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Protection Coordination Practice in Electrical Substation Part-1 Overcurrent and Earth Fault Protection - Case Study of Siddik Kardesler Substation (SKS), Istanbul, Turkey

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Abstract

Protection coordination is the heart of all power systems. To ensure a quality and reliable operation of the power systems, an electrical fault must be cleared within a short time. This can be achieved by proper coordination between the protection relays. In Siddik Kardesler Substation the MV voltage feeders' protection is provided by overcurrent relays. This paper is principally concerned with practical protection coordination of the electrical substation by using Siddik Kardesler Substation substation as a case study. In the Part-2, distance and differential protection will be discussed. Finally, after test and commissioning, the substation is successfully energized without a problem.

1. INTRODUCTION

The power system is among very complex systems which consist of many expensive types of equipment. Especially, Electrical Substations (ESS) are among the critical components of the power system and the availability of a power system is based on their performance. For example, the switching and fault clearing actions of power systems are performed by the ESS. ESS are interconnected by transmission line to make the power system meshed or networked increasing the reliability [1]. Thus, they represent a huge capital investment which has to be operated securely and reliably to minimize the payback period.

Some of the roles of substations in power systems are [2, 3]:

- Stepping up the voltage at generating stations to high voltage levels (generating station);
- Changing between the voltage levels within the high-voltage system (system stations);
- Stepping down to a distribution or medium-voltage level. (distribution stations);
- Interconnect the same voltage levels and etc.

Substations can be either Air Insulated (AIS), Gas Insulated (GIS), compact or hybrid based on [3], the function and location of the power supply, environmental and climatic conditions, specific requirements regarding the locations, and cost and space limitations. A GIS uses sulfur hexafluoride (SF6) to provide insulation while the AIS uses atmospheric air [3, 6]. GIS is more compact structure, reliable and requires less maintenance compared to AIS. In addition, the service life of GIS is longer compared to AIS. But GISs are expensive than AIS and mostly used where space is expensive or not available.

As an important component of power systems, substations are required to operate safely all through their lifetime. The arc-current generated during fault can burn and weld copper conductors of transformer and machines' core laminations in a very short time [6]. In addition, the insulation may break down, causing the flow of current between phases or phase to ground. Consequently, an adequate protection system which detects faults and disconnects elements of the power system during

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*Corresponding author, e-mail: mehmetridatur@artuklu.edu.tr a fault is an essential design subject of the power system. The protection system cannot prevent the occurrence of the fault, but they should act immediately after the occurrence of the fault. The protection system is an arrangement between protection equipment (like relays, fuses, etc.) and other devices (like transformers, circuit breakers, batteries, etc.) which are vital to accomplishing a specified function depending on the protection principles applied [6].

This paper is concerned with the protection coordination (ProC) study of Siddik Kardesler Substation (SKS) which is an AIS type. The protection study is planned to be presented in two parts (Part-1 and Part-2) the first part is concerned with over current and EFPs of the SKS. The second part is concerned with the differential and distance protection aspects of the SKS. This paper (Part-1), is outlined as follows; the components of the SKS and its protection arrangements will be discussed in sections 2 and 3 respectively. The important over current relay characteristics will be discussed in section-4. The overcurrent coordination study of SKS with necessary procedures will be discussed in section-5. Finally, the EFP will be discussed in section-6.

2. COMPONENTS OF THE SKS

The SKS consists of 154 kV and 34.5 kV components that serve numerous purposes. Components like circuit breakers, isolators, current transformers (CTs), surge arrestors, power transformers, meters, control, relay equipment and etc. are shown symbolically upon the substation’s single line diagram as shown in Figure 1. In Tables 1 and 2 brief descriptions of these components are provided.

Table1. *Components of Substation (154 kV)*

154 kV components of substation		
Code	***Name***	***Description***
1/1A	Voltage Transformer	Used to convert the voltage from HV to the level that can be used for protection, control, automation devices and etc.
2	Lin Traps	Used for Power Line Carrier (PLC) Communication.
3/3A	Current Transformer	Used to convert from very high current to the level that can be used for protection, control, automation devices and etc.
4T	Isolator with Grounding blade	For no load opening and closing, and isolate the downstream device to be worked on. The grounding blade is used to ground the isolated part for more safety.
5	Circuit breaker	Make and break all currents within the scoped of their rating.
5T	Circuit Breaker with Auto-reclosing	Circuit breaker with auto-reclosing capability.
4	Isolator	For no load opening and closing, and isolate the downstream device to be worked on.
6	Surge Arrester	To discharge high voltages caused by lightning strikes or switching operations and earth faults**.**
7	Power Transformer	To transform the voltage level from 154 kV to 34.5 kV.

Table 2. *Components of Substation (34 kV)*

34 kV Components of the Substation		
Code	***Name***	Description
8c/8b/8c	Cable	Medium Voltage (MV) XLPE underground cable for transporting the energy.
6a	Surge Arrestor	MV surge arrestor.
5a/5b/5c	Circuit Breaker	MV circuit breaker.
3a/3b/3c	Current Transformers	MV current transformer.
14	Voltage Indicator	Indicates the availability of voltage on each phase.
4t	Grounding Switch	Used to ground the isolated part for more safety.
10	Voltage Transformer	MV voltage transformer.

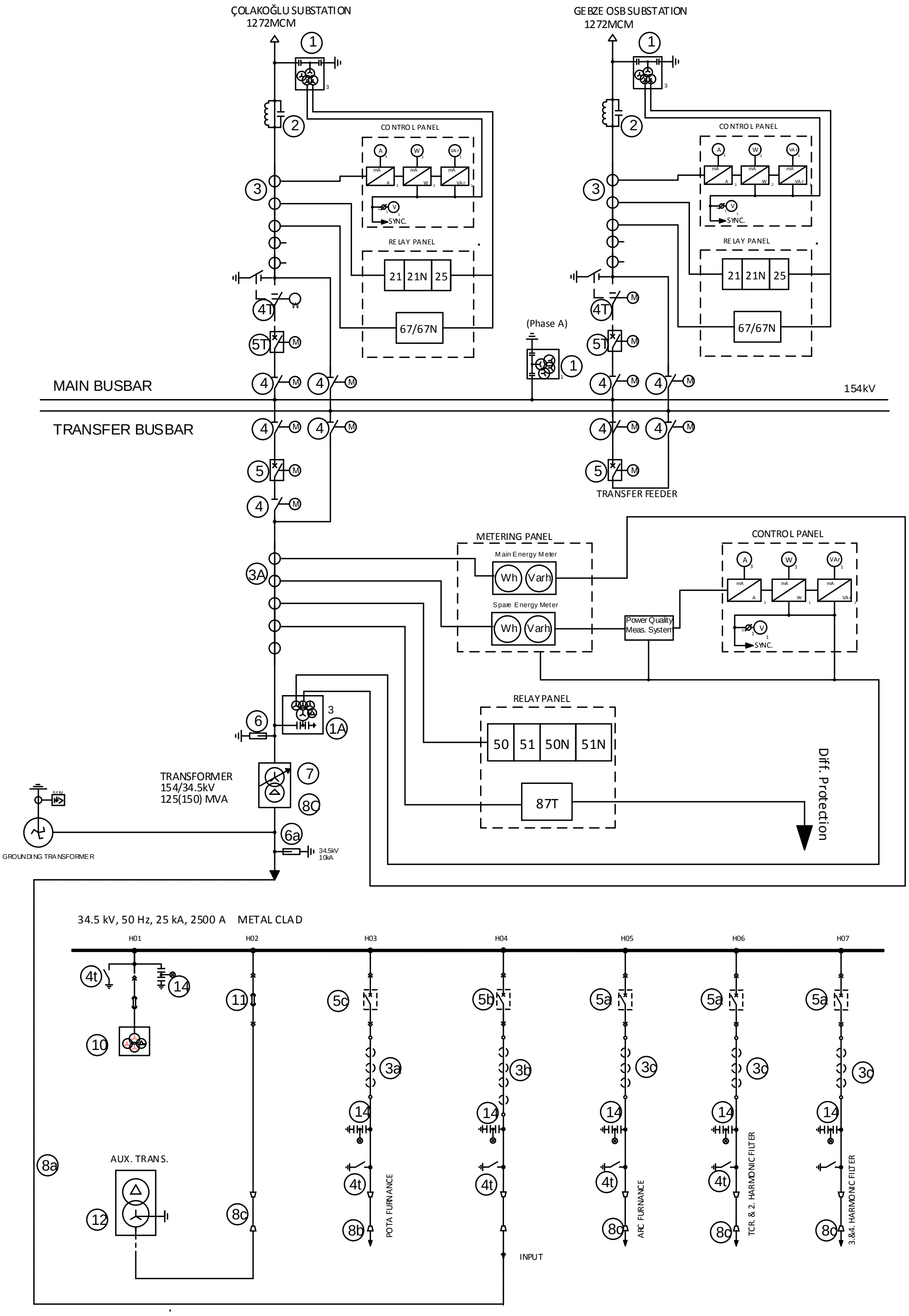


Figure 1. Siddik Kardeşler Substation Single Line Diagram.

3. PROTECTION ARRANGEMENTS OF THE SKS

In Figure 1 protection functions used in SKS are indicated by the American National Standards Institute (ANSI) codes. Based on the single line diagram shown in Figure 1, the protection arrangements for the SKS are as follow:

1. For the 154 kV incoming transmission lines, distance protection (21/21N), directional OCP (67/67N) and frequency protection (25) are implemented.
2. Differential protection (87T), over current and earth fault protections (50/51/50N/51N) are implemented for the power transformer.

3. For the MV outgoing feeders, over current and earth fault protections (50/51/50N/51N) are implemented.
4. Auxiliary Transformer is protected by MV fuse.

4. CHARACTERISTICS OF OVERCURRENT PROTECTION RELAY

4.1. Selectivity

The protection relays have to operate in a way that should provide adequate selectively by isolating the fault through opening the circuit breakers. This requires coordination of protection functions between the protective relays. Time grading, current grading or unit protection methods are commonly used to provide the required coordination between the relays.

In the time grading method, the protection relays in successive zones are arranged in time so that only the relays near to the fault operate first. For this purpose, definite time relays are used and it is independent of the level of fault current. However, as a disadvantage, the relay near to the source (with highest fault level) clears the fault with longer time delay.

Current based grading takes the advantage of variation of fault current at different parts of the network. The variation of impedance according to the location between the fault point and the source is the main cause of the fault current variation. In order to use this approach; there must be an appreciable impedance between the two relaying points.

To overcome the limitations of current based and time-based grading, the inverse time overcurrent relay characteristic was developed. The inverse time characteristics are defined by standard curves. In Table 3, for example, IEC 60255 standard characteristics are shown. In addition, in the modern protection relays, there is also an option for the user to define their own time-current characteristics [7-9].

***Table 3.** IEC 60255 Standard Characteristics [6]*

Relay Characteristics	Equations (IEC 60255)
Standard Inverse (SI)	$t = TMS * \frac{0.14}{(I_r)^{0.02} - 1}$
Very Inverse (VI)	$t = TMS * \frac{13.5}{I_r - 1}$
Extremely Inverse (EI)	$t = TMS * \frac{80}{{I_r}^2 - 1}$
Long Time Standby Earth Fault	$t = TMS * \frac{120}{I_r - 1}$

Where: Ir = I/Is, Is is the relay setting current, I is the measured current, TMS is the Time Multiplier Setting. High-set instantaneous element is used to reduce the tripping time and improve the system grading at high fault currents. This becomes very effective when the source impedance is not large enough when compared to the protected circuit impedance [6].

4.2 Speed

Relays are expected to operate as fast as possible to maintain the reliability of supply by getting rid of each fault before it spreads to healthy systems, causing in loss of synchronism and the blackout of the power system [6]. Speed is the characteristics of the relay which is related with how fast it has to operate to clear the fault.

4.3 Sensitivity

Additionally, relays must be sensitive enough to identify minimum operating fault level (current, voltage, power etc.).

4.4 Reliability

Furthermore, protection relays are required to be highly reliable, by reducing the risk of failure to trip (dependability) and risk of over tripping (security).

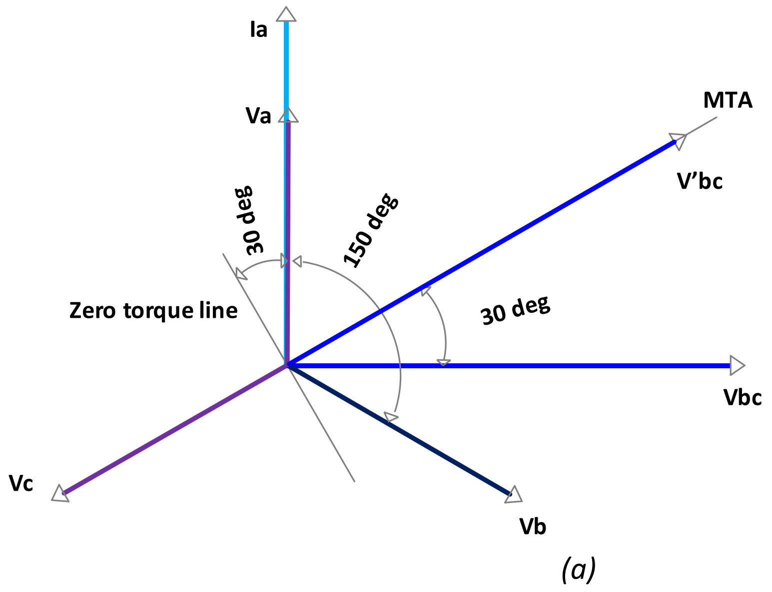
4.5 Directionality

For the parallel feeders, line with two end feeds and ring networks, the OCP cannot provide selectivity. Therefore, directional control facility can be included to the protection relays to provide better selectivity [10]. To determine the direction of the fault current, voltage data is required. The connection of the voltage and current information to the relays depends on the phase angle between the voltage and current to be applied to the relay at unity system power factor [6]. In numerical or digital relays, phase displacements can be obtained by software in contrast to electromechanical and static relays in which the phase displacements are obtained by applying the voltage and the current inputs to the relay [11-12].

The commonly used standard connection for the relays is 90° Quadrature Connection [6]. In this type, two forms of connections are available based on the Relay Characteristic Angle (RCA). The RCA is the angle by which the voltage applied to the relay is shifted to produce maximum sensitivity to the relay. These connections are:

4.5.1 90°-30° Characteristic (30° RCA)

This is obtained by connecting the Phase-A current (Ia) to the phase-A relay element and the Vbc voltage is displaced by 30o in a counter-clockwise direction. In this connection type when the current lags the phase to neutral voltage by 60o the maximum sensitivity will be produced. The correct directional tripping can be obtained for current angle 30o leading to 150o lagging; as shown in Figure 2 (a).



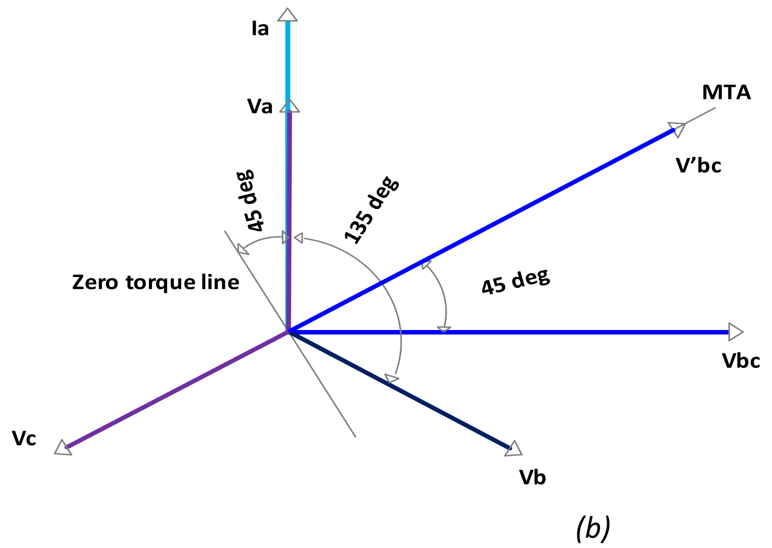


Figure 2. *(a). Vector Diagram for the 90°-30° Connection, (b). Vector Diagram for the 90°-45° Connection*

4.5.2 90°-45° Characteristic (45° RCA)

In this case, phase-A current (Ia) is connected to the phase-A relay element and Vbc is shifted by 45° in a counter-clockwise direction. In the SKS directional over current and EFP (67/67N) are used as the backup protection for the distance relay (21/21N) [10]. The maximum sensitivity is produced for the 45° current lagging from system phase to neutral voltage. The correct directional tripping zone is from 45° leading to 135° lagging as shown in Figure 2 (b).

5. OVERCURRENT PROTECTION COORDINATION STUDY

The coordination study between overcurrent relay requires the following data [6, 12, and 13]:
1. The single line diagram of the system with rating and type of protection system specified on it.

2. The impedance of power system components like cables, transmission lines, transformers, rotating machines and etc.
3. The minimum and maximum short circuit currents estimated to flow through each of the protection relays.
4. The maximum load current through each of the protection device.
5. Starting currents of different types of motors.
6. The thermal withstands, transformer inrush, and damage characteristics curves.
7. The curve showing generators' fault current rate of decay.
8. The current transformers' performance curves.

5.1 Fault Current

For the protection relay coordination, distribution of the fault current throughout the network has to be known. Especially the minimum and the maximum short circuit currents have to be calculated through each relaying points. Short circuit fault study for the coordination of protection relays in the practical application involves the following steps [6]:

1. Identifying the possible operating conditions and stability limits by using network diagram and available data.
2. Calculating minimum and maximum fault currents for each type of fault through each relaying points.
3. Calculating the fault current distribution in the network, especially through each relaying point.

Based on the above steps, the protection system and the classes of protection, such as high or low have to be determined. During the occurrence of the fault in power system, the three-phase current and voltage are no more balanced except in three phase short circuit faults. Therefore, the protection engineer is concerned with symmetrical faults and asymmetrical faults involving phase-to-phase and one or two phases to earth faults [8, 13].

For the analysis of unbalanced fault conditions, balanced symmetrical components are used. Symmetrical components can also be used to detect different types of faults and differentiate between the faults. For example, zero sequence and negative sequence voltages and currents are used mostly in non-directional or directional earth fault OCPs settings. In this study, the analysis of symmetrical components will not be discussed. However, the symmetrical components (voltage and current) which are available in different type of faults are summarized in Table 4.

Table 4. *Symmetrical Components and Fault Types*

Sequence Currents	Single Phase to Earth Fault	Phase-Phase Fault	Phase-Phase to Earth Fault	Three Phase Fault	Three Phase to Earth Fault
I_1	x	x	x	x	x
I_2	x	x	x		
I_0	x		x		

Turkish electricity transmission corporation (TEİAŞ) publishes the maximum and minimum short circuit currents and power each year. The short circuit currents which are taken from the published data [14] for 'Gebze Industrialized Zone' as well as 'Çolakoğlu Substations' are summarized in Table 5. These values are used in the short circuit analysis of the SKS. In this study, the short circuit analysis is realized by using the ETAP power system analysis software. The impedance data of the line, cable, and transformer used in this study can be referred as systems data. Based on these data and the short circuit current from the network side, the short circuit analysis is conducted and the results are summarized in Table 6. The fault current will decrease from the TEİAŞ 154 kV towards the 33 kV side as shown in Table 6. The software can calculate the maximum and minimum fault current through each relaying points based on the IEC 60909 method or other standards. For this study, IEC 60909 method is used.

Table 5. *Minimum and Maximum Short Circuit Currents of the Source Network*

Substations	**Maximum (kA)**		**Minimum (kA)**	
Fault Types	Single Phase	Three Phase	Single Phase	Three Phase
Gebze OSB	26,5	30	16,2	18,4
Çolakoğlu	21,1	23,2	16,9	18,8

Table 6. *Minimum and Maximum Short Circuit Currents of the SKS.*

Busbar	**Maximum (kA)**		**Minimum (kA)**	
	Single Phase	Three Phase	Single Phase	Three Phase
154 kV busbar	30.5	33	25.2	23.6
33 kV busbar	12.9	14.9	12.5	14.4
Arc-Furnace	12.5	14.5	12.2	14
Pota-Furnace	12.5	14.4	12.1	14
TCR and 2nd Harmonic Filter	12.7	14.7	12.4	14.3
3rd and 4th Harmonic Filter	12.7	14.7	12.1	13.9
Auxiliary Transformer	12.8	14.7	12.4	14.3

5.2 Load Current

The protection relay must be set above the maximum load currents for the stable operation. Consequently, the maximum load currents for the system has to be determined before determining the relay setting. The maximum load current through each feeder is calculated by the well-known power formula as follow:

$$I_L = \frac{S}{V * \sqrt{3}} \tag{1}$$

Where: IL is per phase maximum load current; S is the apparent power; V is per phase voltage. The maximum load currents at each relaying points are summarized in Table 7.

Table 7. *Maximum load current*

Feeders	**Pota Furnace**	**Transfor. Feeder**	**Arc Furnace**	**TCR and 2nd HF**	**3rd and 4th HF**
Power (MVA)	12	150	72	100	60
Current (A)	200.82	2510.29	1204.9	1673.53	1004.12

5.3 Instrument Transformers

Proper protection design starts with the selection of appropriate instrument transformers (voltage and current). Instrument transformers supply the relays with current and voltage for measurement and protection purposes by converting the high magnitude current and voltages to the compatible quantities to be injected to the relays.

5.3.1 Current Transformer (CT)

CTs are classified as metering and protection type CTs. The metering CTs are used for the application which requires very high accuracy over the normal range of the load current. Protection CTs are required to operate at many times the full load current (with an error between 5%-10%) [9, 14].

➢ *Current Transformer Ratio*

The CTs has to be selected based on the maximum load current on the primary side and the maximum secondary current under fault condition (generally, 100 times rated secondary current). Additionally, the thermal withstand current during fault must be considered. Based on IEC 60255 standard, the thermal withstand current of the current input has to be 100-times nominal current (100xIn). For example, for the system with fault current of 25 kA, the lowest possible CT rated current must not fall below 25 kA / 100 = 250 A. Consequently, the selection of the primary rated current of 300 A is correct.

➢ *Current Transformer Saturation*

The accuracy of CT depends on the fault current through the primary of the CT. For very high currents, the saturation occurs and the relation between the primary and secondary currents will be no more linear. The point where the linearity is lost is known as knee/excitation point (Figure 3). For correct operation, all the measured values obtained from the relay must be red when the CTs are operating in their linear mode (unsaturated CTs). Thus, appropriate selection of CTs for the relays has to be made in order not to saturate under the applied current.

➢ *Procedures for the Selection of CTs*

The following steps have to be followed for the selection of CTs.

1. It has to be ensured that the primary rating of the CT is greater than or equal to the expected full load current.
2. It has to be ensured that the CT can derive the attached burden (total load resistance of secondary circuit) during maximum fault current without saturating. The burden is calculated as follow:

$$R_B = R_{sCT} + R_{wr} + R_{rb} \tag{2}$$

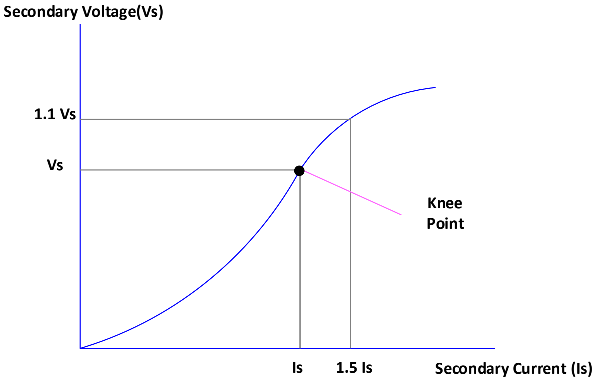


Figure3. *Excitation Curve, CTs Secondary Voltage vs. Secondary Current*

Where: RB is the burden resistance, RsCT is the CT secondary resistance, Rwr is the connection wire resistance, Rrb is relay burden resistance. In order to check whether CT will saturate under the maximum fault current or not, the CT secondary voltage under fault condition has to be determined as follow:

$$CTsv = \frac{R_B * I_{scMax}}{CT\ Conversion\ Ratio} \tag{3}$$

Where: CTsv is the CT secondary voltage and, IscMax is the maximum fault current.
The resulting value from equation (3) is plotted on the CT excitation curve and if it is below the knee point of the CT there would be no saturation and if it is above the knee point there would be saturation. Based on the above procedures, all the CTs in the SKS are determined.

5.3.2 Voltage Transformer (VT)

There are two types of voltage transformers which are used in power industry, namely electromagnetic and capacitive voltage transformers. Electromagnetic voltage transformers are used for accurate metering and used for lower level voltage applications. Capacitive voltage transformers are used for high-voltage transmission line applications. It consists of coupling capacitors, compensating reactor, step-down transformer and Ferro-resonance suppression circuit as shown in Figure 4.

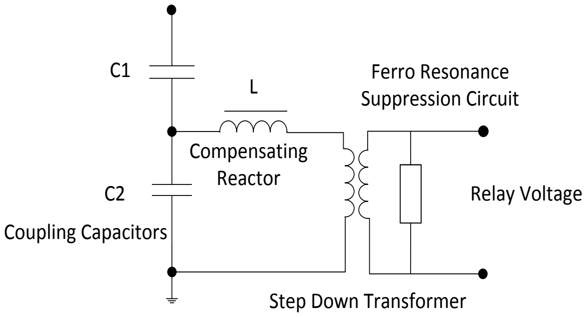


Figure 4. *Capacitive Voltage Transformers*

In voltage transformers, accuracy class and the burden rating are very important. The common accuracy class and the burden ratings are given in Table 8. The voltage transformers used in the SKS for both medium voltage and high voltage are fulfilling the accuracy requirements as per the standard.

Table 8. *Typical Voltage Transformer Accuracy Class and Burden Ratings*

Potential Transformer Accuracy Class			
Common Classes (IEEE)	**Accuracy**	**Designations (IEEE)**	**Accuracy maintained below**
1.2	98.8-101.2%	W	12.5 VA
0.6	99.4-100.6%	X	25 VA
0.3	99.7-100.3%	Y	75 VA
Burden Rating		Z	200 VA
		ZZ	400 VA

5.4 Coordination Procedure

The protection relays have to be set to not operate for the maximum load current but must operate at the minimum expected fault current. Furthermore, the overload protection can also be provided by the relays. It is recommended to use relays with the identical operating characteristics in succession. In addition, the relay which is furthest from the source must have a current setting which is equal to or less than the primary current required to operate the relay behind it. Furthermore, for the relays to operate correctly, sufficient time has to be left which is referred to as grading margin. The grading margin depends on the following factors [8, 13]:

- circuit breaker’s fault current interrupting time
- relay timing errors (variation from the characteristic time delay curve)
- the overshoot time of the relay
- CT errors

- the final margin on completion of the operation

At the relaying point under consideration, initially the grading is carried out for the maximum fault level, but it is checked if the grading margin exists for all current levels between relay pickup current and maximum fault level. Fixed grading margin is popular, but for low fault current levels, it is better to calculate the grading margin at each relaying points. Thus, a proper minimum grading time interval, CTI, can be given as [6]:

$$CTI = \left[\frac{2E_R + E_{CT}}{100}\right] t + t_{CB} + t_0 + t_S \tag{4}$$

Where: ER = relay timing error (as defined in IEC60255-4), ECT = allowance for CT ratio error (%), t = nominal operating time of relay nearer to fault (sec), t_{CB} = CB interrupting time (sec), t_O = relay overshoot time (sec), t_S = safety margin (sec).

5.5 SKS Overcurrent Coordination

For the OCP coordination of the SKS, the protection arrangement shown in Figure 1 has to be referred. The IEC normal inverse characteristic curve is chosen for the inverse time protection relay. Firstly, the operating time and time multiplier setting (TMS) for the furthest relay from the source has to be determined. The smallest available TMS in the relay has to be selected if there are many relays to be coordinated in series (e.g. for REF 615 ABB relay, TMS=0.05 can be used). Then, if the tn, TM'n, In, Ipn are downstream relay's operating time, time multiplier setting, maximum fault current and peak up current respectively, the operating time of the of this relay can be calculated as*:*

Table 9. *Typical Relay Timing Errors – Standard IDMT Relay [6]*

Times	**Relay Technology**			
	Electro-Mechanical	Static	Digital	Numerical
Typical basic timing error (%)	7.5	5	5	5
Overshoot time(s)	0.05	0.03	0.02	0.02
Safety margin(s)	0.10	0.05	0.03	0.03
Typical overall grading margin-relay to relay(s)	0.40	0.35	0.30	0.30

$$t_n = TMS_n * \frac{0.14}{\left(\frac{I_n}{I_{p_n}}\right)^{0.02} - 1} \tag{5}$$

If fixed grading margin is selected for the coordination, which is about 200 ms for the modern IEDs, the time multiplier setting and operating time of an immediate upstream relay can be calculated as follows:

$$TMS_{n+1} = \frac{t_n + 0.2}{\frac{0.14}{\left(\frac{I_n}{I_{p\_n+1}}\right)^{0.02} - 1}} \tag{6}$$

$$t_{n+1} = TMS_{n+1} * \frac{0.14}{\left(\frac{I_{n+1}}{I_{p_n+1}}\right)^{0.02} - 1} \tag{7}$$

Where: I_n is the fault current for the downstream relay; I_{n+1} is the fault current for the upstream relay. $Ip_{\_n+1}$ the pickup current for the upstream relay; TMS_{n+1} is the time multiplier setting for the upstream relay.

Table 10. *Setting Results for MV Protection Relays*

Feeders	***Function***	***Pickup Current***	***TMS***	***Curve (IEC)***	***Time(s)***	***In***
H03/ Pota Furnace, 33 kV	51	0.6 x In	0.3	Normal	-	400/1
	50	4.9 x In	-	Definite Time	0.05	400/1
H04/ Transformer, 33 kV	51	0.9 x In	0.36	Normal	-	3000/1
	50	4 x In	-	Definite time	0.05	3000/1
H05/ ARC Furnace, 33 kV	51	0.46 x In	0.3	Normal	-	3000/1
	50	2 x In	-	Definite time	0.05	3000/1
H06/ TCR AND 2nd HF, 33 kV	51	0.6 x In	0.3	Normal	-	3000/1
	50	2.5 x In		Definite Time	0.05	3000/1
H07/ 3rd and 4th HF, 33 kV	51	0.77 x In	0.3	Normal	-	3000/1
	50	3.4 x In	-	Definite time	0.05	3000/1
Transformer 154 kV	51	0.77 x In	0.45	Normal	-	800/1
	50	3.5	-	Definite time	0.05	800/1

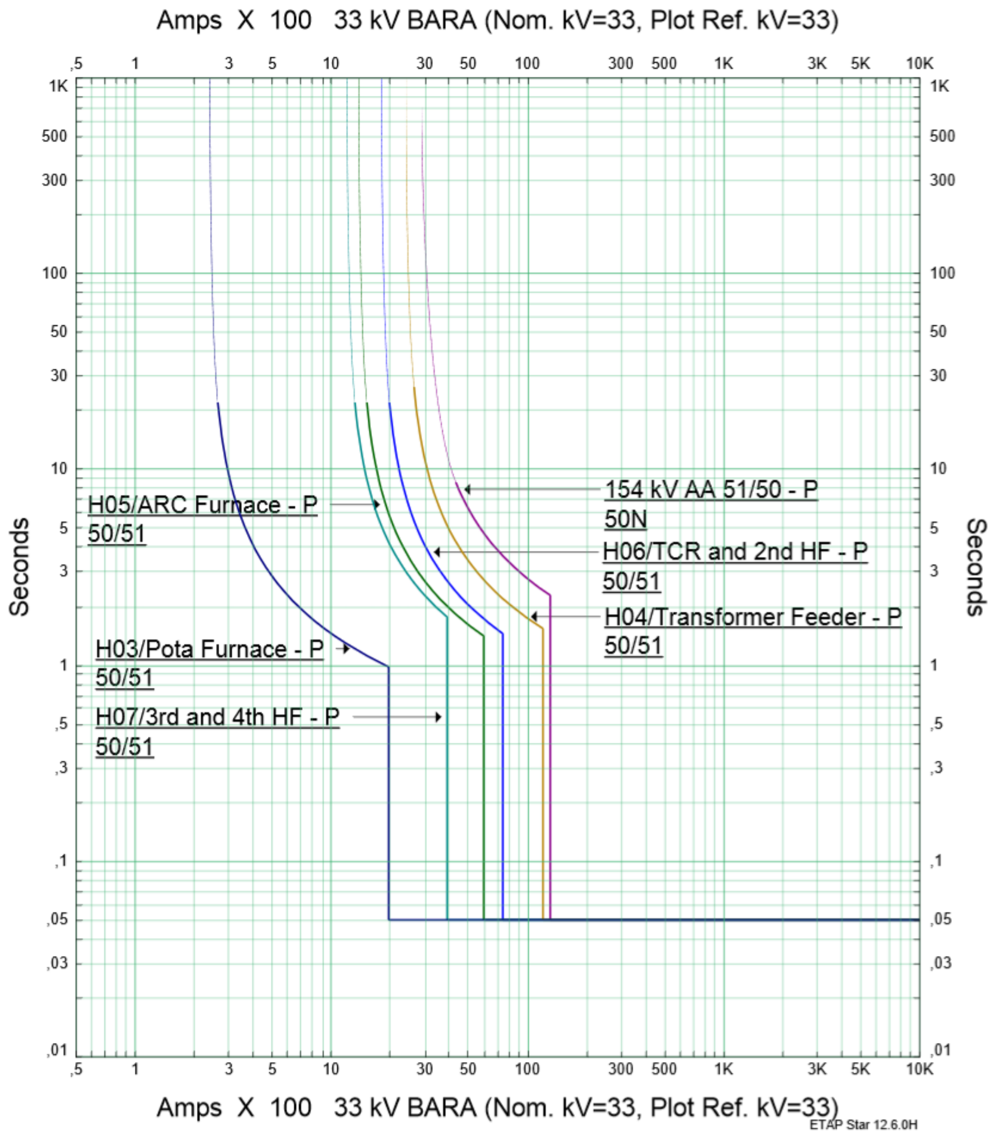


Figure 5. *SKS Relays Coordination Curve*

In the SKS when the maximum fault current occurs at the load terminal, the MV feeders' relays which are nearer to the source than the load feeders' relays have to give 0.5-second gap to ensure the load feeders' relay to operate. By following the above procedures (equations 6-8), this corresponds to TMS of 0.3. The pickup currents are chosen as 1.1 times the maximum load currents. By using equations (6) to (8) the time multiplier settings for all the relays are determined and summarized in Table 8. In Table 8, the pickup settings are normalized with a ratio of current transformer primary currents. The coordination curve is shown in Figure 5. The curve shows the proper coordination between the relays, for example, the upstream relays (154 kV transformer feeder protection) operates only after the MV feeder protection fails to operate for the fault happening on MV side. In addition to the time inverse, short circuit protection is realized by definite time function. The current setting is determined so that it is below the minimum short circuit current and above the load current. The pickup settings and time delay settings are shown in Table 8.

6. EARTH FAULT PROTECTION

Earth fault is the most frequent one of all faults. Its protection is provided by the relay which has a response to the residual current. The load current must not affect the relay that is used for the EFP. Earth contact resistance or neutral earthing impedance can limit the earth fault current. Consequently, to take into consideration this low-level current, the earth fault relay is set to the minimum earth fault current or 20-40% of full-load current flowing through the system being protected [15-17]. Furthermore, similar to the directional OCP, directional earth fault overcurrent can be applied in the following situations [17, 18]:

- when the OCP is done by directional relays,
- in insulated-earth networks or in Petersen coil earthed networks,
- when the sensitivity of EFP is insufficient.

6.1 Influence of Earthing Nature on the Earth Fault Protection

The nature of zero sequence currents which are produced during earth fault is influenced by the method of earthing. Thus, zero sequence currents and voltages which are utilized for the earth fault detection depend on the system connections to the earth and the potential difference between the earthing points resulting in a current flow in the earth paths. In the following sections, the effect of earthing types on the EFP and the techniques to be used for detecting earth fault will be discussed.

6.1.1 Earth Fault Protection on Insulated Networks

In the insulated network, there is no earth fault current pass, so the whole system may remain operational under earth fault condition. The system has to be designed to withstand the high steady-state and transient overvoltage. The disadvantage of such network is the difficulty of detecting earth fault current. In modern relays, the following methods are available.

6.1.1.1 Residual Voltage Method

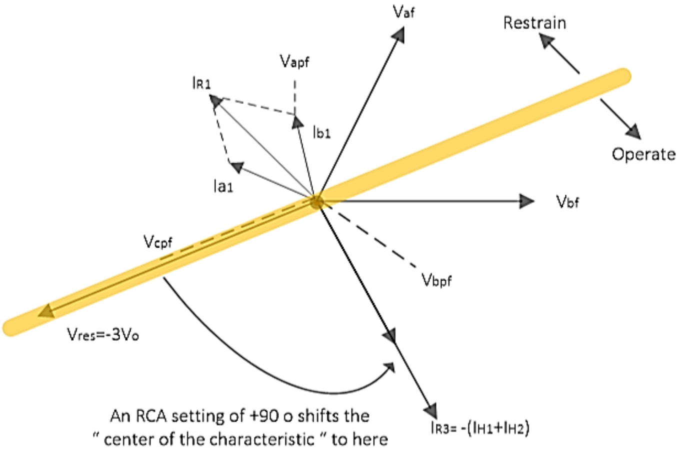
The un-faulted phase voltages magnitude increases by a factor of $\sqrt{3}$ and their sum is no longer zero during the occurrence of single phase to earth fault. Consequently, the earth fault can be detected by the residual voltage element. The advantage of this method is that CTs are not used and only the voltage is being measured. However, the unbalanced voltage happens on the whole affected system and it is difficult to provide any discrimination.

6.1.1.2 Sensitive Earth Fault Method

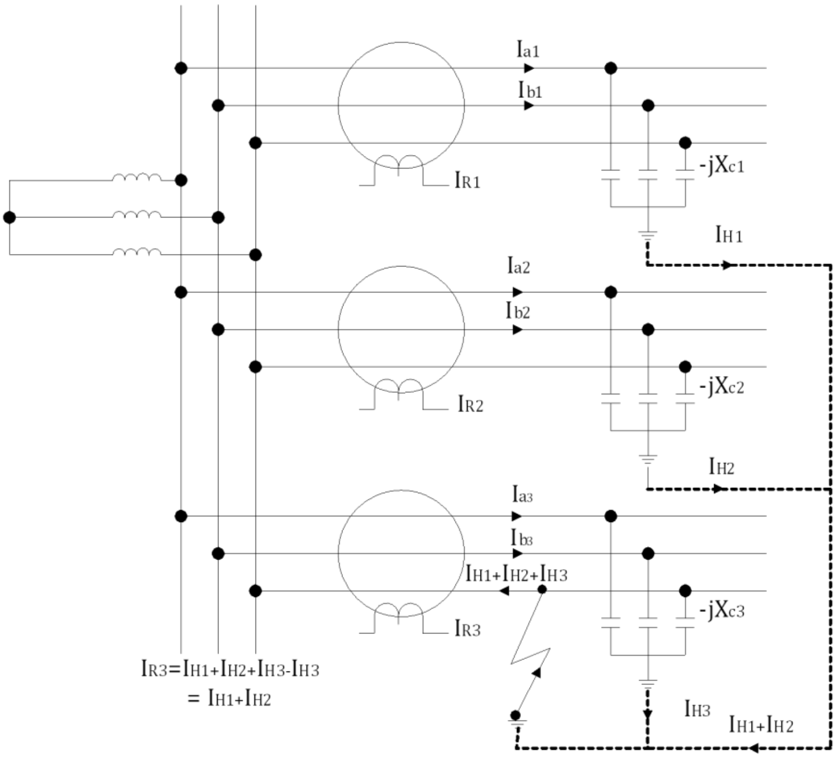
This method is based on detection of imbalance charging currents per phase and mostly used in MV networks. According to this mechanism, the relays on the healthy feeders detects the unbalance in charging currents for their own feeders. In contrast, the relay in the faulted feeder detects the charging currents in the rest of the system, with the current of its' own feeders, canceled out ($I_{H1}+I_{H2}$ for feeder-3 of Figure 5).

In the insulated network due to the capacitive effect, the unbalance current on the un-faulted feeders leads the residual voltage by 90º.

- Due to the fault, the phase to earth voltage and consequently the charging current of healthy phases rise by $\sqrt{3}$ .The resulting residual current will be three times the steady-state charging current per phase.
- Using the advantage of opposite current flow direction between the residual currents on the un-faulted and faulted feeders, discrimination can be provided by using directional earth fault relay.
- To make the residual current seen by the relay lie within the operating zone, the residual voltage which is used as the polarizing quantity is shifted by 90^{o} as shown in Figure 6.



(a)



(b)

Figure 6. *(a). Phasor diagram for insulated system with phase (b) C-earth fault [6]*

6.3.2 Earth Fault Protection on Petersen Coil Earthed Networks

In the Petersen coil earthed systems, reactance which is equal to the system capacitance to ground is used to earth the system (Figure 7). Under steady state conditions, similar to the insulated system, no earth fault current results when a single phase to earth fault occurs.

By using Figure 7 the following equations can be derived.

$$I_f = -I_B - I_C + \frac{V_{an}}{jX_L} \qquad 0 = -I_B - I_C + \frac{V_{an}}{jX_L} \qquad \frac{V_{an}}{jX_L} = I_B + I_C \tag{8}$$

$$I_L = I_{H1} + I_{H2} + I_{H3} + I_F \qquad I_{R3} = I_{H3} + I_F \qquad I_{R3} = I_L - I_{H1} - I_{H2} \tag{9}$$

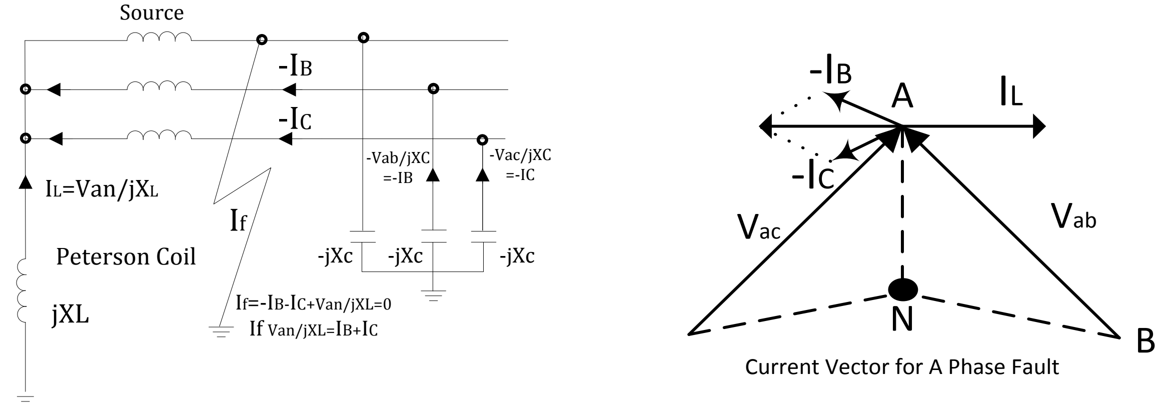


Figure 7. *Earth fault in Petersen Coil Earthed System [6]*

By using equation (9) and Figure *8*. Considering Figure 8, the magnitude of the residual current I_{R1} equals to three times the steady-state charging current per phase. In contrast, the residual current on the faulted feeder is equal to I_L - I_{H1} - I_{H2}. For the residual voltage (V_{res}) polarization, the residual current phase is shifted by an angle less than 90^o on the faulted feeder and greater than 90^o on the healthy feeders due to the presence of resistance effect.

If directional relay with RCA of 0^o is used, the faulted feeder through falls in the 'operate' area while the residual current healthy feeder falls in the 'restrain' area of the relay characteristic. Therefore, in order to increase the angular difference between the residual signals and to ensure a measurable earth fault current, a resistance can be inserted in parallel with the Petersen Coil. It was already mentioned that the method of system earthing also affects the Relay Characteristic Angle (RCA). In the practical applications, there are varieties of grounding systems. The corresponding the RCA values to be used for such systems are listed as follows:

- 0^o RCA can be used for the resistance-earthed system,
- -45^o RCA can be used for the solidly-earthed distribution system and
- -60^o RCA can be used for the solidly-earthed transmission system.

Table 11. *EFP Setting for the SKS.*

H03/ POTA FURNACE, 33 kV					
Function	Pickup Current	TMS	Curve	Time Delay(Second)	In
50N	0.1 x In		Definite Time	0.5	400/1
H04/ TRANSFORMER FEEDER, 33 kV					
Function	Pickup Current	TMS	Curve	Time Delay(Second)	In
50N	0.05 x In		Definite Time	1	3000/1
H05/ ARC FURNACE, 33 kV					
Function	Pickup Current	TMS	Curve	Time Delay(Second)	In
50N	0.03 x In		Definite Time	0.5	3000/1
H06/ TCR AND 2nd HF, 33 kV					
Function	Pickup Current	TMS	Curve	Time Delay(Second)	In
50N	0.04 x In		Definite Time	0.5	3000/1
H07/ 3rd and 4th HF, 33 kV					
Function	Pickup Current	TMS	Curve	Time Delay(Second)	In
50N	0.03 x In		Definite Time	0.5	3000/1

In the SKS the ground fault protection is provided by instantaneous EFP function (50N). The relay used is REF 615 OCP [19]. The setting is selected by considering the maximum unbalance current which is about 20% of the load current. Based on single line diagram of Figure 2 the EFP current and time settings are given in Table 13 and the corresponding characteristic curves are shown in Figure 9.

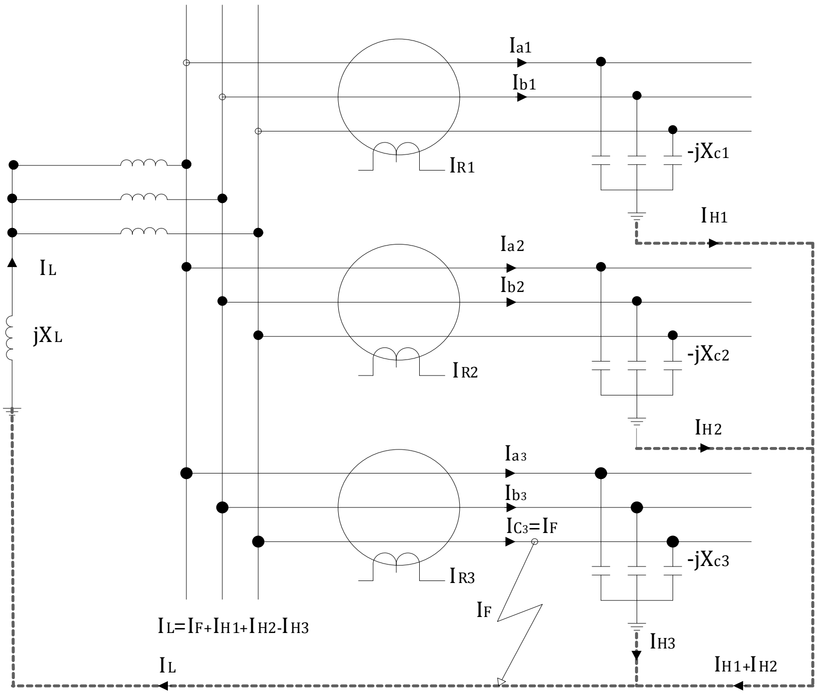


Figure 8. *Distribution of currents during a C-phase-earth fault on radial distribution system [6]*

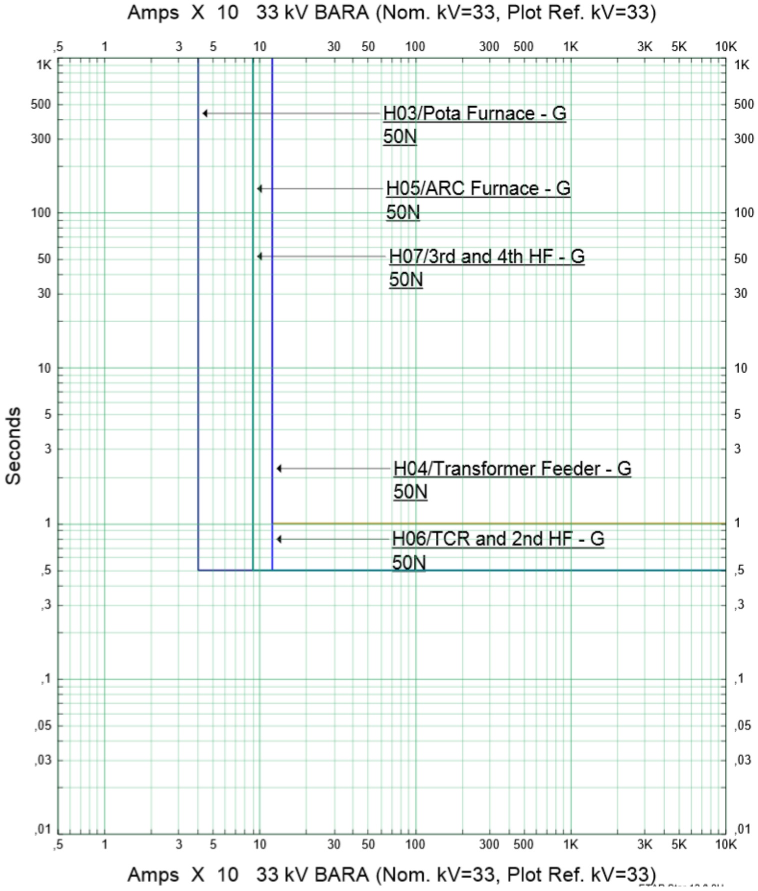


Figure 9. *Ground Fault ProC Curve*

7. CONCLUSION

The electrical power system is expensive investments which have to be designed, implemented and operated with great care so that it provides valuable results. ESS is one of the components of such investment which requires detailed engineering work from its design phase to the implementation phase. If proper protection system design procedure is not followed, the fault currents that may result from abnormal conditions can damage the components of this expensive investment within a fraction of minutes. Thus, during substation design stage, detailed analysis of the system, like a short circuit and load analysis has to be made. Based on the analysis results, protection systems, equipment and techniques have to be properly determined before the implementation stage. This involves the selection of appropriate circuit breakers, fuses, isolators, instrument transformers, protection relays, etc. Moreover, proper coordination among these equipments is a crucial task which has to be handled by protection engineer. In this paper, the proper steps for designing protection system is discussed with a practical case study of SKS project. The engineering steps start from load analysis and short circuit study, which is discussed in this study. The selection of appropriate instrument transformers is also among the fundamental steps for proper operation of the protection system. Based on the requirement of the system to be protected, over-current, differential and distance protection schemes are implemented in the study. However, the distance and differential protection will be covered in the part-2 of this paperwork. Overcurrent and EFP are the earliest protection to be used for the protection of power systems. The engineering issues related to overcurrent and EFP are discussed in detail. In addition, this protection system is designed and implemented for the SKS by providing the necessary coordination among the protection relays. Generally, this paper discussed the necessary engineering steps to be followed for the currently used protection schemes for the modern IEDs. The results from the coordination study are implemented to the substation protection relays. After the necessary test and commissioning of the protection system, SKS is successfully energized.

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