Efficient Design of Hall-Effect Current Transformer for the Measurement and Protection of Power Systems

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Abstract- **This paper proposes the modelling of Hall effect current transformer based on the Hall effect principle into the pre-existing Current Transform (CT). The proposed Hall effect CT (HCT) can measure ac and dc currents even complex waveform with good accuracy and fast time response. It can eliminate ambient interference and does not encounter problems related to saturation. The proposed HCT measures the power current during the operations in measurement systems and protection systems. The equivalent circuit and transfer function model of HCT are simulated in MATLAB/SIMULINK environment. The performances of HCT and CT under various fault conditions are evaluated and analysed.**

Keywords- Current Transformer (CT), Hall effect Current Transformer (HCT), modeling, measurement and protection.

SYMBOLS AND ABBREVATIOINS

i_1 : Primary current, current to be measured
i_2 : Secondary current, compensating current
n_1 : Number of primary turns
n_2 : Number of secondary turns
ϕ_C : Magnetic flux in the core
λ_2 : Flux linked with secondary coil
B_g : Magnetic flux density in air gap
H_g : Magnetic field intensity in air gap
l_g : Air gap length
H_m : Magnetic field intensity in the core
l_m : Mean length of the core
A_c : Cross-sectional area of the core
μ_r : Relative permeability of the core
r_2 : Winding resistance of secondary coil
R_B : Burden resistance
V_H : Hall element output voltage
K_h : Sensitivity of Hall element
V_{out} : Voltage drop across the burden resistor
B_H : Perpendicular component of the magnetic field over the Hall element
$G_{c(s)}$: Compensator transfer function

I. INTRODUCTION

In power system, protection and reliable operation of the power system components are the most important factors that are to be considered. To ensure the secure operation of the power system components various protection schemes have been used to trip the faulted section from the healthy section. To meet the safety and reliability requirements, appropriate CTs are used to measure currents for metering and fault protection. A traditional CT, which is used for current measurement, consists of magnetic core which encounters the ac and dc saturation problems and remagnet magnetisation. These are caused by the effect of hysteresis. It also causes distorted current waveform in the secondary windings. Due to problems related to magnetic saturation CTs produces false responses in current detection and false tripping in the protective devices. Since all problems in the traditional CT is due to magnetic saturation of iron cores, several methods for reducing the effects caused by iron cores has been proposed. These includes the use of air-gap CTs [2], magnetooptical CTs [3] and linear CTs [4]. However in practical applications only linear CTs are used. Linear CTs exhibit better performance than traditional CTs but the cost of linear CTs are high. Reference [5] shows the method for error current compensation of CTs by employing Hall current transducers based on magnetic force balance to detect and compensate the error current so as to eliminate the error of CT caused by its exciting current. The scheme of [6] needs high quality current waveform without harmonics which has high accuracy only at the condition of standard sinusoidal waveform. To overcome the disadvantages of the traditional CTs, several researchers have proposed the current transformer based on the principle of hall effect. Reference [1] proposes the hardware design of the multifunctional HCT by implementation of the actual electronic circuits. The HCT converts power current into Hall voltages and measures current. Reference [7] proposes a method for current measurement using Hall sensors without iron cores. Reference [8] proposes the method for accurate current measurement by combining the HCT, Zigbee communication and a quiscent voltage adjustment unit. This design has unique characteristics of low cost and wireless communication capabilities. In this paper HCT is modelled using MATLAB/ SIMULINK environment. The performances of CT and HCT under various fault conditions are compared by testing in IEEE 14 bus system.

II MODELLING OF HCT

A Hall effect current sensor is designed with closed loop compensation as shown in Figure. 1. A hall element is inserted in the air gap. A conductor carrying current i_1 creates magnetic flux in the core and air gap. The hall element produces voltage v_H is in response to the air gap magnetic field , which is applied by the compensator $G_{C(s)}$ in order to produce counter

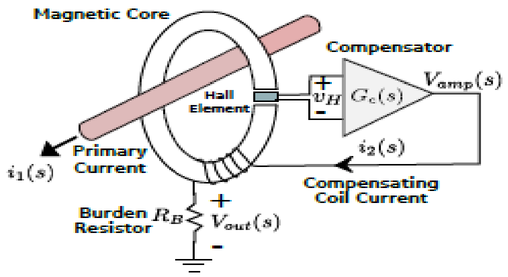

Figure.1:Hall effect sensor with closed loop compensation.

magnetic flux in the core due to compensating coil current i_2 , ensuring that excitation of the magnetic core is kept small and lies in region within the B-H curve of the core material. To model the current sensor various assumptions are made. It is assumed that relative permeability of the magnetic core is kept very high, leakage inductance and inter-winding capacitance of the compensating winding are ignored, position of the conductor with respect to central axis of core does not affect the magnetic flux distribution, presence of the hall element in the air gap does not disturb the field distribution in the air gap and fringing effect in the air gap is ignored. Taking the consideration of the above assumptions the equivalent circuit is derived as follows,
By Ampere's circuital law, and ignoring reluctance offered by the magnetic core we get

$$n_1 i_1 - n_2 i_2 = H_m l_m + H_g l_g \approx H_g l_g \quad (1)$$

Ignoring fringing in air gap, the core flux can be expressed as

$$\phi_C = B_g A_C = \frac{\mu_0 A_C n_2}{l_g} \left(\frac{n1}{n2} i_1 - i_2\right) = \frac{Lm}{n2} i_m \quad (2)$$

where

$$i_m = \left(\frac{n_1}{n_2} i_1 - i_2\right) \text{ and } L_m = \frac{n_2^2 \mu_0 A_c}{l_g} \quad (3)$$

i_m is magnetizing current, and L_m is magnetizing inductance as obtained in equation 3, both referred to secondary side. The voltage induced in secondary winding can be written as expressed in equation 4 and 5.

$$V_2 = \frac{d}{dt}\lambda_2 = \frac{d}{dt}(n_2 \phi_2) = \frac{d}{dt}(L_m i_m) \quad (4)$$

$$V_2 = L_m \frac{d}{dt} i_m \quad (5)$$

As per configuration of the current sensor,

$$V_{amp}(t) + V_2(t) = (r_2 + R_B) i_2(t) \quad (6)$$

$$V_{amp}(s) = G_c(s) v_H(s) \quad (7)$$

The expressions 6 and 7 shows the amplified voltage obtained. Based on 2- 6 the equivalent circuit of current sensor can be represented as shown in Figure 2.

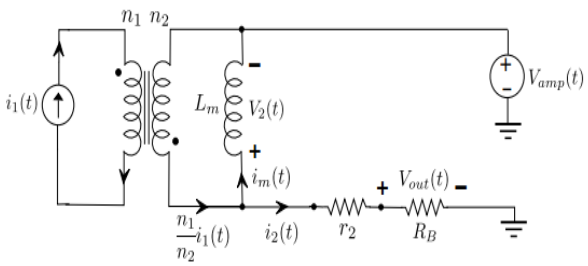

Figure. 2: Equivalent circuit model

Output voltage of the Hall element v_H , is given by the expression 9,

$$v_H = K_h B_H = K_h B_g = K_h \left(\frac{\phi_c}{A_c}\right) \quad (8)$$

Using 2, v_H can be expressed as

$$v_H = K_h \frac{Lm}{n_2 A_c} i_m \quad (9)$$

v_H is the feedback signal corresponding to i_m. It passes through the compensator, $G_{c(s)}$ to change $V_{amp(s)}$, and in turn reduces ϕ_c . Using (7),(8) the equivalent circuit can be represented in s-domain as a block diagram in Figure. 3.

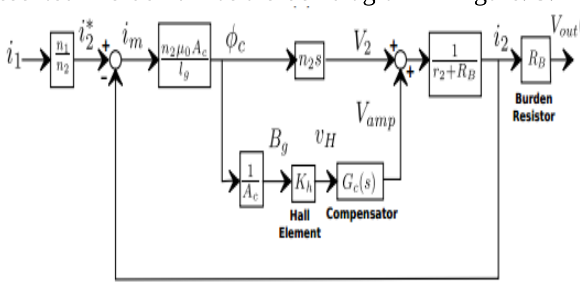

Figure. 3: Block diagram model of Closed loop Hall-effect current sensor.

For accurate measurement of i_1 the secondary current i_2 should be ideally equal to $\frac{n1}{n2} i_1$. In other words, the magnetizing current , i_m and hence the core flux ϕ_c should be brought down close to zero. Based on the s-domain transfer function block shown in Figure 2 a model is created using MATLAB which represents Hall effect current transformer.

III. METHODOLOGY

The process of fault detection and classification approach is done by creating the power system model. The current signals for normal and various fault conditions are obtained for different fault resistances. The obtained current signals are transformed to Hall voltage. The fault resistances and fault type are changed to develop different training data. Hall effect sensors can be applied in many types of sensing devices.

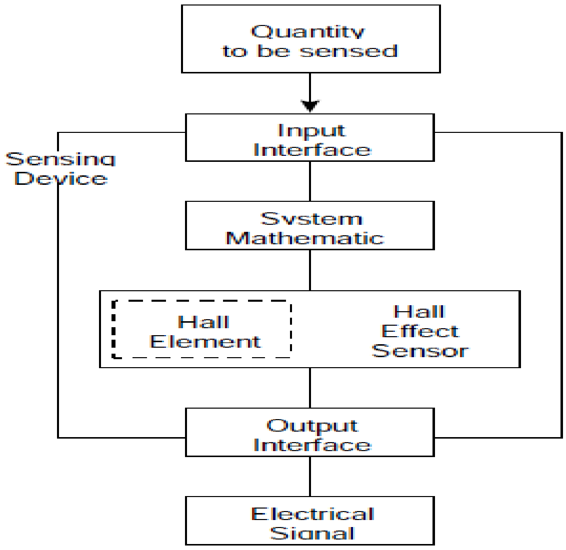

Figure. 4:Genral sensor based on Hall effect

If the quantity (parameter) to be sensed incorporates or can incorporate a magnetic field, a Hall sensor will perform the task. Figure. 4 shows a block diagram of a sensing device that uses the Hall effect. The HCT modeled in MATLAB is shown in Figure. 5.This model is designed based on the specifications shown in Table. 1.

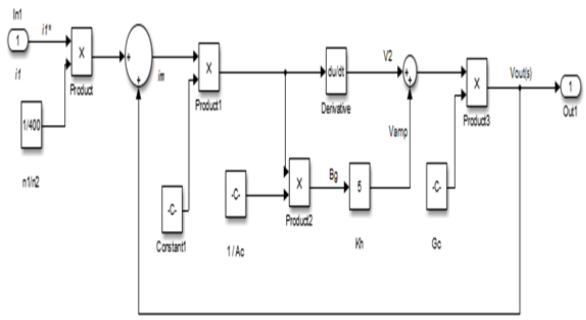

Figure. 5: Simulation model for HCT

Table. 1:Specifications of the modeled current sensor

n1	*n2*	l_g	A_c	K_h	r_2	R_B
1	400	1.1 mm	59.4mm^2	5.0 mV/ mT	36Ω	100Ω

The modeled HCT model is compared with the conventional Current transformer and this models are placed in IEEE 14 Bus system and the performance of HCT and CT are evaluated and analysed.

IV. SYSTEM STUDIED

In order to verify the proposed techniques, the IEEE 14 bus system model is simulated using MATLAB/SIMULINK for normal condition and for various fault conditions. The power system model for IEEE 14 bus transmission system is shown in the Figure 6.

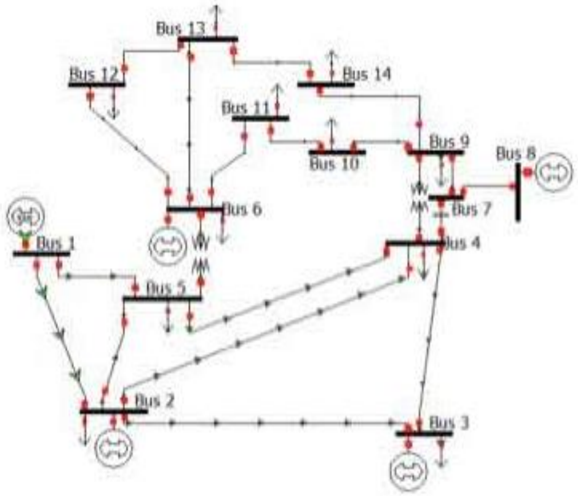

Figure.6: Model of IEEE 14 bus system

The IEEE 14 bus system is modeled and analysed for different fault conditions. It consists of five generators, eleven loads and twenty transmission lines and 14 buses. The system data for IEEE 14 bus system is shown below in Table.2.

Table. 2: IEEE 14 Bus system data

Bus No	Bus code	Voltage Magnitude	Angle degrees	Load		Generator				Injected MVAR
				MW	MVAR	MW	MVAR	Q min	Q max	
1	1	1.06	0	30.38	17.78	40	-40	0	0	0
2	2	1.045	0	0	0	232	0	-40	50	0
3	2	1.01	0	131.88	26.6	0	0	0	40	0
4	0	1	0	66.92	10	0	0	0	0	0
5	0	1	0	10.64	2.24	0	0	0	0	0
6	2	1.07	0	15.68	10.5	0	0	-6	24	0
7	0	1	0	0	0	0	0	0	0	0
8	2	1.09	0	0	0	0	0	-6	24	0
9	0	1	0	41.3	23.24	0	0	0	0	0
10	0	1	0	12.6	8.12	0	0	0	0	0
11	0	1	0	4.9	2.52	0	0	0	0	0
12	0	1	0	8.54	2.24	0	0	0	0	0
13	0	1	0	18.9	8.12	0	0	0	0	0
14	0	1	0	20.86	7	0	0	0	0	0

The different types of single line to ground faults, different double line faults with or without ground and three phase faults with or without ground are simulated and analysed.

V. SIMULATION RESULTS

To analyse the performance of modeled HCT and conventional CT, simulation model are designed as shown in Figure. 7. The input for the system is driven from a 120kVrms voltage source. The output waveform for the system is shown in Figure. 8.

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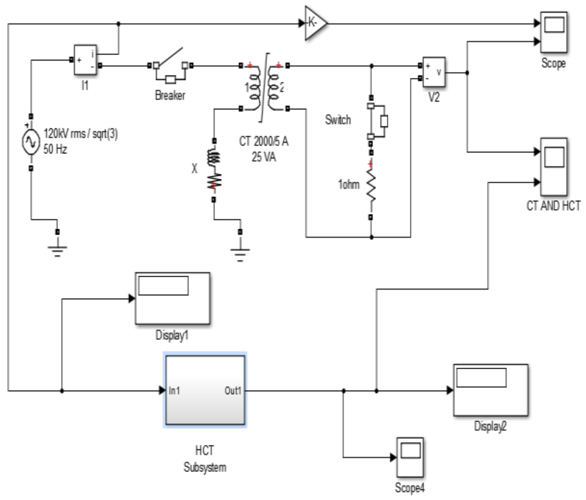

Figure. 7: Simulation model for comparing the performance of HCT and CT

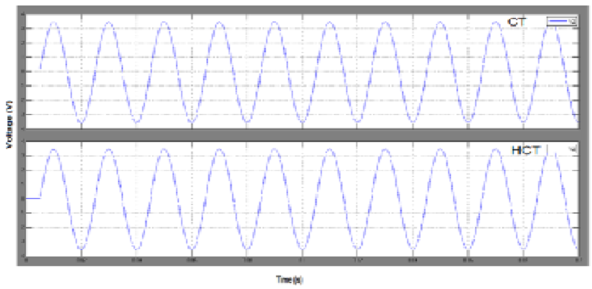

Figure. 8:Output waveform of HCT and CT comparison model.

The output waveform shows that both HCT and CT obtains the output voltage of 3.5 V. Considering the IEEE 14 bus system the waveforms during normal and various fault conditions are obtained. Fault near transformer in Bus 1 is created and the current measurement inputs are given as input to modeled HCT and conventional CT. The output voltage are given as the external control for three phase breaker as shown in Figure. 9.

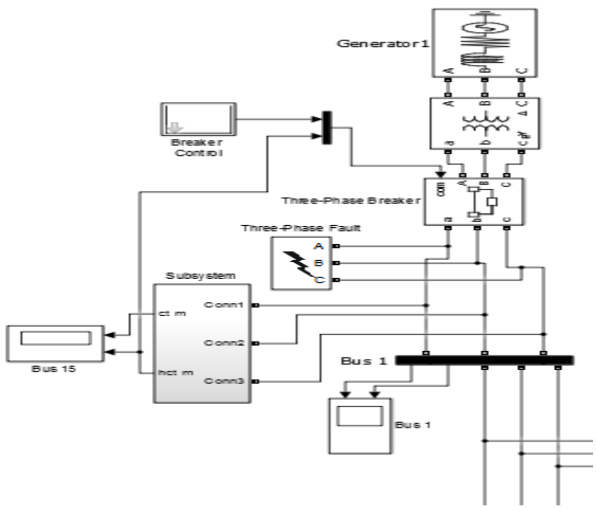

Figure. 9: IEEE 14 Bus system with fault near transformer in bus 1

A. L-G FAULTS

The L-G faults that occur in transmission system are A-G, B-G and C-G faults. A line to ground fault is applied to line 1 in 'A' phase of the transmission line. The output waveform of CT and HCT as shown in figure 10 and 11 is obtained.

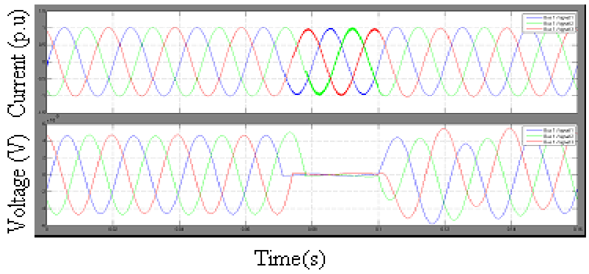

Figure.10:Output waveform from CT in A-G fault near transformer

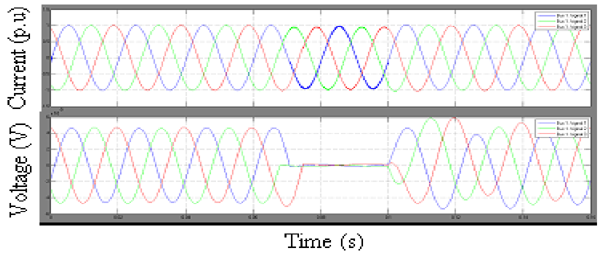

Figure.11:Output waveform from HCT in A-G fault near transformer

B. L-L-G FAULTS

The L-L-G faults that occur in transmission system are A-B-G, B-C-G and A-C-G faults. A double line to ground fault is applied in the phases A and B of the transmission line. . The output waveform of CT and HCT as shown in figure 12 and 13 is obtained

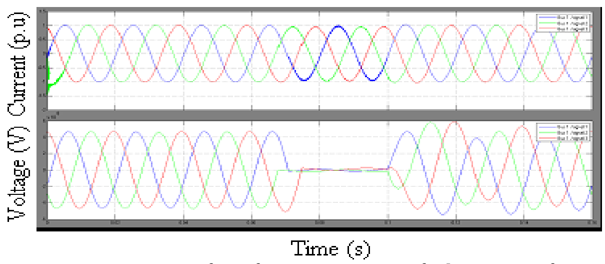

Figure. 12:Output waveform from CT in A-B-G fault near transformer

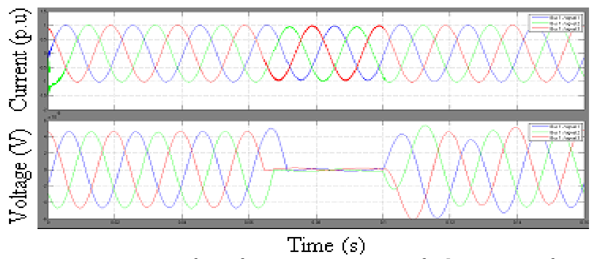

Figure.13:Output waveform from HCT in A-B-G fault near transformer

C. THREE PHASE FAULTS

Three phase faults in transmission system are A-B-C faults and A-B-C-G faults. The simulation results for A-B-C-G faults is applied in line 1 of the test system are obtained as shown in Figures 14 and 15 respectively.

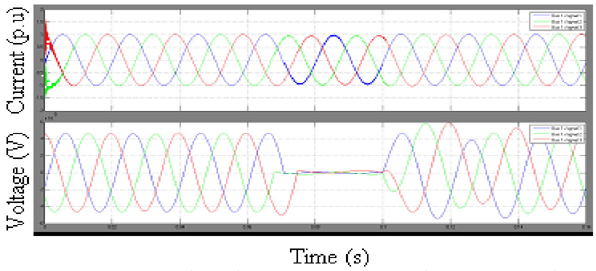

Figure. 14:Output waveform from CT in A-B-C-G fault near transformer

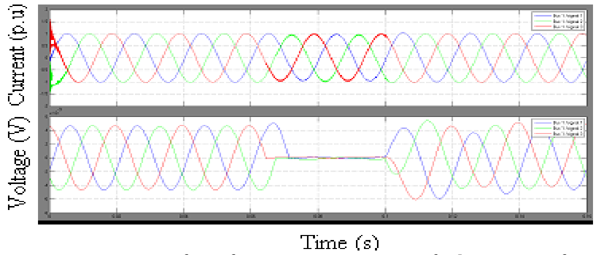

Figure. 15: Output waveform from HCT in A-B-C-G fault near transformer

The breaker time to open the three phase breaker after detecting the fault in L-G, L-L-G, L-L-L-G fault near the transformer in Bus 1are shown in Table. 3.

Table. 3:Breaker timing for CT and HCT for faults near transformer in Bus 1

S.No	Type of fault	CT breaker time (s)	HCT breaker time (s)
1	L-G FAULT In A-G	0.0700	0.0666
2	L-L-G FAULT In A-B-G	0.0650	0.0633
2	L-L-L-G FAULT In A-B-C-G	0.0650	0.0633

Fault near transmission line near Bus 8 is created and the current measurement inputs are given as input to modeled HCT and conventional CT. The output voltage are given as the external control for three phase breaker as shown in Figure. 16.

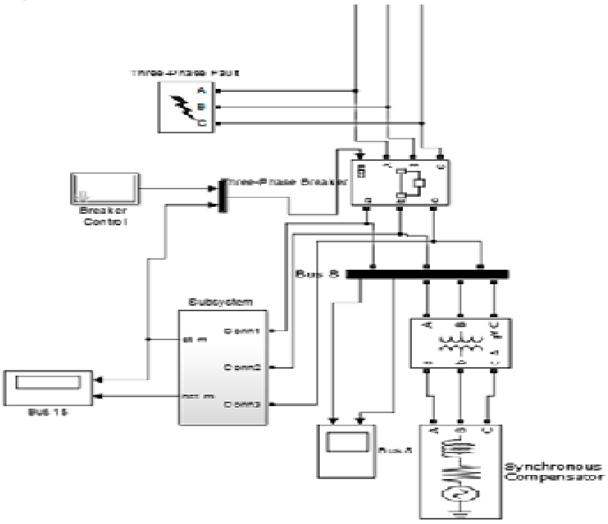

Figure. 16: IEEE 14 Bus system with fault in transmission line near Bus 8.

D. L-G FAULTS

A line to ground fault is applied to transmission line in ‘A’ phase near Bus 8. The output waveform of CT and HCT as shown in figure 17 and 18 is obtained.

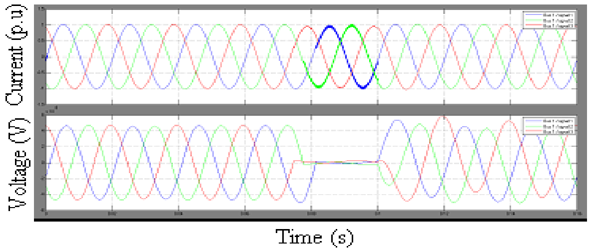

Figure.17:Output waveform from CT in A-G fault in transmission line

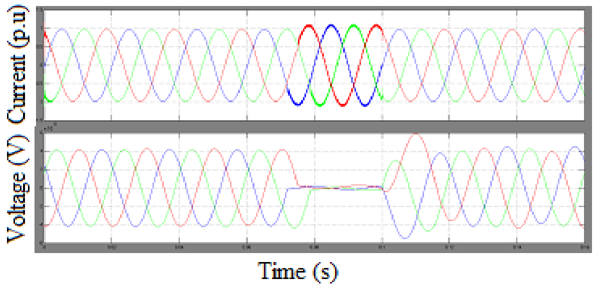

Figure.18:Output waveform from HCT in A-G fault in transmission line

E. L-L-G FAULTS

A double line to ground fault is applied in the phases A and B of the transmission line. The output waveform of CT and HCT as shown in figure 19 and 20 is obtained.

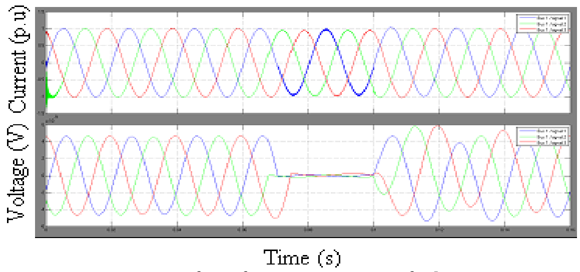

Figure.19:Output waveform from CT in A-B-G fault in transmission line

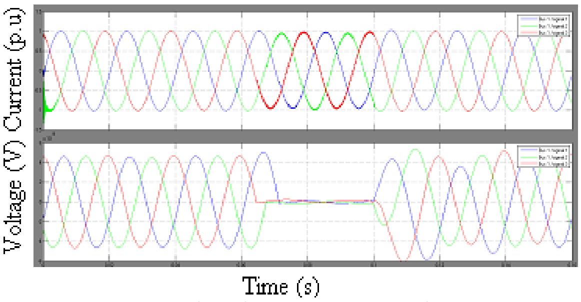

Figure.20:Output waveform from HCT in A-B-G fault in transmission line

F. THREE PHASE FAULTS

The simulation results for A-B-C-G faults is applied in the transmission line of the test system are obtained as shown in Figures 21 and 22 respectively.

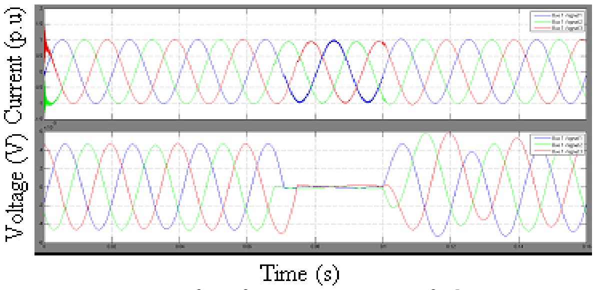

Figure.21:Output waveform from CT in A-B-C-G fault in transmission line

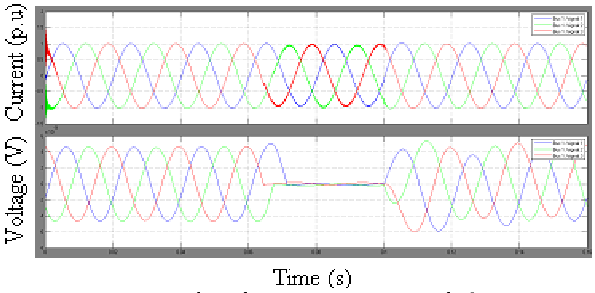

Figure.22:Output waveform from HCT in A-B-C-G fault in transmission line

The breaker time to open the three phase breaker after detecting the fault in L-G, L-L-G, L-L-L-G fault in the transmission line near Bus 8 are shown in Table. 4.

Table. 4:Breaker timing for CT and HCT for faults in transmission line near Bus 8

S.No	Type of fault	CT breaker time (s)	HCT breaker time (s)
1	L-G FAULT In A-G	0.0733	0.0700
2	L-L-G FAULT In A-B-G	0.0650	0.0616
2	L-L-L-G FAULT In A-B-C-G	0.0650	0.0616

VI CONCLUSION

As equivalent circuit of close loop Hall-Effect current sensor is derived, based on the derived values s-domain block represents the equivalent circuit model is obtained. This is used to develop a model of the current sensor with standard specification.

The modeling of current sensor is done using Matlab/Simulink environment and the performance of modeled HCT with conventional CT in standard bus system with different fault conditions are analysed. The result coincides with the performance of conventional current transformer and it gives the trip signal very rapidly to protect the system against fault. The proposed model of HCT can be implemented in SPEED GOAT with MATLAB. So that it acts as a virtual HCT and to test the performance in real time.

VII. REFERENCES

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