Novel Sensitive Current Differential Protection of Transmission Line

Sanjay Dambhare, S. A. Soman, *Member, IEEE,* and M. C. Chandorkar, *Member, IEEE*

***Abstract*— This paper proposes a novel approach for sensitive current differential protection of transmission line. The improvement in sensitivity is a result of adaptive control of the restraining region in a current differential plane. The discriminant function used in differential protection corresponds to the ratio of series branch current in the $\pi - equivalent$ model of the transmission line. It requires time synchronous measurements which can be obtained from Global Positioning System (GPS). Electromagnetic Transient Program (EMTP) simulations on a four machine ten bus system are used to substantiate the claims. The results brings out the superiority of the proposed approach.**

***Index Terms*— Adaptive protection, Current differential protection, GPS.**

I. Introduction

CURRENT differential protection schemes provides absolute selectivity, high sensitivity, fast operation and simplicity. Unlike distance relaying, the current differential protection is immune to tripping on power swings. When such schemes are used for transmission systems protection using pilot wires, they are called as pilot relaying schemes [1]. Two versions of pilot relaying schemes are used in practice, namely, directional comparison and phase comparison schemes. Being legacy systems, both approaches limit the communication requirements.

In 1983, Sun et. al. [2] published a seminal paper describing current differential relay system using fiber optics communication. Fiber provides a better communication channel than metallic wire as it is immune to extraneous voltages like longitudinal induced voltage and station ground mat voltage rise. The basic idea is to transmit sequence current information from one end to another using Pulse Period Modulation (PPM) method. An effective transmission rate of 55 samples per cycle at 60 Hz frequency was achieved in [2]. Since, the differential comparison of the local and remote end current must correspond to the same time instant, a delay equalizer is used with the local sequence current signal to reflect the delay of the modem process of remote quantity.

However, the sensitivity of current differential protection scheme can be compromised because of, effect of the distributed shunt capacitance current of the line, modeling inaccuracies in presence of series compensation, approximate delay equalization between two end currents and Current Transformer (CT) inaccuracies.

Ref. [3], [4], [5] discusses the GPS based conventional current differential protection schemes for transmission line protection. The line charging current component is quite significant for ultra high transmission system voltages. It varies the phase angle of the line current from one end to another. In traditional pilot wire schemes, relaying sensitivity will have to be compromised to prevent the mal-operation. Current differential relay using distributed line model is proposed in Ref. [6] to consider line charging current. An adaptive GPS synchronized protection scheme using Clarke transformation is proposed in [7]. The multi agent based wide area current differential protection system is proposed in [8].

The implications and consequences of digital communication technologies on relaying are discussed in [9], [10]. If the current samples are time stamped by a GPS, then for calculation of differential current, samples corresponding to same time instant can be compared, thereby providing immunity to channel delays, asymmetry, etc. [4], [11]. Differential current can be calculated by extracting the phasors. Further, dynamic estimate of the channel delay can be easily maintained by subtracting the GPS time stamp at the transmit end from the receiving end time stamp. This permits back up operation even during GPS failure modes.

As suggested by Phadke and Thorp [12], pp. 257 and validated by [13], we first estimate the fictitious current I^{ser} in the series branch of the π-*equivalent* line model from the local voltage and current measurements and transmit it to the remote end of the line. In absence of a line fault (internal fault), estimate of phasor I^{ser} computed at both ends of the line will be identical. However, in presence of a fault on the line, the estimate of the series branch current at the two ends of the line will not match. Hence, the differential ΔI^{ser} provides an accurate discriminant for detection of the internal line fault. To provide sensitivity in both phase and earth fault protection, we develop an implementation in phase co-ordinates.

This paper primarily proposes a methodology to improve sensitivity of the current differential protection scheme for transmission line protection without compromising it's security. To meet this objective, we suggest an adaptive procedure to set the restrain region in the current differential plane. We show that the proposed methodology significantly improves sensitivity of the current differential protection scheme without sacrificing the security.

This paper is organized as follows: Current differential protection framework is introduced in section II. In section III,

Sanjay Dambhare is with Department of Electrical Engineering, College of Engineering, Pune (e-mail: dambhare@ee.iitb.ac.in) and S. A. Soman and M. C. Chandorkar are with Department of Electrical Engineering, Indian Institute of Technology Bombay, Mumbai, India (e-mail: soman@ee.iitb.ac.in, mukul@ee.iitb.ac.in)

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the idea of adaptive restrain region is developed. Section IV explains the implementation in phase co-ordinates. In section V, we present simulation case studies in EMTP-ATP package on a 4-generator, 10-bus system with Capacitance Coupled Voltage Transformer (CCVT) model. Section VI concludes the paper.

II. Fundamentals

Let us consider a positive sequence representation of an uncompensated transmission line. As shown in Fig. 1, the line can be represented by an *equivalent* π-model. Equivalent π circuit correctly models the effect of distributed line parameters at the line terminals at the fundamental frequency.

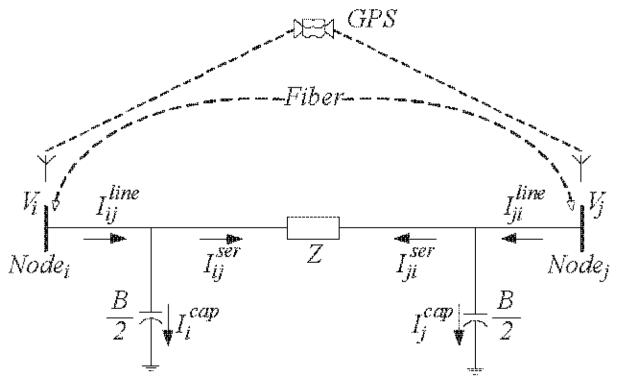

Fig. 1. GPS synchronized current differential protection scheme with *equivalent* π-model of line.

Let the positive sequence component of line current for reference phase a measured at bus i be given by I_{ij}^{line}. Then, the current I_{ij}^{ser} in the series branch of the π-*equivalent* line model at node i can be computed as:

$$I_{ij}^{ser} = I_{ij}^{line} - I_i^{cap} \quad (1)$$

$$\text{where, } I_i^{cap} = j\frac{B}{2}V_i \quad (2)$$

is the current in shunt path at bus i. V_i is the positive sequence voltage of reference phase a.

Similarly, let the line current measured at bus j be given by I_{ji}^{line}; the current I_{ji}^{ser} in the series branch of the π-*equivalent* line model at node j can be computed as:

$$I_{ji}^{ser} = I_{ji}^{line} - I_j^{cap} \quad (3)$$

$$\text{where, } I_j^{cap} = j\frac{B}{2}V_j \quad (4)$$

is the current in shunt path at bus j.

If there is no internal fault on the line then:

$$I_{diff} = I_{ij}^{ser} + I_{ji}^{ser} = 0. \quad (5)$$

Hence, we conclude that a fault is present on the transmission line if and only if the discriminant function I_{diff} is non-zero.

A. Relay Setting in Current Differential Plane

The operating current I_{op} and restraining current I_{re} for the conventional current differential protection scheme can be expressed as follows:

$$I_{op} = |\, I_{ij}^{ser} + I_{ji}^{ser} \,| \quad (6)$$

$$\text{and, } I_{re} = |\, I_{ij}^{ser} - I_{ji}^{ser} \,| . \quad (7)$$

The percentage differential relay pick up and operate when:

$$I_{op} \geqslant I_o \quad (8)$$

$$\text{and, } I_{op} \geqslant KI_{re} \quad (9)$$

where, I_o is a pick up current and K is the restraint coefficient $(0 < K < 1)$. However, it has been shown in [14] that numerical differential relay can be set more accurately in a current differential plane. Using the phase and magnitude information of series branch current, we calculate:

$$ratio = \frac{|I_{ij}^{ser}|}{|I_{ji}^{ser}|} \quad (10)$$

$$\text{and, } ang = \angle(I_{ij}^{ser}) - \angle(I_{ji}^{ser}). \quad (11)$$

In absence of an internal fault, for the proposed discriminant function (5) we have,

$$ratio = 1 \text{ and } ang = 180^o.$$

As shown in Fig. 2, this can be visualized in the current differential plane by point X at $(180^o, 1)$. Ideally, every point other than X indicates an internal fault. However, even in absence of an internal fault, in real life the operating point may deviate from the point $(180^o, 1)$ due to synchronization error, delay equalizer error, modeling restrictions i.e., assumptions, approximations or inaccuracies of the algorithm and CT errors.

Since GPS provides time synchronization of the order of 1μ sec, the synchronization error can be practically eliminated. Also, if the same time stamped samples of two end are processed, delay equalizer error can be eliminated. Further, explicit modeling of the shunt capacitance of the line reduces the modeling errors. Therefore, we can reduce the width of the restrain region in the current differential plane. We use $\pm 20^o$ for phase error and $\pm 150\%$ for magnitude error in current differential plane. Hence, $ratio_{min} = 0.4$, $ratio_{max} = 2.5$, $ang_{min} = 160^o$ and $ang_{max} = 200^o$ (refer Fig. 2). The corresponding value of K in conventional relay setting approach is nearly 0.43.

Now, a fault on the transmission line can be detected by the following algorithm.

1) Set the threshold parameters $ratio_{min}$, $ratio_{max}$, ang_{min} and ang_{max} for detecting differential current.
2) Compute the current I_{ij}^{ser} using GPS synchronized line current and bus voltage measurements at bus i.
3) Compute the current I_{ji}^{ser} using GPS synchronized line current and bus voltage measurements at bus j.
4) Check if:

$$ratio_{min} \leq \frac{|I_{ij}^{ser}|}{|I_{ji}^{ser}|} \leq ratio_{max}$$

AND $ang_{min} \leq \angle(I_{ij}^{ser}) - \angle(I_{ji}^{ser}) \leq ang_{max}$.
If TRUE, then there is no fault on the transmission line. Conversely, if FALSE then there is a fault on the transmission line.

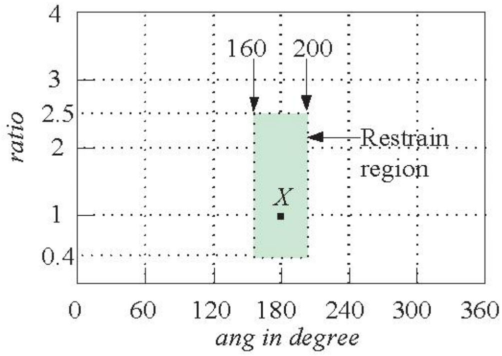

Fig. 2. Trip and the restrain region in current differential plane.

III. Adaptive Control of Restrain Region

A protection engineers strikes balance between dependability and security by controlling the sensitivity. Dependability of a relay can be improved by increasing the sensitivity. Sensitivity of the differential relay can be improved by reducing the area of the restrain region in the Fig. 2. Since, we have already tightened the width of the restrain region, this implies that we should reduce the height of the rectangle representing the restrain region. However, it is equally important to keep it large enough so that relay does not pickup on transients or external disturbance which includes a fault. Too sensitive relay setting increases the possibility of relay maloperation and hence compromises security.

We now propose an important enhancement to improve sensitivity of the current differential relay without compromising on it's security. Basically, sensitivity implies an ability to detect low current or high impedance fault. The proposed enhancement is based on the following observations:

1) high impedance fault may not involve appreciable transients;
2) high impedance faults should not lead to gross errors due to CT saturation and
3) large disturbances e.g., load throw off and external faults will cause large differential currents because 1) the phasor model is not truly valid under situations and 2) CT errors may increase due to partial saturation. Hence, large transients or disturbances call for large restrain region.

The above observations suggest that the height of the restrain region should be a function of the current magnitudes of I_{ij}^{ser} and I_{ji}^{ser}. In particular, we propose the following restraining function:

$$\psi(I_{ij}^{ser}, I_{ji}^{ser}) = \frac{|I_{ij}^{ser}|}{|I_{ji}^{ser}|} - \left[a + m\left(|I_{ij}^{ser}| + |I_{ji}^{ser}|\right)\right] \quad (12)$$

where a and m are suitable constants. We assume that $\frac{|I_{ij}^{ser}|}{|I_{ji}^{ser}|}$ is greater than 1. In case, the ratio is less than one, then numerator and the denominator should be interchanged. The relay trips when either 1) restraining function is greater than zero or 2) when the angular separation criterion described in the earlier section is violated.

1) Selection of constants a and m: Under no fault and ideal conditions, ratio $\frac{|I_{ij}^{ser}|}{|I_{ji}^{ser}|}$ is equal to one. Further, the term $\left(|I_{ij}^{ser}| + |I_{ji}^{ser}|\right)$ depends upon line current and hence can be very small. This suggests that constant a should be at least equal to 1. Further, for sensitive protection, constant a should be chosen close to unity. In particular, we have found $a = 1.3$ and $m = 0.0015$ to be a satisfactory choice. Small magnitude of m is chosen because fault current range is approximately in kiloAmperes. At lower values of a, possibility of relay mal-operation on extreme load throw offs have been observed. We considered different descriptors which correctly describe the properties of the proposed relay setting methodology. The terminology *adaptive* was preferred because with the proposed methodology, relay restrain region adapts according to the current loading of line [12].

IV. Current Differential Protection in Phase Co-ordinates

Positive sequence network is excited by both ground and phase faults. Hence, in principle, current differential protection scheme using a positive sequence network representation can alone detect all possible faults. However, sensitivity using positive sequence component alone will vary with the type of fault. It will be maximum for bolted 3-phase (LLLG) fault. In contrast, for a single line to ground fault, the sensitivity for ground fault detection will be reduced by a factor of 3 approximately. This motivates that either all the sequence networks (positive, negative, zero) be used for decision making, or computation in phase co-ordinates should be employed. We prefer the phase domain approach because of its simplicity and accuracy.

Let us consider the *equivalent-π* model of a three phase transposed transmission line as shown in Fig. 3.

Let Z_s and Z_m be the self and mutual series impedance of the line. For a transposed line, they can be easily computed from the sequence data as follows:

$$Z_s = \frac{1}{3}(Z_0 + 2Z_1) \quad (13)$$

$$\text{and, } Z_m = \frac{1}{3}(Z_0 - Z_1) \quad (14)$$

where, Z_1, Z_2 and Z_0 are the positive, negative and zero sequence impedance of the transmission line. Similarly, B_s and B_m are self and mutual shunt susceptance of the transmission line. They can be computed as follows:

$$B_s = \frac{1}{3}(B_0 + 2B_1) \quad (15)$$

$$\text{and, } B_m = \frac{1}{3}(B_0 - B_1). \quad (16)$$

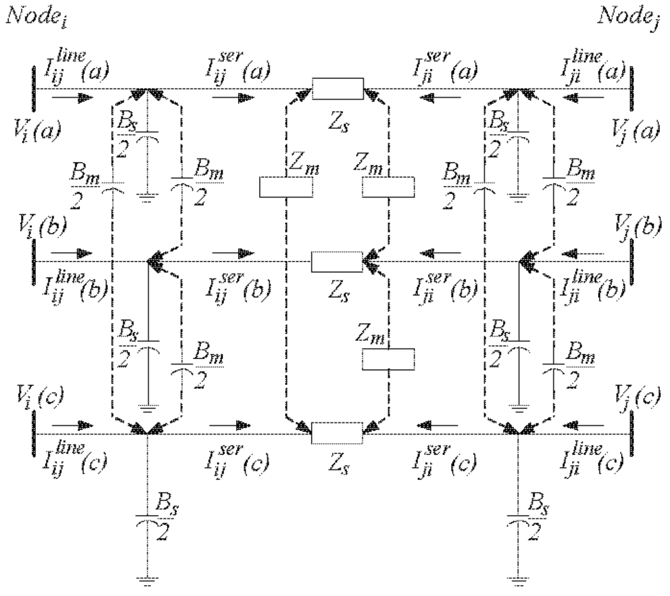

Fig. 3. Equivalent-π model of three phase transposed transmission line [15].

It has to be noted that, usually B_m will be negative as $C_0 < C_1$. Now from Fig. 3, line current equation at bus i in phase co-ordinates can be expressed as follows:

$$\begin{bmatrix} I_{ij}^{line}(a) \\ I_{ij}^{line}(b) \\ I_{ij}^{line}(c) \end{bmatrix} = \begin{bmatrix} I_{ij}^{ser}(a) \\ I_{ij}^{ser}(b) \\ I_{ij}^{ser}(c) \end{bmatrix} + \frac{j}{2} \begin{bmatrix} B_s & B_m & B_m \\ B_m & B_s & B_m \\ B_m & B_m & B_s \end{bmatrix} \begin{bmatrix} V_i(a) \\ V_i(b) \\ V_i(c) \end{bmatrix}. \quad (17)$$

Indices a, b and c represent the respective phases. Similarly, line current equation at bus j can be expressed as follows:

$$\begin{bmatrix} I_{ji}^{line}(a) \\ I_{ji}^{line}(b) \\ I_{ji}^{line}(c) \end{bmatrix} = \begin{bmatrix} I_{ji}^{ser}(a) \\ I_{ji}^{ser}(b) \\ I_{ji}^{ser}(c) \end{bmatrix} + \frac{j}{2} \begin{bmatrix} B_s & B_m & B_m \\ B_m & B_s & B_m \\ B_m & B_m & B_s \end{bmatrix} \begin{bmatrix} V_j(a) \\ V_j(b) \\ V_j(c) \end{bmatrix}. \quad (18)$$

Thus, we conclude that there is no fault on the line *if and only if*:

$$I_{ij}^{ser}(a) + I_{ji}^{ser}(a) = 0 \quad (19)$$

$$I_{ij}^{ser}(b) + I_{ji}^{ser}(b) = 0 \quad (20)$$

$$I_{ij}^{ser}(c) + I_{ji}^{ser}(c) = 0. \quad (21)$$

In practice, each phase tripping logic can be set using the procedures described in the sections II-A and III. The currents phasors I_{ij}^{ser} and I_{ji}^{ser} can be computed from GPS synchronized measurements using (17) and (18). Total twelve GPS synchronized measurements are required, three currents and three voltages at each end. Phasors are computed from samples by full cycle recursive Discrete Fourier Transform (DFT) [12] and are updated with every samples. There is no possibility of inadvertent tripping of the transmission line due to line charging current. This is because the discriminant function value $I_{ij}^{ser} + I_{ji}^{ser}$ will be zero even during line charging. The extension of the above scheme in phase co-ordinates is straight forward. For simplicity of illustration, we have used sequence representation, but all calculations are carried out in phase coordinates.

V. Case Studies

To evaluate performance of the proposed scheme, we report results on a two area, 230 kV, 4 generator, 10 bus system (refer Fig. 4). Detailed generator, load and line data on a 100 MVA base is given in [16]. The two areas are connected by three parallel AC tie lines of 220 km each. The response of power system to disturbances e.g., faults is simulated using EMTP. ATP [15] software has been used for simulations. Samples obtained from the EMTP simulation are fed to a MATLAB program which implements the proposed differential protection scheme. Full cycle recursive DFT algorithm is used to estimate the phasors.

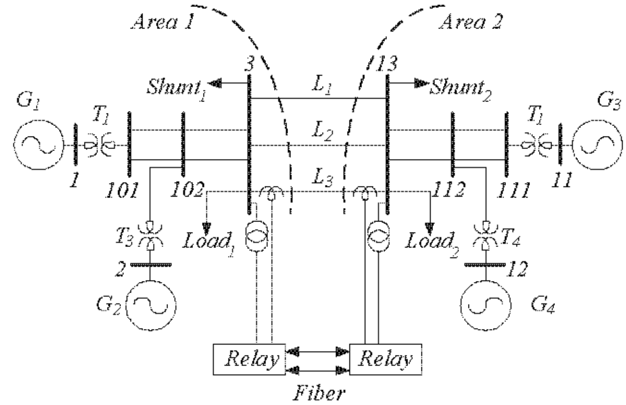

Fig. 4. Single line diagram of 2 area, 4 generator, 10 bus system.

In ATP-EMTP simulation, transmission lines are represented by Clarke's model (distributed parameters) and detailed model is used for representing generators. Initial values of generator voltage magnitude and angles are calculated from the load flow analysis. The proposed scheme is applied for primary protection of one of the tie lines L_3 between node 3 and 13. The fault location is measured from bus 3. ANSI 1200:5, class C400 CT model [17] and 250 kV:100 V CVT model [18], have been used for obtaining realistic CT and CCVT response during EMTP simulations.

Samples obtained from ATP-EMTP simulation correspond to time synchronized GPS samples. The time step used for ATP-EMTP simulations is $20\mu s$. However, relaying system data acquisition rate is set to 1000 Hz.

First, we consider non-adaptive setting of the relay in current differential plane which has already been outlined in section II-A. Then, we provide results with the adaptive scheme.

A. External faults

To ascertain security, it must be ascertained that the differential relay does not operate for any external fault. This verification is usually carried out on the severe external faults. All the four types of external shunt faults (LG, LL, LLG and LLL) are simulated on busses 3 and 13 as well as on adjacent lines 3-102 and lines 13-112 at 25%, 50% and 75% length. In

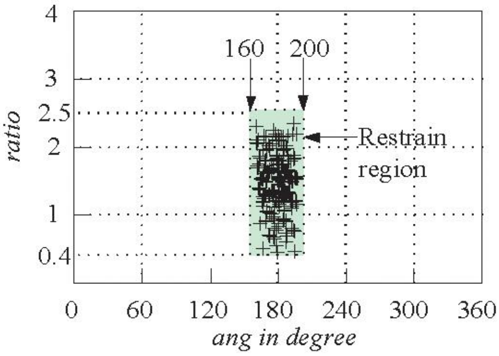

Fig. 5. Performance of proposed current differential protection scheme on external faults. Note that relay does not pick up as all the final operating points are inside the restrain region.

each case, the fault resistance is varied from 0 Ω to 100 Ω in steps of 10 Ω and fault inception angle is varied from 0^o to 300^o in steps of 15^o. For each case, we compute $ratio = \frac{|I_{ij}^{ser}|}{|I_{ji}^{ser}|}$, $ang = \angle(I_{ij}^{ser}) - \angle(I_{ji}^{ser})$, and plot the final operating point (marked by '+' in Fig. 5) on current differential plane. As the '+' always appear in restrain region, it validates that the proposed relay will not trip on load or external fault. The figure also shows that the restrain region cannot be reduced, significantly, without compromising the relay security.

Fig. 6 shows the trajectory of phase-a operating point on current differential plane for the bolted LLL fault on bus 3 (external fault) for the fault inception angle of 270^o. Notice that, as the relay operating point lies inside the restrain region, relay does not pick up on external fault.

Similar investigations carried out with the adaptive relay setting show that the relay does not pick up on any external fault or large disturbance like load throw off etc. We conclude that proposed scheme does not pick up on external faults.

B. *Internal faults*

Sensitivity of the proposed scheme can be evaluated by it's ability to detect a high impedance internal fault. Fig. 7 shows the trajectory of phase-a operating points on current differential plane for one of the cases of LL fault on phase a-b, at the start of line for the fault inception angle of 270^o and a large fault resistance of 600 Ω. Table I shows the highest resistance fault, that can be detected by the differential protection schemes on line L_3, irrespective of fault location and fault inception angle. The relays were set to provide maximum sensitivity without compromising security.

The table clearly shows that with the proposed adaptive setting strategy of the restrain region, the sensitivity of the current differential protection scheme improves by a factor of about 2.5. We emphasize that this improvement in the sensitivity using adaptive setting strategy is not at the cost of the relay security.

TABLE I

SENSITIVITY FOR HIGH RESISTANCE INTERNAL FAULT

Sr No	Protection Scheme	LG Fault R (Ω)	LL Fault R (Ω)	LLL Fault R (Ω)
1	Charging current compensation scheme (Nonadaptive setting)	602	1004	638
2	Proposed scheme (Adaptive setting)	1525	2405	1610

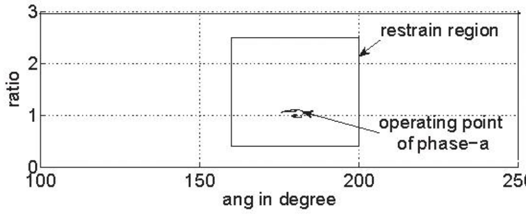

Fig. 6. Trajectory of phase-a operating point for proposed current differential protection scheme on external fault (LLL bolted fault on bus 3, fault inception angle 270^o). Note that the relay does not pick.

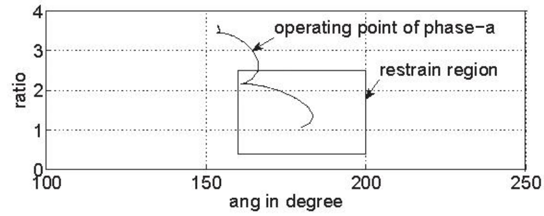

Fig. 7. Trajectory of phase-a operating point of proposed current differential protection scheme for internal fault (LL fault at the start of line, fault inception angle 270^o, fault resistance=600 Ω). Note that the relay pick.

C. *Relaying speed*

In the proposed scheme, the phasors are updated after every sample. The scheme is very fast even if the trip decision is taken on the basis of error exceeding the threshold value consistently for four samples. Simulation results show that the proposed scheme is very fast and takes less than half cycle to operate for low resistance faults. However, it needs 1 to 2 cycles to detect the faults above 500 Ω resistance.

VI. CONCLUSION

An adaptive relay setting procedure to control the area of the restrain region in the current differential plane is proposed in this paper. Area of the restraining region is made a function of line current. At lower currents, restraining area is kept small. This increases the sensitivity of the relay. At larger currents, area of the restraining region is increased in proportion to the current. This increases the security of the relay without compromising the sensitivity. Simulation studies show that this can improve sensitivity of the relay by at least a factor of 2.5.

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Sanjay Dambhare is an Assistant Professor in Department of Electrical Engineering, College of Engineering, Pune. He is currently working towards Ph.D. degree in Department of Electrical Engineering at Indian Institute of Technology-Bombay, Mumbai, India. His research interests include power system protection, numerical relays, power electronics applications in power system and power system computation.

S. A. Soman is a Professor in Department of Electrical Engineering, Indian Institute of Technology-Bombay, Mumbai, India. He has authored a book titled "Computational Methods for Large Power System Analysis: An Object Oriented Approach", published by Kluwer Academic in 2001. His research interests and activities include large scale power system analysis, deregulation, application of optimization techniques and power system protection.

M. C. Chandorkar is an Associate Professor in Department of Electrical Engineering, Indian Institute of Technology-Bombay, Mumbai, India. His research areas include application of power electronics to power quality improvement, power system protection, power electronic converters and control of electrical drives.