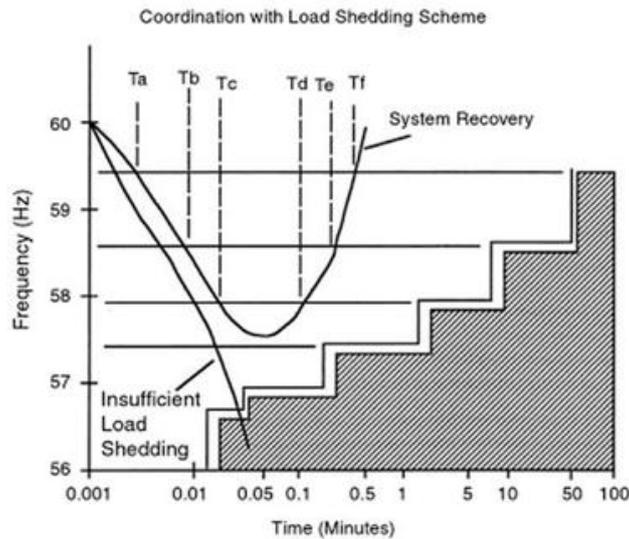


Fig. 4 Example of Coordinated system load shedding in a 60 Hz system [2]

Backup protection for under frequency is employed as a part of generator protection and is necessary to rule out situations of under shedding. Backup generator protection in case of inadequate load shedding would be in the form of multilevel under frequency tripping as shown in Fig.4. A multi-level, time-delayed under frequency function is preferable for each frequency band on turbine manufacturer’s limit curve [3] an example of which is shown in Fig. 5 for a 60 Hz system.

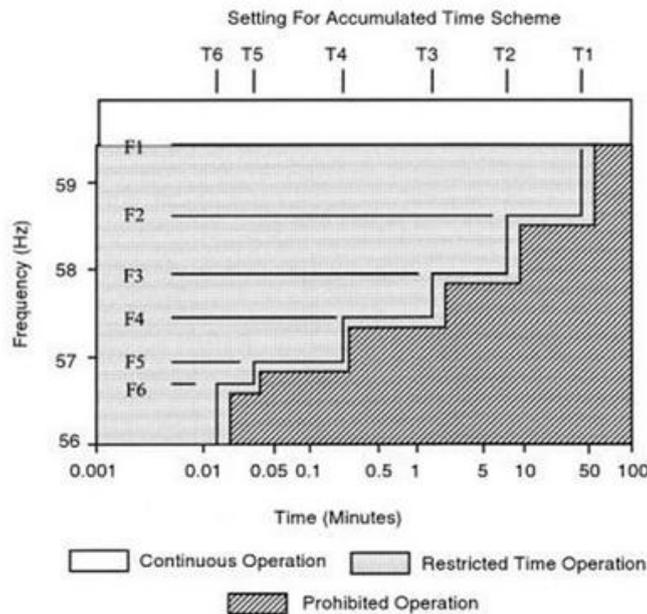


Fig 5. Accumulating timer scheme [3]

IV. MODELING

The generated voltage is stepped up to the transmission level by use of a Generator step-up transformer. For the sake of simplicity of the model, the turbine generator system with governor and generator step up transformer have been considered as a single entity. All the voltages, currents and frequency monitored and illustrated refer to the secondary side of the generator transformer high voltage side.

The anti-motoring device function (32) and abnormal frequency functions which are integral part of a generator multifunction protection relay have been implemented as separate Simulink functional blocks. Abnormal frequency block detects both over frequency (81O) and under frequency (81U) in one unit and also employs turbine-governor loop since frequency is controlled by active power which in turn is regulated by governor.

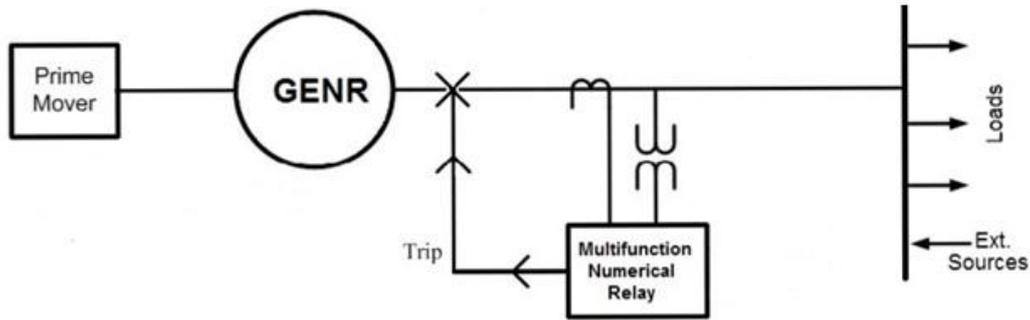


Fig. 6 SLD of power system model

4.1 Modelling Of Anti-Motoring Protection Function

The anti-motoring function is implemented by a directional element that receives current and voltage signals as input. From their phasor relationship, the directional element determines the reversal of power flow. Directional element feeds the input of a time delay cum threshold decision element which decides by the use of integrators and threshold value whether a reverse power condition exists for sufficiently long time period. The output of this stage is fed to trip coil of circuit breaker through a hold logic. In actual power systems, the relay trip decision is given to a lock out relay (ANSI 86) that act as a holding contact ^[11].

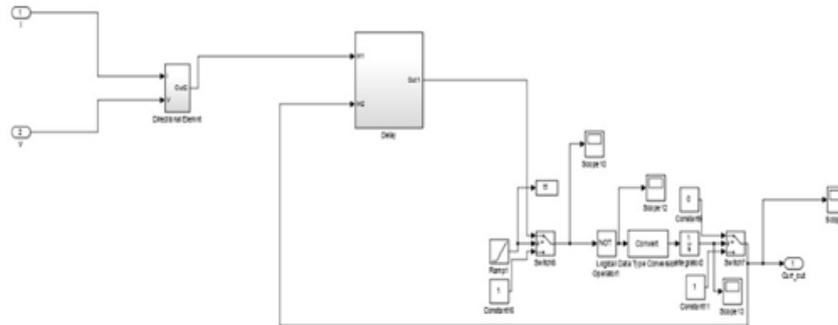


Fig. 7 Simulink based model with directional elements for detection of motoring conditions

4.2 Modelling Of Abnormal Frequency Protection Function

Protection function model for abnormal frequency consist of a Frequency measuring unit that determines the current frequency of the system using the voltage signal input from the voltage transformer.

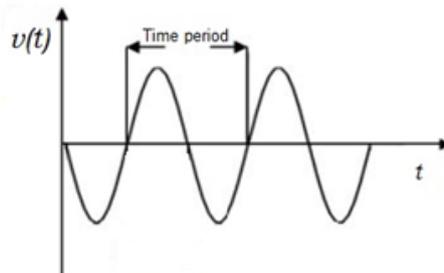


Fig. 8 Frequency measurement ^[11]

The frequency measuring block gives forwards its output to the abnormal frequency detection unit which checks whether the measured frequency is an under frequency condition or an over frequency condition. In either case, a timer delay achieved by threshold value and integrator waits for the predetermined time duration after which trip decision is extended to the circuit breaker ^[12].

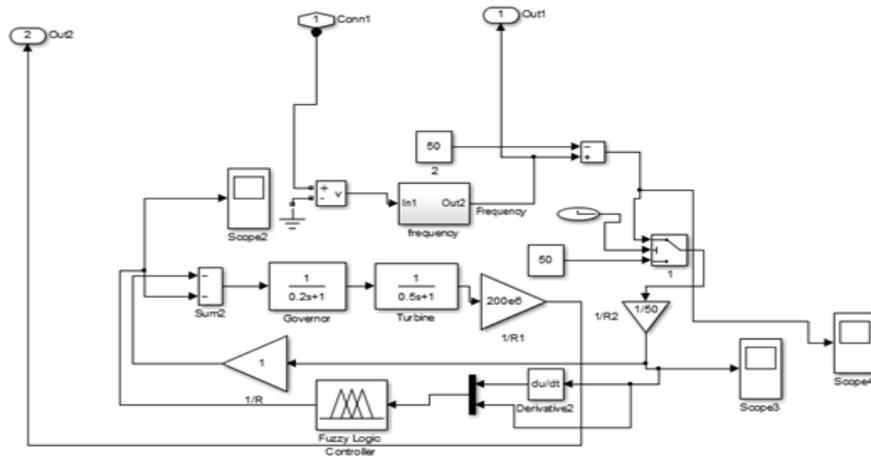


Fig. 9 Abnormal frequency function control signal using fuzzy controller

The measured frequency is also fed through a feedback loop to the turbine governor blocks. The output from the governor block is fed as mechanical input to the synchronous machine via a fuzzy logic controller as shown in Fig.9. Fuzzy Logic is incorporated to control the generator mechanical input in order to cope up with the variation of load demand and frequency occurring in the power system during the running conditions. Fuzzy inference systems also referred as fuzzy models are schematically shown in Fig. 10.

They are composed of 5 blocks.

- A rule- base containing a number of fuzzy if-then rules.
- A database which defines the membership functions of the fuzzy sets used in the fuzzy rules
- A decision-making unit which performs the inference operations on the rules,
- A fuzzification interface which transform the crisp inputs into degrees of match with linguistic values,
- A defuzzification interface which transform the fuzzy results of the inference into a crisp output.

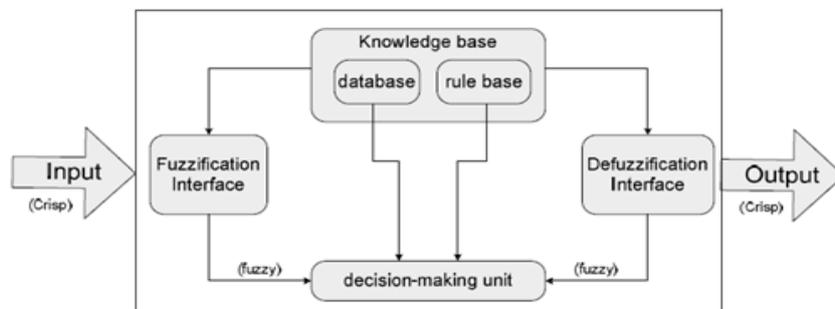


Fig. 10 Fuzzy Input Output Model

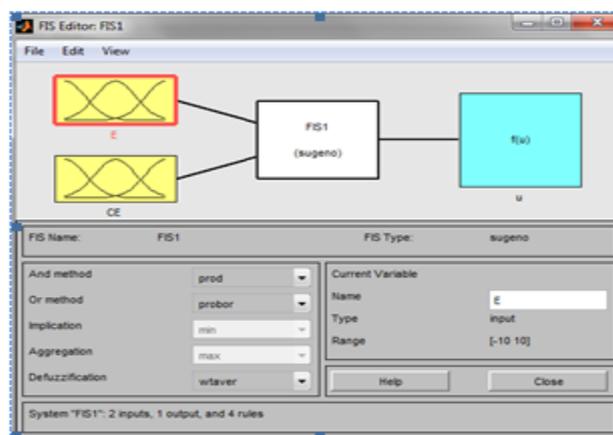


Fig. 11 Fuzzy model

Above figure shows that two inputs are taken into consideration, one is error and another is change in error of the frequency difference from the 50Hz reference.

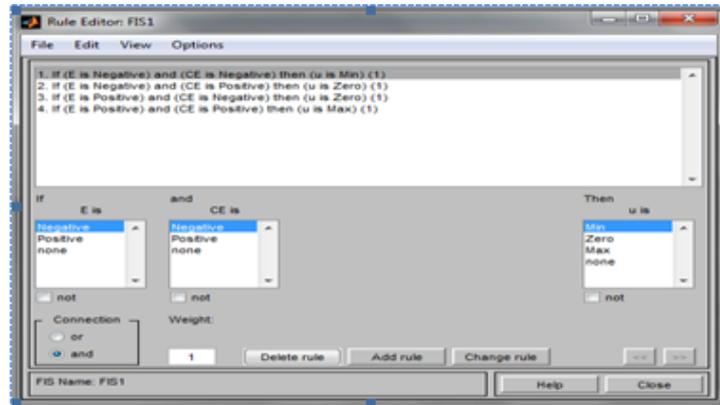


Fig. 12 Rules of fuzzy model

A rule base as shown in Fig. 12 has been implemented using Matlab fuzzy toolbox as listed below:

- If (E is a Negative) and (CE is negative) then output is Min
- If (E is a Negative) and (CE is Positive) then output is Zero
- If (E is a Positive) and (CE is negative) then output is Zero
- If (E is a Positive) and (CE is Positive) then output is Max

Instead of controlling the governor and turbine output using standard PID a fuzzy logic model has been incorporated to improve the stability of the system.

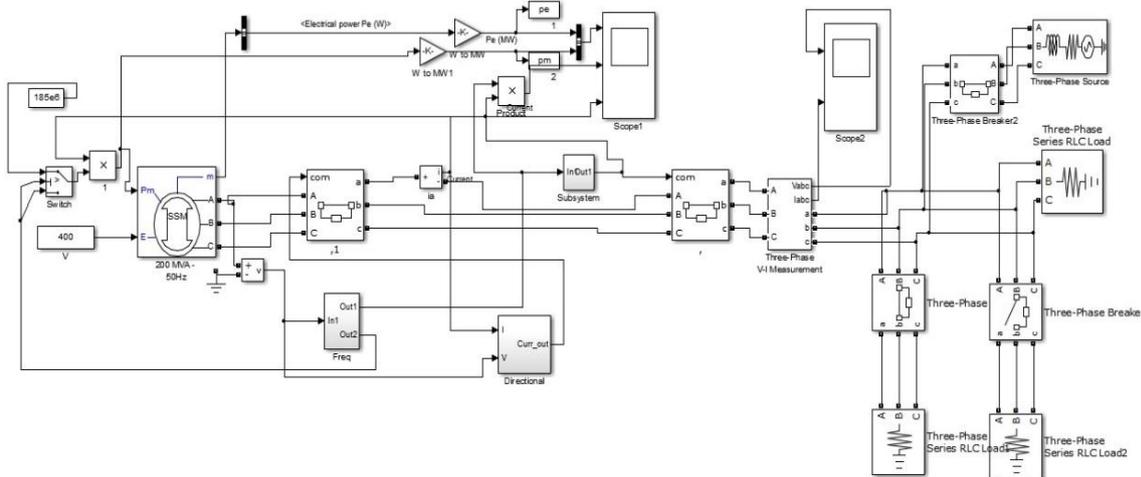


Fig.13 Integrated MATLAB simulation model used for evaluation of both protective functions.

V. SIMULATION AND RESULTS

The generator–transmission network model with anti-motoring and abnormal frequency detection functions are simulated under four different cases. By varying the mechanical input to the synchronous machine as a function of time, anti-motoring conditions have been simulated. A three phase power source is made active during anti-motoring simulations to recreate conditions of other generating resources that may be connected to the network. Likewise, by modulating the loads on the transmission network as a function of time, various conditions of under frequency and over frequency have been simulated. Following are the illustration of results of simulations under four cases.

Case1: Sudden Loss of Load

This case was to simulate over frequency conditions and check for the operation of the relay. Initially the generator was supplying a load of 180 MW. After 50 seconds of operation load has been first decreased from 180 MW to 150 MW thereby disturbing the generation- load balance and creating over frequency conditions.

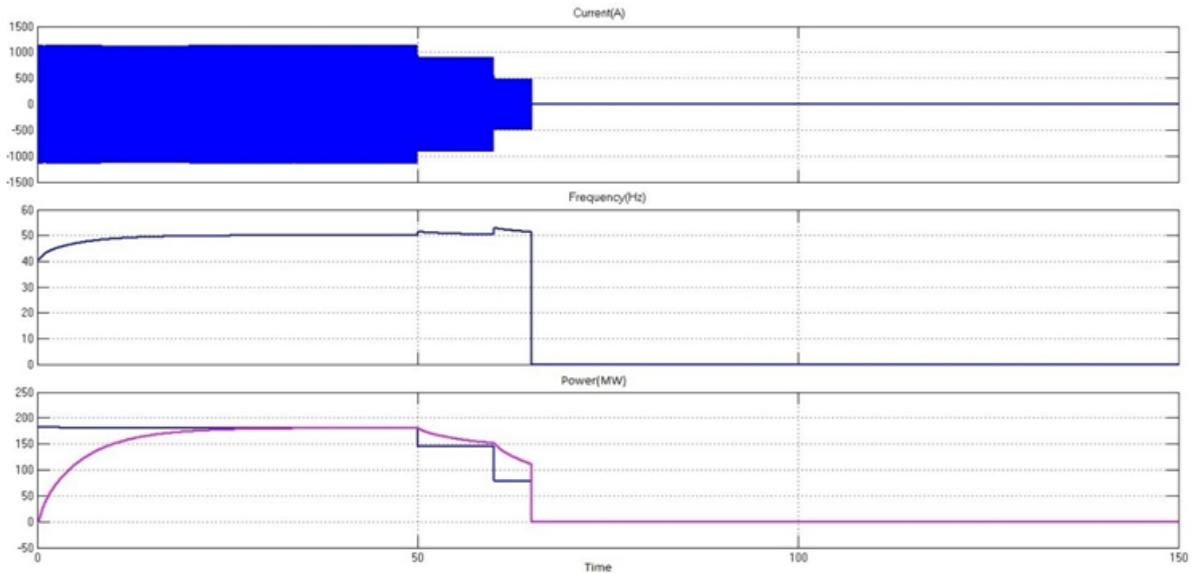


Fig. 14 Response to load loss events (over frequency conditions)

The turbine governor control takes over and generator output is adjusted within 5 seconds. The time delay function inbuilt into the frequency element resets before it could trip there by establishing the stability of the over frequency element of the model. Further after 55 seconds, load on the generator has been further decreased to 80 MW. This large load rejection results in over frequency conditions that could not be compensated by turbine – governor loop within the permitted time window of 5 seconds provided by abnormal frequency function. Relay therefore operates and trips the HV breaker through the over frequency element.

Case 2: Sudden Loss Of Mechanical Input While Generator Is Supplying Normal Load

This case was to simulate reverse power conditions due to mechanical problems in the prime mover. In this case, the machine was catering to a fixed and continuous load of 110 MW when the mechanical shaft torque from the turbine has been increased to 145 MW at 15 seconds. The generating unit adapts to the new input after brief oscillations. After 40 seconds, turbine input was further reduced in a single step to 50 MW. Again the generating unit is found to adapt to the new turbine input with oscillatory response that swings below 0 MW with transient excursions on the negative side.

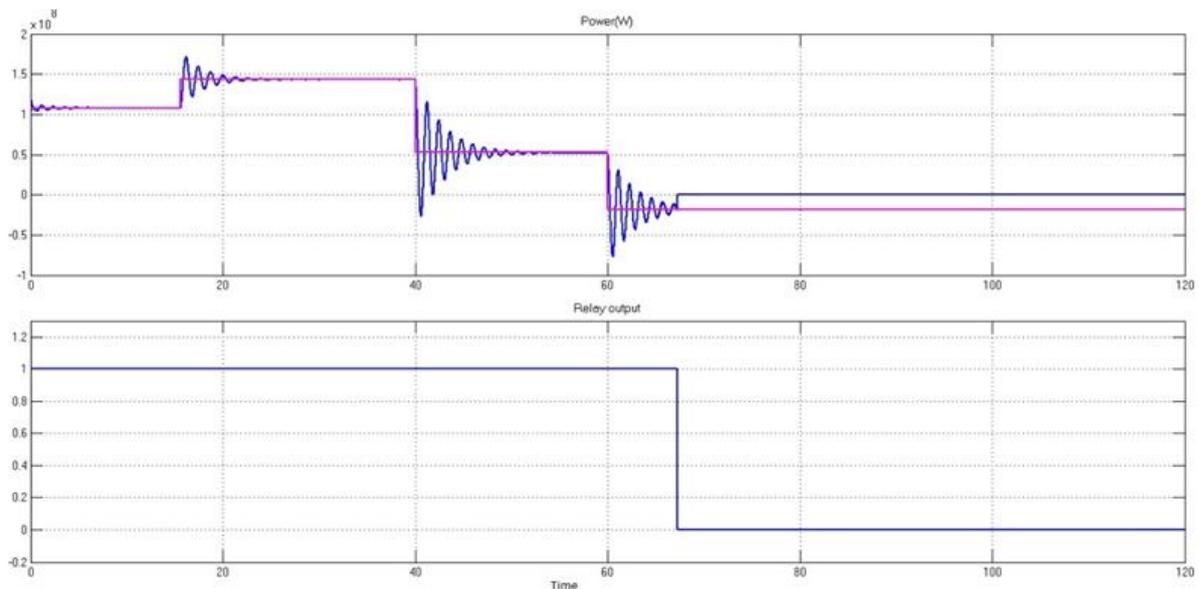


Fig. 15 Response to failure of turbine mechanical input (motoring conditions)

The inbuilt time delay prevents this transient reverse power condition from tripping the unit. Further after 57 seconds, the turbine input was reduced to -15 MW permanently. This resulted in reversal of power flow into the generating unit from the connected grid and anti-motoring protection function picks up after the elapse of time delay at 63 seconds, thereby isolating the generator and its field breaker. It is pertinent to mention that the action of sequential trip logic of the control system has not been taken into account in the model and the machine was to be protected only by the backup anti-motoring protection after a fixed time delay.

Case 3: Sudden Excessive Loading On Generator With Insufficient Generation Resources

This case was to evaluate the performance of the relay during operation of generator in under frequency conditions. In this case the load on the generating unit has been increased from 117 MW to 215 MW after initial operation of 55 seconds. This creates excessive load on the generator that is beyond its capacity. Due to the large imbalance between generation and load the frequency drops to 45.5Hz. This results in an underfrequency condition. The system attempts to compensate by raising the output power as is evident from figure below.

However, even after elapse of 5 seconds time at 60 seconds, under frequency conditions continue to persist and the frequency was still out of range. As a consequence to the above, the underfrequency protection function picks up at 60 seconds and trips the HV breaker isolating the system from the grid. This action of the protection system in real time would have further aggravated the under frequency conditions, but was essential to protect expensive capital equipment such as generating units from damage.

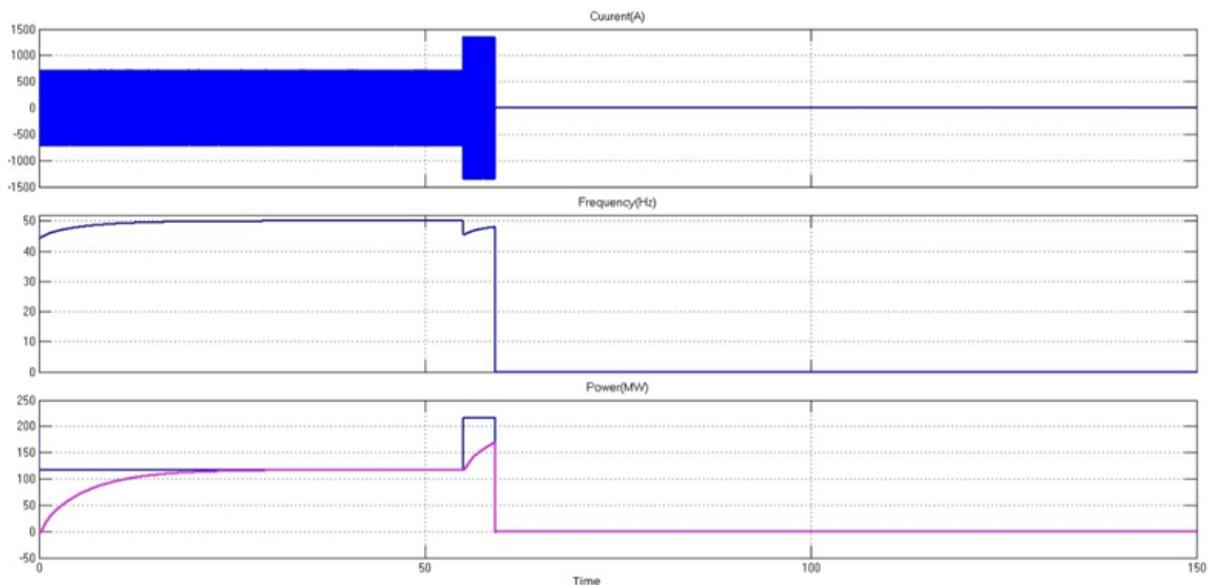


Fig. 16 Response to overloading (under frequency conditions)

Case 4: Cumulative Case To Evaluate Stable Operation With Temporary Load Fluctuations

This case was to evaluate the stability of the generating station to abnormal frequency conditions. In this case, the load on the generating unit has been increased from the normal constant load of 150 MW to 180 MW at 50 seconds. This action results in dip in frequency. The under frequency function is activated but waits for the time delay. However, after 4.9 seconds load was reduced to 120 MW load. The underfrequency element resets before the maximum allowed time delay. However, the over frequency element becomes active and waits for the time delay. Exactly after 4.9 seconds, the load has been restored back to original 150 MW.

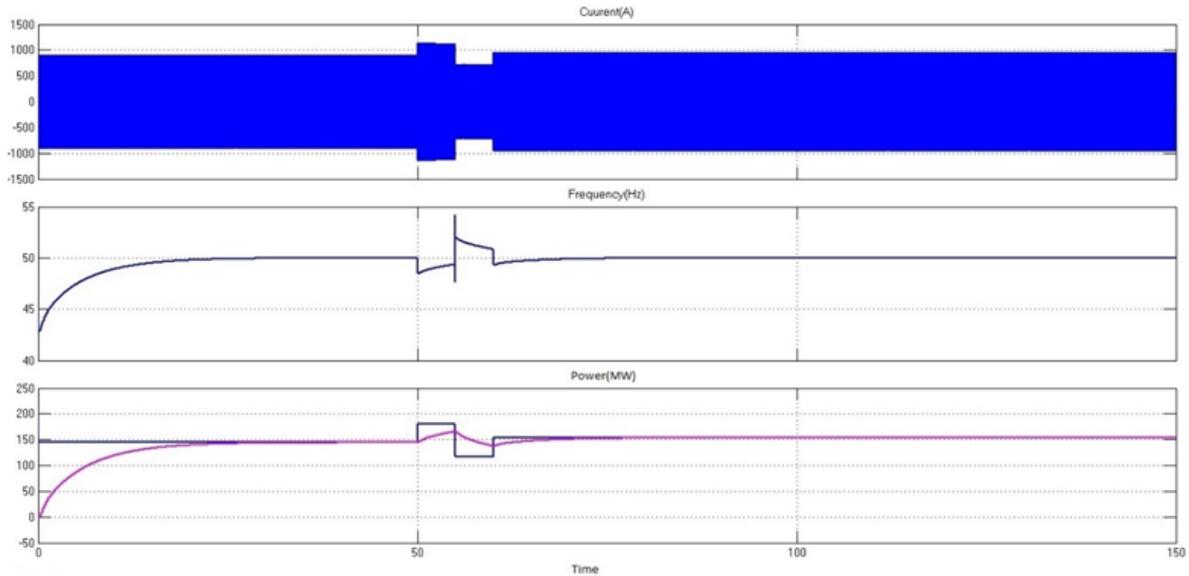


Fig.17 Stability of the model to transient load variations

Though the over frequency function got activated, it was reset as the generation – load imbalance was restored within the permitted time delay and the over frequency device resets. The responses recorded in the traces of Fig.17 establishes the stability of abnormal frequency protection function in the model.

Table I. Summary of Relay Performance Results

Case No.	Description of simulated Event	Activated Protection function	Relay trip decision
1	Load is decreased from 180 MW to 150MW at 50 seconds (normal operation)		Block
	After 55 seconds load is further reduced to 80 MW indefinitely	Over frequency	Trip
2	Generator was supplying a constant load of 110 MW when the mechanical input to the turbine was increased to 145 MW after 15 seconds.		Block
	After 38 seconds mechanical input to the turbine was decreased to 90 MW.		Block
	At 57 seconds, mechanical input from the turbine was reduced (reversed) to -15 MW (motoring) with excitation active.	Anti-motoring	Trip
3	Loading on the generator has increased from 117 MW to 215 MW after 55 seconds resulting in 45.5 Hz frequency	Under Frequency	Trip
4	Load increases from a minimum continuous load of 150 MW to 180 MW after 50 seconds for a duration of 4.9 seconds after which load has been reduced to 120 MW.	Under Frequency	Block
	After further 4.9 seconds Load is restored back to 150 MW.	Over Frequency	Block

VI. CONCLUSION

Generation utilities with large generating units usually deploy integrated, multifunction numerical protection relays for protecting their generators during emergencies. Typical generator multifunction relay can host several protection functions such as differential, stator earth fault, back up impedance, rotor earth fault etc included in one compact single package. Amongst all these protection functions two protection functions viz., anti-motoring and abnormal frequency protections have been discussed. An integrated model comprising of a synchronous generator, loads and sources along with both of these functions has been developed. The simulation results have been illustrated and analyzed to evaluate the performance of these protection functions. The results prove that the protection functions are found to be performing as intended. Incorporation of other protection functions such as differential, stator over current etc. of into the integrated model can be taken up as a future work.

Appendix

The power system model used for simulation and demonstration of the protection functions consist of the following components

- a. Synchronous generating unit –Active Power = 200 MW; rated speed = 166.6 rpm, Frequency, 50 Hz with shaft connected hydraulic prime mover and inbuilt governor and separately excited, 400V static exciter.
- b. Transmission voltage $V_{\text{line-line}} = 132$ KV; Suitable step up transformer arrangement (not included in the model) is presumed to be part of the generating unit.
- c. SF6 based High Voltage Circuit Breaker of 1000A and SC rating of 40 KA
- d. Network variable load varying from 180 MW to 80 MW.
- e. External Generating resource = 200 MW.

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