Modeling and Simulation of Digital Frequency Relay for Generator Protection

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Abstract- **Modeling tools are useful for educational and industrial use. Such tools help the new engineers to simulate the power system under normal and faulted conditions. This paper presents the design and various data conversion steps of a digital frequency relay. The designed relay will cover both over and under frequency conditions. The digital relay has superiority over electromechanical relay in terms of accuracy and speed. The large frequency variations could lead to complete power system blackout. History has seen several blackouts due to frequency instability, either due to supply-demand unbalance or N-1 contingency. After distributed generation and the possible islanding issues, frequency relay has again gain the attention of the researchers and industrialists. The performance of proposed digital frequency relay will be observed under different system dynamics on MATLAB/ SIMULINK®.**

Keywords — **Frequency Relay; Swing Equation; Relay Modeling.**

I. Introduction

Stability of system is one of the major issues of power system. Voltage, Angle and Frequency instability are the basic instability problems [1]. After power system restructuring and the incorporation of distributed generation in power system, stability and protection coordination issues have become a centre of concern for power researchers. Modelling tools are utilized to simulate the system and see the possible impacts during abnormalities. MATLAB, most widely used educational and research software, is also among these tools [2-4]. However, currently MATLAB power system library has no tool box for power system protection. In this paper, a digital frequency block is designed. The design block offers flexibility in terms of further research and improvement.

Frequency instability problem arises when there is a large mismatch between demand and supply or due to N-1 contingency. Mechanical power is produced from turbine and transferred to the generator shaft. A generator converts the mechanical power into the electrical power P_e. Mechanical Torque T_m is created on the turbine from the water or steam power and electrical torque T_e is as a result of load connection. The difference between the two torques (known as acceleration torque), causes the fluctuation on the generators speed, and thus resulting in speed variation of the frequency of the power system.

The swing Eqn. (1) demonstrates the relationship between the deviation of the torque and variation of angular acceleration [5].

$$J\frac{d\omega}{dt} = T_m - T_e \tag{1}$$

$$J\omega_m \frac{d\omega}{dt} = P_m - P_e \tag{2}$$

Where J is the total moment of inertia of the rotor mass, ω_m is the angular mechanical velocity, P_m and P_e are the mechanical and electrical power , given by Eqn. (3).

$$P_m = \omega_m T_m \quad ; \quad P_e = \omega_m T_e \tag{3}$$

A normalized inertia constant (H) is defined as:

$$H = \frac{\text{Stored kinetic energy at sync. speed (MJ)}}{\text{Generator MVA rating}} \tag{4}$$

$$H = \frac{J\omega_s^2}{2S_{rated}} \tag{5}$$

If P is the number of poles in synchronous machine then the mechanical speed (ω_m) is related to the electrical speed (ω) by Eqn. (6)

$$\omega = \frac{P}{2} * \omega_m \tag{6}$$

Substituting Eqns. (5) and (6) into Eqn. (2) results in

$$\frac{2H}{\omega_s} \times S_{rated} \times \frac{d\omega}{dt} = P_m - P_e \tag{7}$$

Dividing the Eqn. (7) by S_{base}

$$\frac{2H}{\omega_s} \times S_{rated} \times \frac{d\omega}{dt} = \frac{P_m}{S_{base}} - \frac{P_e}{S_{base}} \tag{8}$$

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Now, the Eqn. (8) can appear in per unit

$$\frac{2H}{\omega_s} \times \frac{d\omega}{dt} = P_{m(pu)} - P_{e(pu)} \tag{9}$$

Where P_e (pu) and P_m (pu) are the per unit electrical power and mechanical power.

From Eqn. (9), the relation between change in frequency and power could be developed, given by Eqn. (10).

$$\frac{df}{dt} = \frac{f_n}{2H} \times \Delta P \tag{10}$$

Where f_n is the system frequency or rated frequency. From Eqn. (10), it can be observed that the mismatches between demand and supply results in frequency change. Thus in order to measure the real time power frequency, different techniques have been developed namely; Newton method; level crossing technique; modified zero-crossing technique least-square error technique; Discrete Fourier Transform (DFT); leakage effect technique; Kalman filter technique; and phasor-based technique and Prony Method [6-7]. However in practical system, most of the relays worked on the principle of zero crossing detection [8-9].

II. Over-Under Frequency Relay

Frequency relay is commonly used in order to protect the power system from blackout in case of major generation/load loss or during N-1 contingency. The relay is also used to detect the islanding operation. Islanding operation normally occurs in case of distributed generation due to loss of mains. The resulting system consisting of distributed generator and local load is often known as "Power Island". This presents a threat to the system in terms of power balancing and controlling. A major threat comes when the power island is reconnected to the rest of the system without synchronising first. Loss of mains is often detected by measuring rate of change of frequency (ROCOF). However ROCOF method cannot reliably discriminate between changes in frequency due to loss of mains and changes due to other disturbances [10]. In [10], the author has also proposed the comparison of rate of change of frequency (COROCOF) for loss of main protection.

Stable frequency operation is always demand of customer. Different countries have their own grid codes to ensure that the quality (voltage and frequency) of electricity supply is maintained within specified standards. For example, in UK following the Electricity Supply Regulations 1989 and the Grid Code the frequency delivered to the consumer must not vary more than ±1%. Also ±6% variation in voltages is allowed below 132 kV whereas ±10% regulation is allowed for voltages higher than 132 kV [11].

III. Modeling of Digital Frequency Relay

The Digital Frequency Relay consists of two parts, Frequency Measuring Unit (FMU) and Under-Over Frequency Detection Element (FDE), as shown in Fig. 1. FMU is used to measure the digital value of frequency from the PT while FDE takes appropriate action based on Over-Under frequency limit.

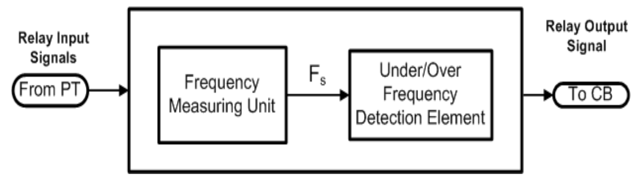

Fig. 1. Block Diagram for Implementing Over-Under Frequency Relay

A. Frequency Measuring Unit (FMU)

The FMU is used to measure the frequency of a voltage signal from the Potential Transformer (PT). To measure the frequency, the time difference between the two consecutive zero crossing (*T1* and *T2*) is measured, as shown in Fig 2.

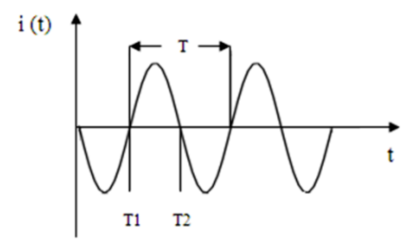

Fig. 2. Measuring Frequency of a Signal

However to measure the total time of a complete waveform, the difference between T1 and T2 is multiplied by factor of 2, as shown in Eqn. (11).

$$T = 2 \times (T_2 - T_1) \tag{11}$$

$$Frequency = \frac{1}{TimePeriod(T)} = \frac{1}{2(T_2 - T_1)} \tag{12}$$

The FMU unit implemented on SIMULINK is shown in Fig. 3.

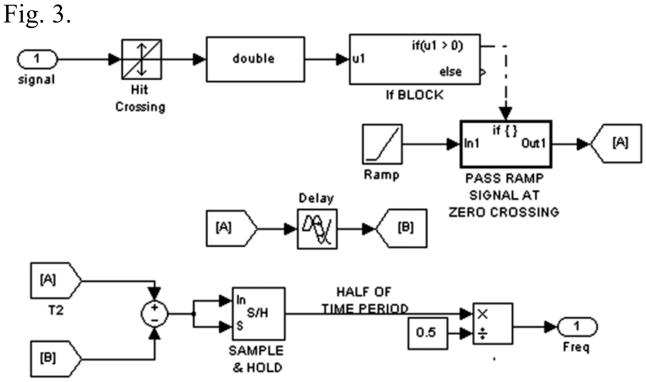

Fig. 3. Measuring Frequency of Voltage Signal on Simulink®.

'*Hit Crossing'* block is used to detect the zero crossing. The block passes the input signal at its zero crossings to the '*if'* block, which in starts sending ramp signal to the output. The time duration of generated ramp is measured and saved to a variable 'A'. The variable A is stored in another variable B using the '*Transport Delay*' block and the time of the next zero crossing is measured. Subtracting B from A at any instant will give half the time period whose value is held by the 'Sample and Hold' block, till the next zero crossing. After performing the necessary computations, given by Eqn. (13), the instantaneous frequency is achieved. The output (measured frequency) from FMU sends to the FDE for necessary tripping action, in case of fault.

B. Frequency Detection Element

The FDE is used to take the necessary action in case of Over Frequency (OF) and Under Frequency (UF). The output from OF and UF are logically AND. The output of FDE or relay under normal case is set at 1, otherwise 0 (for tripping). The complete block diagram of the FDE is shown in Fig. 4.

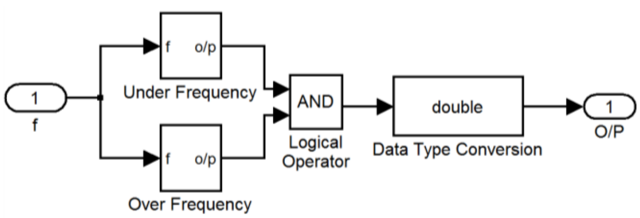

Fig. 4. Frequency Detection Element

The relay setting is given in Table 1. These limits are generalized and could be set to some other values based on country standards.

TABLE I
FREQUENCY RELAY SETTINGS

Nominal Frequency	Frequency Relay	Limit	Threshold Time
50	OF	51	5 sec
	UF	48.6	5 sec

Fig.5 shows the logic diagram for the implementation of a frequency relay in case of an under-frequency situation. The frequency of the voltage signal is first measured by the frequency measuring unit (FMU) and then compared with the threshold under frequency limit i.e. Fu (48.6Hz). If under-frequency condition occurs, the measured frequency 'f' less than Fu), 1 will be sent to the integrator and integration will occur. The output of the integrator is then compared with the set value of K (5secs). If the integrator output exceeds the K value, the relay will trip. This is also a check to see the abnormality is transient or continuous. If the abnormality persists for K seconds the relay trips. Otherwise either integrator is reset by the reset logic or no integration occurs under normal conditions. Under normal condition, the integrator input is set at "0", thus the relay does not operate.

The inside Simulink® model of Under and Over frequency block is shown in Fig. 6 and Fig. 7 respectively. The explanations of the blocks are left to the reader.

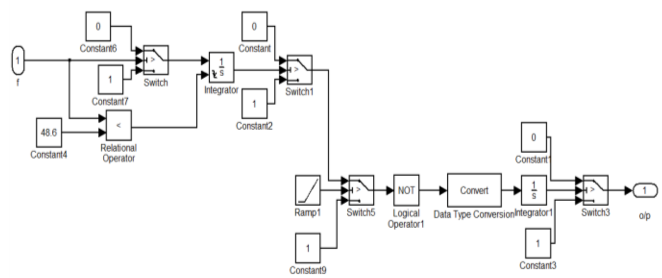

Fig. 6. Under Frequency Detection Block

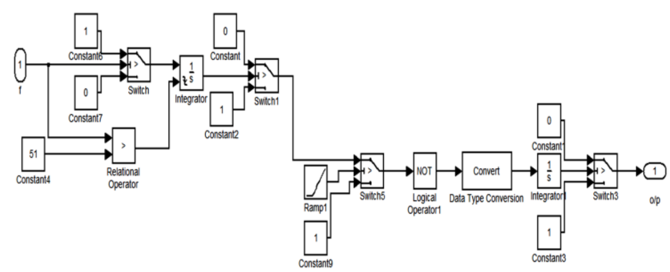

Fig. 7. Over Frequency Detection Block

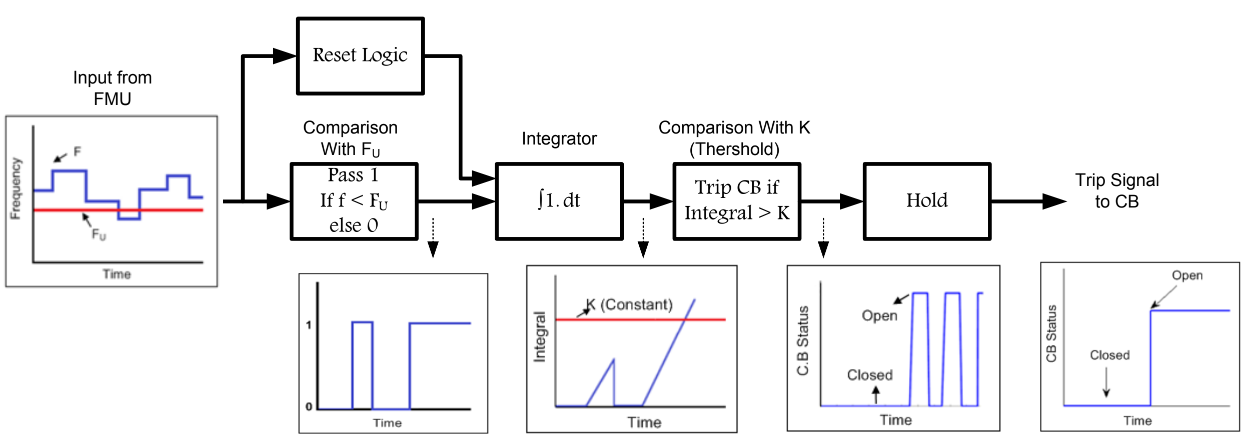

Fig. 5. Logic Diagram for Implementing Under Frequency Block

IV. Simulations and Results

For relay testing and simulation, a 132kV two bus network is considered. The single line diagram of the network is shown in Fig. 8.

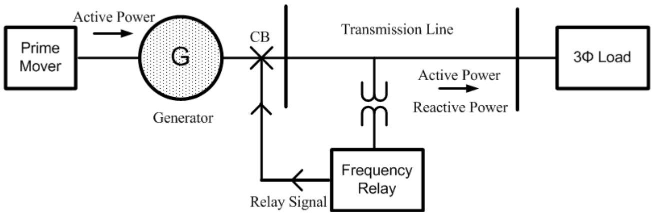

Fig. 8. Single Line Diagram of a Two Bus System

The relay is tested under different test conditions. These tests conditions are given below. Cases 1 and 2 are over-frequency cases, while Cases 3 and 4 are under-frequency cases.

A. Case 1:

In the first case, the load is shed in two stages. Initially from 190MW to 150MW at 70sec, later on further load shed of 70MW is made at 120sec and the relay behaviour is observed. Fig. 9 represents the current and relay status under different load conditions.

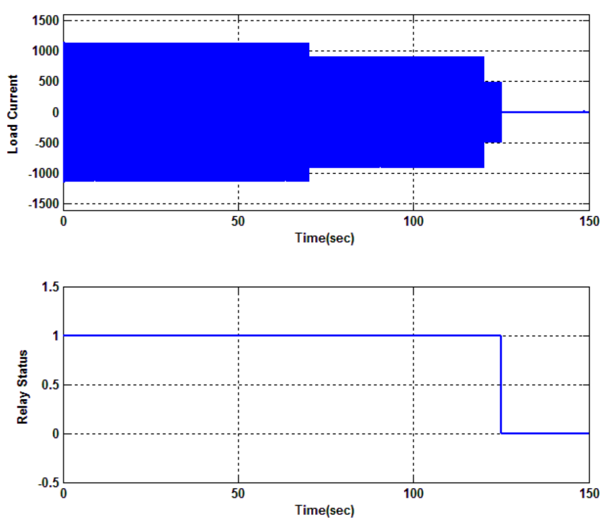

Fig 9. Relay performance (a) Current (b) Relay Status

In first stage the relay does not trip. However a huge decrement in load of 70MW results in relay tripping. Fig. 10 represents the behaviour of electrical frequency.

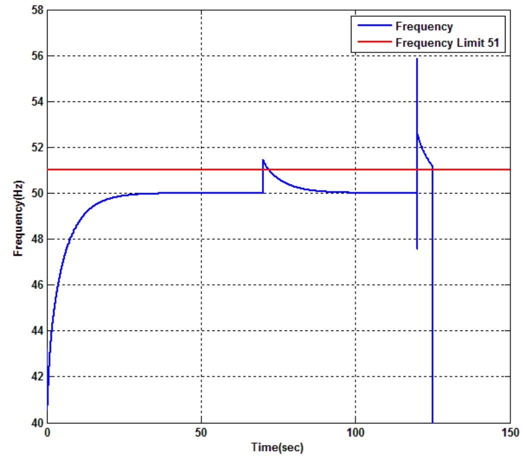

Fig. 10. Output Frequency

B. Case 2:

In second case, the behaviour of relay under transient condition is observed. One of the load is momentarily disconnects and then restore, within 5sec. In this case, the system load changes from 160MW to 80MW at 70sec, however at 75 sec, 80MW load restore. Fig. 11 represents the current and relay status under different load conditions.

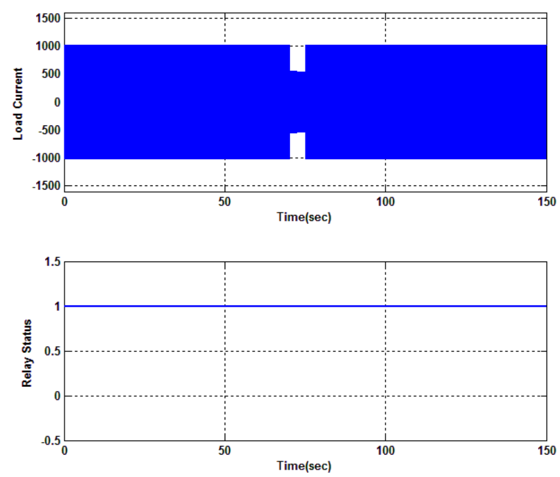

Fig 11. Relay performance (a) Current (b) Relay Status

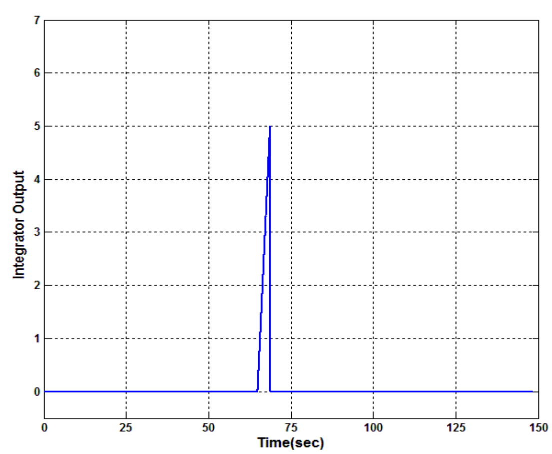

Fig. 12. Integrator Output

Fig. 12 represents the integrator output. Here it could be observed that the integrator try to reaches the threshold value of 5. However due to transient conditions, the integrator output could not become greater than 5, thus the relay does not trip.

C. *Case 3:*

In this case, 40MW is added at 70 sec in addition to base load of 150MW. Later on further load shed of 50MW is done at 120sec. Fig. 13 represents the current and relay status under different load conditions.

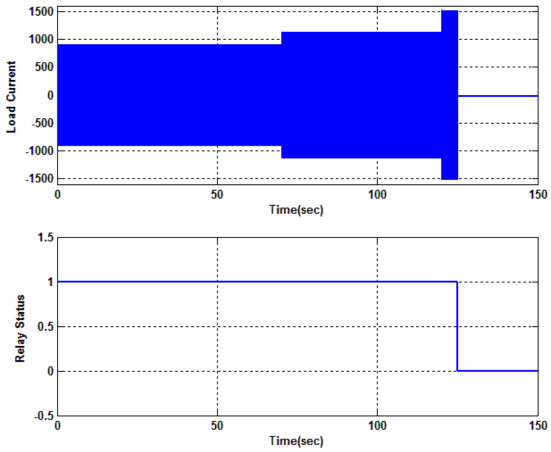

Fig 13. Relay performance (a) Current (b) Relay Status

In first stage the relay does not trip. However a huge increment load of 50MW results in relay tripping. Fig. 14 represents the behaviour of electrical frequency.

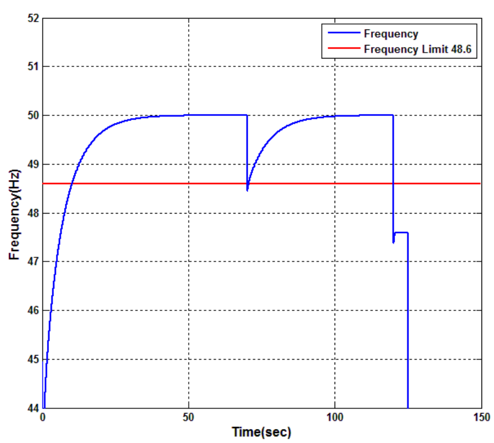

Fig. 14. Output Frequency

D. *Case 4:*

In this case, the behaviour of relay under transient condition is observed. In this case, the system load changes from base case of 150MW to further addition of 80MW at 70sec. However at 74 sec, 80MW load restore. In second stage 80MW load is added for indefinite period at 120 sec. Fig. 15 represents the current and relay status under different load conditions.

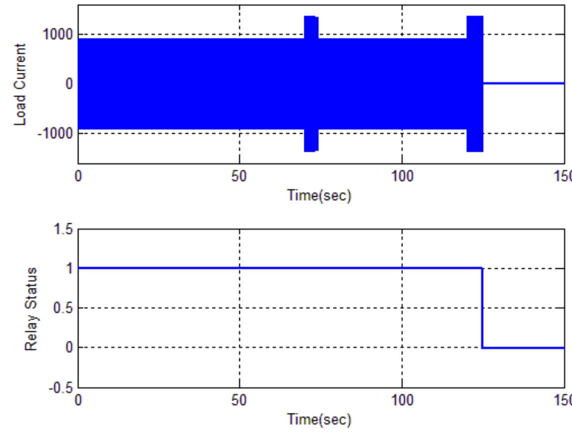

Fig 15. Relay performance (a) Current (b) Relay Status

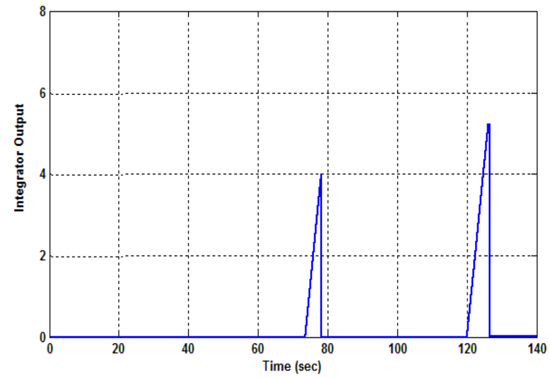

Fig. 16. Integrator Output

Fig. 16 represents the integrator output. Here it could be observed that the integrator try to reaches the threshold value of 5. However due to transient conditions, the integrator output could not become greater than 5, thus the relay does not trip. However in second stage, the integrator output reaches the threshold value of 5 and thus the relay trip.

Table II summarizes the relay output summary for all case studies.

TABLE II
RELAY TRIPPED STATUS SUMMARY

Case No.	Event	Relay Tripped Status
	Over Frequency	
1	Load is shed from 190MW to 150MW at 70sec. Later on, at 120sec, further load shed of 70MW is made.	No Yes
2	Load shed from 160MW to 80MW at 70sec, momentarily for 4 seconds. However at 75 sec, 80MW load restore.	No
	Under Frequency	
3	40 MW load is added to base load of 150MW. Further load shed of 50MW is done at 120sec.	No Yes
4	Load changes from base case of 150MW to further addition of 80MW at 70sec. At 74 sec, 80MW load restore. At 120 sec, 80MW load is added for indefinite period.	No Yes

V. Conclusion

The paper has presented the modelling of the digital frequency relay on MATLAB/SIMULINK ®. The effectiveness of the proposed relay has been verified by considering different examples as case studies. The complete details of the model with their case studies have also been contributed to MATLAB online resources to support their Power System Tools [12]. The proposed model offer effective means for explaining the behaviours of over-under frequency relay under various operating conditions and changing the design parameters. The digital relay has good advantage in terms of their sensitivity and wide range controlling.

Acknowledgment

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