**Military Technical College**

**Kobry El-Kobbah,**

**Cairo, Egypt**

**8th International Conference on Electrical Engineering**

I. ICEENG 2012

# Novel Unit Protective Relaying Concept for EHV Interconnected Networks

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***Abstract*****—**In interconnected network, the fault at any section may appear as a forward or a backward at more than one relaying station. This may deceive any protection system using the current signal only. This paper presents a novel principle solution for such problem. The proposed protection is based on extracting the transient components, initiated by faults, using the fourth sequential overlapping derivative, (SOD), concept. SOD is applied to the current and the voltage signals at both protected line terminals. The multiplier of the produced transient components is used as a novel relaying signal. The polarity of the initial change of this relaying signal is depending on the fault direction. Exchanging data between relaying stations using a suitable communication channel enable us to discriminate between internal and external faults and send a tripping signal to the prober circuit breakers. Simulation tests are carried out by ATP program while the relaying concept is established by using MATLAB program. Extensive number of simulation cases, including fault type, fault resistance, fault inception time and load switching effects are presented. Results showed a high sensitivity for internal faults, and high security and stability for external faults. Moreover, no need for samples synchronization and current transformer saturation compensation.

***Index Terms*****— EHV interconnected transmission network, SOD, unit protection, relaying system**

## II. Introduction

Current differential relaying is a method of extending the benefits of differential protection as applied to transformers, buses or generators to the protection of transmission lines. Comparing current flowing into a line with the current flowing out of the same line allows for a simple protection scheme with high sensitivity and high speed simultaneous tripping of both line terminals. At the same time, the differential scheme is unaffected by external effects such as faults, load and power swings. The differential current can be measured with different methods as magnitude comparison, phase comparison, phasor comparison (magnitude and angle), charge comparison and Combinations of the previous [1].

References [2-7] present different differential protection relaying techniques. Ref.[2] presents adaptive fuzzy relay scheme that combines strengths of both current and phase comparison protection criteria. This relay stabilization characteristic is adapted on-line depending on the output of the fuzzy reasoning scheme supplied with information from the phase comparison unit. Ref.[3] presents a current differential relay principle based on Marti model. Compared with Bergeron model based differential protection, the frequency-dependent characteristic of line parameters is taken into account in this principle, so that the calculating result is more accurate. Ref.[4] presents an approach for a current differential protection of the transmission lines. This approach is based on the Clarke-Concordia transformation and principal component analysis. First the acquired current signals are transformed into “αβo” components by applying the Clarke-Concordia transformation. This allows obtaining typical patterns. To identify these patterns a principal component analysis is performed. Ref.[5] presents a transmission line differential relaying scheme based on the comparison of the transient energy in the current signals at both ends of the transmission line. Discrete wavelet transform (DWT) has been employed to extract the transient energy in the current signals. A sliding data window with a length equivalent to half cycle of the fundamental power frequency is used to achieve high speed relaying. Ref.[6] calculates the transient components in pre-fault and in faulty conditions and uses the differential admittance determined in pre-fault conditions to enable significant enhancement of the fault detection sensitivity. Differential protection relays may false tripping for external faults due to current transformer (CT) saturation [7].

Although most of the differential relaying schemes achieve high speed and relaying sensitivity, the performance due to faults in interconnected network are not examined. In interconnected network, the fault at any section may appear as a forward or a backward at more than one relaying station. This may deceive any protection system using the current signal only. In this paper a novel differential protection for such problem is presented. The proposed protection uses the fourth sequential overlapping derivative [8] of both current and voltage signals to extract the transient components initiated due to fault occurrence at both line terminals. The produced transient components from voltage signal and its corresponding in the current signal are multiplied and then used as a novel relaying signal. Fault direction, now, is depending on the polarity of the initial change of this relaying signal. Negative polarity at the relay location will indicate forward direction while positive polarity will indicate backward direction. Suitable communication channel is used to exchange data between the relaying stations to discriminate between internal and external faults and send a tripping signal to the prober circuit breakers. Intensive simulation fault tests carried out in ATP model, including fault type, fault resistance, fault inception time and switching effects. The proposed principle provides sensitive protection for internal faults, and high security and stability for external faults and load switching effects. This principle avoids the CT saturation problems and does not need synchronization.

## III. The Proposed Relay Concept

The proposed protection is a line differential relay assumes having two relays, equipped with sending-receiving units, one at each end of the protected line, (s. Fig 1). Each relay applies the SOD concept on both voltage and current signals to extract the transient components as following:

$$SV(n)=V(n)-[4*V(n-1)]+[6*V(n-2)]-[4*V(n-3)]+V(n-4) \quad (1)$$

$$SI(n)=I(n)-[4*I(n-1)]+[6*I(n-2)]-[4*I(n-3)]+I(n-4) \quad (2)$$

Where, $V$ and $I$ represent the instantaneous phase voltage signal and phase current signal respectively, $n$ is the instantaneous sample number. The process will continue over the interested period, five samples, of the original signal as the new samples, $V(n)$ and $I(n)$, are entered the old samples, $V(n-4)$ and $I(n-4)$, are exit. The produced transient components from both voltage and current signals are used as a novel relaying, $SP(n)$, as following;

$$SP(n)= SI(n) * SV(n) \quad (3)$$

The novel differential relaying concept is composed of starting criteria and selection criteria. The following two sections will discuss them respectively.

### *A. Starting Criteria*

As the SOD concept is an extractor to the transient components and an eliminator to both of the dc and the fundamental components, its outputs are affected by the sampling frequency. So the fault is detected as soon as the SOD signals exceed a predetermined threshold limit, £. The threshold limit £ will be defined as follows:

$$£= V_m/f_s \quad (4)$$

Where, $V_m$ is the peak value of the phase voltage of the studied interconnected system and $f_s$ is the sampling frequency chosen for simulation.

### *B. Selection Criteria*

The proposed selection criteria is mainly based on detecting the polarities of the relaying signals, SP(n), at both ends of the protected section. This is done as the relaying signals exceed the predetermined threshold limit, £. Using the convention of direction of current transformers as shown by Fig. 1, the fault is forward when the polarity of the first edge of the $SP(n)$ is negative, -ve, otherwise the fault is considered backward. Therefore, the internal fault is defined when the polarities of the first edge of the *SP(n)* at each relay location are negative. Otherwise the fault is considered external. Table 1 illustrates the *SP(n)* polarities and the relay decision.

TABLE 1
SP(n) POLARITIES AND RELAY DECISION

| Relay A | | Relay B | | Fault Location | Relay Decision |
|---|---|---|---|---|---|
| Polarity | Direction | Polarity | Direction | | |
| - | F | - | F | Internal | Tripping |
| + | B | - | F | External | Blocking |
| - | F | + | B | External | Blocking |
| + | B | + | B | External | Blocking |

## IV. Test Results

The analysis is performed within the mathematical programming environment of MATLAB with the signals generated via the ATP program. The system parameters are taken from the 500 kV Egyptian Unified Power System. The power system and transmission lines data are listed in Appendix A. The sampling frequency used in simulation studies is chosen to be 100kHz. So, the predetermined threshold limit, £, according to equation 4 is 4.8 *V/Hz*.

The proposed relaying scheme is applied on the interconnected system shown by Fig.1. The protection response for relays *R1, R2, R3, R4, R5* and *R6* is studied under five conditions as following;

1. Faults in line AB, F1
2. Faults in line BC, F3
3. Faults in line AC, F5
4. Faults at busbars A, B and C, F4, F2 and F6 respectively.
5. Load switching at busbars A, B and C

Relays performances for such conditions are visualized by Fig.2, Fig.3, Fig.4, Fig.5 and Fig.6 respectively. Each figures show the response of the six relays (*R1, R2, R3, R4, R5* and *R6*). Table 2 summarized all the relays decisions.

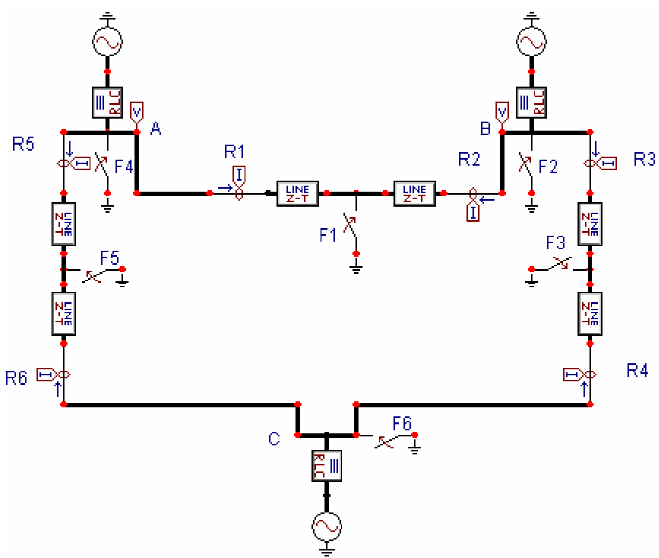


Fig.1.The studied interconnected network

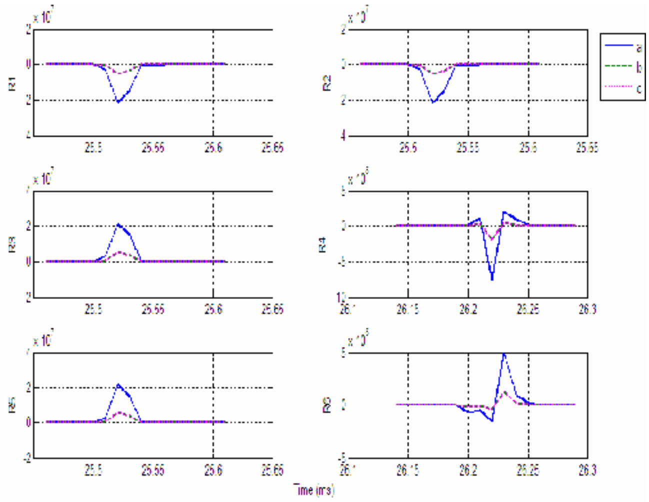

Fig.2. Relays response for Fault located at F1, in line AB

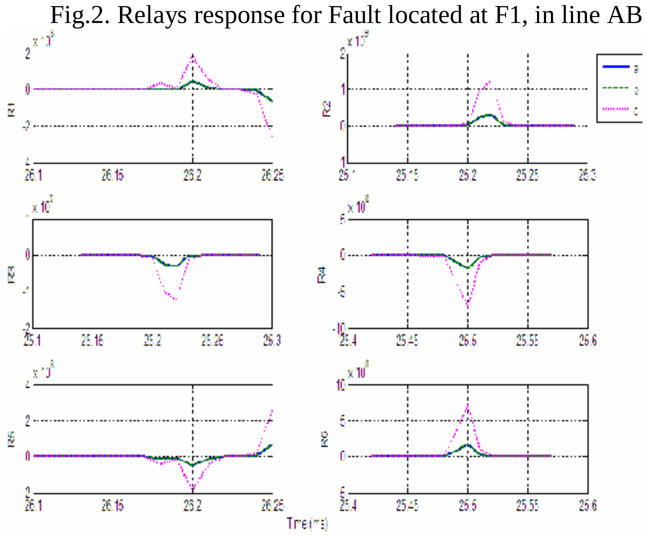

Fig.3. Relays response for Fault located at F3, in line BC

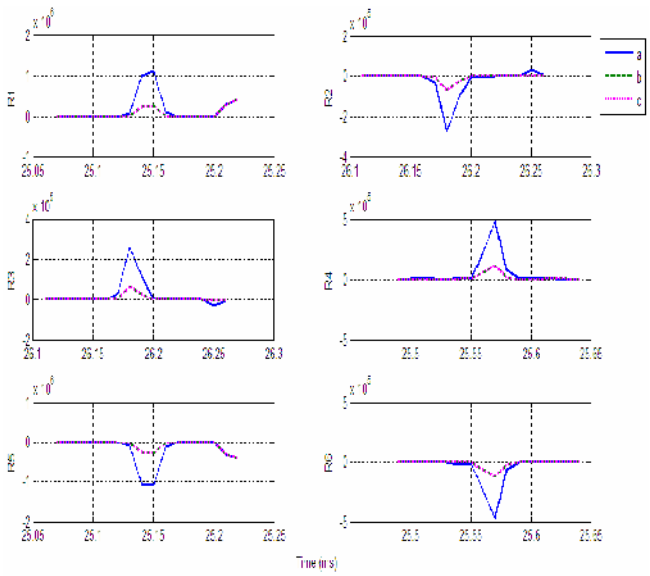

Fig.4. Relays response for Fault located at F5, in line AC

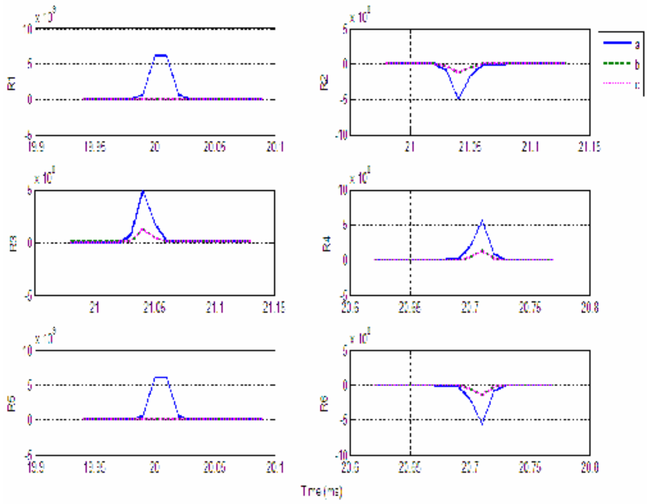

Fig.5. Relays response for Fault located at bus A, F4

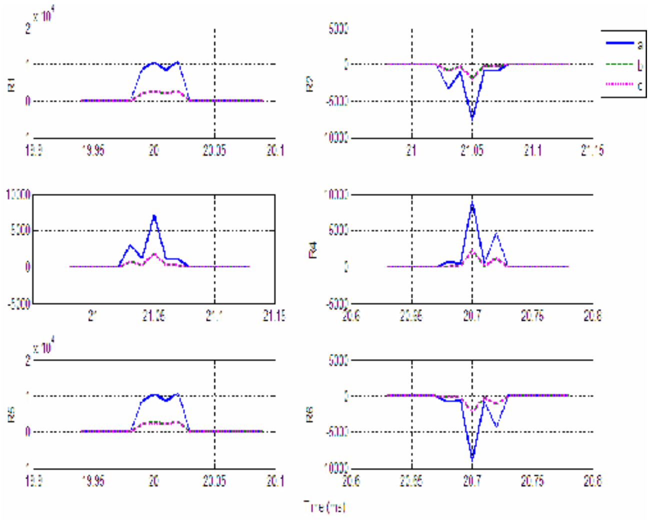

Fig.6. Relays response for load switching at bus A

TABLE 2
RELAYING STATIONS RESPONSE

| Case no | Fault At | Location (km) | *R1* | *R2* | *R3* | *R4* | *R5* | *R6* | Protection Decision |
|---|---|---|---|---|---|---|---|---|---|
| 1 | F1 | 150 from A | - | - | + | - | + | + | Trip line AB |
| 2 | F3 | 40 from B | - | + | - | - | + | + | Trip line BC |
| 3 | F3 | 60 from B | + | + | - | - | - | + | Trip line BC |
| 4 | F5 | 40 from A | + | - | + | + | - | - | Trip line AC |
| 5 | F5 | 60 from A | + | + | - | + | - | - | Trip line AC |
| 6 | F4 | At bus A | + | - | + | + | + | - | Blocking |
| 7 | F2 | At bus B | - | + | + | - | + | + | Blocking |
| 8 | F6 | At bus C | + | + | - | + | - | + | Blocking |
| 9 | Load switching at bus A | | + | - | + | + | + | - | Blocking |
| 10 | Load switching at bus B | | - | + | + | - | + | + | Blocking |
| 11 | Load switching at bus C | | + | + | - | + | - | + | Blocking |

It is clear evident that a tripping signal is initiated to disconnect the faulted line when the fault is internal. This is done if the initial changes of the polarities at the two relays protecting the line are negative, see Fig.2, Fig.3 and Fig.4 for lines AB, BC and AC internal faults respectively. This is cleared by the first five rows of Table 2 for F1, F3 and F5 faults. Blocking decisions are taken by all relays for busbars faults, F2, F4 and F6. Also Blocking decisions are taken by all relays for load switching condition at busbars A, B and C. It is well known that internal faults in certain line will appear for the others relays as external faults. This is due to the non negative polarities recognized at both protected line ends. It is interesting to know that, F3 faults, for example, may be seen by R1 as a forward or a backward depending on which current paths, F3-B-A or F3-C-A, is shorter. Although of this the proposed relaying system succeeded to select the faulted line and send a tripping signal to the proper circuit breakers.

## V. Fault Condition Effects

Various fault types, fault locations, fault resistances and fault inception times are studied to examine the proposed relaying technique for *R1* and *R2*. Fault location is varied along the protected line length (line AB); at F1. Fault resistance is varied from 0.0Ω to 2000Ω and fault inception time is varied along the waveform. Results are presented in the following subsections by Figs.7-19 and Tables 3- 6.

### *a. Fault Location Effect*

The effect of changing fault location on the proposed concept is discussed here. Fig.7, Fig.8 and Fig.9 present R1 and R2 response due to phase a to ground faults, 25Ω fault resistance and 25ms inception time at fault locations 3km, 150km and

297Km from bus A at transmission line AB which its length is 300km respectively. Table 3 summarized the SP(n) values at the detection instant due to these cases.

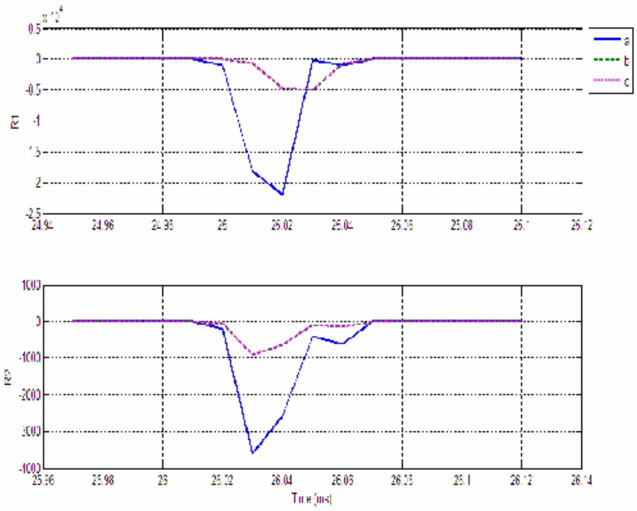

Fig.7. R1 and R2 responses due to phase a to ground fault located at 3 Km from bus A

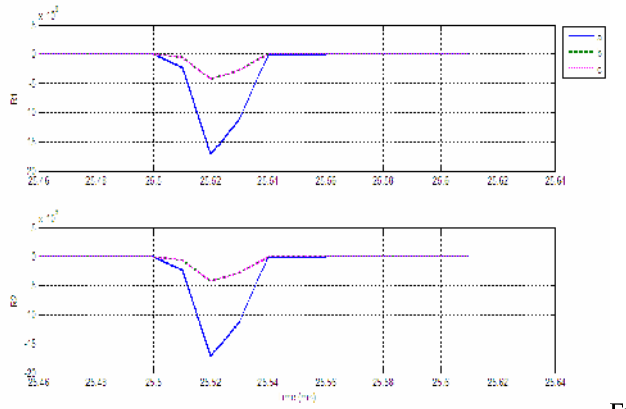

Fig.8. R1 and R2 responses due to phase a to ground fault located at 150 Km from bus A

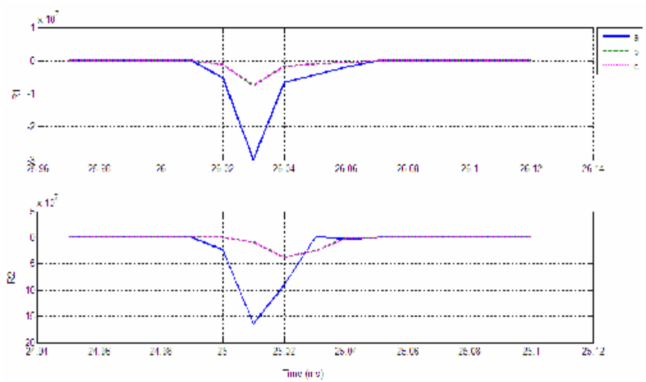

Fig.9. R1 and R2 responses due to phase a to ground fault located at 297 Km from bus A

TABLE 3
FAULT LOCATION EFFECT

| Fault Location from A (km) | | | 3 | 150 | 297 |
|---|---|---|---|---|---|
| SP(n) | Phase a | R1 | -949 | -2,271,000 | -5,230,300 |

| | | | | | |
|---|---|---|---|---|---|
| values at the detection instant | | R2 | -215 | -2,271,000 | -23,076,000 |
| | Phase b | R1 | -8 | -567,750 | -1,307,600 |
| | | R2 | -54 | -567,750 | -196,310 |
| | Phase c | R1 | -8 | -567,750 | -1,307,600 |
| | | R2 | -54 | -567,750 | -196,310 |
| **Decision** | | | **Trip** | **Trip** | **Trip** |

It is clear that, the relaying signals, SP(n), exceed the threshold limit, £=4.8, and all the relaying signals are negative at both line ends. This means that, the proposed protection is successfully detecting the close up and the remote end faults.

*b. Fault Type Effect*

Figs 10, 11, 12 and 13 present BG, AB, AB-G and ABC faults. These faults are set at 200 km from bus A at transmission line AB which its length is 300km, 20ms inception time and 100Ω fault resistance for the ground faults. Values of the SP(n) at the detection instant due to these cases are summarized by Table 4.

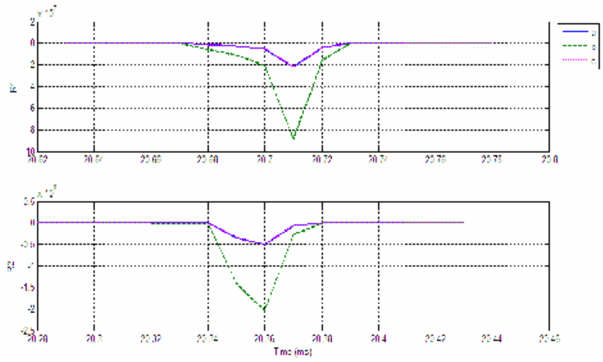

Fig.10. R1 and R2 responses due to phase b to ground fault

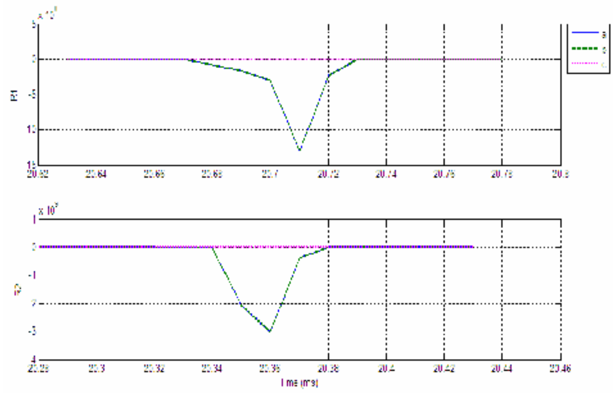

Fig.11. R1 and R2 responses due to phase ab fault

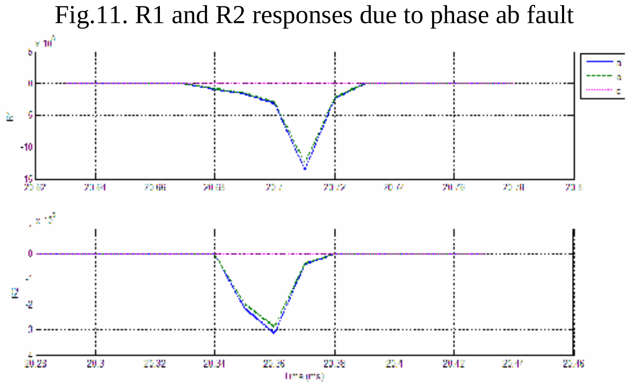

Fig.12. R1 and R2 responses due to phase ab to ground fault

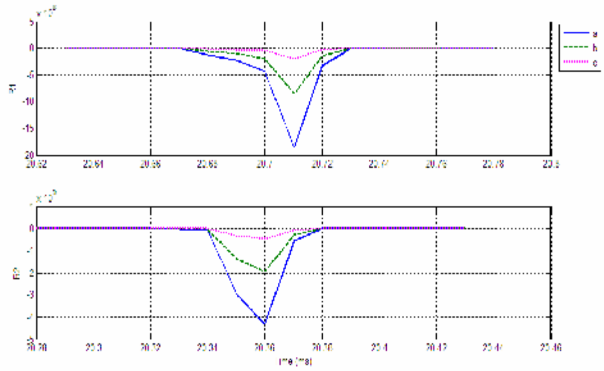

Fig.13. R1 and R2 responses due to phase symmetrical fault

TABLE 4
FAULT TYPE EFFECT

| Fault type | | BG | AB | ABG | ABC |
|---|---|---|---|---|---|
| Phase a | R1 | -1,455,100 | -86,211,000 | -89,857,000 | -123,350,000 |
| | R2 | -366,640 | -21,723,000 | -22,642,000 | -31,082,000 |
| Phase b | R1 | -5,820,300 | -86,211,000 | -82,641,000 | -55,703,000 |
| | R2 | -1,466,500 | -21,723,000 | -20,823,000 | -14,036,000 |
| Phase c | R1 | -1,455,100 | — | -151,020 | -13,272,000 |
| | R2 | -366,630 | — | -38,052 | -3,344,100 |
| decision | | Trip | Trip | Trip | Trip |

It is evident that the proposed protection gives correct response to all fault types. For phase to phase faults, the un-faulted phase is not affected.

*c. High Fault Resistance Effect*

Detection of high impedance faults (HIFs) is generally difficult by conventional over-current protection devices, because they have high impedance at the fault point and don't cause an excessive change of current in the affected line. Therefore, detection of HIFs is critically important [9]. Figs.14. 15 and 16 show the relaying signals, SP(n), response for phase c to ground fault, at 290km from bus A at transmission line AB which its length is 300km and 22 ms inception time through fault resistance 0Ω, 400Ω and 2000Ω respectively. The SP(n) values at the detection instant due to these cases is summarized by Table 5.

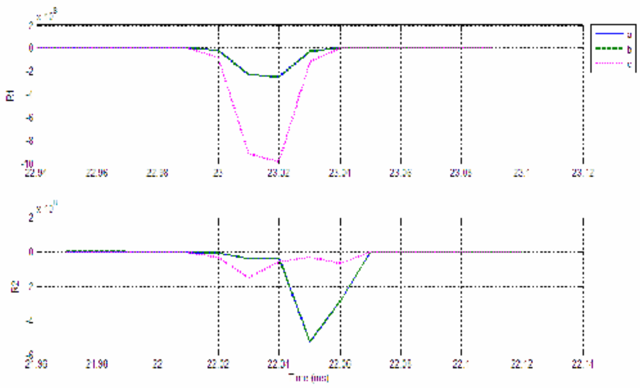

Fig.14. R1 and R2 responses due to solidly phase c to ground fault

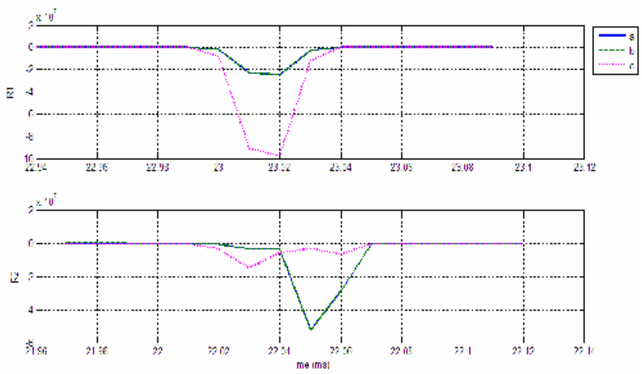

Fig.15. R1 and R2 responses due to phase c to ground fault through 400Ω fault resistance

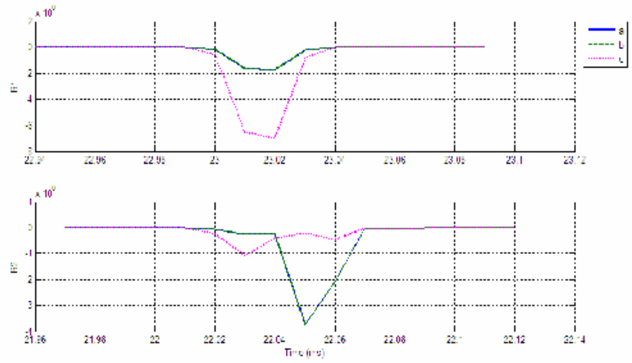

Fig.16. R1 and R2 responses due to phase c to ground fault through 2000Ω fault resistance

TABLE 5
FAULT RESISTANCE EFFECT

| **Fault resistance (Ω)** | | | 0 | 400 | 2000 |
|---|---|---|---|---|---|
| **SP(n) values at the detection instant** | Phase a | R1 | -83,978 | -8,385 | -601 |
| | | R2 | -8,665,900 | -865,220 | -61,986 |
| | Phase b | R1 | -83,979 | -8,385 | -601 |
| | | R2 | -8,665,900 | -865,230 | -61,986 |
| | Phase c | R1 | -335,910 | -33,539 | -2,403 |
| | | R2 | -34,664,000 | -3,460,900 | -247,940 |
| Decision | | | Trip | Trip | Trip |

Results indicate that fault resistance reduces the relaying signal magnitude, while the high frequency noise still exists. The relaying signal succeeded in detecting transient component for the remote end faults with high fault resistance up to 2000Ω as the signals exceeds the threshold limit; £. High fault resistance does not affect the relaying signals polarities.

### *d. Fault Inception Time Effect*

Inception time is another important factor that affects the high frequency component initiated due to faults. Figs. 17, 18 and 19 present the simulation results for solidly phase c to ground fault located at 150 km from bus A at transmission line AB which its length is 300km at inception time 20ms, 25ms and 28ms respectively. Table 6 summarized the values of the SP(n) at the detection instant due to these cases.

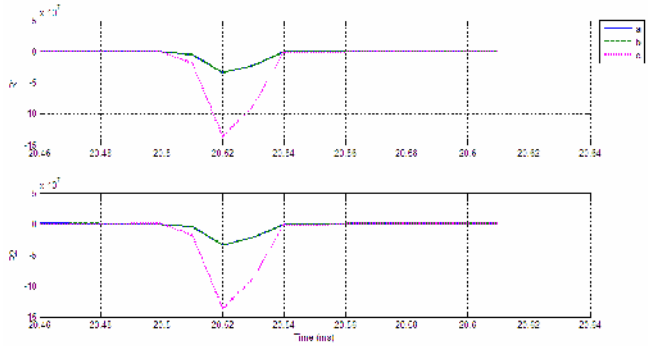

Fig.17. R1 and R2 responses due to phase c to ground fault at 20ms inception time

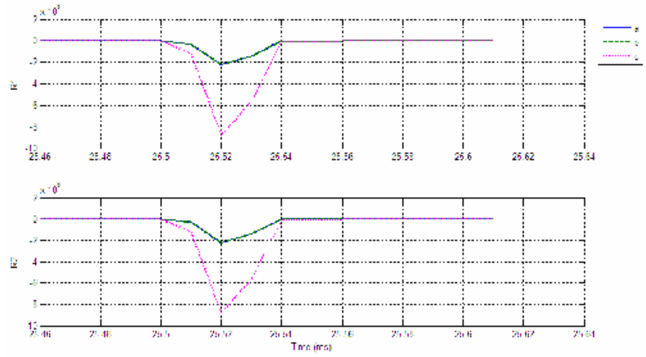

Fig.18. R1 and R2 responses due to phase c to ground fault at 25ms inception time

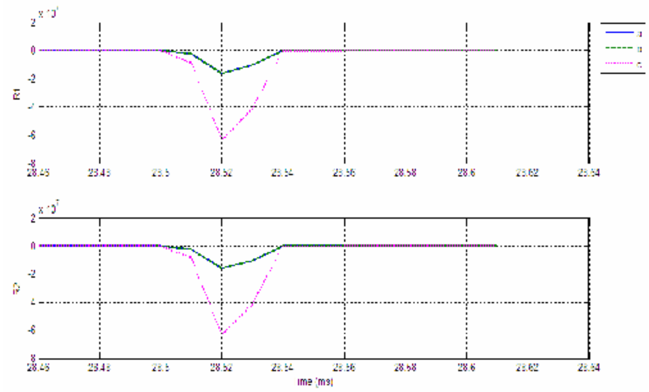

Fig.19. R1 and R2 responses due to phase c to ground fault at 28ms inception time

TABLE 6
FAULT INCEPTION TIME EFFECT

| **Inception time (ms)** | | 20 | 25 | 28 |
|---|---|---|---|---|
| Phase a | R1 | -4,619,500 | -29,524,000 | -2,116,900 |
| | R2 | -4,619,500 | -29,524,000 | -2,116,900 |
| Phase b | R1 | -4,619,500 | -29,524,000 | -2,116,900 |
| | R2 | -4,619,500 | -29,524,000 | -2,116,900 |
| Phase c | R1 | -18,478,000 | -118,090,000 | -8,467,500 |
| | R2 | -18,478,000 | -118,090,000 | -8,467,500 |
| **Decision** | | Trip | Trip | Trip |

Table 6 shows that, inception time does not affect the relaying signal polarity.

## VI. Conclusion

This paper presents a novel differential protection concept for EHV interconnected transmission networks. In such networks, faults may be seen forward or backward at more than one relaying station. This may deceive the protection system especially those which using the current signal only. The proposed protection extracts the transient components initiated applying the fourth sequential overlapping derivative concept to both current and voltage signals. Transient components produced from both voltage and current signals are multiplied to be used as a novel relaying signal. The novel differential relaying concept is composed of starting criteria and selection criteria. The starting criteria ends as soon as relaying signals exceed the predetermined threshold limit. At this instant, the selection criteria records the polarities of such signals. Fault direction is depending on these polarities. If these polarities are negative, -ve, fault is forward to the relaying station otherwise fault is backward. Therefore, the internal fault is defined when these polarities at both relays protecting a certain line are negative. Otherwise the fault is considered external. Suitable communication channel is used to exchange data between the relaying stations to discriminate between internal and external faults and send a tripping signal to the prober circuit breakers. Fault type, fault location, fault resistance, fault inception time and load switching effects are studied. The proposed protection provides sensitive protection for internal faults, and high stability for external faults and the load switching condition. It responses sensibly for faults even the earth fault via a high resistance. The proposed principle avoids the CT saturation problems and does not need any synchronization.

## Appendix A

The following data are valid for this application:

- Positive sequence resistance, reactance and capacitance are 0.0217Ω/km, 0.302Ω/km and 3.96µMho/km.
- Zero sequence resistance, reactance and capacitance are 0.247Ω/km, 0.91Ω/km and 2.94µMho/km.

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