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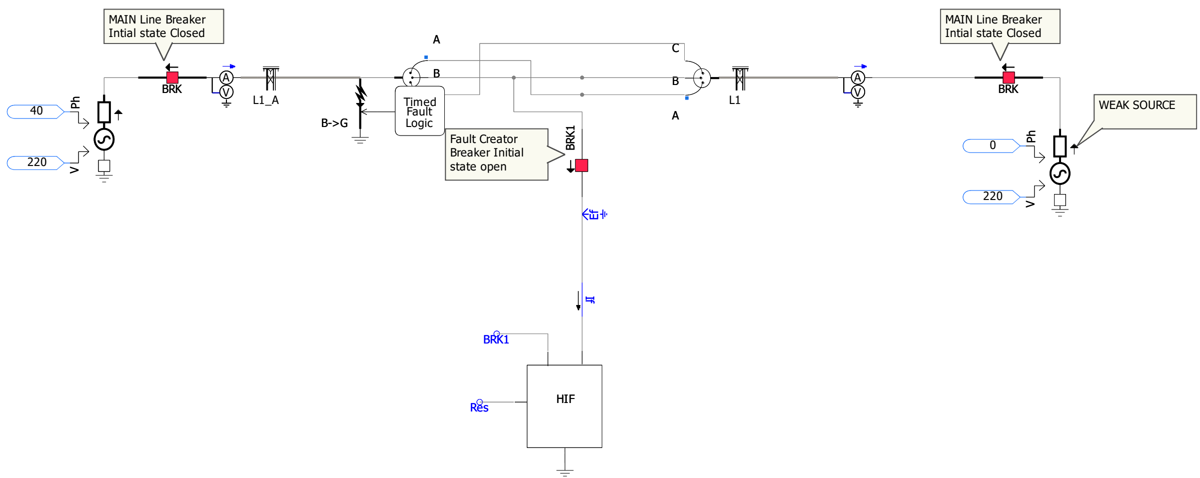

Fault Impedance Characterization for High Voltage Applications in Power Systems

Master Thesis in Electrical Engineering

Master Thesis report in Sustainable Electric Power and Electromobility Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

The thesis investigates the effects of the characteristics of high impedance faults on the performance of line distance protection. Two typical models are implemented. The verification of those models is done both with conventional sources and with a renewable source of Type-3 and Type-4 wind turbines. The results are compared with the standard PSCAD fault block model available in the software library. When modeling the conventional source and considering the time-varying characteristic of high-impedance fault, the difference is mainly observed in the fault detection time and the final impedance calculation by the relay. This is due to the time-variant and asymmetric nature of high Impedance Faults. The impact is that the fault detection time for high impedance faults is higher, e.g., 70 ms compared to the standard PSCAD fault block cases with a constant fault resistance whose fault detection time is 30 ms. Also, a simple compensation block for correcting the resistance is implemented and analysis is done. The renewable source study is done to understand why traditional fault calculation techniques cannot be applied due to the system behavior during the fault scenario. The time-variant behavior of high-impedance faults has been found to affect the fault detection time. The asymmetric behavior affects the final impedance calculated by the relay which could lead to the relay not detecting the fault.

Keywords: High Impedance faults, distance protection

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Rangarajan Swaminathan, Gothenburg, June 2024

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Introduction

1.1 Background

Power system fault detection and protection are one of the main methods to keep the reliability of existing power system in proper operation. There are different faults occurring within existing power systems either due to natural events such as lightning or unexpected insulation breakdown, etc. To detect faults and provide quick protection to isolate these faults in a timely manner, protection systems are provided and installed in power systems as a guard to detect and isolate faults. Within existing protection systems, distance protection is one of the main protection for transmission lines. Faults with high impedance have been a challenge for distance protection, especially in zone 1 owing to their highly nonlinear nature. Traditionally, fault impedance has been modeled as a unit step change after fault inception (e.g., impedance is assumed to reach a certain value instantaneously). However, due to the nature of fault impedance, the fault current characteristics may be exposed to other characteristics like time-variant decaying DC, harmonic distortion, and DC offset due to asymmetricity which may create complications for the relay algorithm.

Due to the arcing nature of short circuit faults, high impedance fault characteristics are not the same as it is assumed traditionally for a constant fault impedance value. The characteristic depends a lot on the ground type, soil type, and moisture content and there is no straightforward direct technique to generalize the results since the work done currently where various authors have designed the model is based on their requirements.

Researchers have modeled the high impedance fault mainly the resistive part as a time-varying function. Sharaf and Wang model [1] implements a time-varying resistance with a constant fault inductance. Emanuel model[2] uses the arc theory as background to formulate a model which has a constant resistance and constant inductance with anti-parallel diodes indicating the asymmetricity. Nam *et.al* model [3]has two time-varying resistors which denote the characteristics of the high impedance fault right at the fault inception and once it reaches its steady state.

The major challenge with the models is they are designed for distribution-level voltage, and the requirement is whether the same models can be replicated for transmission-level voltages. Authors in [4] have proposed a model in which the resistor is designed as an exponentially decaying function (in the rest of the thesis this model is named as Three parameter model). Authors in [5] have designed the resistor as a polynomial decay function (in the rest of the thesis this model is named Feraz *et.al* model).

1.2 Motivation and Research question

The main motivation behind the thesis work is to understand the role of high-impedance fault characteristics in the operation of distance protection because the fault impedance has traditionally been taken as a constant value. The main research questions are as under
1. How does HIF affect the distance protection?
2. Does it have an impact on the operation of distance relay?
3. Do we really have to consider all the characteristics of HIF for distance relay?

1.3 Goals

The goal is to design a high impedance fault model (HIF) that takes into consideration the typical characteristics of HIF which are mainly buildup, shoulder, non-linearity, and asymmetricity, and implement the model in an actual fault scenario involving a distance protection scheme and test its validity for zone 1 protection for both conventional as well as converter interfaced power systems.The main expectations are

- To check how HIF's characteristics affect the distance relay's final impedance calculation.
- How much is there a delay in detecting the high impedance fault by the relay with the models considered and how can it be improved?

1.4 Limitations

The major limitation is most of the research work for HIF is done at distribution level voltage. At HV and UHV systems a lot of research is done in HIF detection, but the characteristics of HIF were not considered mostly. The fault impedance value was taken as a constant value and calculations were carried out.

1.5 Organisation of the Thesis

The organization of the thesis is as follows

- Introduction to HIF characteristics and different models.
- Implementing the models designed for Transmission level voltage in PSCAD.
- Analyzing the results from the models mainly deviations in terms of final impedance calculation and fault detection time. Subsequently designing the compensation block mainly for conventional source model case.
- Lastly, understanding the main difference when it comes to fault characteristics for a converter interfaced system mainly type 3 and type 4 windfarms.

2

Theory

2.1 Introduction to HIF

The two major types of faults that occur in power systems are mainly bolted faults where the fault resistance is zero ohm and non-bolted faults where there is the presence of fault resistance.HIF is a type of fault that occurs when a conductor comes in contact with objects like trees leading to no proper connection to the ground. This phenomenon subsequently leads to arcing and the fault current is less. When it comes to distance protection, the main philosophy is when the impedance falls in the zone of protection, the relay operates. However due to HIF, the current being less, the relay under-reaches because the impedance calculated by the relay is high and out of its protection zone. The impact of HIF is disastrous leading to fire hazards affecting human beings. So, it's vital to identify HIF and isolate as fast as possible. Research says that HIF is time-varying that is initially the value is higher and decreases over time. There are 4 aspects of HIF which has been identified through field experiment data.

- Buildup- The fault current builds up slowly during this phase.
- Shoulder- The fault current stays at a particular value for some cycles.
- Non-Linear- The voltage and current characteristic of HIF is non-linear.
- Asymmetry-The positive and negative peak values of fault current are different at steady state.

Buildup and shoulder characteristics come under the transient state whereas non-linear and asymmetry come under the steady state.

2.2 HIF Models

2.2.1 Sharaf and Wang model

The model mainly consists of a constant inductance in series with a variable resistance R_{f} where the variable resistance is formulated as below

$$R_{\text{f}} = R_{\text{f0}} * (1 + \alpha(\frac{i_{\text{f}}}{i_{\text{f0}}})^{\beta}) \tag{2.1}$$

where R_{f0} is the initial fault resistance ,i_{f0} is the initial fault current ,i_{f} is the present fault current,α and β are predetermined parameters. The model gives information on the asymmetry and the nonlinearity of the HIF. This model was formulated only for distribution level voltage.Figure 2.1 shows a simple arrangement of the model

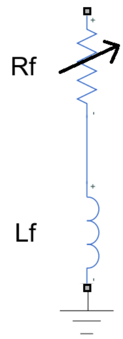

Figure 2.1: Sharaf and Wang Model

2.2.2 Emanuel model

The model mainly depicts the non-linearity and asymmetricity in the HIF.The model takes into consideration the arc theory and same is depicted in the form of anti-parallel diodes. The DC voltage sources V_p and V_n which are called arc voltages depend highly on the ground surface. A high moisture content surface will have a lesser value of V_p whereas a dry surface has a higher value of V_p. The model was designed for a distribution-level system. Figure 2.2 shows a simple arrangement of the model. The positive peak of fault current is greater than the negative peak value and so V_n is kept greater than V_p.

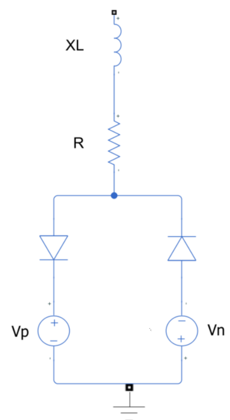

Figure 2.2: Emanuel Model

2.2.3 Nam *et.al* model

This model considers 2 time-varying resistors depicting all the characteristics of the HIF fault mainly build-up, shoulder, asymmetry, and non-linearity. As shown in figure 2.3, $R_1(t)$ depicts the steady state behavior which is non-linearity and asymmetricity, and $R_2(t)$ depicts the behavior during the initial stage mainly buildup and shoulder. The model was designed for distribution voltage. $R_1(t)$ is calculated by linearizing the voltage-current characteristics and $R_2(t)$ is calculated by subtracting $R_1(t)$ from $R(t)$, where $R(t)$ is obtained when the voltage and current reach their maximum in every cycle. Figure 2.3 shows the arrangement of the model.

$$R(t) = R_1(t) + R_2(t) \tag{2.2}$$

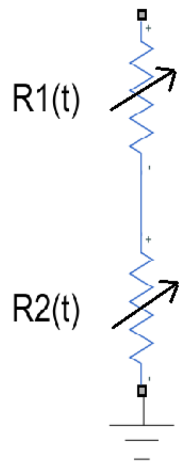

Figure 2.3: Nam *et.al* model

2.2.4 Three Parameter Model

The model was designed for 500kV transmission voltage. The characteristic of HIF is considered resistive, the fault resistance was designed as an exponential decay function. The equation formulation as

$$R_{\mathrm{f}}(t) = A + B * e^{(-c*(t-t_0))} \tag{2.3}$$

where A is Final Resistance,B is R_{finitial}-A at t=t_0 ,c is decay constant,t_0 is the fault inception time.
The three parameters which are input to this model are R_{finitial},A and c. This model considers the fact that the voltages and currents are in phase during the fault period which implies it is a resistive fault. The initial and final values of resistances were estimated through the regression technique and were compared with actual values during a fault event. During the initial duration, the deviation between actual and modeled resistance was significant and this was due to simplified assumptions while performing regression analysis. The model works well since it resembles the characteristic of HIF especially time-varying non-linear behaviour.

2.2.5 Feraz *et.al* Model

The model was designed for 230kV transmission voltage. This model was built taking the Emanuel model as a reference, the fault resistance was designed as a polynomial function as

$$f(t) = \begin{cases} a_{\mathrm{n}} * t^n + a_{\mathrm{n\text{-}1}} * t^{n-1} + a_1 * t + a_0, & t_{\mathrm{fi}} \leq t \leq t_{\mathrm{ss}} \\ a_0 & t \geq t_{\mathrm{ss}} \end{cases} \tag{2.4}$$

where a_{n},$a_{\text{n-1}}$,a_0 are coefficients which were obtained based on different surfaces ,t_{fi} is the fault inception time and t_{ss} is the steady state time. The main aspect of this model was that the nonlinear polynomial was linearised and made linear time-variant and was subsequently solved. To get all the characteristics of HIF, the duration has to be long enough when using this model, but when it comes to protection, the detection has to be quick so in the section 4.2 some important aspects about a slight modification to this model shall be touched upon.

3
Model Implementation

3.1 Transmission Line Model

Since faults are considered as transients in the power system, the model implementation was carried out in PSCAD. There are two transmission line models which are available in PSCAD namely the Bergeron line Model [6] and the Frequency-Dependent (Phase) line Model[7]. The Bergeron Model is a constant frequency model. It is based on the traveling waves. It shouldn't be used in situations where transient or harmonic behavior is crucial but can be helpful in investigations where obtaining the accurate steady-state impedance/admittance of the line or cable is crucial. The Frequency-dependent (Phase) line model is a time domain model. It is mainly used in studies involving the transient and harmonic behavior of transmission lines. The Frequency-Dependent (Phase) model was chosen since the requirement is the transient behavior of transmission lines. The frequency-dependent phase model parameters given by Hitachi Energy are shown in Figure 3.1.

Frequency Dependent (Phase) Model Options

Travel Time Interpolation:	On
Curve Fitting Starting Frequency:	0.5
Curve Fitting End Frequency:	1.0E6
Total Number of Frequency Increments:	500
Maximum Order of Fitting for Yc:	20
Maximum Fitting Error for Yc:	2 [%]
Max. Order per Delay Grp. for Prop. Func.:	20
Maximum Fitting Error for Prop. Func.:	2 [%]
Dc Correction:	Disabled
Passivity Checking:	Disabled
Passivity Enforcement:	Disabled

Figure 3.1: Frequency Dependent Phase Model Parameters

Tower and grounding configuration details given by Hitachi Energy as shown in Figure 3.2.

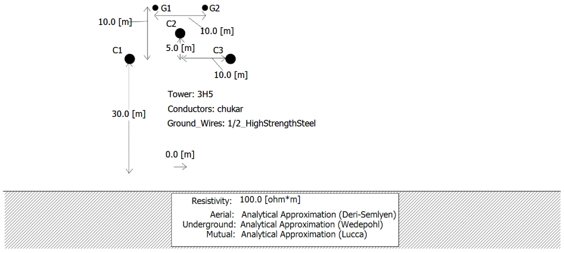

Figure 3.2: Tower and Ground Parameters

The transmission line parameters used for conventional source and Type 3 windfarm studies are shown in Table 3.1.

Line Length	100Km
System Frequency	50Hz
No of Conductors	3
Positive Sequence Impedance	3.46+42.33j ohm
Negative Sequence Impedance	3.46+42.33j ohm
Zero Sequence Impedance	30+114j ohm

Table 3.1: Line Parameters

The transmission line parameters used for Type 4 windfarm studies are shown in Table 3.2.

Line Length	100Km
System Frequency	50Hz
No of Conductors	3
Positive Sequence Impedance	1.89+32.63j ohm
Negative Sequence Impedance	1.89+32.63j ohm
Zero Sequence Impedance	18.68+182.7j ohm

Table 3.2: Line Parameters

3.2 Conventional Source Model

Conventional Sources 1 and 2 were considered with their parameters as shown in Table 3.3 and Table 3.4 respectively. Source 2 was considered a weak source so it had minimal contribution of fault current.

Frequency	50Hz
Voltage	220kV
Base MVA	100
Load Angle (δ)	40°
Positive Sequence Impedance	2.65+30.31j ohm
Negative Sequence Impedance	2.65+30.31j ohm
Zero Sequence Impedance	2.63+9.88j ohm

Table 3.3: Source 1 Parameters

Frequency	50Hz
Voltage	220kV
Base MVA	100
Load Angle (δ)	0°
Positive Sequence Impedance	52.09+295.44j ohm
Negative Sequence Impedance	52.09+295.44j ohm
Zero Sequence Impedance	104.19+590.88j ohm

Table 3.4: Source 2 Parameters

3.3 Renewable and conventional Source Model

A windfarm was placed in the place of source 2, source 1 was an R-R//L [8] positive sequence impedance type conventional source taken from PSCAD library with details listed in tables 3.5 and 3.6 for Type 4 and Type 3 respectively.

Frequency	50Hz
Voltage	230kV
Base MVA	200
Positive Sequence Impedance	4.51+25.6j ohm
Negative Sequence Impedance	4.51+25.6j ohm
Zero Sequence Impedance	4.51+25.6j ohm
Load Angle (δ)	0°

Table 3.5: Source 1 Parameters for Type 4 windfarm

Frequency	50Hz
Voltage	220kV
Base MVA	300
Positive Sequence Impedance	1.74+9.84j ohm
Negative Sequence Impedance	1.74+9.84j ohm
Zero Sequence Impedance	6.94+38.39j ohm
Load Angle (δ)	20°

Table 3.6: Source 1 Parameters for Type 3 windfarm

PSCAD standard Type 4 and Type 3 wind farms were used ,the models were given by Hitachi Energy.Table 3.7 lists the main details of type 4 and type 3 wind farms.

Frequency	50Hz
Rated voltage of converters/machine	0.69kV
Turbine Rated Active power	2MW
Wind speed	10 m/s

Table 3.7: Parameters for Type 4 and 3 windfarms

3.4 Step Up Transformer

The step-up transformer was mainly used in the simulation involving the windfarms since the windfarm was rated for 33kV. Details of the step-up transformer are shown in the table 3.8 and figure 3.3 shows the symbol of the transformer.

Frequency	50Hz
Primary Voltage (Delta)	33kV
Secondary Voltage(Star grounded)	230kV
Rating	200MVA
Leakage reactance	0.025 pu

Table 3.8: Step up Transformer details

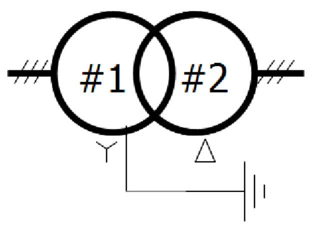

Figure 3.3: Step up transformer

3.5 HIF Block model

PSCAD has the functionality to create a custom block as per the requirements, the same was utilized to create a custom block named HIF. This is shown in figure 3.4 where BRK1 is the fault creation breaker input signal and Res is the output resistance from the block.

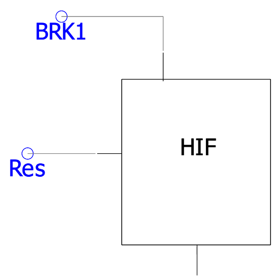

Figure 3.4: HIF Block

Figure 3.5 shows the details inside the HIF block.

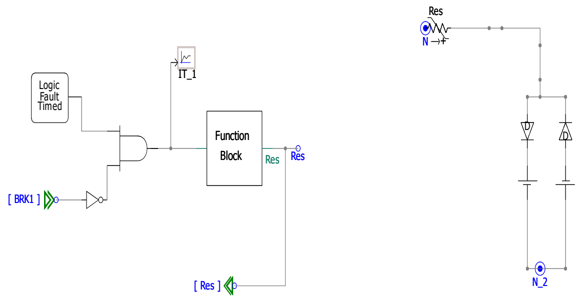

Figure 3.5: HIF Detailed Block

N and N_2 are the electrical nodes used for connecting this HIF block to the main system. The main code is implemented inside the Function Block. The variable resistor takes the resistance values named Res coming out of the function block. More details of the operation of the function block are explained in section 3.5.1. Sources S1 and S2 and diodes D1 and D2 are considered to replicate the asymmetric behavior of the fault current as stated in the Emanuel model.D1 and D2 are standard diodes taken from the PSCAD master library. Source S1 and S2 details are stated in table 3.9. The value of S2 was taken higher than S1 because during the steady state positive peak value of the fault current is higher than the negative peak value. This is as said in the research paper [2].

Source	Voltage
S1	1 kV
S2	7 kV

Table 3.9: DC Source Parameters

3.5.1 Function block model

As shown in figure 3.6, the input to the function block is named Timeinput which goes high when the output of the AND gate is 1. This is a major condition in the Fortran code. The Logic Fault Timed block is used for fault application time as well as the duration of the fault. Once the simulation time equals the application time the output of this block is 1 and stays until the duration time is reached. .

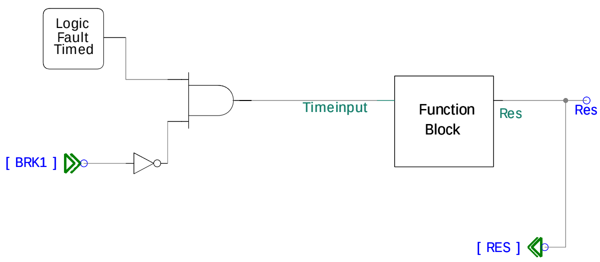

Figure 3.6: Function block

BRK1 comes from the breaker signal block as shown in figure 3.7. This is the fault inception breaker which is initially open and closed at a particular time. Since the breaker is open initially at t_0, once it is closed the output of the Timed Breaker Logic block gives 0 as shown in figure 3.7 at t=1 second, and stays until the second breaker operation time is reached where it is opened back. This is the main reason for having a NOT gate after the BRK1 in figure 3.6.

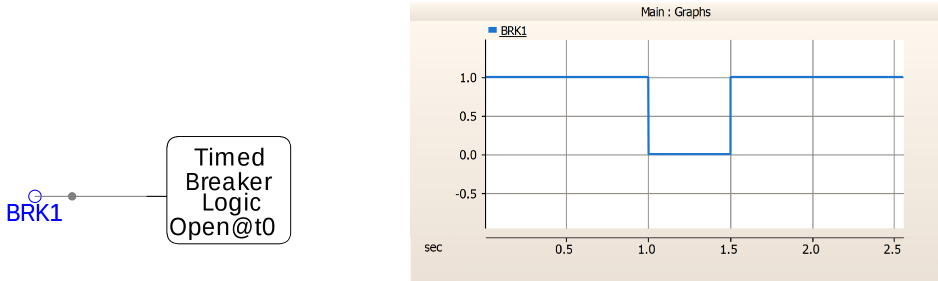

Figure 3.7: Breaker Signal block and its output

3.5.1.1 Function Block Code

The main parameters for the Function block code are the initial value of resistance, the final value of resistance and the decay constant(c) for the Three Parameter model approach, and for the Feraz *et.al* model approach, it shall be just the initial value and final value of resistance. Figure 3.8 shows the code implementation in general, the function after the else statement in the code was changed for different model approaches.

```
#LOCAL REAL time1
#STORAGE REAL:1
       time1 = STORF(NSTORF) !storage array for the time variable
       If($Timeinput.LT.1) THEN
       $Res=80
       time1=TIME + DELT !update the time variable
       ELSE
       $Res=$Rf+($R0*EXP(-$c*(time-time1)))
           !why time-time1 because it has to take the time lapsed as the start point
       END IF
       STORF(NSTORF) =time1 !update the storage array with the new time
       NSTORF = NSTORF + 1 !update the storage pointer
```

Figure 3.8: Function block code

A simple explanation of code in figure 3.8 is below

- If the the Timeinput value is less than 1 that is the output of AND gate in figure 3.6 is 0, keep the Res value as 80 which is the initial value of resistance.
- Update the Time1 variable with (simulation time (TIME)+Timestep(DELT)).
- Once the Timeinput becomes 1 that is the output of the AND gate in figure 3.6 is 1, then the function after the ELSE statement will be executed.

3.6 Current Transformer (CT) Model

The current Transformer (CT) is used for measurement and stepping down the current that the relay can measure. Standard CT as given by Hitachi Energy [9] was employed for simulation. Table 3.10 lists main CT parameters and figure 3.9 shows the CT implementation where I_s is three-phase current measured from the multimeter and I_{sa},I_{sb} and I_{sc} are respective phase secondary currents.

Model No	IMB 245
CT Ratio	1/1000
Frequency	50Hz
Burden Resistance	0.5 ohm
Burden Inductance	0.8 mH
Secondary Resistance	20 ohm
Secondary Inductance	0.8 mH

Table 3.10: CT Parameters

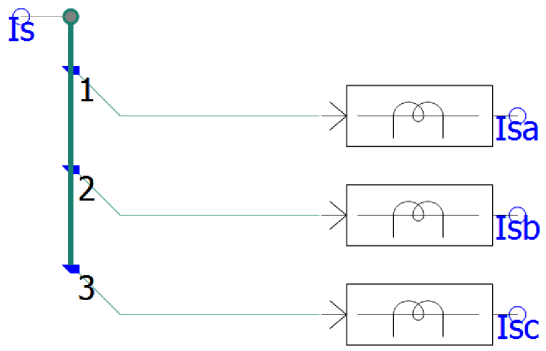

Figure 3.9: CT connection

3.7 Capacitive Voltage Transformer Model

Capacitive Voltage Transformer (CVT) is used for the measurement of Voltage and stepping down the Voltage that the relay can measure. A scaling factor of 2.223 is included in the CVT output since the relay is on the secondary side to avoid confusion of impedance measurement and transferring it to the primary side. The scaling factor makes sure we are on the primary side so there is no requirement of primary to secondary value transfer. The advantage of using a Capacitive Voltage transformer is that the bushing size of the Voltage transformer can be reduced when it comes to High Voltage as Voltage is inversely proportional to Capacitance.
Figure 3.10 shows a typical arrangement of Capacitive Voltage Transformer given by Hitachi Energy [10]. The main parameters of the circuit in figure 3.10 are described below
C_1 and C_2 : stack capacitances

L : compensating inductance
R_F,L_F and C_F : resistance, inductance and capacitance of ferro-resonance suppression circuit
R_B : burden resistance

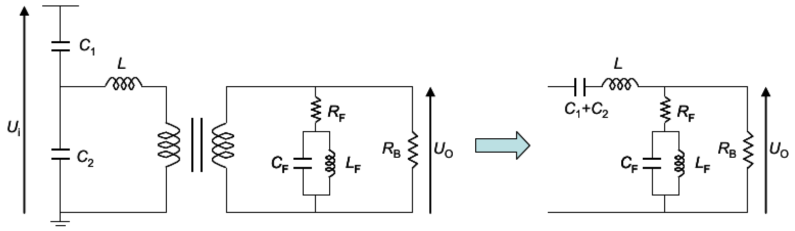

Figure 3.10: CVT equivalent circuit

Table 3.11 lists the main CVT parameters used for simulation.

Model No	CPB 245
VT Ratio	203.51
Frequency	50Hz
Stack Capacitance (C_1)	7800 pF
Stack Capacitance (C_2)	77600pF
Compensating Inductance (L)	100 H
Burden Resistance (R_B)	785 ohm

Table 3.11: CVT Parameters

A simple implementation of CVT block in simulation is shown in figure 3.11 where E_s is the three-phase voltage measured by the multimeter and V_{sa},V_{sb} and V_{sc} are secondary voltages.

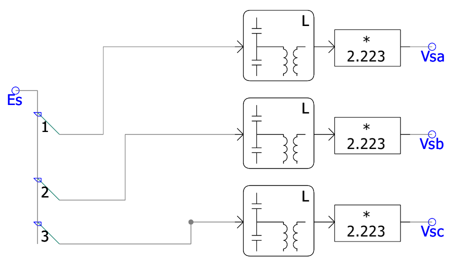

Figure 3.11: CVT connection

3.8 Fast Fourier Transform (FFT) Block

Fast Fourier Transform block was used to get the fundamental phase and magnitude component of currents and voltages measured by CT and CVT respectively. The standard FFT block is available in the PSCAD library and the same was used for the simulation. The FFT block and configuration details are shown in figure 3.12.

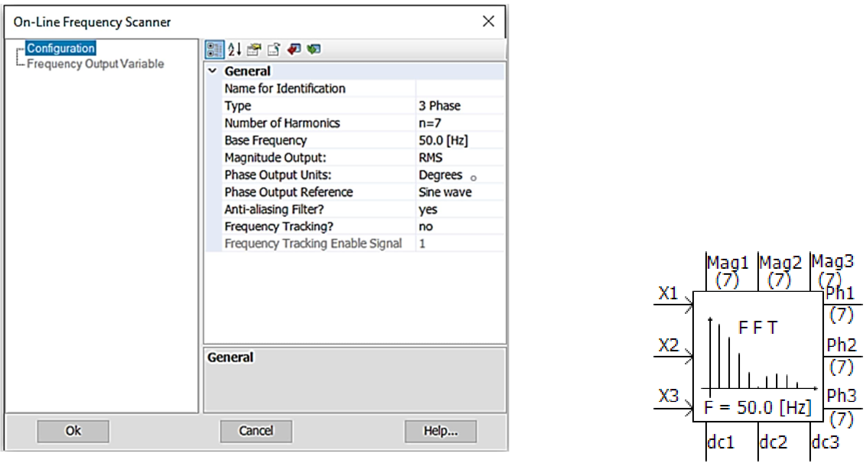

Figure 3.12: FFT Block symbol and configuration parameters

3.9 Multimeter Block

One three-phase multimeter is used for current and voltage measurements .E_s and I_s are the signal outputs of instantaneous voltage and current respectively. Multimeter symbol and configuration details are shown in figure 3.13.

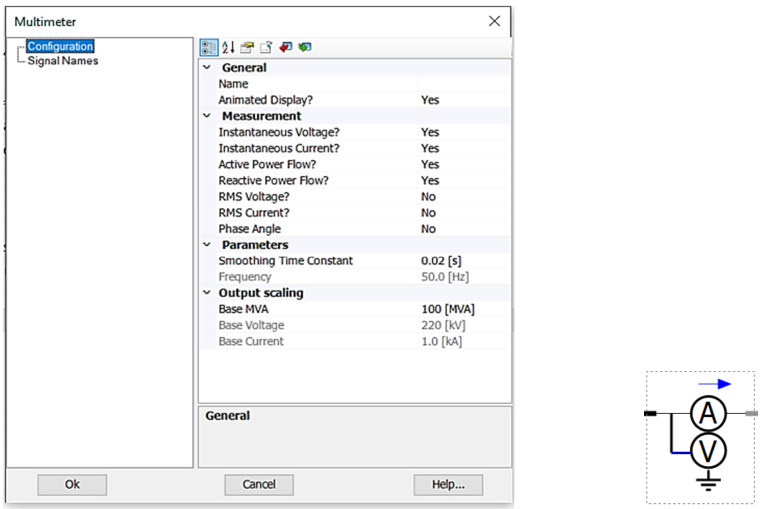

Figure 3.13: Multimeter Block symbol and configuration parameters

3.10 Sequence Filter block

The standard Phase to Sequence components conversion block named Sequence Filter available in the PSCAD master library block was employed. Figure 3.14

shows the details and block representation. Inputs are mainly each phase current magnitude and phase angle and output is the sequence with their respective phase and magnitude. Table 3.12 lists each signal name for Figure 3.14. The same sequence filter block can be used for converting phase voltages to sequence components.

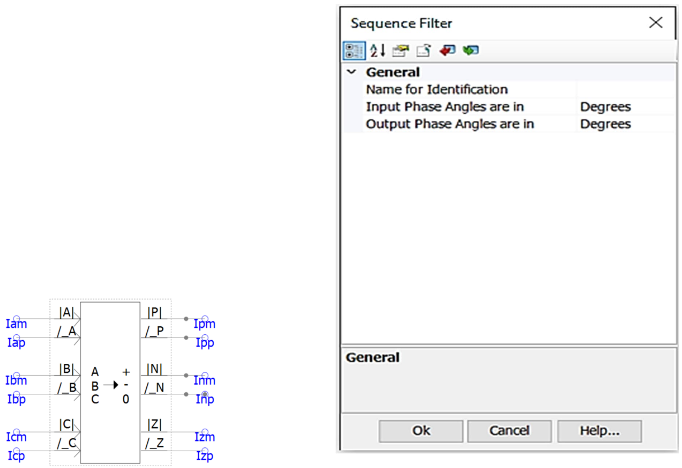

Figure 3.14: Phase to Sequence components block representation and details

Quantity	Description	Unit
I_{am}	Phase a Current magnitude	kA
I_{ap}	Phase a phase angle	Degree
I_{bm}	Phase b Current magnitude	kA
I_{bp}	Phase b Current phase angle	Degree
I_{cm}	Phase c Current magnitude	kA
I_{cp}	Phase c Current phase angle	Degree
I_{pm}	Positive Sequence Current magnitude	kA
I_{pp}	Positive Sequence Current phase angle	Degree
I_{nm}	Negative Sequence Current magnitude	kA
I_{np}	Negative Sequence Current phase angle	Degree
I_{zm}	Zero Sequence Current magnitude	kA
I_{zp}	Zero Sequence Current phase angle	Degree

Table 3.12: Sequence Parameters signal names

The phase components are converted to their sequence components by the Fortescue theorem. The conversion matrix from phase to sequence components and vice versa is shown below and the same has been implemented in the Sequence Filter block.The value of α is

$$\alpha = 1 * e^{i\frac{2\pi}{3}}$$

$$\begin{bmatrix} Zero\ Sequence \\ Positive\ Sequence \\ Negative\ Sequence \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} Phase\ A \\ Phase\ B \\ Phase\ C \end{bmatrix}$$

$$\begin{bmatrix} Phase\ A \\ Phase\ B \\ Phase\ C \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} Zero\ Sequence \\ Positive\ Sequence \\ Negative\ Sequence \end{bmatrix}$$

3.11 Impedance Calculation Block

PSCAD has separate Impedance calculation blocks for Single Line to Ground and Line to Line fault. The impedance block used for Line to Line fault is the same as for the double Line to Ground fault. In the simulation results chapter more details shall be touched upon. This section provides an overall view of the impedance block and the parameters for the same. The output of this block is given to the distance relay which will be touched upon in the upcoming section.

3.11.1 SLG Fault impedance calculation block

Figure 3.15 shows the impedance block symbol and its parameters used for SLG fault, as a reference only phase A is shown but it shall be the same if Phase B to ground or Phase C to ground fault occurs. The parameter k is calculated using the below equation

$$k = \frac{Z_0 - Z_1}{Z_1} \tag{3.1}$$

where Z_1 is Positive sequence line impedance and Z_0 is Zero sequence line impedance. The value of K as shown in Figure 3.15 was obtained by using line parameters listed in Table 3.1.

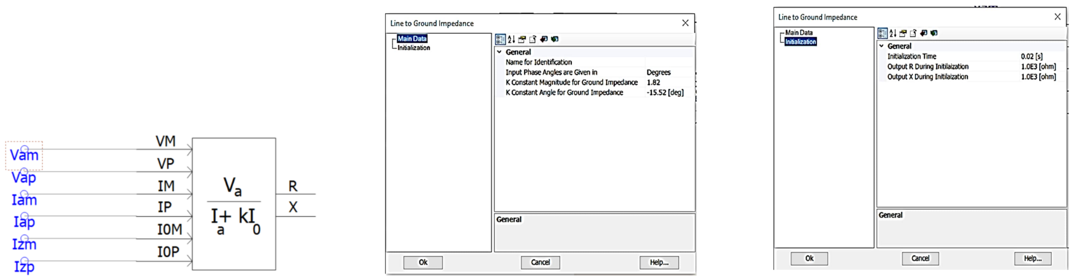

Figure 3.15: SLG Fault Impedance block symbol and details

Initialization values as shown in figure 3.15 are done to freeze the output during the start of the simulation because the system quantities like the magnitude and phase angles undergo some transients. Table 3.14 List the main input and output parameters of the impedance block shown in figure 3.15.

Quantity	Description	Unit
V_{am}	Phase a Voltage magnitude	kV
V_{ap}	Phase a Voltage phase angle	Degree
I_{am}	Phase a Current magnitude	kA
I_{ap}	Phase a Current phase angle	Degree
I_{zm}	Zero Sequence Current magnitude	kA
I_{zp}	Zero Sequence Current phase angle	Degree
R	Output Resistance	ohm
X	Output Reactance	ohm

Table 3.13: Parameter Description for SLG fault Impedance calculation block

3.11.2 LL and LLG Fault impedance calculation block

Figure 3.16 shows the impedance calculation block for LL and LLG fault case, as a reference fault in phase A and phase B is shown, it shall be the same if the fault occurs between phase A and phase C or phase B and phase C.Same understanding goes for LLG fault case.

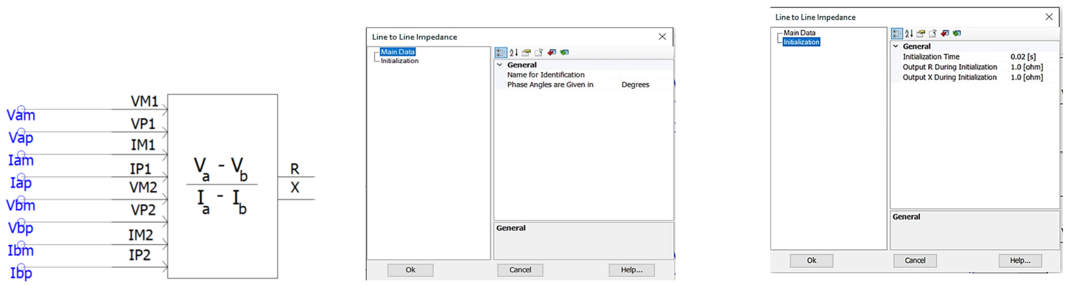

Figure 3.16: LL and LLG Fault Impedance block symbol and details

Table 3.14 List the main input and output parameters of the impedance block shown in figure 3.16.

Quantity	Description	Unit
V_{am}	Phase a Voltage magnitude	kV
V_{ap}	Phase a Voltage phase angle	Degree
I_{am}	Phase a Current magnitude	kA
I_{ap}	Phase a Current phase angle	Degree
V_{bm}	Phase b Voltage magnitude	kV
V_{bp}	Phase b Voltage phase angle	Degree
I_{bm}	Phase b Current magnitude	kA
I_{bp}	Phase b Current phase angle	Degree
R	Output Resistance	ohm
X	Output Reactance	ohm

Table 3.14: Parameter Description for LL and LLG fault Impedance calculation block

For a three-phase to ground fault, any impedance block outputs can be taken since the impedance measured by both blocks described in sections 3.11.2 and 3.11.1 are the same.

3.12 Trip Polygon block

The output of the impedance block is given to the trip polygon, if the impedance is within its set points then the output of the trip polygon block is 1. This is the way how distance protection is implemented in PSCAD. Figure 3.17 shows a simple symbol of Trip polygon block and its parameter setting will be explained in the results chapter. The trip characteristic chosen for studies is quadrilateral.

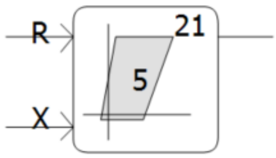

Figure 3.17: Trip Polygon Block symbol

3.13 System representation and Simulation setup

Figure 3.18 shows conventional source systems implemented for study purposes. In the simulation results chapter, detailed information will be focussed on and explained mainly the connection of the HIF custom block. Tables 3.16 list the main simulation settings for conventional source and wind farm studies.

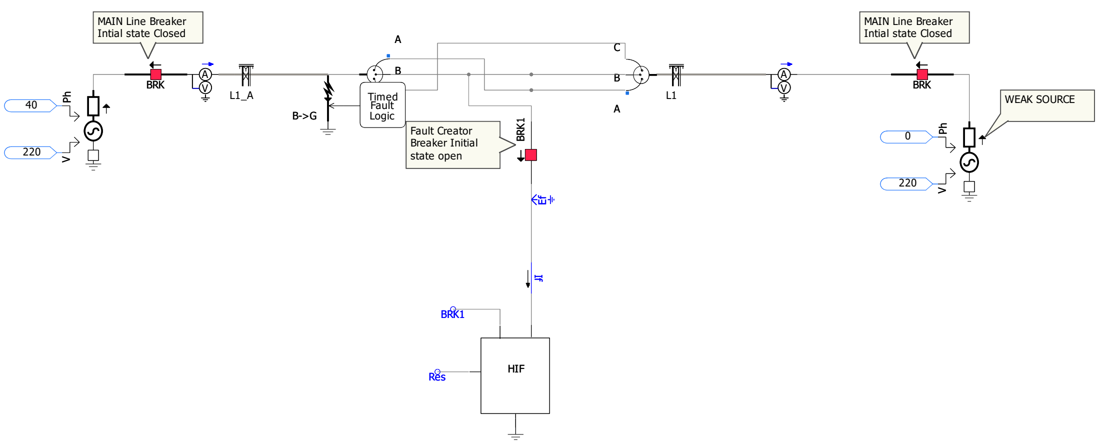

Figure 3.18: Conventional Sources System Representation

Run Duration	3 second
Solution Time step	10 µs
Channel plot step	250 µs

Table 3.15: Simulation setup parameters for conventional source studies

Run Duration	5 second
Solution Time step	10 µs
Channel plot step	250 µs

Table 3.16: Simulation setup parameters for windfarm studies

Figures 3.19 and 3.20 show the system setup for Type4 and Type 3 wind farms along with the conventional source respectively.

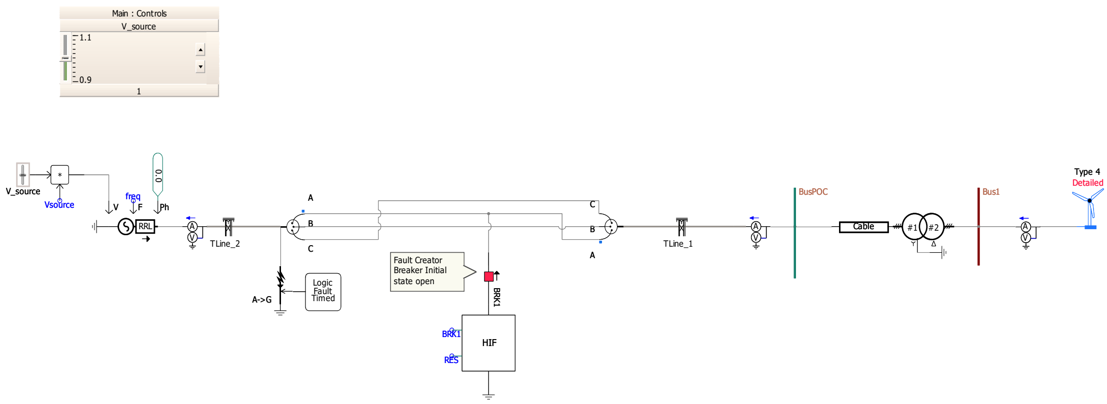

Figure 3.19: System Representation with type 4 windfarm

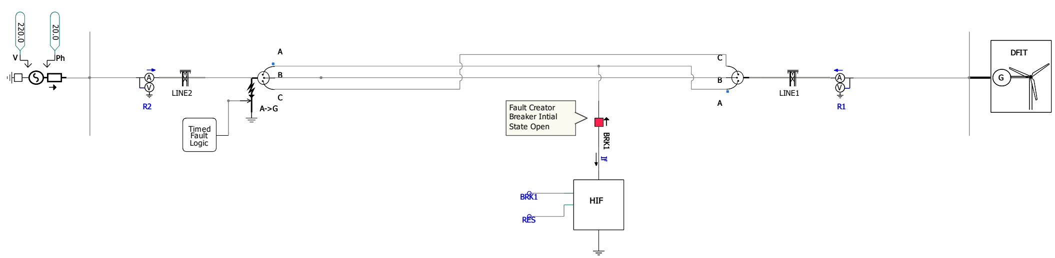

Figure 3.20: System Representation with type 3 windfarm

4

Simulation Results and Discussion

4.1 Exponential Response Study and Results

4.1.1 Resistance Exponential Characteristic

Firstly, the HIF response based on the Three Parameter approach mentioned in section 2.2.4 was carried out, Figure 3.18 shows the general arrangement of the system where the circuit breaker called Fault creator breaker BRK1 was closed at time t=1.5 seconds and the parameters of equation 2.3 are listed in table 4.1.

Breaker BRK1 closing time (t_0)	1.5 second
Breaker BRK1 opening time	2.5 second
A	50 ohm
B	30 ohm
R_{finitial}	80 ohm
c	100

Table 4.1: Input parameters to HIF block

The output resistance response is shown in figure 4.1, before the breaker BRK1 was open the resistance was at 80 ohm and once the breaker was closed at t=1.5 second, the exponential decay response was observed. The final value of 50 ohm was obtained at around 1.575 seconds. The time duration required to reach the final value can be made faster by increasing the decay constant c.The resistance response is nonlinear and it varies with time.

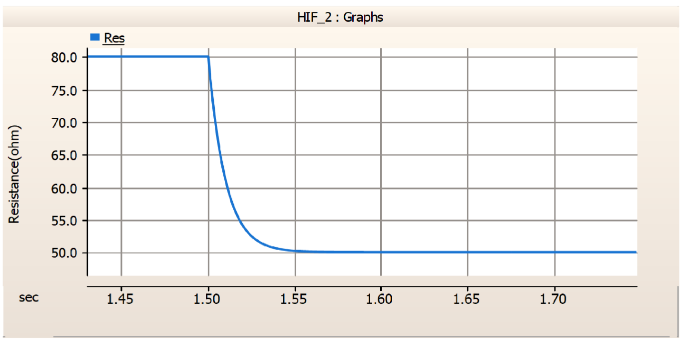

Figure 4.1: Resistance Response

4.1.2 Fault Current Characteristic

To get the fault current characteristic as described in section 2.1 and considering the Three parameter model approach as described in section 2.2.4 the main interest here is to observe the buildup and asymmetric characteristic since the shoulder characteristic with the exponential case doesn't significantly show up.To see the characteristic in the fault current the decay constant c was reduced and the exponential response slowed down. The table 4.2 lists updated settings for getting Fault current characteristic.

Breaker BRK1 closing time (t_0)	1.5 second
Breaker BRK1 opening time	2.5 second
A	50 ohm
B	30 ohm
R_{finitial}	80 ohm
c	10

Table 4.2: Input parameters to HIF block

Figure 4.2 shows the fault current response and resistance response, it is seen that initially the current builds up from a lower value since the resistance is higher initially as shown in figure 4.3 and as time progresses the current builds up to a higher value and attains a steady state value around time t=2.3 second when the resistance has reached its final value. During the steady state the positive maximum is at 2kA and the negative maximum is at 1.5kA ,this verifies the characteristic mentioned in sections 2.2.2.

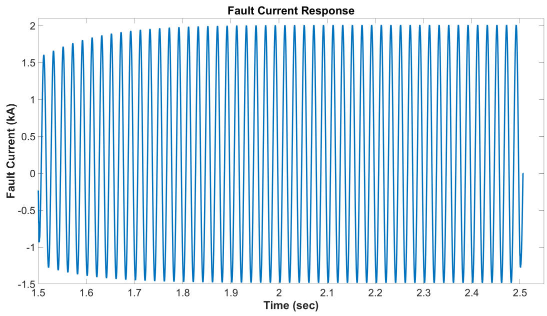

Figure 4.2: Fault current response

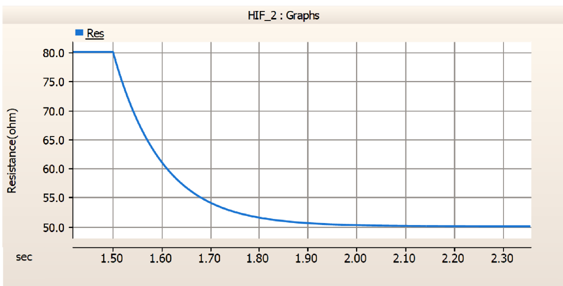

Figure 4.3: Resistance response

4.1.3 Symmetrical and Unsymmetrical fault analysis

Symmetrical and Unsymmetrical fault analysis were carried out with the exponential response model and was compared with the standard fault block in PSCAD mainly the resistance values obtained by the distance relay since the reactance value calculation didn't have much impact. Four types of faults were carried out mainly Single line to Ground (SLG), Line to line (LL), Double Line to Ground (LLG), and Three phase to ground (LLLG)fault. The fault was created every 10km of the 100km of the transmission line.

4.1.3.1 Single Line to Ground Fault (SLG)

A typical arrangement for the single line to ground fault is shown in figure 4.4 and the transmission line was split into two sections L1_A and L1 through a phase splitter. Fault creation time details for both standard PSCAD fault block and custom-made HIF block are shown in tables 4.3 and 4.1.

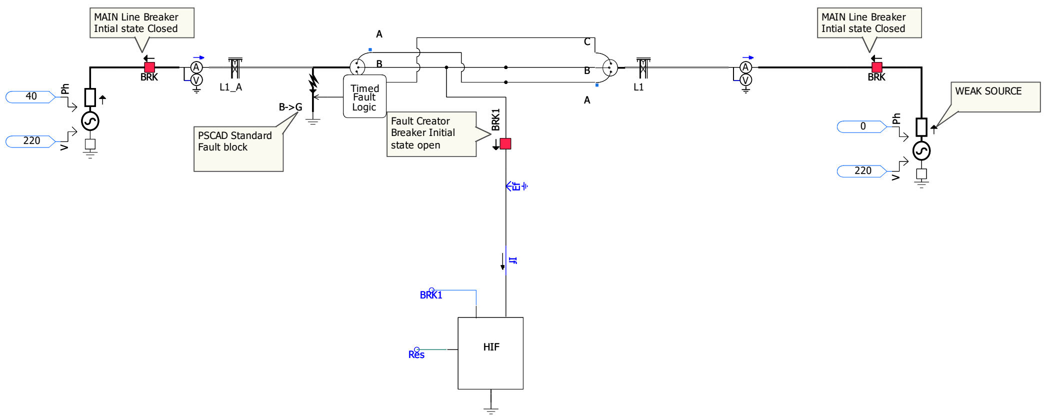

Figure 4.4: SLG Fault implementation

Fault Type	B-G
Fault creation Time	0.5 second
Fault Duration	0.4 second
Fault resistance	50 ohm

Table 4.3: SLG:Fault parameters for standard PSCAD block

Source 2 is a weak source so it doesn't contribute much to the fault so the focus was kept only the contribution of Source 1 to the fault. To study the characteristics of the fault current for the standard PSCAD and HIF block, from the standard PSCAD fault block the fault current component of phase B was taken out named as I_{bb} and I_f is the fault current from the HIF block. Figures 4.5 and 4.6 show the characteristic for a fault current case at 80km of line L1_A for both standard and HIF case respectively.In order to replicate the full characteristic of fault current the decay constant was considered as 10.As seen in Figure 4.5, fault current I_{bb} has the shape of a traditional fault current where we have the DC component at the start and then it stabilizes. Figure 4.6 indicates that the shape of the fault current from the HIF block is different and has a smaller value at the start and rises and stabilizes at 2.3 seconds. For the standard fault case the positive and negative peak values are the same and for the HIF case, it is different as it was conveyed in section 2.2.2.For further simulation, the decay constant was considered as 100.

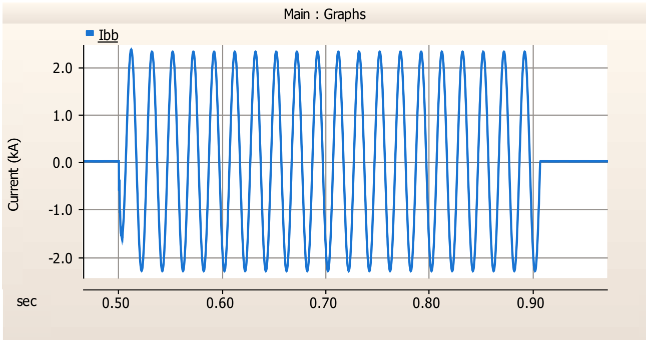

Figure 4.5: SLG:Fault current response for standard PSCAD fault block

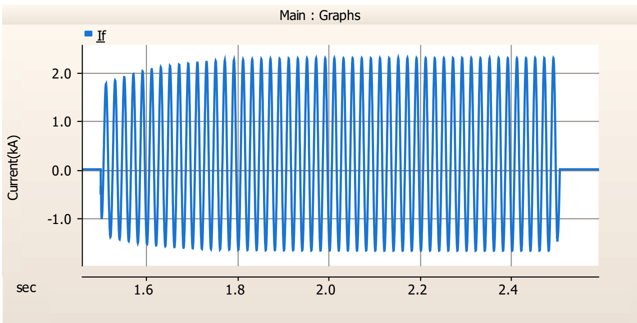

Figure 4.6: SLG: Fault current response for the HIF block

The impedance calculation block as mentioned in section 3.11.1 gives out the value that corresponds to the equation 4.1. The background of this equation was taken from the book [11]. The apparent impedance seen by the relay Z_{app} is given as

$$Z_{\text{app}} = (a * Z_1) + Z_{\text{f}} * \frac{3 * a * Z_1}{(2 * a * Z_1) + (a * Z_0)} \tag{4.1}$$

where Z_1 is Positive sequence line impedance,Z_0 is Zero sequence line impedance,Z_{f} is fault impedance which is only taken as resistance and a is the percentage of the line where the fault occurs. The table 4.4 lists the values of Resistances measured by the relay for faults at different line lengths for both standard block and HIF block case.

Line Length	Resistance measured during PSCAD fault block scenario	Resistance measured during the HIF block scenario
10km	31.2Ω	40.3Ω
20km	32Ω	41.5Ω
30km	32.8Ω	42.6Ω
40km	33.7Ω	43.4Ω
50km	34.3Ω	44.7Ω
60km	35.2Ω	45.4Ω
70km	36.06Ω	46.5Ω
80km	36.6Ω	47.4Ω

Table 4.4: Measured resistance for SLG fault

The deviation of values of HIF block from the standard fault block is due to the asymmetric nature of the fault current where the positive and negative peak values aren't the same for the fault current. But the error remains constant after the steady state is attained and can be compensated easily by a compensation block as shown in figure 4.7 just for phase B , but it shall be the same if a fault occurs in the other phases. An important point to be noted is if the values are directly substituted in the equation 4.1 then the values obtained will slightly deviate from the values obtained from standard PSCAD fault block simulation. This is due to fact that we have considered source 2 doesn't contribute to the fault while considering the equation 4.1 but in actuality there is a contribution so the current measured by the relay gets divided, it doesn't measure the actual fault current. Like for instance for a fault at 80km the resistance value obtained directly substituting in the equation 4.1 is 34 ohm while the simulation value is 36.6 ohm so not a big deviation.

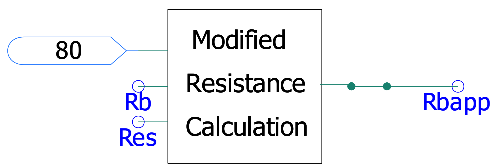

Figure 4.7: Compensation block for SLG fault

The inputs to the block are mainly line length, the resistance value coming from the impedance block, and the resistance value coming from the HIF block. This compensation block will be operated once the resistance value has reached 50 ohm otherwise it will stay at a higher value in this case it was kept at 500 ohm. The code as shown in figure 4.8 indicates that basically based on line lengths and resistance requirement as per standard fault case, the impedance block calculated resistance is subtracted. The output of this block is then given to the trip polygon block which checks if it's under the protection zone and accordingly trip signal is given.

```
IF ($L.GE.10 .AND. $L.LT.20 .AND. ABS($Res-50.04).LE.0.009) THEN
$Ra1=$Ra-9.84
ELSEIF ($L.GE.20 .AND. $L.LT.30 .AND. ABS($Res-50.04).LE.0.009) THEN
$Ra1=$Ra-9.5
ELSEIF ($L.GE.30 .AND. $L.LT.40 .AND. ABS($Res-50.04).LE.0.009) THEN
$Ra1=$Ra-9.8
ELSEIF ($L.GE.40 .AND. $L.LT.50 .AND. ABS($Res-50.04).LE.0.009) THEN
$Ra1=$Ra-9.7
ELSEIF ($L.GE.50 .AND. $L.LT.60 .AND. ABS($Res-50.04).LE.0.009) THEN
$Ra1=$Ra-10.4
ELSEIF ($L.GE.60 .AND. $L.LT.70 .AND. ABS($Res-50.04).LE.0.009) THEN
$Ra1=$Ra-10.2
ELSEIF ($L.GE.70 .AND. $L.LE.80 .AND. ABS($Res-50.04).LE.0.009) THEN
$Ra1=$Ra-11
ELSE
$Ra1=500
END IF
```

Figure 4.8: Compensation block code for SLG fault

As mentioned in section 3.12 the trip polygon block is taken as a quadrilateral characteristic type the set points decided as per the zone 1 impedance value requirement as well as taking into consideration the fault resistance are given in the figure 4.9. A 4-point polygon was considered.

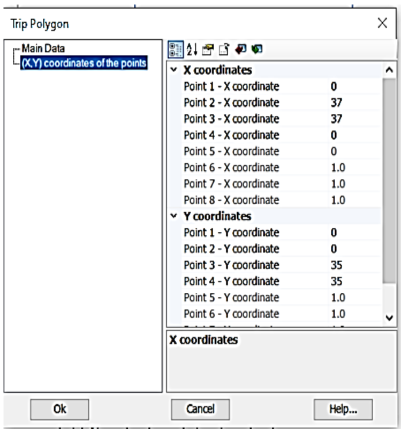

Figure 4.9: Relay setpoints for SLG fault

A sample fault case at 80km was simulated for the HIF block with the settings and the inception and trip times are shown in table 4.12.

Fault inception time	1.5 second
Signal from the trip polygon block	@1.57
Breaker operation time	60ms
Fault clearing time	@1.63 second

Table 4.5: SLG:Operation times

Figure 4.10 shows the R-X plot for HIF faults at various lengths of the line considering zone-1 protection and compensation in calculation as well.

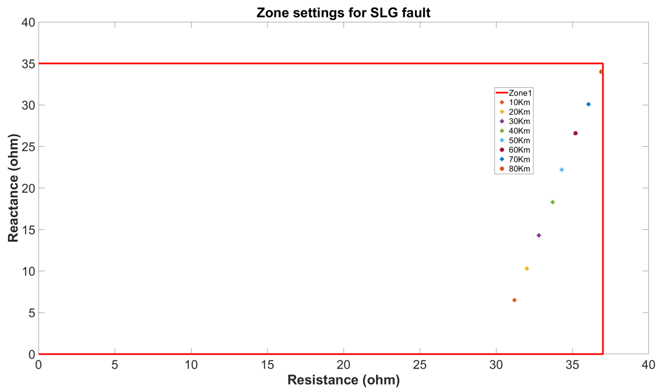

Figure 4.10: Zone-1 RX plot for SLG fault

4.1.3.2 Line to Line (LL) fault

Going with the assumption that Source 2 is a weak source , most of the fault current contribution comes from Source 1. A typical arrangement for line-to-line fault is shown in figure 4.11.

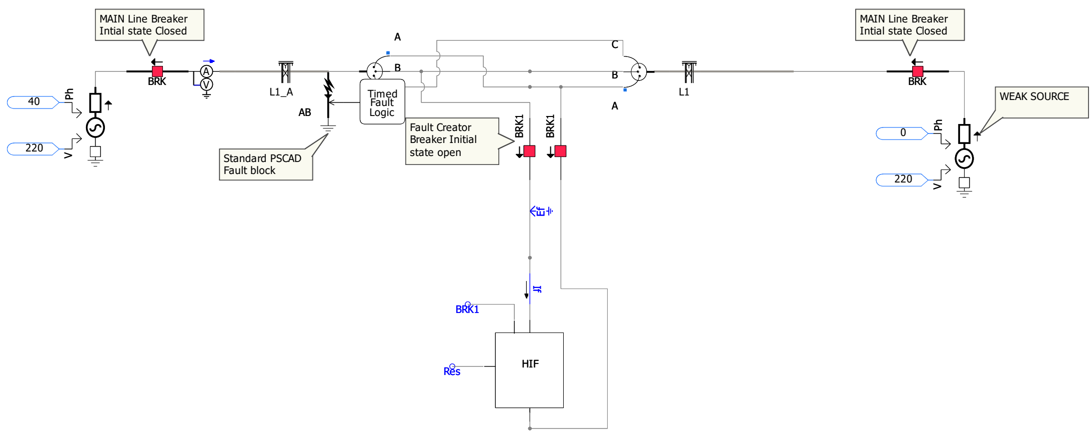

Figure 4.11: LL fault arrangement

Fault creation time details for both standard PSCAD fault block and custom-made HIF block is shown in tables 4.6 and 4.2 .

Fault Type	AB
Fault creation Time	0.5 second
Fault Duration	0.4 second
Fault resistance	50 ohm

Table 4.6: LL:Fault parameters for standard PSCAD block

Fault current response during standard PSCAD fault block events and HIF events are different and the reason goes the same as mentioned for Single line to Ground fault case. Figures 4.12 and 4.13 indicate the response of the current. For further simulation, the decay constant was considered as 100.

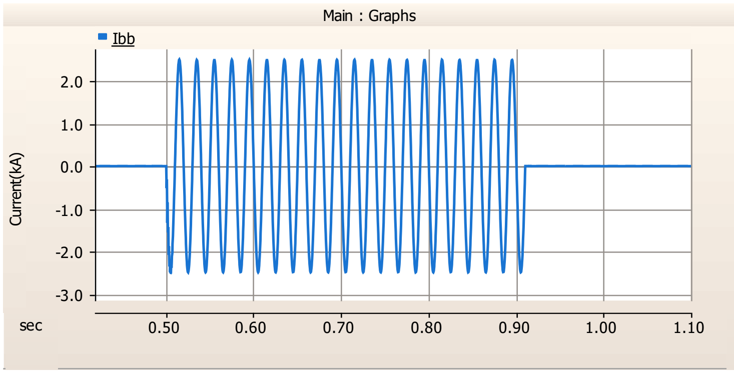

Figure 4.12: LL: Fault current response for standard PSCAD fault block

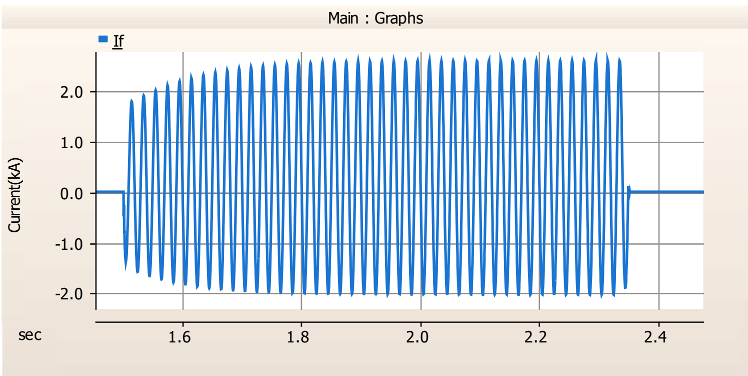

Figure 4.13: LL: Fault current response for the HIF block

The impedance calculation block as mentioned in section 3.11.2 gives out the value that corresponds to the equation 4.2. The background of this equation was taken from the book [11]. The apparent impedance seen by the relay Z_{app} is given as

$$Z_{\text{app}} = (a * Z_1) + \frac{Z_{\text{f}}}{2} \tag{4.2}$$

where Z_1 is the Positive sequence line impedance and Z_{f} is fault impedance which is only taken as resistance and a is the percentage of the line where the fault occurs. The table 4.7 lists the values of Resistances measured by the relay for faults at different line lengths for both standard PSCAD block and HIF block case.

Line Length	Resistance measured during PSCAD fault block scenario	Resistance measured during the HIF block scenario
10km	26.08Ω	33.6Ω
20km	26.7Ω	34.3Ω
30km	27.5Ω	35.7Ω
40km	28.1Ω	35.7Ω
50km	29Ω	36.5Ω
60km	29.2Ω	37.3Ω
70km	29.9Ω	38.19Ω
80km	30.6Ω	39.05Ω

Table 4.7: Measured resistance for LL fault

An important point to be noted, is if the values are directly substituted in the equation 4.2 then the values obtained will slightly deviate from the values obtained from standard PSCAD fault block simulation. This is due to fact that we have considered source 2 doesn't contribute to the fault while considering the equation 4.2 but in actuality there is a contribution so the current measured by the relay gets divided it doesn't measure the actual fault current. Like for instance for a fault at 80km the resistance value obtained directly substituting in the equation is 28 ohm while the simulation value is 30.6 ohm so not a big deviation. The deviation of values of HIF block from the standard fault block is due to the asymmetric nature where the positive and negative peak values aren't the same for the fault current. But the error remains constant after the steady state is attained and can be compensated easily by a compensation block as shown in figure 4.14 just for phase AB but it shall be the same if a fault occurs in between the other two phases.

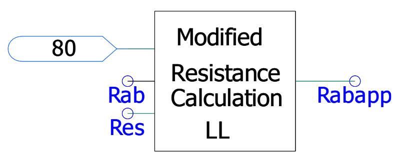

Figure 4.14: Resistance compensation block for LL fault

The inputs to the block are mainly line length, the resistance value coming from the impedance block, and the resistance value coming from the HIF block. This compensation block will be operated once the resistance value has reached 50 ohm otherwise it will stay at higher value in this case it was kept at 500 ohm. The code as shown in figure 4.15 indicates that basically based on line lengths and resistance requirement as per standard fault case, the impedance block calculated resistance is subtracted. The output of this block is then given to the trip polygon block which checks if it is under the protection zone and accordingly trip signal is given.

```
IF ($L.GE.10 .AND. $L.LT.20 .AND. ABS($Res-50.04).LE.0.009) THEN
$Rabapp=$Rab-7.52
ELSEIF ($L.GE.20 .AND. $L.LT.30 .AND. ABS($Res-50.04).LE.0.009) THEN
$Rabapp=$Rab-7.6
ELSEIF ($L.GE.30 .AND. $L.LT.40 .AND. ABS($Res-50.04).LE.0.009) THEN
$Rabapp=$Rab-7.62
ELSEIF ($L.GE.40 .AND. $L.LT.50 .AND. ABS($Res-50.04).LE.0.009) THEN
$Rabapp=$Rab-7.6
ELSEIF ($L.GE.50 .AND. $L.LT.60 .AND. ABS($Res-50.04).LE.0.009) THEN
$Rabapp=$Rab-7.5
ELSEIF ($L.GE.60 .AND. $L.LT.70 .AND. ABS($Res-50.04).LE.0.009) THEN
$Rabapp=$Rab-8.3
ELSEIF ($L.GE.70 .AND. $L.LE.80 .AND. ABS($Res-50.04).LE.0.009) THEN
$Rabapp=$Rab-8.4
ELSE
$Rabapp=500
END IF
```

Figure 4.15: Compensation block code for LL fault

As mentioned in section 3.12 the trip polygon block is taken as a quadrilateral characteristic type, and the set points decided as per the zone 1 impedance value requirement as well as taking into consideration the fault resistance are given in the figure 4.16. A 4-point polygon was considered.

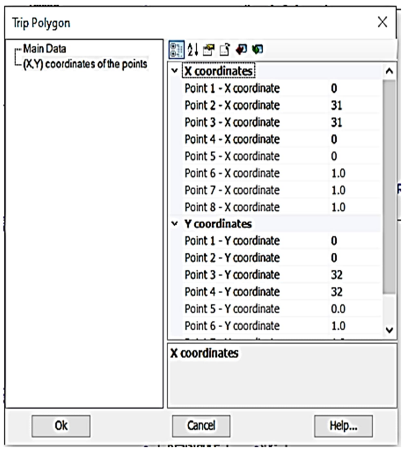

Figure 4.16: Relay setpoints for LL fault

A sample fault case at 80km was simulated for the HIF block with the settings and the inception and trip times are shown in table 4.12 and it can be seen there is no change in fault clearing time compared to the SLG fault case.

Fault inception time	1.5 second
Signal from the trip polygon block	@1.57 second
Breaker operation time	60ms
Fault clearing time	@1.63 second

Table 4.8: LL:Operation times

Figure 4.17 shows the R-X plot for HIF faults at various lengths of the line considering zone-1 protection and compensation in calculation as well.

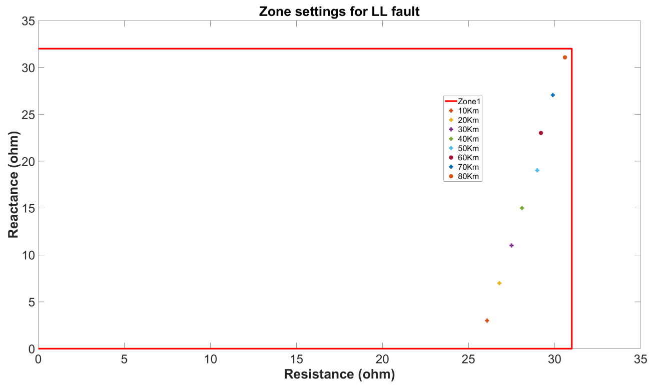

Figure 4.17: Zone-1 RX plot for LL fault

4.1.3.3 Three phase to Ground fault

To realize this fault, the fault properties of standard PSCAD block [12] was taken as reference and the arrangement for the HIF block was implemented as shown in figure 4.18. Res2 and Res3 as shown in the output of the HIF block are just for simulation purposes but one value of resistance is enough as an input to the compensation block which will be touched upon in the upcoming paragraph.

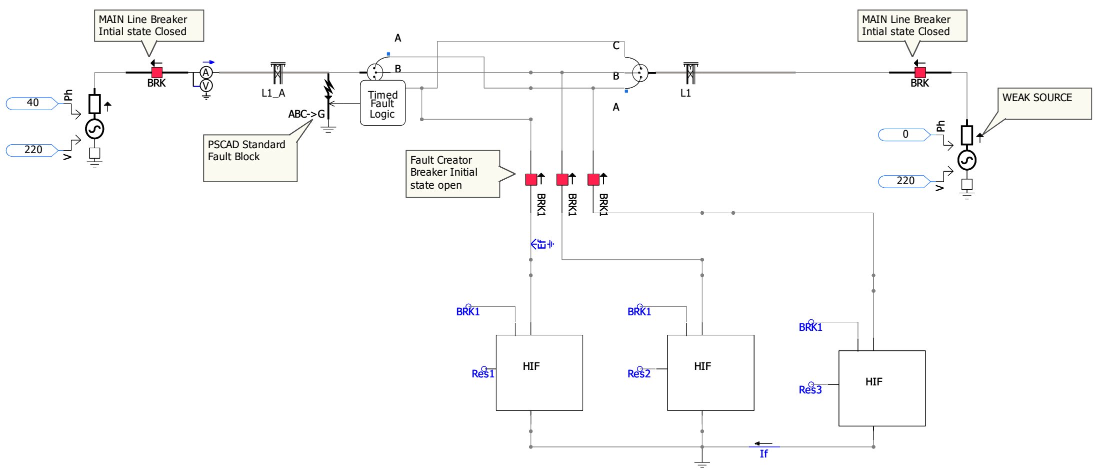

Figure 4.18: Three phase to Ground fault implementation

Fault creation time details for both standard PSCAD fault block and custom-made HIF block is shown in tables 4.9 and 4.2 .

Fault Type	ABC-G
Fault creation Time	0.5 second
Fault Duration	0.4 second
Fault resistance	50 ohm

Table 4.9: LLLG:Fault parameters for standard PSCAD block

Since the three-phase to ground fault is a balanced fault, so in order to compare the characteristic of fault current between the standard PSCAD fault block and HIF block, from the standard fault block phase A fault current was taken and compared with I_f of the HIF block. In order to replicate HIF characteristics, the decay constant in the HIF block was set to 10.Figures 4.19 and 4.20 indicate the response of the current and the reason for the difference is the same as explained in Line to line and single line-to-ground fault case. For further simulation, the decay constant was considered 100.

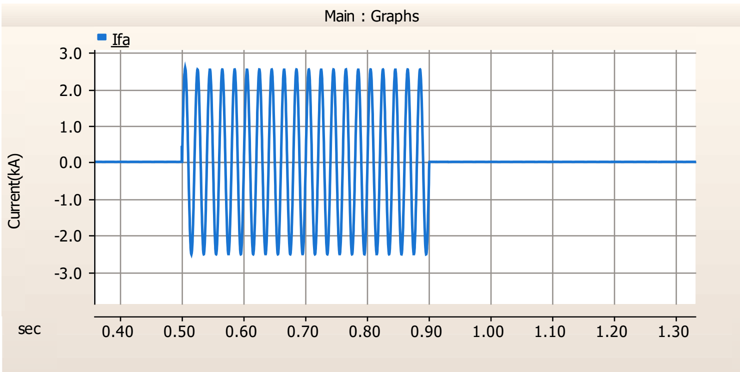

Figure 4.19: LLLG:Fault current response for standard PSCAD fault block

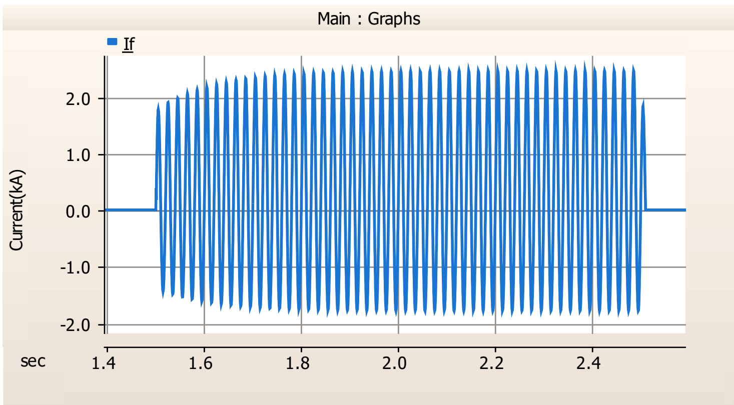

Figure 4.20: LLLG:Fault current response for the HIF block

The impedance calculation block as mentioned in section 3.11.1 and 3.11.2 gives out the same value that corresponds to the equation 4.3. The background of this equation was taken from the book [11]. The apparent impedance seen by the relay Z_{app} is given as

$$Z_{\text{app}} = (a * Z_1) + Z_{\text{f}} * \frac{I_{\text{fa}}}{I_{\text{a}}} \tag{4.3}$$

where Z_1 is Positive sequence line impedance,I_{fa} is the total phase A fault current contributed by both the sources,I_{a} is the fault current measured by the multimeter block near source 1 and a is the percentage of the line where the fault occurs. The table 4.10 lists the values of Resistances measured by the relay for faults at different line lengths for both standard block and HIF block case.

Line Length	Resistance measured during PSCAD fault block scenario	Resistance measured during the HIF block scenario
10km	49.4Ω	63.4Ω
20km	50.3Ω	64.13Ω
30km	51.13Ω	65.35Ω
40km	52Ω	66.3Ω
50km	52.89Ω	67.3Ω
60km	53.82Ω	68.5Ω
70km	54.7Ω	69.69Ω
80km	55.7Ω	70.7Ω

Table 4.10: Measured resistance for LLLG fault

The deviation of values of the HIF block from the standard fault block is due to the asymmetric nature where the positive and negative peak values aren't the same for the fault current. But the error remains constant after the steady state is attained and can be compensated easily by a compensation block as shown in figure 4.21 just for phase A as it will be the same for other phases but implementation is not required since a three-phase fault is a balanced fault.

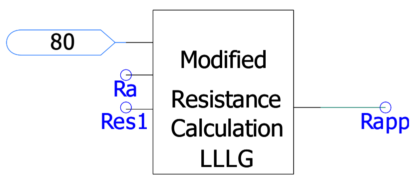

Figure 4.21: Resistance compensation block for LLLG fault

The inputs to the block are mainly line length, the resistance value coming from the impedance block, and the resistance value coming from the HIF block. This compensation block will be operated once the resistance value has reached 50 ohm, otherwise, it will stay at higher value in this case it was kept at 500 ohm. The code as shown in figure 4.22 indicates that based on line lengths and resistance requirement as per standard fault case, the impedance block calculated resistance is subtracted. The output of this block is then given to the trip polygon block which checks if it's under the protection zone and accordingly trip signal is given.

```
IF ($L.GE.10 .AND. $L.LT.20 .AND. ABS($Res1-50.04).LE.0.009) THEN
$Rapp=$Ra-14
ELSEIF ($L.GE.20 .AND. $L.LT.30 .AND. ABS($Res1-50.04).LE.0.009) THEN
$Rapp=$Ra-13.83
ELSEIF ($L.GE.30 .AND. $L.LT.40 .AND. ABS($Res1-50.04).LE.0.009) THEN
$Rapp=$Ra-14.22
ELSEIF ($L.GE.40 .AND. $L.LT.50 .AND. ABS($Res1-50.04).LE.0.009) THEN
$Rapp=$Ra-14.3
ELSEIF ($L.GE.50 .AND. $L.LT.60 .AND. ABS($Res1-50.04).LE.0.009) THEN
$Rapp=$Ra-14.41
ELSEIF ($L.GE.60 .AND. $L.LT.70 .AND. ABS($Res1-50.04).LE.0.009) THEN
$Rapp=$Ra-14.68
ELSEIF ($L.GE.70 .AND. $L.LE.80 .AND. ABS($Res1-50.04).LE.0.009) THEN
$Rapp=$Ra-15
ELSE
$Rapp=500
END IF
```

Figure 4.22: Compensation block code for LLLG fault

As mentioned in section 3.12 the trip polygon block is taken as a quadrilateral characteristic type the set points decided as per the zone 1 impedance value requirement as well as taking into consideration the fault resistance are given in the figure 4.23. A 4-point polygon was considered.

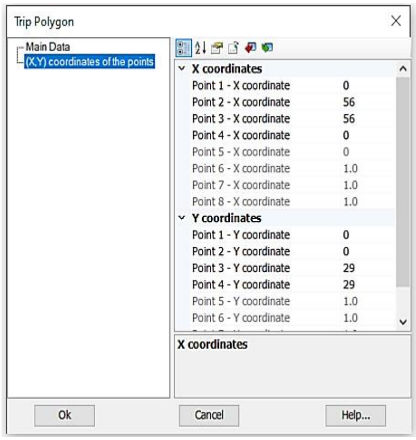

Figure 4.23: Relay setpoints for LLLG fault

A sample fault case at 80km was simulated for the HIF block with the settings and the inception and trip times are shown in table 4.12 and it can be seen there is no change in fault clearing time compared to the SLG fault case.

Fault inception time	1.5 second
Signal from the trip polygon block	@1.57 second
Breaker operation time	60ms
Fault clearing time	@1.63 second

Table 4.11: LLLG:Operation times

Figure 4.24 shows the R-X plot for HIF faults at various lengths of the line considering zone-1 protection and compensation in calculation as well.

Figure 4.24: Zone-1 RX plot for Three phase-Ground fault

4.1.3.4 Double Line to Ground Fault

The fault scenario arrangement was done according to the theory mentioned in [11] since the standard fault block PSCAD interpretation in [12]is not correct as per the understanding of double Line to Ground fault. The arrangement for this fault study is shown in figure 4.25 and to validate and check for deviations in the HIF block model,an arrangement with a constant fault resistance of 50 ohm was done through the fault inception breaker BRK3. The table 4.12 shows the details of the fault details.

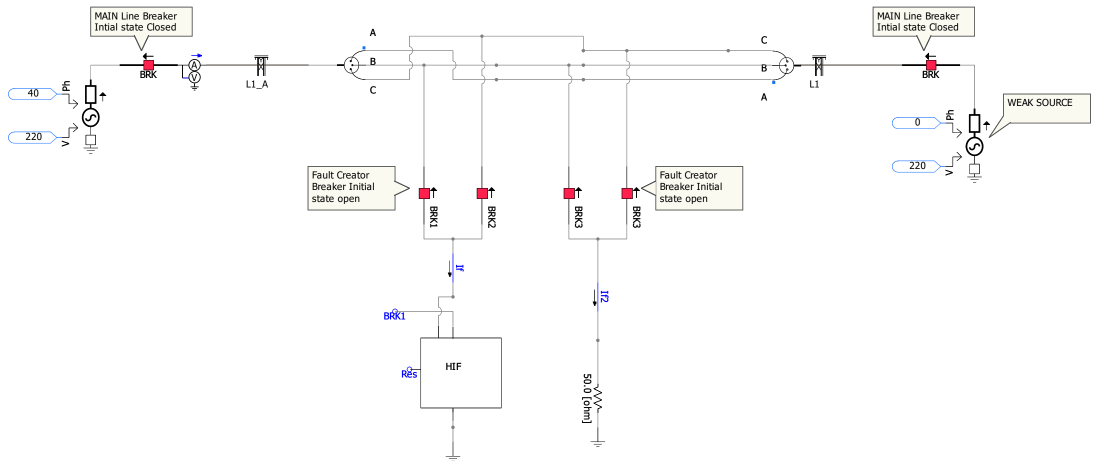

Figure 4.25: LLG fault implementation

Fault Type	BC-G
Breaker BRK1 and BRK2 closure time	1 second
Breaker BRK1 and BRK2 opening time	1.5 second
Breaker BRK3 closure time	2 second
Breaker BRK3 opening time	2.5 second

Table 4.12: Fault details

I_f and I_{f2} are the fault current response from the HIF block and the constant resistance scenario respectively and shown in figures 4.27 and 4.26. It's clear that the response is similar to what was explained in the previous section for SLG, LL, and three phase to ground fault.

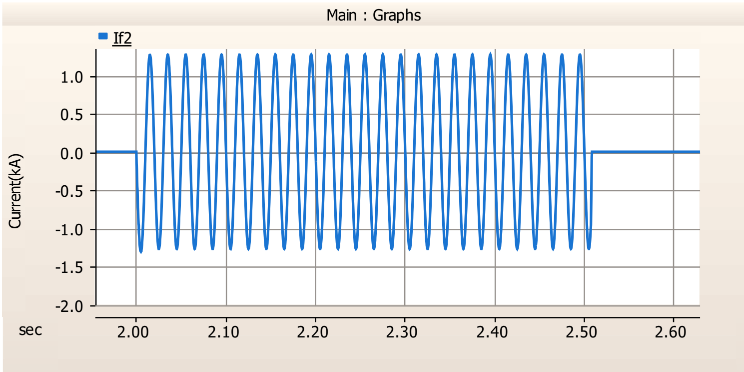

Figure 4.26: LLG:Fault current response with constant 50ohm resistance

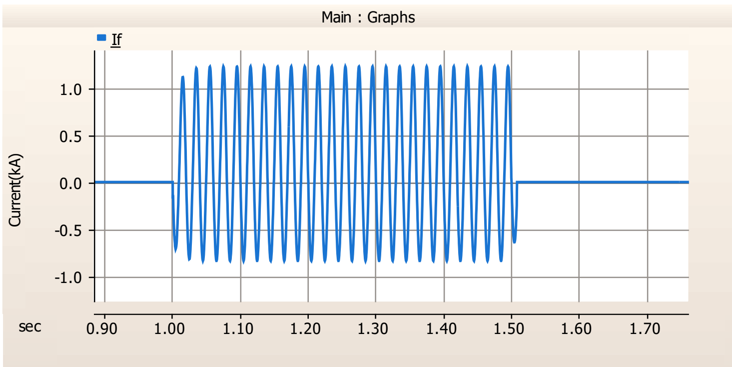

Figure 4.27: LLG:Fault current response of HIF block

In the literature [13] the impedance calculation block which is used for line to line fault case is used for double line Ground fault as well.In order to be sure about the correctness of the impedance calculation, a detailed analysis was done in MATLAB basically calculating the sequence components of the current, voltage converting them to phase quantities, and calculating the quantities seen by the relay.The results were compared with the simulation outputs mainly the magnitudes.The process of calculating every quantities was done based on the formulas for Double line to ground fault as mentioned in the literature [11]including the fault resistance in the formula. Table 4.13 lists the main parameters computed from MATLAB and obtained from simulation for both HIF case and constant resistance case.A fault at 80km was simulated for this purpose and the assumption that source 2 doesn't contribute to the fault was considered during the theoretical calculation which was done on MATLAB.The slight deviation between the values of HIF block and constant fault resistance case can be attributed to the fact the fault current has asymmetry and this affects the calculation as the positive and negative peak values aren't the same. Overall the deviation is not much so it can be concluded that the model is working and the important fact is the final impedance measured from the block is according to the equation 4.4 as the distance relay only considers the positive sequence impedance and compares it with the zone settings

$$Z_{\text{app}} = (a * Z_1) \tag{4.4}$$

where Z_{app} is the apparent impedance measured by the relay,Z_1 is the Positive sequence line impedance and a is the percentage of the line where the fault occurs.

Parameters	MATLAB output	HIF block case output	Constant fault resistance case output
Relay Positive Sequence voltage	94.1kV	94.8kV	93.8kV
Relay Negative Sequence voltage	27.5kV	28.3kV	27.3kV
Relay Zero Sequence voltage	2.9kV	2.03kV	2.63kV
Fault current (3*zero sequence current)	0.85kA	0.73kA	0.88kA

Table 4.13: Parameter Verification

For example, the fault at 80km gave the output impedance as 2.73+33.9j ohm which is 80% of the positive sequence line impedance as mentioned in table 3.1. When it comes to attaining a stable value considering this fault case for both HIF block and the constant resistance fault case the steady state is achieved after 120ms of fault inception because of slight oscillation in the computation of the values of resistance and reactance. But yes around 30-40 ms instant the expected resistance and reactance value is computed but it doesn't stay there so techniques can be used to capture the value and give the trip signal to the breaker. Since the work was mainly focussed on understanding the impact of characteristics of high impedance fault on distance protection,only for this fault case the time taken to attend steady-state value was long but there is no big deviation in parameters mentioned in table 4.13. Figure 4.28 shows the R-X plot for HIF faults at various lengths of the line considering zone-1 protection.

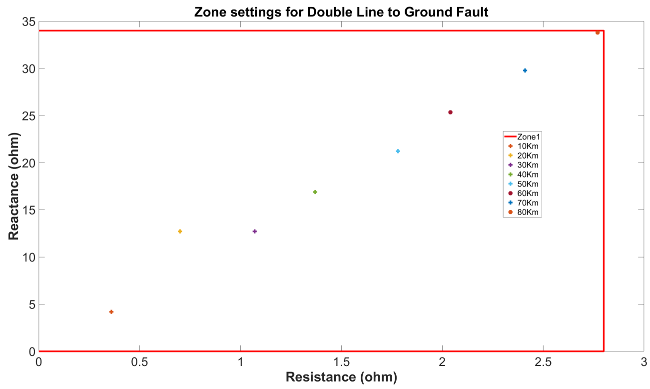

Figure 4.28: Zone-1 RX plot for LLG fault

4.2 Polynomial Response Study and Results

In order to understand the response, one set of values mainly the coefficients were taken from the paper[5] just for simulation purposes and since it is a polynomial function, a condition was put to stop the response once the 50-ohm value is reached. This was because to get all the characteristics of the HIF fault the time duration is long and this is not acceptable when it comes to protection system operation. Most of the work in the paper was carried out based on experimental data and the equation was formulated. A sample simulation code case is shown in figure 4.29, there was no change in the setup and it is the same as mentioned in section 3.13.The initial and final values were set the same as it was done for the exponential response.

```
#LOCAL REAL time1
#STORAGE REAL:1
        time1 = STORF(NSTORF) !storage array for the time variable
        If($Timeinput.LT.1) THEN
        $Res = 80
        time1 = TIME + DELT !update the time variable
        ELSE
        $Res = 80+(0*(time-time1)**9)+(1.016*10**7*(time-time1)**8)+(-2.223*10**7*(time-time1)**7 )
       +(2.017*10**7*(time-time1)**6)+(-9.818*10**6*(time-time1)**5)
       +(2.775*10**6*(time-time1)**4)+(-4.613*10**5*(time-time1)**3)
       +(4.396*10**4*(time-time1)**2)+(-2.279*10**3*(time-time1)**1)
       !why time-time1 because it has to take the time lapsed as the start point
        IF ($Res <= 50) $Res = 50.0
        END IF
        STORF(NSTORF) = time1 !update the storage array with the new time
        NSTORF = NSTORF + 1 !update the storage pointer
```

Figure 4.29: Polynomial response code

Figure 4.30 shows the resistance response and it can be seen that the response looks similar to a straight line since the 50 ohm is reached within 20ms. With this observation, a simple straight-line equation was also designed which will be talked about in the upcoming section. The BRK1 breaker was closed at 1 second and opened at 1.5 second.

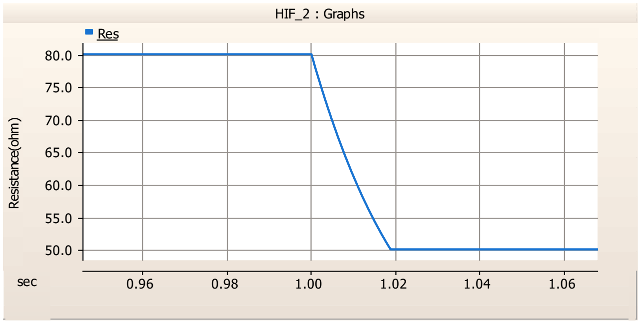

Figure 4.30: Polynomial:Resistance response

4.2.1 Fault Current response

Since the response time when the resistance reaches 50 ohm is fast, so when it comes to fault current response only the buildup and shoulder characteristics shall be seen and it is shown in the figure 4.31. As compared to figure 4.2 the response is similar in terms of shape and magnitude, the only difference being the steady state value reaches fast with the polynomial case.

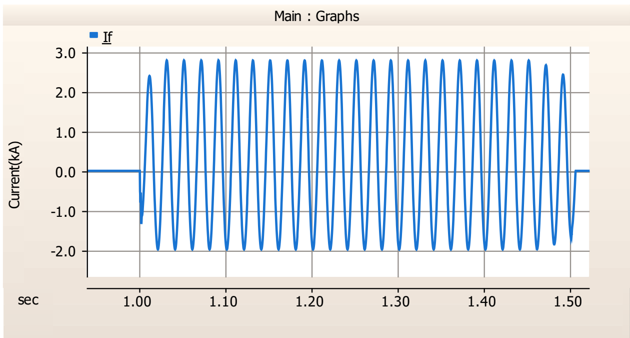

Figure 4.31: Polynomial:Fault Current response

4.2.2 Symmetrical and Unsymmetrical fault analysis

Symmetrical and Unsymmetrical fault analyses were carried out with the Feraz response model and was compared with the standard fault block in PSCAD mainly the resistance values obtained by the distance relay since the reactance value calculation didn't have much impact. Four types of faults were carried out mainly Singleline to Ground (SLG), Line to Line (LL), Double Line to Ground (LLG) and Three phase to ground (LLLG) faults. The fault was created every 10km of the 100km of the transmission line.

The main observation was that for all the faults carried out, the fault current response was the same as it was for the exponential response and even the resistance values. The major difference was only observed for fault detection time and it is shown in table 4.14

Model	Fault Detection Time
Standard PSCAD fault model	30ms
HIF Feraz *et.al* model	35 to 40ms
HIF exponential model	70ms

Table 4.14: Time response

One observation was that even though the resistance of 50 ohm is reached at 20ms after the fault inception, the steady state resistance is obtained at 35 to 40ms, this can be due to the computation time taken by the software. For the double line to ground as mentioned in section 4.1.3.4 it was the same case when it came to Feraz's polynomial response.

4.3 Linear Response Study and Results

The detection time for a relay has to be fast, as seen in figure 4.30 the response can be linearised for a short duration and the same was done. A straight line equation was implemented and the characteristic was checked. Figure 4.32 shows the code and the time to reach the final resistance value of 50 ohm was taken as 40ms. The complete setup was the same with the initial and final values as it was done for the exponential response.

```
#LOCAL REAL time1
#STORAGE REAL:1
time1 = STORF(NSTORF) !storage array for the time variable
If($Timeinput.LT.1) THEN
$Res = 80
time1 = TIME + DELT !update the time variable
ELSE
$Res = (-750*(time-time1)**1)+80 !why time-time1 because it has to take the time lapsed as the start point
IF ($Res <= 50) $Res = 50.0
END IF
STORF(NSTORF) = time1 !update the storage array with the new time
NSTORF = NSTORF + 1 !update the storage pointer
```

Figure 4.32: Linear response code

Figure 4.33 shows the resistance response where the breaker BRK1 was closed at 1.5 seconds and opened at 2 seconds.

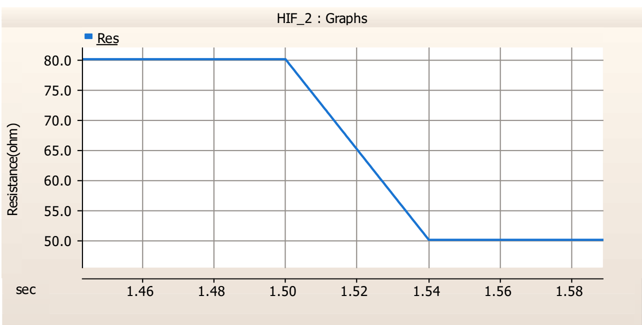

Figure 4.33: Linear:Resistance Response

4.3.1 Fault Current response

Since the response time when the resistance reaches 50 ohm is fast, so when it comes to fault current response only the buildup and shoulder characteristics shall be seen and it is shown in the figure 4.34.As compared to figure 4.2 the response is similar in terms of shape and magnitude, the only difference being the steady state value reaches fast with the linear straight line case.

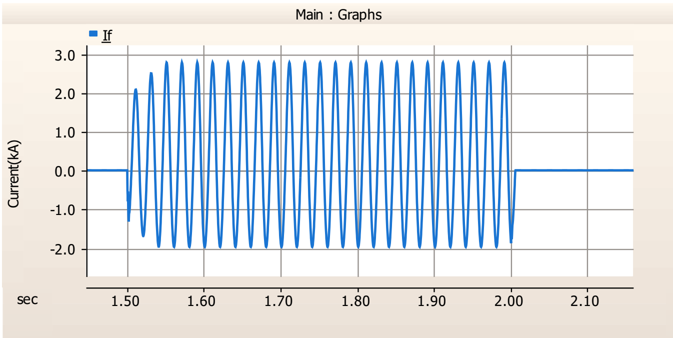

Figure 4.34: Linear:Fault Current Response

4.3.2 Symmetrical and Unsymmetrical fault analysis

Symmetrical and Unsymmetrical fault analyses were carried out with the Feraz response model and was compared with the standard fault block in PSCAD mainly the resistance values obtained by the distance relay since the reactance value calculation didn't have much impact. Four types of faults were carried out mainly Singleline to Ground (SLG), Line to Line (LL), Double Line to Ground (LLG) and Three phase to ground (LLLG) faults. The fault was created every 10km of the 100km of the transmission line.
The main observation was that for all the faults carried out, the fault current response was exactly the same as it was for the exponential response and even the resistance values. The major difference was only observed for time to detect the fault and it is shown in table 4.15

Model	Fault Detection Time
Standard PSCAD fault model	30ms
HIF straight line model	60ms
HIF exponential model	70ms

Table 4.15: Time response

One observation was that even though the resistance 50 ohm is reached at 40ms after the fault inception, the steady state resistance is obtained at 60ms, this can be due to the computation time taken by the software. For the double line to ground as mentioned in section 4.1.3.4 it was the same case when it came to the Linear straight-line response.

4.4 Windfarm Studies

Type 3 and Type 4 windfarms were taken for studies, the main intention was to understand that when it comes to windfarms, the fault current contribution is not the same as a traditional synchronous generator. The reason is, there is an inverter in the case of windfarms and the power electronic switches can not contribute the same way as a synchronous generator does during the fault due to its rating and thermal limitations. Also, the fault current from a wind farm is not same as compared to a synchronous generator which shall be explained in upcoming sections, basically, the wind farm is a non-linear source and traditional fault calculation techniques can not be applied. For the windfarm studies the fault resistance was taken as 0 ohm for both standard fault block and HIF block case. For HIF block case the parameters were the same as table 4.1 with the value of A as 0 ohm and B as 80. .Only exponential response was taken into study since as mentioned in the previous sections 4.2 and 4.3 there is no difference in fault current response when it comes to polynomial and linear straight line response. The arrangement for the faults was exactly same as it was done for the conventional source case with the final value being 0 ohm.

4.4.1 Type 4 Windfarm study

Unsymmetrical and symmetrical faults were created and the setup was followed same as section 4.1.3 with source 2 replaced with Type 4 windfarm.The same was done for type 3 wind farm case, which shall be explained in the upcoming sections. The measurements were done from the multimeter as shown in figure 3.19 which is near the windfarm side.

4.4.1.1 Single Line to Ground Fault

A single line to ground fault was created at a distance of 20km from the windfarm side on phase A. Table 4.16 list details related to fault inception and duration timings

Model	Fault Inception Time (Second)	Duration(Second)
PSCAD fault model	3.086	0.5
HIF model	1.97	0.59

Table 4.16: Fault Timings

Figures 4.35 and 4.36 shows the fault current during the standard PSCAD fault and HIF case respectively.It clearly indicates that even though the fault is in phase A ,but phase B and C currents have also increased. This is because of the non-linearity in windfarm when it comes to fault contribution. The asymmetricity can be seen in figure 4.36 in the fault currents as per the high impedance fault theory. Phase A voltage has dipped.V_{aw},V_{bw},V_{cw},I_{aw},I_{bw} and I_{cw} are respective phase voltage and currents measured by the multimeter on the windfarms side.

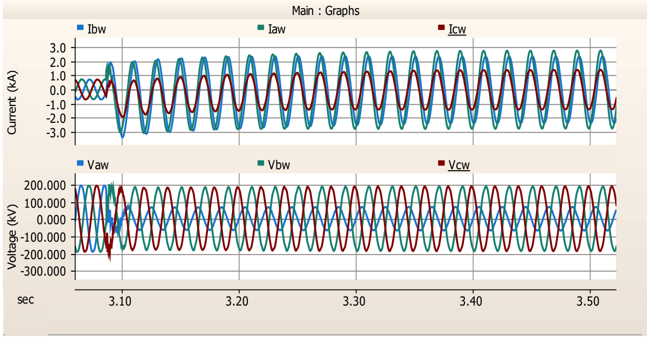

Figure 4.35: Type4:PSCAD Fault Block response for SLG fault

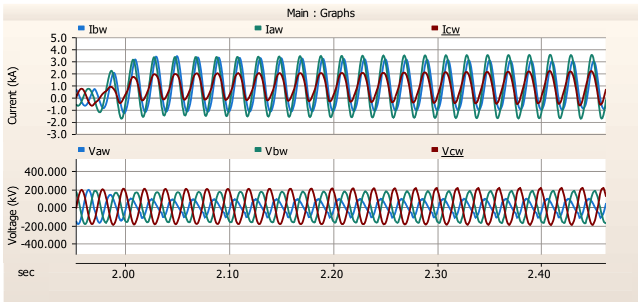

Figure 4.36: Type4:HIF Block response for SLG fault

For a single line to ground fault all the sequence currents are equal as per theory in [11], but when it comes to the windfarm model the negative sequence current contribution is pretty less for both standard PSCAD fault and HIF case as shown in figure 4.37 .I_{pm},I_{nm} and I_{zm} are positive, negative and zero sequence currents. This also shows that traditional fault calculation cannot be applied when we have windfarms due to this behavior.

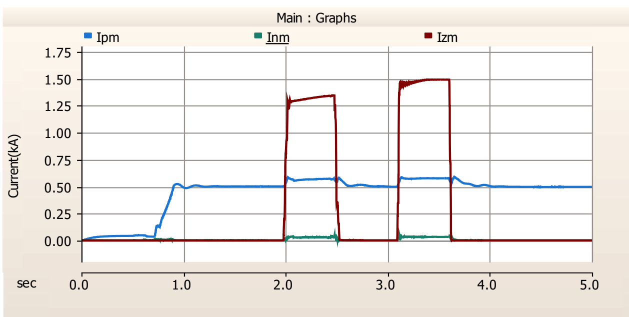

Figure 4.37: Type4:Sequence currents during SLG fault

4.4.1.2 Line to Line fault

A line to line fault was created between phase A and phase B at 20km from the windfarm side. The fault inception details are the same as mentioned in table 4.16.

Figures 4.38 and 4.39 show the respective system response during the standard and HIF case . It is seen that even though there is no fault in phase C but still phase C current has increased. Figure 4.39 shows that there is asymmetricity in the voltage waveforms where the positive peak voltage is not equal to the negative peak value and this also has an impact that the voltages in the fault phases are not same.In order to be sure that the asymmetricity creates this response, the diodes and the DC sources in the HIF fault block were removed and the simulation was performed again. Figure 4.40 clearly shows the voltages in the fault phases are equal and they have a symmetric nature.

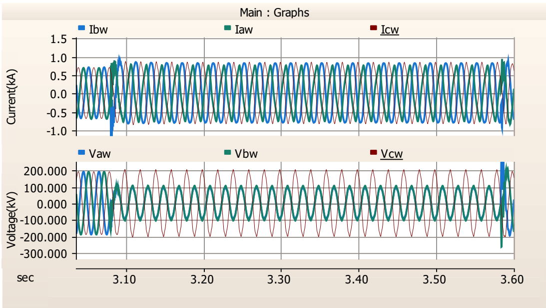

Figure 4.38: Type4:PSCAD Fault Block response for LL fault

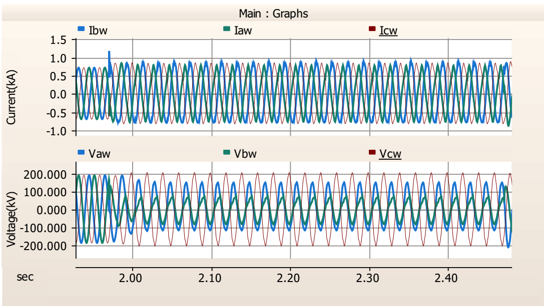

Figure 4.39: Type4:HIF Block response for LL fault

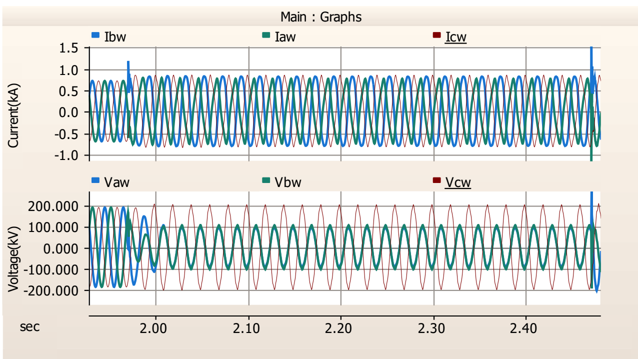

Figure 4.40: Type4:Response during HIF case with no Diode and DC source

For a line-to-line fault, the positive and negative sequence currents are equal in magnitude but have an opposite sign as said in [11], but figure 4.41 shows that the windfarm doesn't contribute negative sequence current which is equal to the positive sequence current.

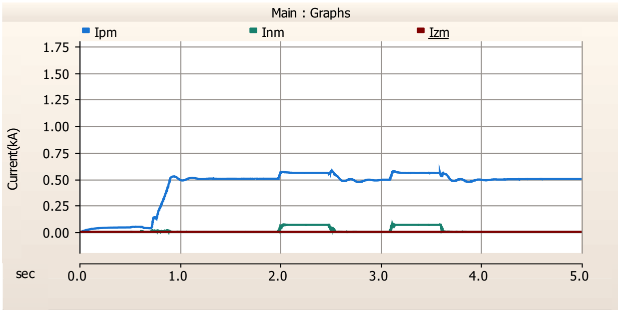

Figure 4.41: Type4:Sequence currents during LL fault

4.4.1.3 Three phase to ground fault

A three-phase to ground fault was created at 50km from the wind farm side. The fault inception details are the same as mentioned in table 4.16. Figure 4.42 shows the waveforms and for the HIF case, due to model limitation it was not performed

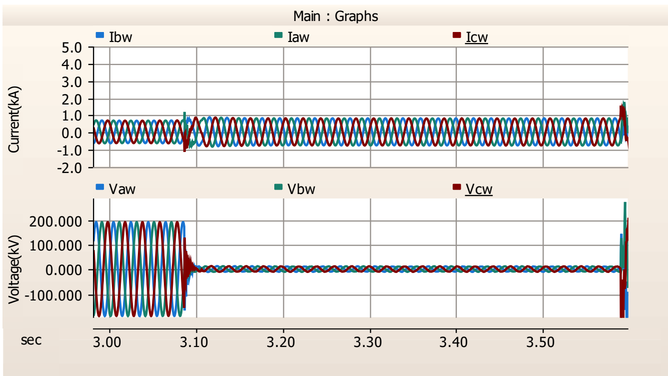

Figure 4.42: Type4:PSCAD fault Block response for LLLG fault

4.4.1.4 Double Line to Ground fault

Double line to ground fault was created with the same setup similar to 4.1.3.4 .In this case ,the fault was done between phases B and C to ground and was created at 20km from the windfarm side.For a double line to ground fault the voltages in phase B and C should be equal as per [11] during the fault period and the same was verified from the simulation and figures 4.43 and 4.44 show the results where Vbw and Vcw are equal during the fault period for both standard and HIF case. The figure 4.44 shows the HIF case with the asymetricity.

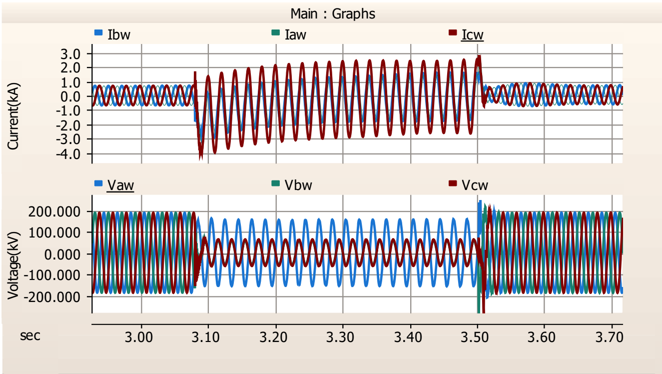

Figure 4.43: Type4:PSCAD Fault Block response for LLG fault

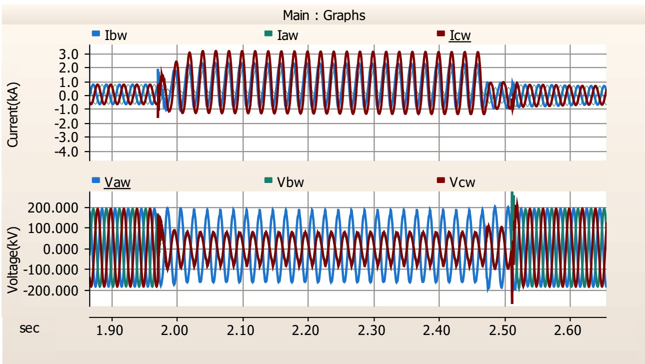

Figure 4.44: Type4:HIF Block response for LLG fault

When it comes to sequence currents, the zero sequence is more than the positive and negative sequence currents and the negative sequence contribution is less from the windfarm side. Figure 4.45 shows the sequence currents.

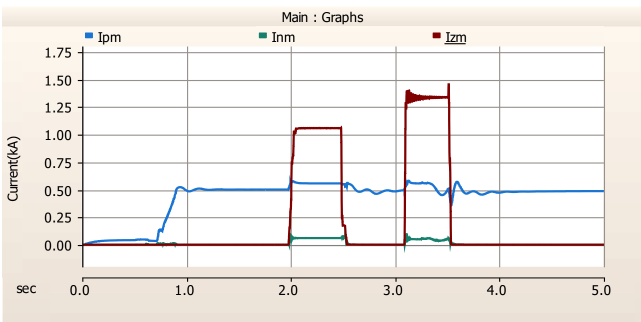

Figure 4.45: Type4:Sequence currents during LLG fault

4.4.2 Type 3 Windfarm study

Symmetrical and unsymmetrical fault analysis was done for type 3 windfarm studies, the setup was same as it was done for the conventional source with source 2 replaced with type 3 windfarm.

4.4.2.1 Single Line to Ground fault

Single line to fault was created and in order to study the characteristics fault was created by taking one model at a time basically the standard PSCAD fault block and HIF case.The fault was incepted at 2.687 second and the duration was 0.313 second since the system was taking time to attain a stable value before the fault could not be created. The fault was created at 50km from the windfarm side.The fault was created between phase A and ground. Figures 4.46 and 4.47 show the waveform during the standard PSCAD and HIF case. The results are similar to type 4 windfarm where currents in unfaulted phases increased and asymmetricity was seen in the HIF case.

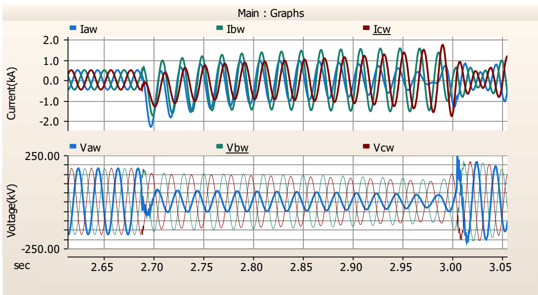

Figure 4.46: Type3:PSCAD Fault Block response for SLG fault

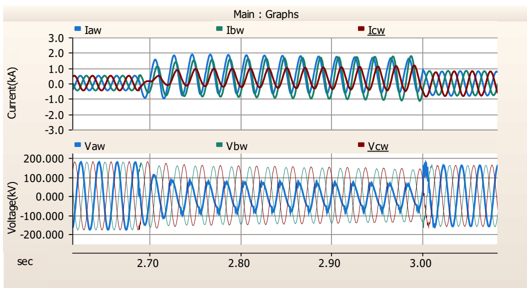

Figure 4.47: Type3:HIF Block response for SLG fault

4.4.2.2 Line to Line fault

Line-to-Line fault was created between phase A and B and at 50km from the wind farm. The fault was incepted at 2 seconds and for 0.3 seconds duration. Figures 4.48 and 4.49 show the waveform for standard PSCAD and HIF case and the results are similar to Line to Line fault case done for type 4 windfarm.The slight difference between the voltages of phase A and B during the fault period is due to the fact the lines are not perfectly transposed,if the fault is near to the windfarm then the voltages become equal and same is shown in figure 4.50 where the fault was created at 20km from the windfarm side.For the HIF case the voltage difference was there due to the presence of assymetricity as it was explained in the Line to Line fault case for Type 4 windfarm.

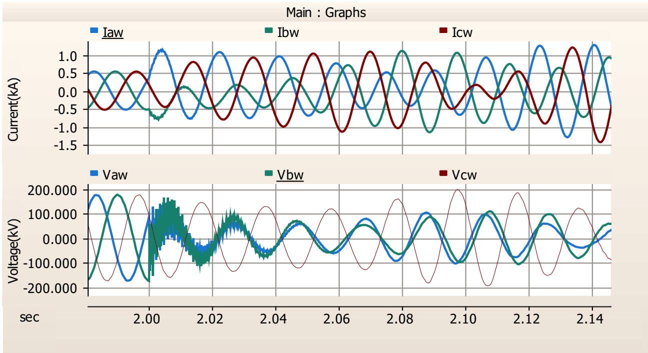

Figure 4.48: Type3:PSCAD Fault Block response for LL fault

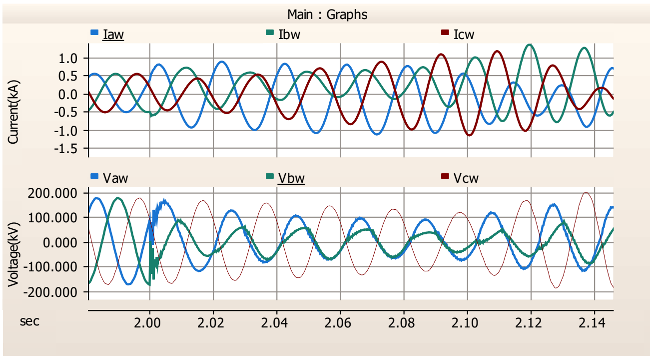

Figure 4.49: Type3:HIF Block response for LL fault

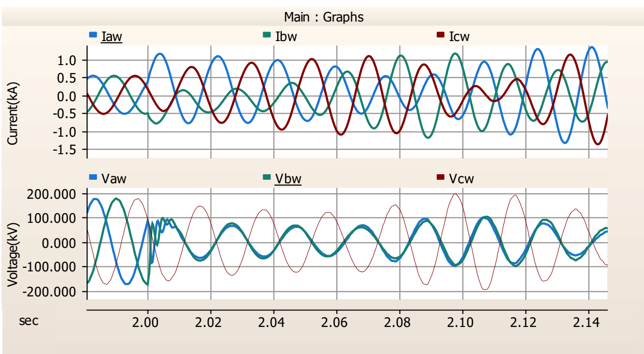

Figure 4.50: Type3:Response for a fault at 20km from windfarm for PSCAD fault case

4.4.2.3 Three Phase to Ground fault

A three-phase to ground fault was created at 50km from the wind farm. The fault was incepted at 2 seconds and the duration was 0.3 seconds. Figure 4.51 shows the waveforms and for the HIF case, it was not simulated because of model limitation.

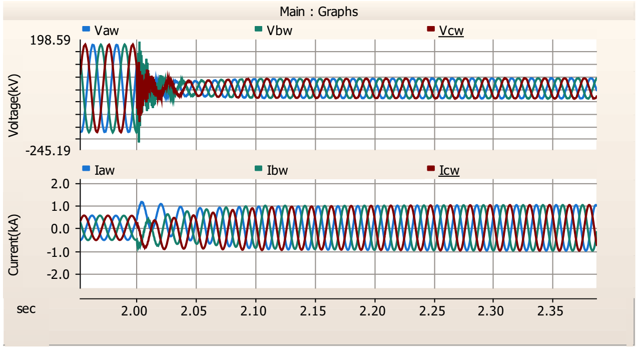

Figure 4.51: Type3:PSCAD Fault Block response for LLLG fault

4.4.2.4 Double Line to Ground fault

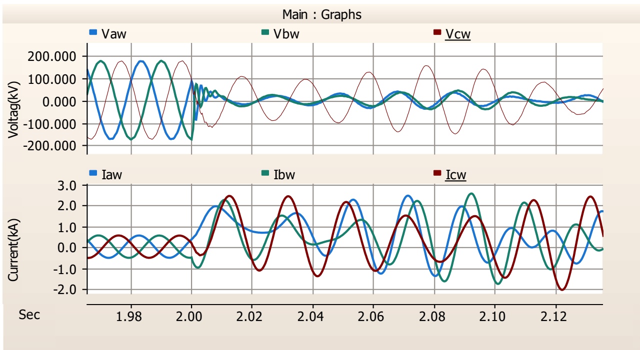

Figure 4.52: Type3:PSCAD Fault Block response for LLG fault

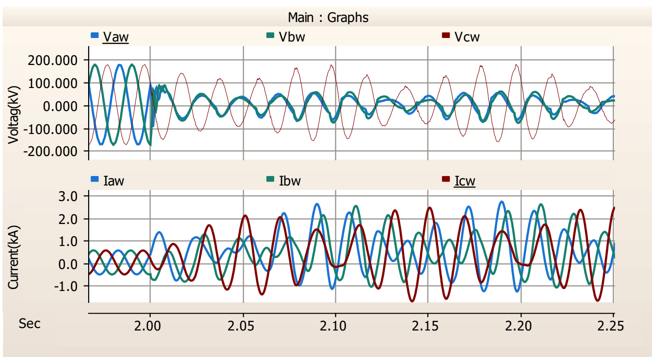

Figure 4.53: Type3:HIF Block response for LLG fault

Double line to ground fault was simulated at 20km from the wind farm, setup was the same as type 4 wind farm. The fault was incepted at 2 seconds and the duration was 0.5 seconds between phases A and B to ground. Figures 4.52 and 4.53 show the waveform where the voltage of phase A and phase B are the same which is true for a double line to ground fault and asymmetricity is seen for the HIF case and figure 4.53 indicates the same.

5 Conclusion

When it comes to power system protection, the sooner the fault is detected and isolated the more stable the system is. High impedance faults have always been difficult to detect due to their peculiar behavior, as mentioned in the section 2.1. The purpose of the thesis was to study the impact of the high impedance fault characteristic on distance protection especially on the calculation front. Two models mainly the three-parameter and Feraz *et.al* model were employed and analyzed for different types of faults. The major characteristics observed in the models is buildup, shoulder, and asymmetricity. The resistance is time variant that can be modeled as an exponentially decaying function as well as a polynomial function. The key findings based on the characteristic are mentioned below mainly for the conventional source model since the renewable model was simulated for understanding purposes when it comes to current measurement and characteristics.

- The time-variant characteristic has an impact on the fault detection time when HIF occurs. It increases the fault detection time for instance it was 30ms for standard PSCAD fault model constant resistance whereas it was 70ms for HIF block case.
- The time-variant behavior didn't have an impact on the final impedance calculated by the relay.
- The asymmetricity mainly had an impact on the value of final resistance calculated by the distance relay. This can be easily compensated with the compensation block.
- For the case of Double line to Ground fault, there was no impact of high impedance fault characteristic in the final impedance calculation, there was only an issue where it took 120ms to reach a stable value. One observation is, that as soon as the fault was incepted the expected resistance value for that particular line length was achieved but did not remain stable at that value.
- For the renewable source case, the expected characteristic was achieved but due to windfarm being a non-linear source, traditional fault calculation techniques cannot be applied.

5.1 Future Work

Detailed analysis for faults in renewable source model and impact on distance protection is considered for future work.

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