Case Study of Using Negative Sequence Element in Power System Faults' Detection

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Abstract—**Symmetrical components method is a very significant tool for power system engineers in simplifying unbalance faults. Short circuit studies are the key factor in evaluating the power system stiffness and stability. In this paper, a case study of a simple power system consisting of 132KV OHL feeding a power transformer (132/33) KV of STAR-DELTA connection is considered. The aim is to provide a backup protection at 132KV OHL, for the power transformer in case its main protection fails to detect and isolate the faults on 33KV busbar. All types of faults on 33KV busbar have been analyzed and studied, and it is found that the ONLY effective way to detect the single line to ground fault on 33KV busbar is by using the negative sequence element, which represents an application of how the symmetrical components are often the only feasible solution for power system faults detection during certain power system configurations and faults scenarios.**

Keywords— Symmetrical components, Negative Sequence Element

I. INTRODUCTION

The most effective approach to simplify and analyze the power system voltages and currents during unbalance conditions is applying what is so called symmetrical components method, where it depends on the fact of converting the unbalance conditions for the voltage and current of the power system during disturbances to an equivalent balanced voltage and current profiles, so the power system can be dealt with conveniently [1]. The method was firstly introduced and developed on 1918 by a Canadian engineer Charles LeGeyt Fortescue during the Annual Convention of the American Institute of Electrical Engineers. Thereafter, it has been become an essential tool in simplifying multiphase electrical circuits [2]. While symmetrical components are commonly known to be used for fault analysis purpose [3], it is widely adopted in variety of power system applications such as protection, power system operation in addition to power system planning field [1]. In protection field, with the development of electronic and numerical relays, the symmetrical component method has been adopted in order to enhance the performance of distance and differential protections [1], and it has been also suggested to improve overcurrent protection scheme [4]. In transformer differential protection system, negative sequence element might often be used to increase the sensitivity to inter-turn faults compared to traditional differential schemes [5]. Symmetrical components utilization extends to be used in electrical machines, where it aids in detecting the inter-turn induction motor stator faults [6]. It can also be used as filters for Power System Protection Based on Converters with Rotating Magnetic Field [7]. In FACTs, devices, an algorithm based on symmetrical component which employs the negative sequence current is suggested in detecting inter-turn faults in phase shift transformer device [8]. The symmetrical components theory contributes positively even in DC power lines, where it provides a benefit of analyzing and controlling Bipolar LVDC grids [9]. Symmetrical components method has also an advantage of identifying non-electrical equipment problems such as monitoring pitch bearing defects in wind turbines [10]. The mentioned examples explain how the symmetrical components are important in multiple aspects in electrical fields.

In this paper, a case study will be taken as one of the applications that necessitates using of symmetrical components in increasing the electrical protection system security and reliability. The remainder of the paper is arranged as follows. Section II presents the problem description; Section III illustrates system parameters and the study data. Section IV demonstrates the mathematical formulation for the problem. Section V shows the study results and the discussion of the study is on Section VI. Finally, Section VII provides the final conclusion for the study.

II. PROBLEM DESCRIPTION

The problem focuses on how the symmetrical components can be used in power system protection field in a sense of making use of symmetrical components characteristic in detecting the power system faults, by assuming a simple power system consisting of (132/33) KV power transformer is fed from a high voltage network of a voltage level 132KV, through a radial transmission line see figure 2. The power transformer has a complete set of protection system. However, it is a common practice to implement a remote backup protection on the transmission line, in order to serve in isolating the transformer in case of failure occurs to any of the transformer protections or in case of a failure occurs to any of transformer's circuit breakers (HV circuit breaker or LV circuit breaker), in both cases, it is necessary to trip the line circuit breaker in order to save the transformer.

The simplest type of backup protection is going to be used, which is an overcurrent relay. The overcurrent relay consists of two elements: overcurrent element, which measures and monitors the current values on each phase separately and earth fault elements that detects the residual current of the three phases. Figure 1 shows the structure of the overcurrent relay.
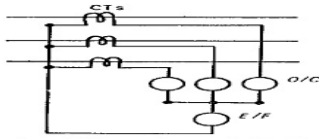
Figure 1: Overcurrent Relay Structure [11]

Figure 1 demonstrates the simplest structure for the overcurrent relay, however the recent numerical overcurrent relays have the capability to derive the symmetrical components, from the phases' measurements, so all types of symmetrical components, positive sequence, negative sequence and zero sequence quantities are evaluated and calculated by the relay.

In this case study, It is worth to mention that, the application of a backup protection at the 132KV OHL for a the transformer if it is solidly grounded with STAR- STAR vector group connection, is far easy to be implemented, since the fault currents on the transformer LV side will be quite high, and easily to be detected by the overcurrent relay on 132KV OHL side for all types of faults. Unlike if we a have a power transformer of a DELTA – STAR connection or STAR – DELTA connection, since the delta winding prevents the flow of the zero-sequence current across the transformer and hence the ground faults can never be detected using the earth fault element at the 132KV OHL side, but it can ONLY be detected by overcurrent element in some cases with the following conditions:

- The power transformer (132/33) KV has DELTA-STAR vector group and the STAR winding (33KV side) is solidly grounded, and hence the ground faults at 33KV side will be high enough to reflect high currents into 132KV side, so the overcurrent element could detect the fault.

- The power transformer (132/33) KV has STAR-DELTA vector group so the DELTA winding (33KV side) is grounded through a grounding transformer of very low impedance, and hence the ground faults at 33KV side will be high enough to reflect high currents into 132KV OHL side, so the overcurrent element could detect the fault.

However, in case DELTA-STAR transformer is not solidly grounded or the STAR-DELTA transformer is grounded through high impedance grounding transformer, the ground faults at 33KV side will be low and therefore will reflect very low currents at 132KV OHL side which would present a challenge to the 132KV OHL overcurrent relay to detect the ground faults occur on 33KV side. Based on the above in this case study, a transformer of vector group STAR-DELTA is going to be assumed where the DELTA winding is grounded through a grounding transformer of high impedance that limiting the ground faults to values lower than the normal load conditions (see figure 2). The results of the study, would prove that there is no choice to provide a backup for similar cases unless using negative sequence element for ground faults detection.

The power system topology that is going to be studied is as shown in figure 2. The power system consists of a reduced model for a huge high voltage network so its equivalent Thevenin impedance is small, a 132KV OHL line, assumed to be short line so its length can be considered as 80KM and a power transformer of 100MVA, voltage rating (132/33) KV.
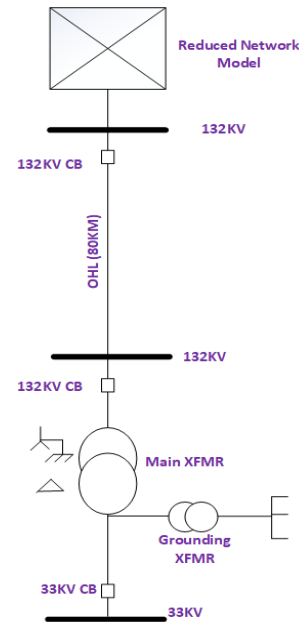

Figure 2: Power System Case Study Topology

III. SYSTEM PARAMETERS AND STUDY DATA

132KV Reduced Network Model:

The necessary part in the reduced network model is the equivalent Thevenin impedance of the network, the network equivalent impedance especially for the huge network is very low compared with the 132KV OHL of 80KM, so the equivalent Thevenin impedance is going to be neglected for simplicity.

132KV OHL Parameters:

Assuming that the OHL conductor is Aluminum Cable Steel Reinforced Conductor (ACSR). Reference to the table of the Characteristics of Aluminum Cable Steel Reinforced Conductors [12].

Table 1: Drake conductor specification

Conductor Code	Resistance (mΩ/Km), AC (60Hz) at 50°C	GMR (mm)	X1 (Ω/Km)	X0 (Ω/Km)
Drake	81.2	11.43	0.337	0.203

The OHL length is 80KM (short line), so the complete data for the impedances (Postive, Negative and Zero) is as follows:

$XL^+ = 0.337 * 80 = 26.96$ Ohm.

$XL^0 = 0.203 * 80 = 16.24$ Ohm.

XL^- = 0.337 * 80 = 26.96 Ohm. (Usually, the negative sequence impedance = positive sequence impedance)

It is to be noted that the positive line resistance and the zero-sequence line resistance is going to be neglected for simplicity where the nature of the transmission lines is inductive and has very low resistances compared with reactance values.

(132/33) KV Transformer Parameters:

Table 2 shows the recognized minimum values of short circuit impedance for two windings transformers based on IEC 60076-5 standard [13].

Table 2: Short Circuit Impedance for power transformers

Short-circuit impedance at rated current	
Rated power	**Minimum short-circuit impedance**
kVA	%
Up to 630	4,0
631 to 1 250	5,0
1 251 to 2 500	6,0
2 501 to 6 300	7,0
6 301 to 25 000	8,0
25 001 to 40 000	10,0
40 001 to 63 000	11,0
63 001 to 100 000	12,5
Above 100 000	>12,5

NOTE 1 Values for rated power greater than 100 000 kVA are generally subjected to agreement between manufacturer and purchaser.

NOTE 2 In case of single-phase units connected to form a three-phase bank, the value of rated power applies to three-phase bank rating.

In this study a 100MVA transformer of two windings (132/33) KV (STAR/DELTA) will be selected which should have a short circuit impedance (positive sequence impedance) = 12.5% as per table 2. The zero-sequence impedance of the transformer is assumed to be same as positive sequence impedance and of course the negative sequence impedance equals the positive sequence impedance. Hence, the complete transformer data in PU is as follows:

XT^+ = 0.125, XT^0 = 0.125, XT^- = 0.125Ohm.

33KV Grounding Transformer Parameters:

Refence to the problem description, where it has been mentioned the assumption of using a grounding transformer of high zero sequence impedance to limit the ground faults currents to values lower than the load current i.e., lower that power transformer rated current. The power transformer (100MVA) at 33KV side = 1750A. so a grounding transformer limiting the fault current to 1000A can be used.

The grounding transformer zero sequence impedance is therefore:

G. XFMR (XG^0) = $\frac{(33000 / \sqrt{3})}{1000/3}$ = 51.16 Ohm/phase

In the study the selected base values are as below:

MVAb = 100

KVb at 132KV side = 132KV

KVb at 33KV side = 33KV

Base Current (Ib) at 132KV side = $\frac{100}{132\sqrt{3}}$ = 0.437 KA

Base Current (Ib) at 33KV side = $\frac{100}{33\sqrt{3}}$ = 1.75 KA

Based Impedance (Zb) at 132KV side = $\frac{132^2}{100}$ = 174.24 Ohm

Based Impedance (Zb) at 33KV side = $\frac{33^2}{100}$ = 10.89 Ohm

From the power system data of the 132KV line, (132/33) KV transformer and 33KV grounding transformer, and the base quantities, the PU values can be obtained which are depicted on table 3.

Table 3: Power System Data in PU

132KV OHL	
$XL^'$(PU)	0.155
XL^-(PU)	0.155
XL^0(PU)	0.093
POWER TRANSFORMER	
$XT^'$(PU)	0.125
XT^-(PU)	0.125
XT^0(PU)	0.125
GROUDING TRANSFORMER	
XG^0(PU)	4.69

IV. PROBLEM MATHEMATICAL FORMULATION

In this section, the system under study will be represented into the symmetrical components circuits for each type of fault, from the circuits representations, a mathematical formulation will be deduced for the fault current during each type of fault.

System Modelling during Three Phase Fault on 33KV bus-bar

During the three-phase fault, on the 33KV busbar, there will not be any appearance for the symmetrical components (negative sequence and zero sequence) since the three-phase fault is balanced. the power system is modelled by a series impedance (Line positive impedance + transformer positive impedance), (see figure 3)
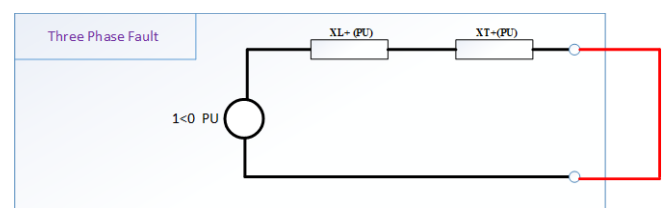

Figure 3: Power System Modelling during Three Phase Fault

The current flows on the circuit :

$$I_{3\emptyset\,(pu)} = \frac{1 < 0}{XL^+ + XT^+} \quad \text{.......... (1-1)}$$

Since during the three-phase fault scenario, the system is balanced each phase current is as below:

$$Ia = I_{3\emptyset\,(pu)} \quad \text{............... (1-2)}$$

$$Ib = I_{3\emptyset\,(pu)} < -120 \quad \text{...... (1-3)}$$

$$Ic = I_{3\emptyset\,(pu)} < 120 \quad \text{.......... (1-4)}$$

System Modelling during Double Line fault on 33KV busbar

During double phase fault scenario, it is going to be two symmetrical components quantities available (positive sequence & negative sequence) both are connected in series as can be seen in figure 4.
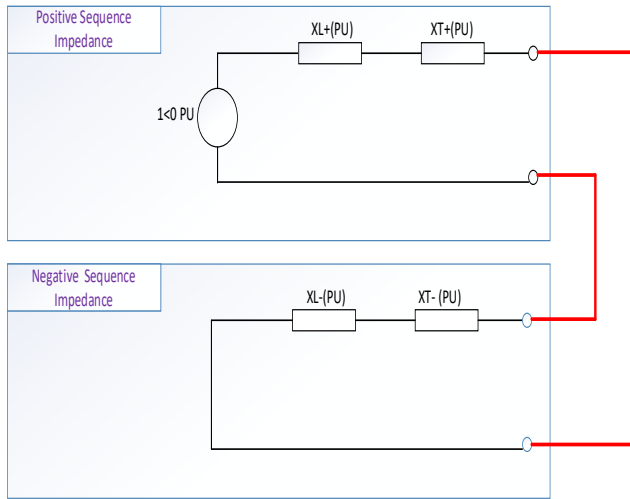
Figure 4: Power System Modelling during Double Phase Fault

The total current flows on the above circuit is:

$$I_{2\emptyset F\ (pu)} = \frac{1<0}{XL^+ +\ XT^+ +\ XL^- +\ XT^-}\ \dotsc\dotsc (2\text{-}1)$$

From figure 4 , it can be deduced the following formulation for the symmetrical components currents quantities

$$I^+_{(pu)} = I_{2\emptyset F\ (pu)}\dotsc\dotsc\dotsc (2\text{-}2)$$

$$I^-_{(pu)} = I_{2\emptyset F\ (pu)}\dotsc\dotsc\dotsc (2\text{-}3)$$

$$I^0_{(pu)} = 0 \dotsc\dotsc\dotsc\dotsc (2\text{-}4)$$

It is worth to mention that, both sides (132KV & 33KV) sides have the same phases currents in PU system.

System Modelling during Single Line to ground fault on 33KV busbar

During single phase to ground fault scenario, it is going to be all symmetrical components quantities available (positive sequence, negative sequence and zero sequence) all are connected in series as can be seen in figure 5 .
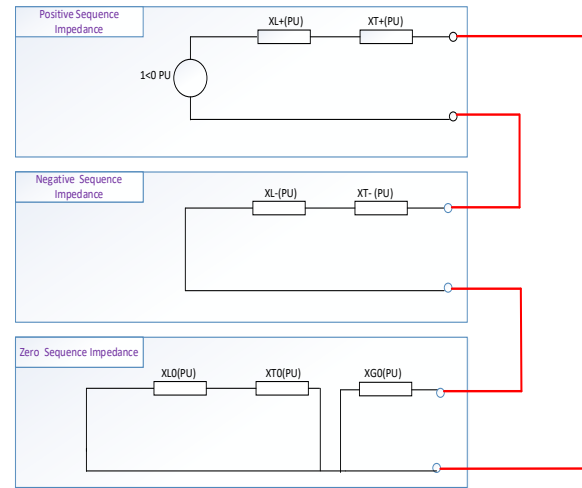
Figure 5: Power System Modelling during Single Phase to Ground Fault

It can be observed from figure 5 that the zero sequence impedances of the line and the power transformer will not be considered in the fault current calculations because of the existence of the Delta winding which prevents the follow of the zero-sequence current across the transformer.

The total current flows on the above circuit is:

$$I_{F(1\emptyset - E)\ (pu)} = \frac{1<0}{XL^+ +\ XT^+ +\ XL^- +\ XT^- +\ XG^0}\ \dotsc\dotsc\dotsc (3\text{-}1)$$

From figure 5, it can be deduced the following formulation

$$I^+_{(pu)} = I_{F(1\emptyset - E)\ (pu)}\dotsc\dotsc\dotsc (3\text{-}2)$$

$$I^-_{(pu)} = I_{F(1\emptyset - E)\ (pu)}\ \dotsc\dotsc\dotsc (3\text{-}3)$$

$$I^0_{(pu)} = I_{F(1\emptyset - E)\ (pu)}\ \dotsc\dotsc\dotsc (3\text{-}4)$$

System Modelling during Double phase to ground fault on 33KV busbar

During Double phase to ground fault scenario, all symmetrical components quantities are available, same as the case during single line to ground fault, however the symmetrical components impedances are connected in parallel as can be seen in figure 6.
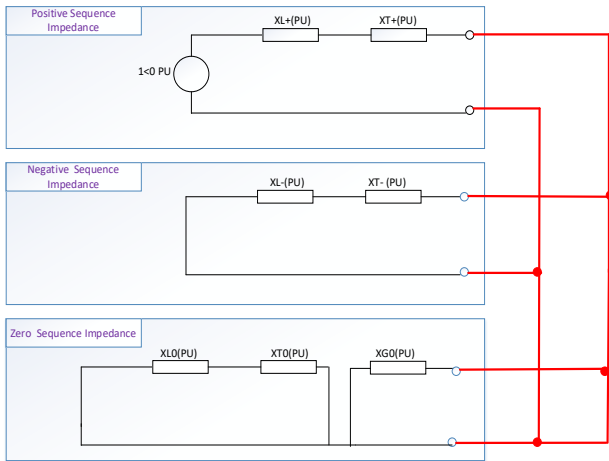
Figure 6: Power System Modelling during Double Phase to Ground Fault

It can be observed from figure 6 that the zero sequence impedances of the line and the power transformer will not be considered in the fault current calculations because of the existence of the Delta winding which prevents the follow of the zero-sequence current across the transformer.

The total current flows on the above circuit is:

$$I_{F(2\emptyset-E)\,(pu)} = \frac{1<0}{(XG^0)//(XL^- +\ XT^-)//(XL^+ +\ XT^+)} \quad \ldots\ldots\ldots\ldots\ (4\text{-}1)$$

From figure 6, it can be deduced the following formulation for the symmetrical components:

$$I^+\,(pu)\ = I_{F(2\emptyset-E)\,(pu)} \quad \ldots\ldots\ldots\ldots(4\text{-}2)$$

$$I^-_{(pu)} = I_{F(2\emptyset-E)\,(pu)}\ *\ \frac{XG^0}{XG^0 + XL^- +\ XT^-} \quad \ldots\ldots\ (4\text{-}3)$$

$$I^0_{(pu)} = I_{F(2\emptyset-E)\,(pu)}\ *\ \frac{XL^- +\ XT^-}{XG^0 + XL^- +\ XT^-} \quad \ldots\ldots\ldots(4\text{-}4)$$

Phase Currents Formulation

The phase currents during (single line to ground fault, double line fault and double line to ground fault) scenarios, can be obtained by applying the transformation matrix, converts symmetrical components quantities to phase quantities:

$$\begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I^0 \\ I^+ \\ I^- \end{bmatrix} \quad \ldots\ldots\ldots\ldots\ (5\text{-}1)$$

V. RESULTS

As has been mentioned in the problem description, it is required to set up a backup protection for the power transformer on the 132KV OHL, because of this fact, the focus on the fault current calculations will be the current values on the 132KV OHL. Based on the problem mathematical formulation and the selected base values, the symmetrical components current values and the phase current values can be calculated as follows:

Three phase fault current calculations on 132KV OHL:

Reference to (1-1), (1-2), (1-3) and (1-4) formulas, the fault current during three phase fault scenarios on 132KV side is as shown in table 4

Table 4: Three Phase Fault Current Level

Fault current	Symmetrical Components			Phase currents			
	I^0	I^+	I^-	I_a	I_b	I_c	IN
In PU	0	3.57<0	0	3.57<0	3.57<0	3.57<0	0
In KA	0	1.56<0	0	1.56<0	1.56<-120	1.56<120	0

Phase currents from table 4:

Ia = 1560<0 A.

Ib = 1560<-120 A.

Ic = 1560<120 A .

Double phase fault current calculations on 132KV OHL:

Reference to (2-1), (2-2), (2-3) and (2-4) formulas, the fault current during double phase fault scenario 132KV side is as shown in table 5:

Table 5: Double Phase Fault Current Level

Fault current	Symmetrical Components			Phase currents			
	I^0	I^+	I^-	I_a	I_b	I_c	IN
In PU	0	1.78<-90	1.78<-90	3.56<-90	1.78<90	1.78<90	0
In KA	0	0.777<-90	0.777<-90	1.55<-90	0.777<90	0.777<90	0

Phase currents from table 5:

Ia = 1550<-90 A.

Ib = 777 <90 A.

Ic = 777 <90A.

Single line to ground fault current calculations on 132KV OHL:

Reference to (3-1), (3-2), (3-3) and (3-4) formulas, the fault current during three phase scenarios on 132KV side is as shown in table 6:

Table 6: Single Phase to Ground Fault Current Level

Fault current	Symmetrical Components			Phase currents			
	I^0	I^+	I^-	I_a	I_b	I_c	IN

| In PU | 0 | 0.19<-90 | 0.19<-90 | 0.38<-90 | 0.19<90 | 0.19<90 | 0 |
| In KA | 0 | 0.083<-90 | 0.083<-90 | 0.166<-90 | 0.083<90 | 0.083<90 | 0 |

Phase currents from table 6:

Ia = 166<-90 A.

Ib = 83 <90 A.

Ic = 83 <90A.

Double line to ground fault current calculations on 132KV OHL:

Reference to (4-1), (4-2), (4-3) and (4-4) formulas, the fault current during three phase scenario on 132KV side is as shown in table 7:

Table 7: Double Phase to Ground Fault Level

Fault current	Symmetrical Components			Phase currents			IN
	I^0	I^+	I^-	I_a	I_b	I_c	
In PU	0	1.84<-90	1.736<-90	3.57<-90	1.79<90	1.79<90	0
In KA	0	0.804<-90	0.758<-90	1.56<-90	0.782<90	0.782<90	0

Phase currents from table 7:

Ia = 1560<-90 A.

Ib = 782<90 A.

Ic = 782<90 A.

VI. DISCUSSION

As has been mentioned on the beginning of this paper of making a backup protection for the power transformer from the 132KV OHL, by making use of overcurrent protection. It is worth to mention that, the overcurrent function is primarily depending upon the fault current, in a sense that the setting of overcurrent function should never be put below than or equal the current of the normal load conditions, in order to avoid any erroneous operation i.e., the fault current should be considerably higher than the normal load conditions. If the fault current is near or not noticeably more than the load current the traditional overcurrent protection cannot be used for protection.

The normal load current is the rated current of the transformer which can be calculated as follows:

Rated current = $\frac{100}{132*\sqrt{3}}$ = 0.437KA.

Fortunately, the fault current from the obtained results during all fault scenarios is far higher than the normal load current except for single line to ground fault, so there will not be any problem of making a backup protection for the transformer or the 33KV busbar during three phase fault,

double phase fault as well as double phase to ground fault. However, in case of single line to ground fault, the phase currents are very low (Ia = 166A, Ib = 83A, Ic=83A), compared with the rated current and applying a setting able to detect single line to ground fault at 33KV side requires to loading the transformer less than 62.7% of its full rating current, otherwise wrong operation is going to happen during very light loads (36% of full load) so overcurrent function cannot be used to detect the fault scenario of single line to ground fault. However, from the fault analysis results, it is obvious that there is no choice but using the negative sequence current to provide a backup protection for the single line to ground fault on 33KV side. The negative sequence current from the analysis of the single line to ground fault = 80A. It is therefore, practical using the negative sequence overcurrent element with a setting of 80A to cater the single line to ground fault scenario. Adopting this solution allows and guarantees more reliable supply for the load and prevents any undesired interruption.

VII. CONCLUSIONS

From the case study results and analysis, it has been clearly proven how feasible and effective to use the negative sequence element for detecting system faults during certain network configurations. It has been found that all types of faults on 33KV busbar except single line to ground fault, is easily to be detected and isolated by employing simple overcurrent relay at the 132KV OHL side. In case of single line to ground fault on 33KV busbar, neither resultant residual current at 132KV side enable using of earth fault element nor a considerable phase currents values allow using the overcurrent relay for protection. It has been found that the negative sequence overcurrent element is effective to be employed, in spite the fact of its low value, because it would ONLY appear in case of un-symmetrical faults. From the case study, it can be concluded that, using of negative sequence element in fault detection can be considered one of the most effective ways in detecting unsymmetrical faults due to the following reasons:

- Negative sequence element is superior to positive sequence element in regards of the fact that, it is only appearing during abnormal conditions, and can be used to detect very low fault currents, while the positive sequence element is limited to be used for very high currents (more than normal load conditions) otherwise it would lead to un-necessary operation.

- Negative sequence element is superior to zero sequence element in regards of the fact that it is independent of the network configuration, unlike the zero-sequence element which depends on transformers vector group. Transformers of vector group such as DELTA-STAR or STAR-DELTA blocks the flow of the zero-sequence current across the transformer, and hence, the zero-sequence current can be lost in some parts of power system during faults and disturbances.

Finally, during three phase fault scenario (Symmetrical fault), negative sequence element can never be used, However,

detection of three phase fault normally is not a concern, since three phase fault causes very high currents with a severe voltage drop, so applying any type of protection is going to be sufficient for a proper detection and isolation.

ACKNOWLEDGMENT

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