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A novel algorithm for improving the differential protection of power transmission system

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ABSTRACT

Current differential protection is simple in principle and is immune to power swings, load encroachment and mutual coupling problems. It provides simultaneous tripping at both ends of the transmission line and multi phase auto reclosing can be easily enabled because of its accuracy in determining the faulted phase and its communication channels. Conventional differential protection has certain issues to be dealt with before using it as a best alternative to distance protection for power transmission lines. Many researchers strive to improve the sensitivity of the current differential protection. Sensitivity and safety are opposing elements and increased sensitivity may sacrifice safety. In this paper, a new differential protection algorithm is proposed using the polarity of the terminal current DC transients. Different cases are studied in order to illustrate the applicability of the proposed differential approach. The proposed algorithm is able to detect high resistance faults and is not affected by line charging current, CT saturation. It improves the sensitivity without compromising the safety of the system. Simulations are carried out on 10 Bus system using PSCAD® software and obtained results are used for illustrating the efficiency of the proposed differential protection.

1. Introduction

Transmission lines play a vital role in electrical power systems as they provide path to transfer power between generation and load to reach end consumers. The probability of occurring faults on power transmission lines is very high compared to other components as they are generally long enough and runs through open atmosphere. Utilities are pressurized to operate transmission lines close to their operating limits due to deregulated market environment, right of way clearance, economics and environmental requirements. In such a power system network, any fault if not detected and isolated quickly will results in cascade tripping causing wide spread outages. Hence, transmission line protection should be secure and sensitive enough in reliably detecting and isolating the faults.

Distance protection [1] is the most widely used protection since many years for power transmission lines as it provides instantaneous tripping over fixed reach, independent of source impedance variations and is inherently directional. But distance protection have certain drawbacks [2,3] like it is susceptible to unwanted operation during high load conditions and power swings which may result in cascaded trippings and wide spread blackouts and mal-operation due to mutual impedance and high resistance faults. The distance protection depends on voltage and is affected by infeed and outfeed effects. Hence going for an alternative to distance protection is very much necessary and differential protection is chosen as the best alternative due to advancement in communication technology.

Current differential protection is simple in principle and is immune to power swings and load encroachment problems. It provides simultaneous tripping at both ends for 100% of line length and voltage inputs are not required. Differential protection is immune to mutual coupling and multi phase auto reclosing can be easily enabled because of its accuracy in determining the faulted phase and its communication channels. But conventional current differential protection still have some problems that need to be addressed like maloperation due to existance of the differential current because of line charging current, high resistance faults in heavily loaded lines, CT saturation, cross country faults and sampling misalignment. Many methods were developed for mitigating the drawbacks of the conventional differential protection.

In long transmission lines due to distributed nature of the capacitance, the sending end current will not be equal to receiving end current which results in differential current. If this is more than restraining current, protection operates unnecessarily. Most of the utilities employs setting desensitization by keeping the threshold value above charging

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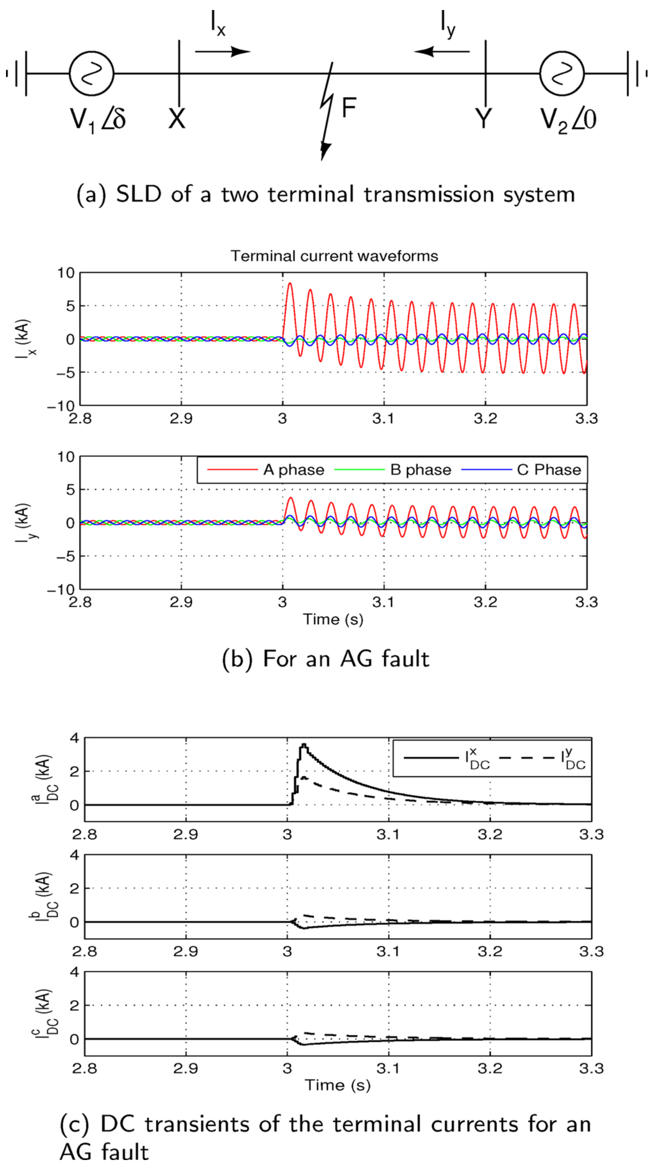


Fig. 1. SLD of the two terminal transmission line along with the waveforms pertains to an internal AG fault at the midpoint of the line X-Y.

current which compromises the sensitivity. Voltage based compensation for charging current by considering equivalent π model of the transmission line for different transmission networks was proposed by [4,3,5]. Bi et al. [6] proposes a voltage based compensation calculating the capacitance from voltage and current measurements. But the compensation depends on voltage and may not operate for loss of potential. Aziza et al. [2] uses power for differential operation. Though it is not much effected by charging current, different phase faults cannot be identified. Xu et al. [7] proposes a steady state distributed parameter transmission line model which takes care of distributed capacitance inherently but depends on point of comparison and accurate parameters. Yining et al. [8] proposes a time domain compensation from π equivalent circuit of transmission line, but it largely depends on precise measurement of parameters.

Ha et al. [9] proposes a method using travelling forward and backward waves for differential comparison but sensitivity is effected by load. Sivanagaraju et al. [10] first calculates the fault location and then the currents using the distributed parameters from both sides at the fault point for comparison. Dengl et al. [11] proposes an active current proportional to voltage for comparison which is independent of capacitive current. Ma et al. [12] and Bolandi et al. [13] proposes a virtual impedance from fault component of voltage and current for comparison. All these methods are based on distributed parameter transmission line modelling which requires exact values of line parameters and modelling is also very difficult.

CT saturation is of more concern during external faults with heavy fault current with one of the CT getting into saturation. In order to mitigate maloperation due to CT saturation, external fault detection algorithms are employed such that settings can be adapted accordingly. Villamagna et al. [14] mitigates the effect of CT saturation by monitoring rate of change of zero sequence components of differential current. Bagleybter et al. [15] describes transient bias technique which is a function of deltas of differential and bias currents. AI-Fakhri [16] proposed a method based on incremental currents. Hao et al. [17] proposes phaselet algorithm which can accurately obtain the basic frequency component of fault current with the unsaturated data segment of CTs distorted secondary current in a relatively short time window. But through fault at the time of desensitization is of concern.

Cross differential protection employed for parallel transmission lines uses data from only one end of transmission line and hence does not require communication. Wang et al. [18] developed a cross differential protection using current amplitudes of double lines. Eissa et al. [19] compares the incremental currents. Pasand et al. [20] proposes an adaptive differential relay with a combination of cross differential and impedance based techniques. Li et al. [21] proposes a transverse differential protection based on impedance comparison of the parallel circuits measured at one end. Cross differential protection alone cannot operate if one of the transmission line is out of service.

For mitigating high resistance faults the methods used are of adaptive in nature. Gang et al. [22], Shi et al. [23] implements an adaptive dispersed phase current differential protection combining instantaneous value with fault current instantaneous value. Miao et al. [24] proposes an algorithm in which restrain coefficient "K" is made adaptive. Wang et al. [25] proposes a virtual restrain current which contains phase information of bigger current and amplitude information of smaller current. Villamagna et al. [26] proposes a method in which polarizing quantity i.e., the phase domain differential angles provides a reference to which the sequence domain differential angles are referred. Linlin et al. [27] proposes a criterion based on combination of the amplitude and phase difference of fault current. Altuve et al. [28], Kasztenny et al. [29] and Silva et al. [30] proposed current differential protection on alpha plane, which has advantages of easily accumulating sampling misalignment errors.

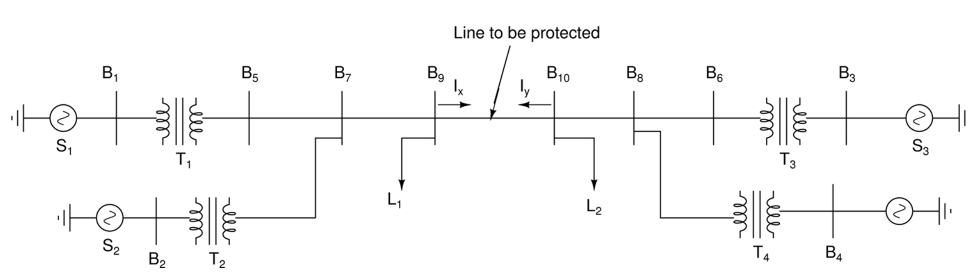


Fig. 2. SLD of a 10 bus system.

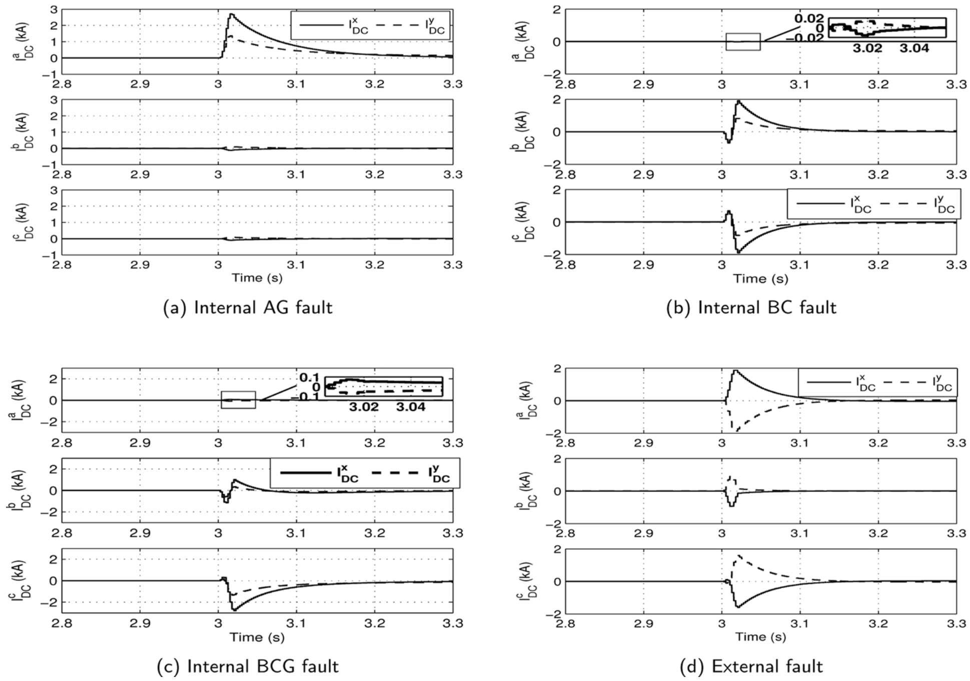


Fig. 3. DC transients of terminal currents for different types of internal and external faults at the midpoint of Transmission line between B_9 and B_{10}.

Table 1
Fault identification logic for different types of fault for two terminal transmission line.

(1)	(2)	(3)	Decision	Type of fault
×	✓	✓	Internal Fault	BCG/BC
✓	×	✓	Internal Fault	CAG/CA
✓	✓	×	Internal Fault	ABG/AB
✓	×	×	Internal Fault	AG
×	✓	×	Internal Fault	BG
×	×	✓	Internal Fault	CG
✓	✓	✓	Internal fault	ABC/ABCG
×	×	×	External fault	External fault

✓⇒ satisfying condition.
×⇒ not satisfying condition.

All the proposed methods are specialized for mitigating one or two drawbacks of the conventional differential protection. Some sophisticated methods with many advantages are very complex in nature and are difficult to adopt. Some methods operating for one type of network may not operate for other types of transmission line networks. Hence there is a need for identifying a method such that it mitigates almost all the drawbacks of conventional differential protection with minimal modifications and should operate reliably and is easy for implementation. In this paper, a current differential protection based on DC transients of the terminal currents is proposed which can detect high resistance faults and is not effected by line charging currents, CT saturation and can be applied for different network configurations.

2. Basic principle of proposed differential protection

A new differential protection is proposed based on DC transients of the terminal currents, of the transmission line to be protected [31]. The scheme is based on sign of the DC transients. For an internal fault the DC transients will have the same sign and for an external fault DC transients have the opposite sign with the convention of current directions. The sign of the DC transients depends upon the current flow direction and fault inception angle. For an external fault the current flows in one direction and hence I_x and I_y will be opposite to each other there by the sign of the DC transients will also be opposite. In case of internal fault, the current flow in the transmission line will have the same sign and is the same for corresponding current DC transients. The criteria for confirming an internal or external fault is that the sign of the DC transients either same or opposite to each other should last for atleast half a cycle.

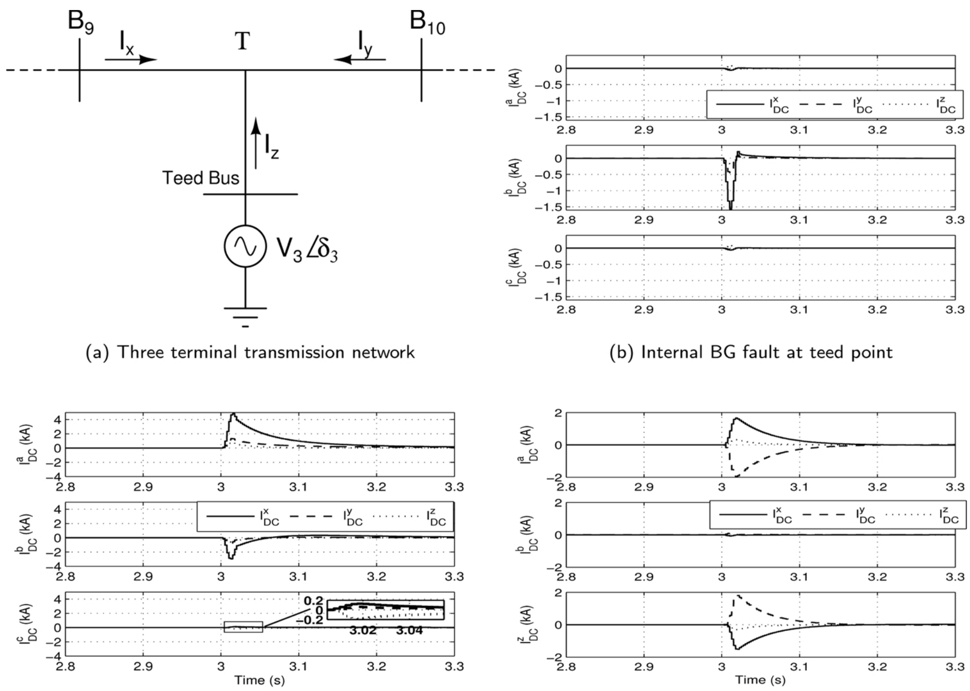
In order to prove the behavior of the DC transients at both the terminals of the transmission line mathematically, a simple single-phase circuit, composed of two RL line sections in cascade (with the fault resistance between them), and two Thevenin equivalents (each one connected to one of the line terminals) is considered. The mathematical derivation of the proposed circuit is given in Appendix B.

Considering a transmission line shown in Fig. 1a, the concept of proposed differential protection can be explained. An A-G fault is considered at the mid-point of the transmission line (of length 100 km). Fault is applied at 3 s. The terminal current waveforms of the transmission line are shown in Fig. 1b. The DC transients of the terminal currents I_x and I_y for an AG fault are given in Fig. 1c. The DC transients of A phase currents are having the same sign and the DC transients of B and C phases have opposite sign in convention with the current directions taken as shown in Fig. 1a, as the fault involves A phase, as discussed.

2.1. Illustration of proposed scheme for a two terminal transmission line

For illustrating the logic of the proposed differential protection in identifying different types of faults, a 10 Bus system shown in Fig. 2 is considered for simulation in PSCAD® software. The parameters of the system are given in Appendix A. Applying an AG fault on the system shown in Fig. 2 at the midpoint between the buses B_9 and B_{10}, DC transients of the terminal currents are shown in Fig. 3a. It is observed that DC transients of one of the phases are having same sign, hence it is an internal fault and as that phase is A phase and DC transients of the other phases are having opposite sign, the fault can be identified as AG fault.

DC decaying components are extracted using FFT with a sampling frequency of 800 Hz. The decision in determining the internal and external faults can be made even after few samples from the behavior of the DC transients. But, in order to avoid nuisance tripping sometimes a



(a) Three terminal transmission network (b) Internal BG fault at teed point

(c) Internal ABG fault at teed point (d) External fault

Fig. 4. DC transients of terminal currents for different types of faults at Teed point between B_9 and B_{10}.

Table 2
Fault identification logic for different types of fault for Teed Transmission line.

(4)	(5)	(6)	Decision	Type of fault
×	✓	✓	Internal fault	BCG/BC
✓	×	✓	Internal fault	CAG/CA
✓	✓	×	Internal fault	ABG/AB
✓	×	×	Internal fault	AG
×	✓	×	Internal fault	BG
×	×	✓	Internal fault	CG
✓	✓	✓	Internal fault	ABC/ABCG
×	×	×	External fault	External fault

✓⇒ satisfying condition.
×⇒ not satisfying condition.

time period of around half a cycle is taken for deciding the type of the fault, provided the data from the other end is readily available for comparison.

Similarly, BC fault is considered on the system. The DC transients of terminal currents are shown in Fig. 3b and is observed that the DC transients of B and C phases are having same sign which indicates that the fault involves B and C phases and change observed in the DC transient waveforms of A phase is very small as ground is not involved in the fault. Now, a BCG fault is applied on the system. The DC transients of three phases from both the terminals are shown in Fig. 3c. The DC transients of B and C phases from both the terminals are having same sign and DC transients of A phase are having opposite sign and the magnitude of transients is significant compared to Fig. 3b, from which it can be identified that fault is on B & C phases and involves ground. However, there is no significance in identifying whether it is BC or BCG fault in protection point of view. And for an external fault on the transmission line between the buses B_{10} and B_8, the DC transients are shown in Fig. 3d and is observed that the DC transients of all the three phases are having opposite sign.

From the above observations, decision on internal and external faults and different types of the faults can be identified from the sign of the DC transients. Based on the observations, the fault identification logic is shown in Table 1. The conditions described in Table 1 are given below:

$$\{(I_{DC}^{ax} > 0)\&(I_{DC}^{ay} > 0)\}(\mathrm{OR})\{(I_{DC}^{ax} < 0)\&(I_{DC}^{ay} < 0)\} \quad (1)$$

$$\{(I_{DC}^{bx} > 0)\&(I_{DC}^{by} > 0)\}(\mathrm{OR})\{(I_{DC}^{bx} < 0)\&(I_{DC}^{by} < 0)\} \quad (2)$$

$$\{(I_{DC}^{cx} > 0)\&(I_{DC}^{cy} > 0)\}(\mathrm{OR})\{(I_{DC}^{cx} < 0)\&(I_{DC}^{cy} < 0)\} \quad (3)$$

If any of the three conditions (1)–(3) satisfies, it is an internal fault and if all the three conditions does not satisfies it is an external fault. Further the faulty phases can be identified with the DC transients having same sign for the respective phases as given in Table 1.

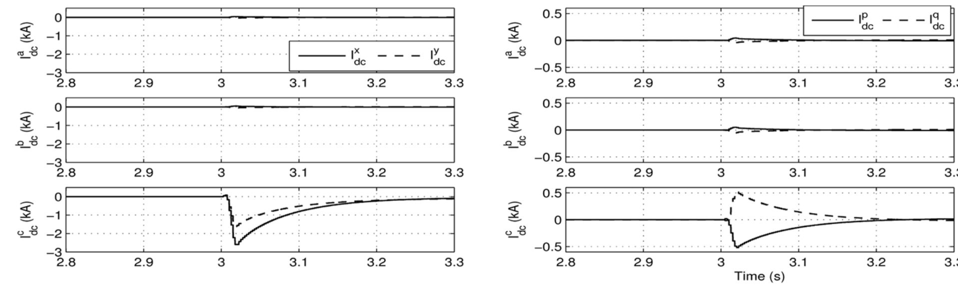
2.2. Application of proposed differential protection for Teed transmission network

A three terminal transmission network shown in Fig. 4a is included between the buses B_9 and B_{10} of the system shown in Fig. 2. Simulations are carried out with different types of faults for identifying internal/external faults and type of the fault on a three terminal transmission network.

BG fault is applied at the Teed point and DC transients of the three terminal currents are shown in Fig. 4b. It is observed that DC transients of B phase of all the three terminals are having the same sign and DC transients of the other two phases are not having same sign indicating B phase fault. ABG fault is considered at Teed point and DC transients are shown in Fig. 4c from which it is observed that transients are having the same sign for A and B phases and not having the same sign for C phase which indicates an AB/ABG fault. Now an external fault is considered between the buses B_{10} and B_8. The DC transients of the terminal currents are shown in Fig. 4d and is observed that all the DC transients are not in the same direction, which indicates an external fault.

Apart from identifying internal/external faults, different types of the faults can be identified by observing DC transients and are given in Table 2. The conditions mentioned in Table 2 are given in (4)–(6).

$$\{(I_{DC}^{ax} > 0)\&(I_{DC}^{ay} > 0)\&(I_{DC}^{az} > 0)\}(\mathrm{OR})\{(I_{DC}^{ax} < 0)\&(I_{DC}^{ay} < 0)\&(I_{DC}^{az} < 0)\} \quad (4)$$



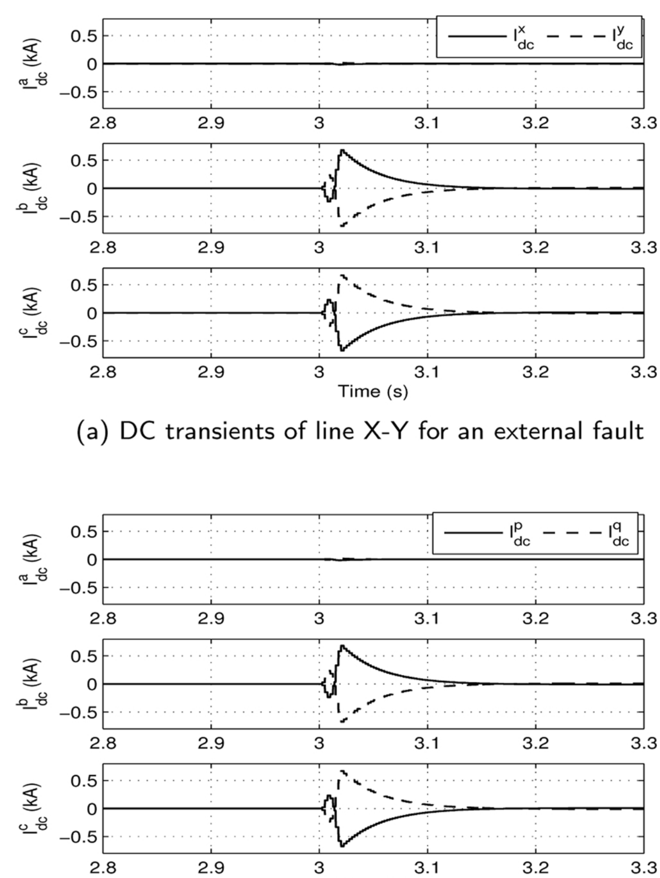
(a) DC transients of line X-Y for an internal CG fault on line X-Y

(b) DC transients of line P-Q for an internal CG fault on line X-Y

(c) DC transients of line X-Y for an internal BG fault on line P-Q

(d) DC transients of line P-Q for an internal BG fault on line P-Q

Fig. 5. DC transients of the terminal currents for internal faults on line1 and line2 of double circuit transmission line between B_9 and B_{10}.



(a) DC transients of line X-Y for an external fault

(b) DC transients of line P-Q for an external fault

Fig. 6. DC transients of the terminal currents of line1(X-Y) and line2(P-Q) for an external fault between B_{10} and B_8.

$$\{(I_{DC}^{bx} > 0)\&(I_{DC}^{by} > 0)\&(I_{DC}^{bz} > 0)\}(\mathrm{OR})\{(I_{DC}^{bx} < 0)\&(I_{DC}^{by} < 0)\&(I_{DC}^{bz} < 0)\} \quad (5)$$

$$\{(I_{DC}^{cx} > 0)\&(I_{DC}^{cy} > 0)\&(I_{DC}^{cz} > 0)\}(\mathrm{OR})\{(I_{DC}^{cx} < 0)\&(I_{DC}^{cy} < 0)\&(I_{DC}^{cz} < 0)\} \quad (6)$$

If any of the conditions (4)–(6) satisfies it is an internal fault and if all the three conditions does not satisfies it is an external fault. Further the faulty phases can be identified with the DC transients having same sign for the respective phases as given in Table 2.

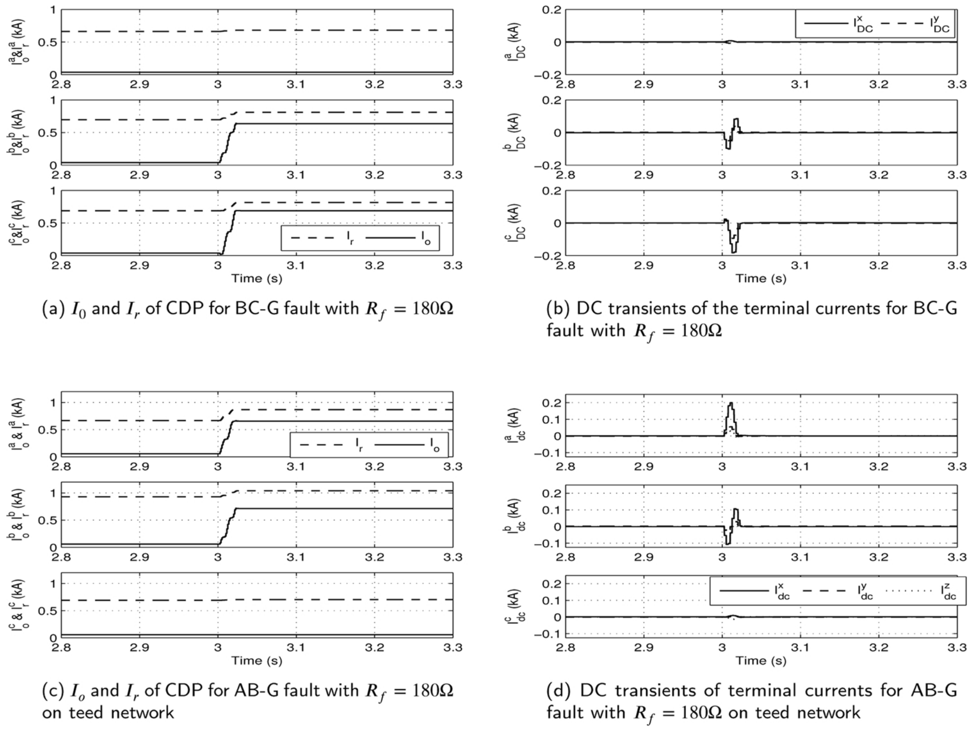
2.3. Application of the proposed scheme for parallel transmission line

Double circuit transmission line is considered in between buses B_9 and B_{10} of length 100 km. In order to identify the behavior of DC transients for different fault types, some simulation studies are carried out on double circuit transmission lines. CG fault is applied at the midpoint on transmission line 1 (X-Y). DC transients of the terminal currents pertains to line 1 (X-Y) are shown in Fig. 5a and that of line 2 (P-Q) in Fig. 5b. It is observed that DC transients of C phase pertains to line 1 (X-Y) are having the same sign and all the other DC transients of line 1 (X-Y) and line 2 (P-Q) are opposite to each other which indicates C phase fault on line 1 (X-Y).

Now B-G fault is applied at midpoint on transmission line 2 (P-Q). DC transients of terminal currents pertains to line 1 (X-Y) are shown in Fig. 5c and that of line 2 (P-Q) in Fig. 5d. As the fault is BG on line 2 (P-Q), the DC transients pertains to B phase terminal currents of line 2 (P-Q) are having the same sign.

External BC fault is applied on the transmission line between the buses B_{10} and B_8. The DC transients pertains to line 1 (X-Y) are shown in Fig. 6a and that of line 2 (P-Q) in Fig. 6b. It is observed that the DC transients of all the phases pertains to both the parallel lines are having sign opposite to each other which indicates an external fault. Hence by observing the sign of the DC transients faulted phase and faulted line of the parallel transmission line can be easily identified.

For whatever fault on the transmission line P-Q, the DC transients of line X-Y will not satisfy all the three conditions (1)–(3), which is the case of an external fault. Hence the fault can be identified based on DC



(a) I_0 and I_r of CDP for BC-G fault with $R_f = 180\Omega$

(b) DC transients of the terminal currents for BC-G fault with $R_f = 180\Omega$

(c) I_o and I_r of CDP for AB-G fault with $R_f = 180\Omega$ on teed network

(d) DC transients of terminal currents for AB-G fault with $R_f = 180\Omega$ on teed network

Fig. 7. Waveforms showing the response of CDP and proposed differential protection for High resistance faults on two terminal and Teed network.

Table 3
Other methods sensitivity for high resistance internal fault.

Sl.No.	Method implemented	LG fault (Ω)	LLG fault (Ω)	LLLG fault (Ω)
1	Ref. [5] non adaptive	170	170	170
2	Ref. [5] adaptive	750	700	700
3	Ref. [10]	1100	1100	1250
4	Ref. [25]	150	140	140

transients of line P-Q as given in Table 1 with x & y replaced with p & q. Similarly, for the fault on X-Y, the DC transients of line P-Q will not satisfy all the three conditions (1)–(3) with x & y replaced with p & q, which is the case of an external fault for whatever the fault on line X-Y. Hence the fault can be identified based on DC transients of line X-Y as given in Table 1.

3. Simulation results

For evaluating the performance of the proposed differential protection, different case studies are simulated in the subsequent sections. The proposed differential protection is compared with the conventional differential protection in the following case studies.

Current differential protection (CDP) principle is based on current comparison, in which the operating current is compared with the restraining current which is a function of restrain coefficient. Percentage restrain characteristics are adopted for overcoming the erroneous differential current due to errors from different ratios of CT, CT saturation, channel delay measurement and finite sampling frequency. The restraint coefficient 'K' should be selected in such a way that it balances the safety and sensitivity. Lower value of 'K' provides high sensitivity at low current levels (like high resistance faults where the fault current is low), but reduces the safety for external faults, etc. And higher value of 'K' provides high safety for higher current levels (like CT saturation), but reduces the sensitivity during normal operation. The value of K chosen in this manuscript is 0.5.

3.1. High resistance faults

One of the drawbacks of conventional differential protection is that it is not sensitive for high resistance faults on heavily loaded line. Different simulations are carried out on various network configuration for illustrating the behavior of the proposed differential protection with high resistance faults.

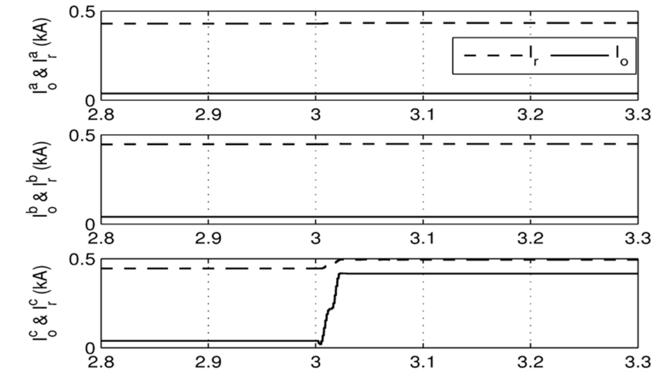
BC-G fault is considered at midpoint of the transmission line between the buses B_9 and B_{10} with fault resistance $R_f = 180\Omega$. The I_o and I_r of CDP is shown in Fig. 7a and is observed that I_r is more than I_o even for the faulty phases B and C. DC transients of the terminal currents are shown in Fig. 7b and is observed that the faulty phases can be identified which are B and C phases as given in Table 1.

Different methods proposed in the literature are implemented in the given network configuration for comparing the sensitivity for high resistance faults and are given in Table 3. The proposed method based on DC transients can detect very high resistance faults even upto 3000Ω which depends upon the precision of the Current Transformer and the system configuration adopted.

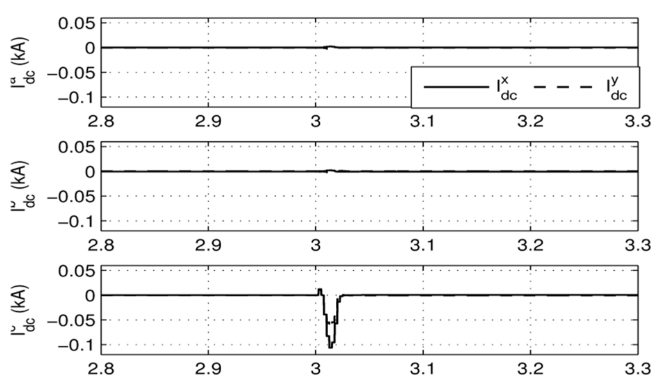
For illustrating the sensitivity of the proposed method in identifying high resistance faults on Teed transmission network, AB-G fault is applied at Teed point on the Teed network of Fig. 4a with $R_f = 180\Omega$. The I_o and I_r of CDP is shown in Fig. 7c and is observed that the CDP fails to operate as the I_r is more compared to I_o. The sign of the DC transients shown in Fig. 7d is in accordance with Table 2 for an internal AB-G fault. Hence the proposed method is working properly even for high resistance faults of Teed network.

Similarly, on double circuit transmission lines, a C-G fault is considered on line 1 with fault resistance $R_f = 300\Omega$. The I_o and I_r of CDP is shown in Fig. 8a. DC transients of line 1 is shown in Fig. 8b and that of line 2 is shown in Fig. 8c. From Fig. 8a it is observed that CDP does not operate for the above case whereas the proposed method based on DC transients operates well which is observed from Fig. 8b and c.

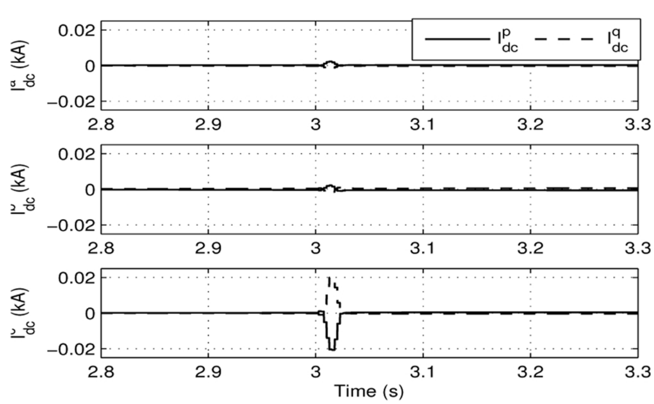
Hence the proposed criteria is able to detect high resistance faults.



(a) I_o and I_r of CDP for C-G fault with $R_f = 300\Omega$ on line 1 of parallel transmission lines



(b) DC transients of terminal currents of line 1 for C-G fault with $R_f = 300\Omega$ on line 1

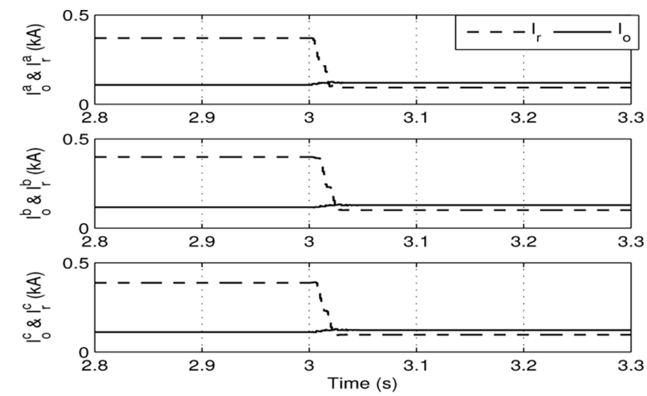


(c) DC transients of terminal currents of line 2 for C-G fault with $R_f = 300\Omega$ on line 1

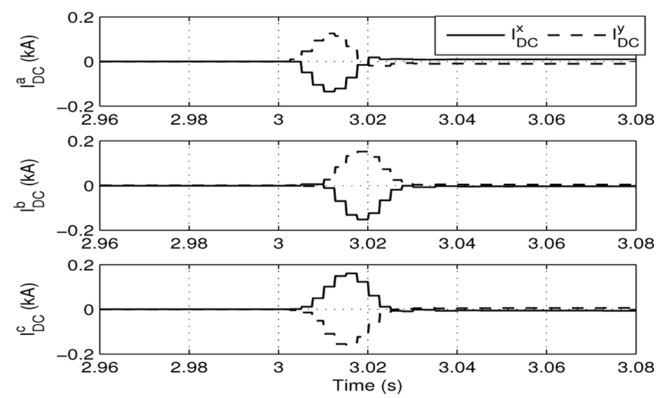
Fig. 8. Waveforms showing the response of CDP and proposed differential protection for High resistance faults on parallel transmission lines.

3.2. Line charging currents

In order to illustrate the effect of line charging current, a long transmission line of length 300 km is considered between the buses B_9 and B_{10} with a load of $L_2 = 500MW + j100MVAR$ on bus B_{10}. At 3 s the load is cut down to $L_2 = 50MW + j10MVAR$. Then the current flowing in the line is predominantly line charging current. I_o is more than I_r due to high line charging current shown in Fig. 9a. Hence the protection operates even though there is no actual fault on the line which is a maloperation. Considering the proposed criteria, the DC transients of the terminal currents for the above case is shown in Fig. 9b. Observing DC transients shown in Fig. 9b, due to sudden load cut off initially there are DC transients and sign of the transients is opposite to each other which clearly shows that there is no internal fault. Hence the proposed criteria is immune to line charging currents.



(a) I_o and I_r of CDP for the case of load thrown-off at 3 sec

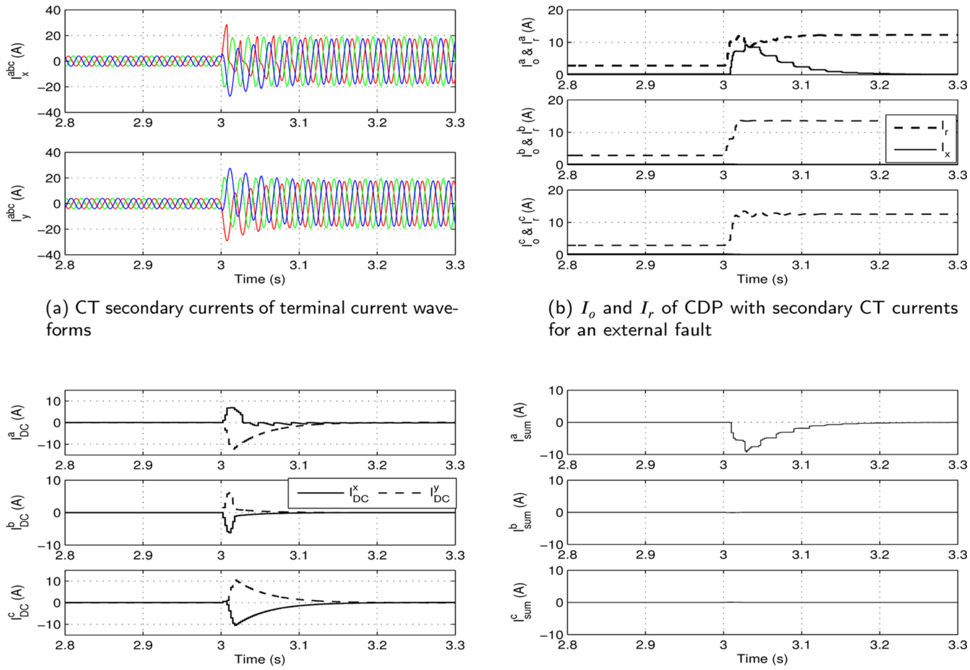


(b) DC transients of the terminal currents for the case of load thrown-off at 3 sec

Fig. 9. Waveforms showing the effect of Line Charging Currents on CDP and proposed differential protection.

3.3. CT saturation

Considering an external A-G fault between the buses B_{10} and B_8 with ideal generators, 1000/5 A CTs on B_9 side, the terminal current waveforms are given in Fig. 10a. It is observed that A phase secondary current got saturated. The I_o and I_r of CDP is given in Fig. 10b and is observed that I_o exceeds I_r even for an external fault due to CT saturation. From Fig. 10c, though the effect of CT saturation is observed in the DC transient waveforms, from the transients which are not distorted, fault can be identified as external fault as it lasts for more than a cycle and hence the relay will not mis-operate. Further for an external fault, the amplitude of DC transients of both terminals will be same and have opposite sign. Hence, if the fault is identified as an external fault from initial transients and if difference is observed in the amplitude of DC transients shown in Fig. 10d, then CT saturation condition can be identified.



(a) CT secondary currents of terminal current waveforms

(b) I_o and I_r of CDP with secondary CT currents for an external fault

(c) DC transients of the CT secondary currents for an external fault

(d) Sum of DC transients of I_x and I_y

Fig. 10. Waveforms showing the effect of CT saturation.

3.4. Effect of different fault inception angles

An internal A-G fault is applied at the mid-point of the transmission line between the buses B_9 and B_{10}. The fault inception angles are varied at an interval of 9^0 and the peaks of the DC transients of both the terminal currents are plotted for different values of fault inception angles and are given in Fig. 11a. And an external fault is considered on the transmission line between the buses B_{10} and B_8 and fault inception angles are varied. The peaks of the DC transients of the terminal currents are given in Fig. 11b. It is observed that, significant DC transients are observed and whatever may be the fault inception angle the DC transients of the terminal currents I_x and I_y are having the same sign for an internal fault and are having opposite sign for external fault, which is as per the proposed criteria.

During the worst case conditions where DC transients does not exists on any of the phase fault currents, and a raise in phase currents above the over current protection pickup setting is observed, then the trip decision can be taken based on the output of the conventional differential protection in order to improve sensitivity.

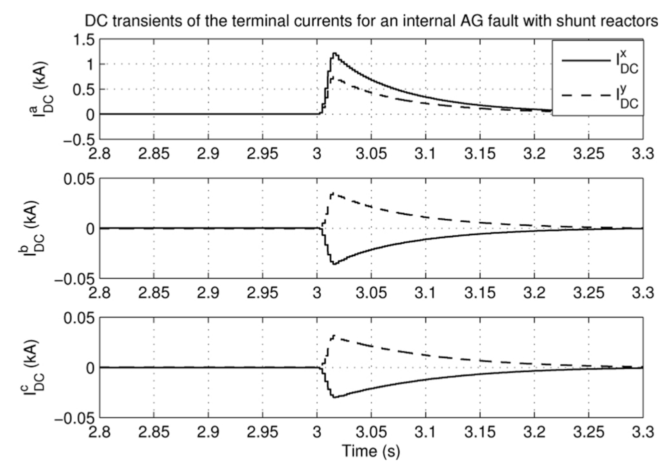
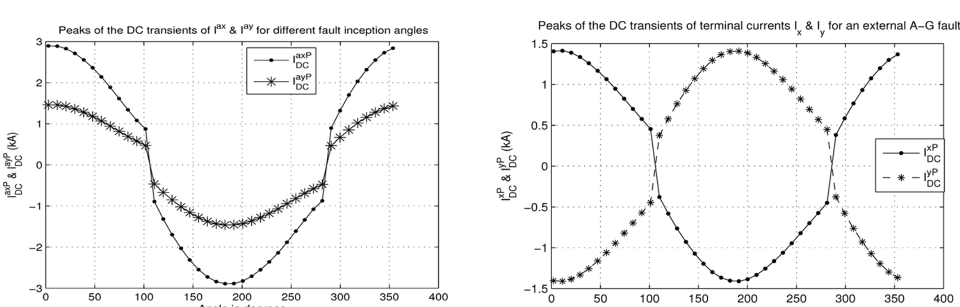


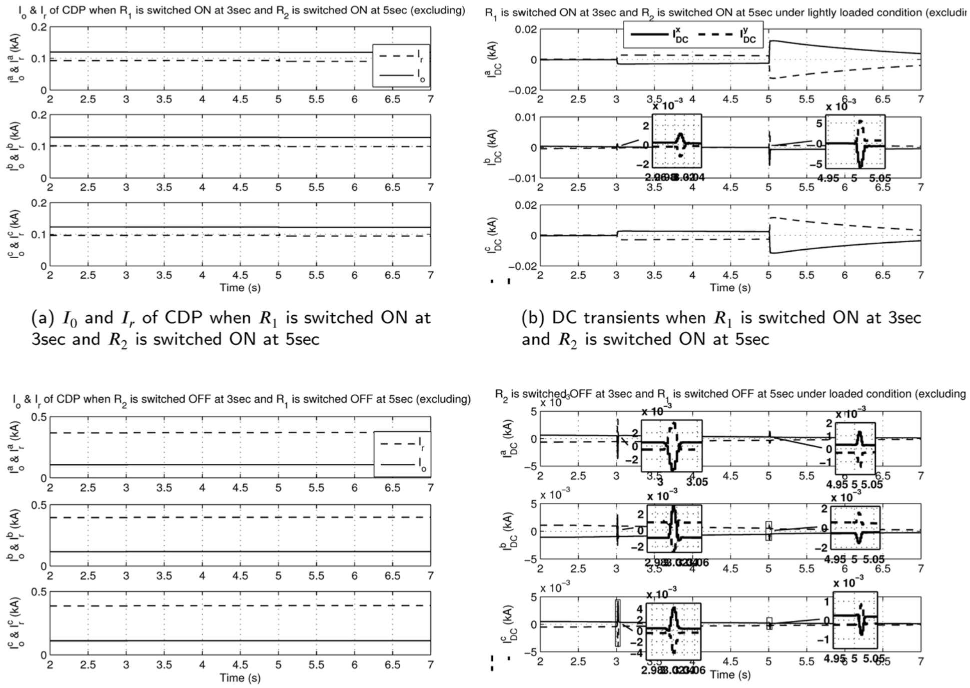
Fig. 12. DC transients of terminal currents I_x and I_y for an internal A-G fault with the presence of Shunt reactors.



(a) Peaks of the DC transients for an internal fault for different fault inception angles

(b) Peaks of the DC transients for an external fault for different fault inception angles

Fig. 11. Peaks of the DC transients of terminal currents I_x and I_y for different fault inception angles.



(a) I_0 and I_r of CDP when R_1 is switched ON at 3sec and R_2 is switched ON at 5sec

(b) DC transients when R_1 is switched ON at 3sec and R_2 is switched ON at 5sec

(c) I_o and I_r of CDP when R_2 is switched OFF at 3sec and R_1 is switched OFF at 5sec

(d) DC transients when R_2 is switched OFF at 3sec and R_1 is switched OFF at 5sec

Fig. 13. Waveforms showing the response of CDP and proposed method for shunt reactor switching ON/OFF.

3.5. *Effect of the Shunt reactors*

In general, the shunt reactor is used in long or medium transmission lines where the charging capacitance effect is more during lightly loaded conditions. Hence, for this particular case, a transmission line of 300 km is considered between the buses B_9 and B_{10} of the 4 machine 10 bus system for illustrating the effect of the Shunt reactor. Shunt reactor for 70% compensation of the line charging capacitance for the transmission line is considered.

With the shunt reactors on each end of the transmission line, an internal A-G fault is considered at 40% of the transmission line i.e., at 120 km from bus B_9. The DC transients of the terminal currents are given in Fig. 12. . From the figure, it is observed that the DC transients of the A-phase are having the same sign as it is an internal A-G fault and that of B and C phases are having opposite sign. Hence even with shunt reactors the proposed method is working satisfactorily in determining type of the fault and faulted phase.

In the practical scenario, most of the utilities exclude the shunt reactors from the line protection and a separate protection is employed for shunt reactors. For evaluating the response of the proposed method under shunt reactor switching ON/OFF, different case studies are considered while excluding the shunt reactors from the line protection and the simulation results are given in Fig. 13. R_1 is the shunt reactor at B_9 end and R_2 is the shunt reactor at B_{10} end of the system considered in Fig. 2. In the first case, R_1 is switched ON at 3 s and then R_2 is switched ON at 5 s during lightly loaded condition. It is observed from Fig. 13a that the CDP mal-operates due to lack of charging current compensation as the shunt reactors are excluded from the line protection. However, the proposed method operates correctly as shown in Fig. 13b, as it is not affected by charging currents. In the second case, as the transmission line is loaded, the shunt reactor R_2 is switched OFF at 3 s and R_1 is switched OFF at 5 s. In this case, CDP operates correctly as the load current is predominant than the charging current and proposed method also operates correctly as shown from Fig. 13c and d. Hence the proposed method based on DC transients operates satisfactorily during shunt reactor switching ON/OFF, whereas the effectiveness of the CDP depends on the proper charging current compensation.

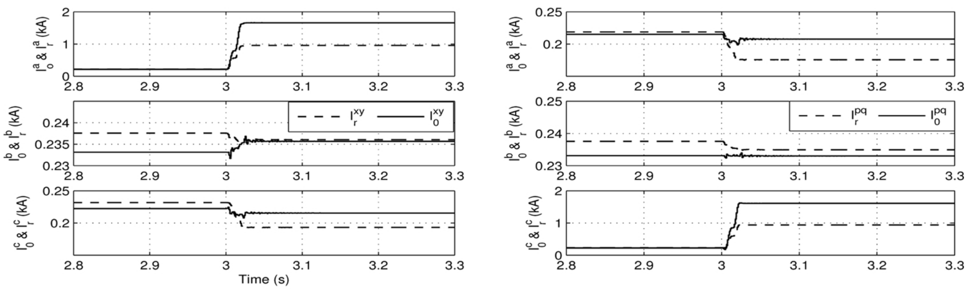
3.6. *Cross country faults*

Considering an A-G fault on line 1 (X-Y) and C-G fault on line 2 (P-Q) at 10 KM from the sending end on 560 km double circuit transmission line between buses B_9 and B_{10} with $R_f = 75\Omega$ at 3s. The I_o and I_r of CDP of line 1 (X-Y) are shown in Fig. 14a and of line 2 (P-Q) are shown in Fig. 14b.

It is observed that I_o is more than I_r for both A and C phases for line1 and line2. CDP identifies that the fault involves both A and C phases on lines 1 & 2 and maloperates. While the DC transients of the terminal currents for the same case of lines 1 and 2 are given in Fig. 14c and d and is observed that only A phase fault is identified on line 1 (X-Y) and C phase fault is identified on line 2 (P-Q) correctly. Hence the proposed method is immune to cross-country faults.

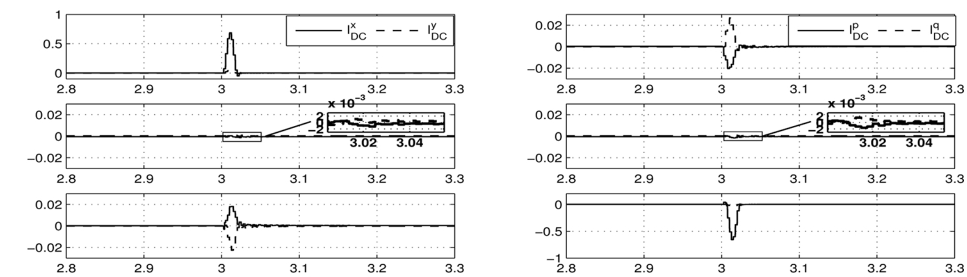
3.7. *Channel delay*

Line current differential relay will samples the current at one end and sends the processed data to the other end through digital communication link which results in some time delay which can be seen in the form of phase shift. Time synchronization can be achieved either by measuring and compensating the delay or synchronizing to an external reference like GPS, available to both terminals [32]. Ping-pong algorithm is used for measuring the channel delay. But if the sending end communication path is different from receiving end path, then error may occur in calculating channel delay and in compensating that delay. Synchronizing to an external reference can be achieved through GPS, which gives time synchronized samples. So that the samples that are time synchronized are compared for deciding the operation of line current differential protection. Combination of the two provides a reliable solution even in the case of GPS failure. With the implementation of time synchronized samples, the proposed method based on DC



(a) I_o and I_r of CDP of line 1 (XY) for an internal A-G fault on line 1 and C-G fault on line 2

(b) I_o and I_r of CDP of line 2 (PQ) for an internal A-G fault on line 1 and C-G fault on line 2



(c) DC transients of terminal currents of line 1 (XY) for an internal A-G fault on line 1 and C-G fault on line 2

(d) DC transients of terminal currents of line 2 (PQ) for an internal A-G fault on line 1 and C-G fault on line 2

Fig. 14. Waveforms showing the effect of cross country faults on parallel transmission line.

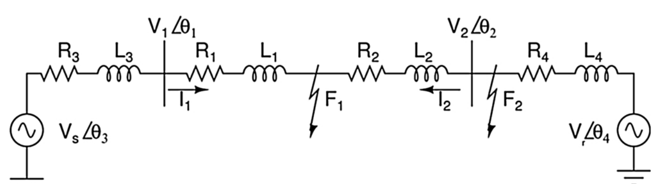


Fig. 15. System considered for derivation of mathematical proof of concept for the proposed approach.

transients operates satisfactorily even with incorporating some error in synchronization, as the transients last for more than half a cycle for comparison.

4. Conclusion

A novel differential protection for transmission lines using DC transients is proposed in this paper. The accuracy of detecting faults in different types of networks like two terminal, Teed and double circuit configuration are showcased with the simulations carried out in PSCAD® on a 10 Bus system and fault identification logic is also presented. Different types of faults where the conventional differential protection fails to operate are considered and tested for applicability of the proposed approach. The proposed criteria can detect high resistance faults in any network configuration and is inherently not affected by line charging currents which improves the stability. The proposed approach is also not effected by cross country faults in double circuit transmission lines and CT saturation. For the worst cases where DC transients does not exist but raise in phase currents from its steady state value is observed above the overcurrent protection pickup setting, the trip decision can be taken based on the output of the conventional differential protection. Further, the decision can be made within 1 cycle after the inception of the fault makes the proposed differential protection approach suitable for fast relaying. Hence it is concluded that, with the proposed approach based on DC transients, sensitivity is improved without compromising the safety and vice versa.

Author contributions

Conceived and designed the analysis: Adharapurapu Hema Latha, Ravikumar Bhimasingu

Collected the data: Adharapurapu Hema Latha, Ravikumar Bhimasingu

Contributed data or analysis tools: Adharapurapu Hema Latha, Ravikumar Bhimasingu

Performed the analysis: Adharapurapu Hema Latha, Ravikumar Bhimasingu

Wrote the paper: Adharapurapu Hema Latha, Ravikumar Bhimasingu

Conflicts of interest

The authors declare no conflicts of interest.

Appendix A

The parameters of the 10 bus 50 Hz system are as follows:

- S1: $r = 0.00912875\Omega$, $L = 0.2038$ mH, 25 kV, $\delta = 10^0$.
- S2: $r = 0.00912875\Omega$, $L = 0.2038$ mH, 25 kV, $\delta = 0^0$.
- S3&S4: $r = 0.07303\Omega$, $L = 1.6304$ mH, 25 kV, $\delta = 0^0$.
- T1 & T2: 900 MVA, 25 kV/230 kV, Z = 12.5%
- T3: 200 MVA, 25 kV/230 kV, Z = 12.5%
- T4: 200 MVA, 25 kV/230 kV, Z = 12.5%
- L1: 50MW+j25MVAR, 230 kV
- L2: 500MW+j100MVAR, 230 kV
- Distributed parameter model of transmission line is considered. Length of the transmission line from $B_5 - B_7 = 20$ km, $B_7 - B_9 = 20$ km, $B_9 - B_{10} = 100$ km, $B_{10} - B_8 = 80$ km, $B_8 - B_6 = 20$ km.

Appendix B

A single phase transmission line of the form shown in Fig. 15 is considered.
Initially, before applying fault, the voltage equation is:

$$v_1(t) = R_1 i(t) + L_1\frac{\mathrm{di}(t)}{\mathrm{dt}} + R_2 i(t) + L_2\frac{\mathrm{di}(t)}{\mathrm{dt}} + v_2(t)$$

Initial value of the inductor current is:

$$\begin{aligned} V_1 &= I(Z_1 + Z_2) + V_2 \\ I &= \frac{(V_1 - V_2)}{(Z_1 + Z_2)} \end{aligned}$$

B.1 Derivation for an internal Fault (F_1)

Now an internal fault (F_1) is applied on the transmission line, with fault resistance R_f.
Fault current $I_f = I_1 + I_2$

$$\begin{aligned} v_1(t) - v_f(t) &= R_1 i(t) + L_1\frac{(\mathrm{di}(t))}{\mathrm{dt}} \\ v_2(t) - v_f(t) &= R_2 i(t) + L_2\frac{(\mathrm{di}(t))}{\mathrm{dt}} \end{aligned}$$

Applying Laplace transform:

$$\begin{aligned} V_1(s) - V_f(s) &= (R_1)I_1(s) + (L_1)(\mathrm{sI_1}(s) - I(0)) \\ I_1(s) &= \frac{(V_1(s) - V_f(s) + (L_1)I(0))}{((R_1) + \mathrm{sL_1})} \end{aligned}$$

Similarly,

$$I_2(s) = \frac{(V_2(s) - V_f(s) + (L_2)I(0))}{((R_2) + s(L_2))} \tag{7}$$

Substituting $V_f(s) = (I_1(s) + I_2(s))R_f$ in the equation of $I_1(s)$:

$$I_1(s) = \frac{(V_1(s) - V_f(s) + (L_1)I(0))}{((R_1) + s(L_1))} \tag{8}$$

$$I_1(s) = \frac{(V_1(s) - (I_1(s) + I_2(s))R_f + (L_1)I(0))}{((R_1) + s(L_1))} \tag{9}$$

$$I_1(s) = \frac{(V_1(s) - R_f I_2(s) + (L_1)I(0))}{(R_1 + R_f + s(L_1))} \tag{10}$$

From Eq. (7)

$$\begin{aligned} I_2(s) &= \frac{(V_2(s) - V_f(s) + (L_2)I(0))}{((R_2) + s(L_2))} \\ I_2(s)(R_2 + \mathrm{sL_2}) &= V_2(s) - (I_1(s) + I_2(s))R_f + L_1 I(0) \\ I_2(s)(R_2 + R_f + \mathrm{sL_2}) &= V_2(s) - I_1(s)R_f + L_1 I(0) \end{aligned}$$

Substituting $I_1(s)$ from Eq. (10) in the above equation:

$$I_2(s) = \frac{(V_2(s)(R_1 + R_f + \mathrm{sL}_1) - V_1(s)R_f + (L_2(R_1 + R_f + \mathrm{sL}_1) - L_1R_f)I(0))}{((R_1 + R_f + \mathrm{sL}_1)(R_2 + R_f + \mathrm{sL}_2) - R_f^2)}$$

Similarly,

$$I_1(s) = \frac{(V_1(s)(R_2 + R_f + \mathrm{sL}_2) - V_2(s)R_f + (L_1(R_2 + R_f + \mathrm{sL}_2) - L_2R_f)I(0))}{((R_1 + R_f + \mathrm{sL}_1)(R_2 + R_f + \mathrm{sL}_2) - R_f^2)}$$

Let the roots of the second order polynomial $(R_1 + R_f + \mathrm{sL}_1)(R_2 + R_f + \mathrm{sL}_2) - R_f^2$ be a & b, then $I_1(s)$ can be:

$$I_1(s) = \frac{(V_1(s)(R_2 + R_f + \mathrm{sL}_2))}{(L_1L_2(s + a)(s + b))} - \frac{(V_2(s)R_f)}{(L_1L_2(s + a)(s + b))} + \frac{((L_1(R_2 + R_f + \mathrm{sL}_2) - L_2R_f)I(0))}{(L_1L_2(s + a)(s + b))}$$

Factorizing the above equation and converting to time domain, the inrush currents of $i_1(t)$ are:

$$\left(\frac{(V_1(\mathrm{aL}_2 - (R_2 + R_f)))}{(L_1L_2(b-a)(a+\theta_1+j\omega))} + \frac{(L_1((R_2+R_f) - \mathrm{aL}_2) - L_2R_f)}{(L_1L_2(b-a))I(0)} + \frac{(V_2R_f)}{(L_1L_2(a+\theta_2 j\omega)(b-a))}\right)e^{-\mathrm{at}} + \left(\frac{(V_1(\mathrm{bL}_2 - (R_2+R_f)))}{(L_1L_2(a-b)(b+\theta_1+j\omega))} + \frac{(L_1((R_2+R_f) - \mathrm{bL}_2) - L_2R_f)}{(L_1L_2(a-b))}I(0) + \frac{(V_2R_f)}{(L_1L_2(b+\theta_2+j\omega)(a-b))}\right)e^{-\mathrm{bt}}$$

The inrush currents of $i_2(t)$ are:

$$\left(\frac{(V_2(\mathrm{aL}_1 - (R_1 + R_f)))}{L_1L_2(b-a)(a+\theta_2+j\omega)} + \frac{L_2((R_1+R_f) - \mathrm{aL}_1) - L_1R_f)}{(L_1L_2(b-a))}I(0) + \frac{V_sR_f)}{(L_1L_2(a+\theta_1+j\omega)(b-a)}\right)e^{-\mathrm{at}} + \left(\frac{V_r(\mathrm{bL}_1 - (R_1+R_f))}{(L_1L_2(a-b)(b+\theta_2+j\omega)} + \frac{L_2((R_1+R_f) - \mathrm{bL}_1) - L_1R_f)}{L_1L_2(a-b)}I(0) + \frac{V_sR_f}{(L_1L_2(b+\theta_1+j\omega)(a-b))}\right)e^{-\mathrm{bt}}$$

In order to make comparision of $I_1(s)$ and $I_2(s)$, the above equation is simplified by assuming $R_1 = R_2 = R$, $L_1 = L_2 = L$, $\theta_1 = \theta_2 = \theta$ and $R_f = 0\,\Omega$.

Then the above equation becomes:

$$I_1(s) = \frac{V_1(s) + I(0)}{((R + \mathrm{sL}))}$$

Similarly,

$$I_2(s) = \frac{V_2(s) + I(0))}{((R + \mathrm{sL}))}$$

Converting into time domain, the inrush currents of $i_1(t)$ are:

$$\left(\frac{-V_1\sin(\theta - \tan^{-1}(\frac{\omega}{(R+\theta)}))}{\sqrt{((R+\theta)^2 + \omega^2)}} + I(0)\right)e^{\frac{-\mathrm{Rt}}{L}}$$

Inrush currents of $i_2(t)$:

$$\left(\frac{-V_2\sin(\theta - \tan^{-1}(\frac{\omega}{(R+\theta)}))}{\sqrt{((R+\theta)^2 + \omega^2)}} + I(0)\right)e^{\frac{-\mathrm{Rt}}{L}}$$

From the above inrush currents of $i_1(t)$ and $i_2(t)$, it can be observed that, the DC transients are having the same sign for different fault inception angles whether positive or negative for an internal fault.

B.2 Derivation for an External Fault F_2

Now an external fault (F_2) is applied as shown in Fig. 15:

The currents I_1 and I_2 of the transmission line of interest can be obtained as:

$$v_1(t) = (R_1 + R_2)i_1(t) + (L_1 + L_2)\frac{\mathrm{d}i_1(t)}{\mathrm{dt}} + v_2(t)$$

$$v_2(t) = (R_1 + R_2)i_2(t) + (L_1 + L_2)\frac{\mathrm{d}i_2(t)}{\mathrm{dt}} + v_1(t)$$

Applying Laplace transform for the above equations:

$$V_1(s) = (R_1 + R_2 + s(L_1 + L_2))I_1(s) - (L_1 + L_2)I(0)$$

$$I_1(s) = \frac{(V_1(s) + (L_1 + L_2)I(0)) - V_2(s)}{R_1 + R_2 + s(L_1 + L_2)}$$

Similarly,

$$I_2(s) = \frac{(V_2(s) - (L_1 + L_2)I(0)) - V_1(s)}{R_1 + R_2 + s(L_1 + L_2)}$$

Converting into time domain:

The transient currents of $i_1(t)$ and $i_2(t)$ for an external fault are:

Inrush currents of $i_1(t)$:

$$\left(\frac{-V_1}{(R_1+R_2) + (j\omega + \theta_1)(L_1 + L_2)} + \frac{V_2}{(R_1+R_2) + (j\omega + \theta_2)(L_1 + L_2)} + I(0)\right)e^{-\frac{(R_1+R_2)t}{L_1+L_2}}$$

Inrush currents of $i_2(t)$:

$$\left(\frac{V_1}{(R_1+R_2) + (j\omega + \theta_1)(L_1 + L_2)} - \frac{V_2}{(R_1+R_2) + (j\omega + \theta_2)(L_1 + L_2)} - I(0)\right)e^{-\frac{(R_1+R_2)t}{L_1+L_2}}$$

The above two equations for DC Transients of $i_1(t)$ and $i_2(t)$ for an external fault are having opposite sign.

From the above, it can be observed that, the DC transients are having the same sign whether it is positive or negative for an internal fault and the

DC transients for the external fault are having opposite sign to each other of both ends of the transmission line under study. Hence the presence of the DC transients and criteria of the proposed differential protection based on sign of the DC transients is proved with mathematical derivation.

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