A Method for Selecting Secure Slopes in Maximum Restraint Type Differential Relays

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***Abstract*—Current differential relaying is a powerful method for detecting faults in power system equipment. Differential relays typically operate on a restrained slope characteristic where they issue a trip if the differential current exceeds a settable percentage (the slope) of the restraint current. When selecting this slope setting, a relay engineer must balance sensitivity against security. Unequal CT saturation is a security concern which can lead to misoperation of a differential relay for external faults. This paper develops a formula which relay engineers can use to select a secure slope setting for maximum restraint type relays based on the expected worst case CT saturation in their application.**

I. INTRODUCTION

Current differential relaying based on Kirchoff's current law is a common and effective method for detecting faults in power system equipment. It is an intuitive technique which, in theory, can provide perfect selectivity between internal and external faults, although practical considerations can challenge this assertion. Unequal current transformer (CT) saturation due to magnetic remanence, high X/R ratios and/or mismatched CTs can cause false differential currents to be measured by a relay's differential element during external faults, possibly leading to unwanted trips. Many numerical differential relays cope with this by employing some form of percentage restraint characteristic. The magnitude of the differential (operate) current, calculated as the vector sum of all currents entering and leaving the protected zone as in equation (1), is compared against a restraint current. If the differential current is greater than a settable percentage (the slope) of the restraint current then the relay will operate.

$$I_{diff} = I1 + I2 + \ldots + In \tag{1}$$

$$I_{rest.total} = |I1| + |I2| + \ldots + |In| \tag{2}$$

$$I_{rest.max} = max(|I1|, |I2|, \ldots, |In|) \tag{3}$$

$$Diff_{Op} = \begin{cases} Trip & \text{if } I_{diff}/I_{rest} > k \\ No\ Trip & \text{otherwise} \end{cases} \tag{4}$$

A previous work, [1], developed the formula shown in equation (5) by studying a system as shown in Figure 1. This formula gives an estimate of the secure slope setting required to avoid misoperation for external faults due to unequal CT saturation as a function of the saturation voltage across the CT secondary burden, V_s. This formula is based on computer simulations of CT secondary current under various conditions and is valid for total restraint type differential relays where the restraint current is the sum of the magnitudes of the currents entering or leaving the protected zone as in equation (2). This formula has been successfully applied in many applications of total restraint differential relays.

$$k_{secure.total} = 0.824V_s - 0.00242V_s^2 \tag{5}$$

$$V_s = 20\frac{(1+\frac{X}{R})\frac{I_{fault}}{CTR}Z_{burden}}{V_{rated}(1-\%Remanence)} \tag{6}$$

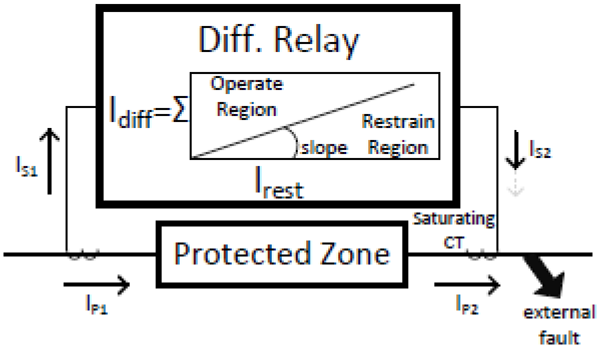


Fig. 1. Simulated system, only 1 CT saturates

There is another style of relay, the maximum restraint type, which selects the restraint current as the maximum of the magnitudes of the currents entering/leaving the protected zone as in equation (3). The formula developed for total restraint type relays is not applicable to maximum restraint style relays. For the system in Figure 1, when the level of distortion in the saturated CT is low, $I_{rest.max}$ is roughly equal to $I_{rest.total}/2$ and the secure slope setting required by a maximum restraint type relay would be approximately twice that prescribed by equation (5). Where moderate to heavy unequal CT saturation is a possibility, there is no relationship between $I_{rest.max}$ and $I_{rest.total}$. Thus, in order to maintain security during external faults and avoid needlessly penalizing relay sensitivity, a different criteria for selecting secure slope settings for maximum restraint style relays is required.

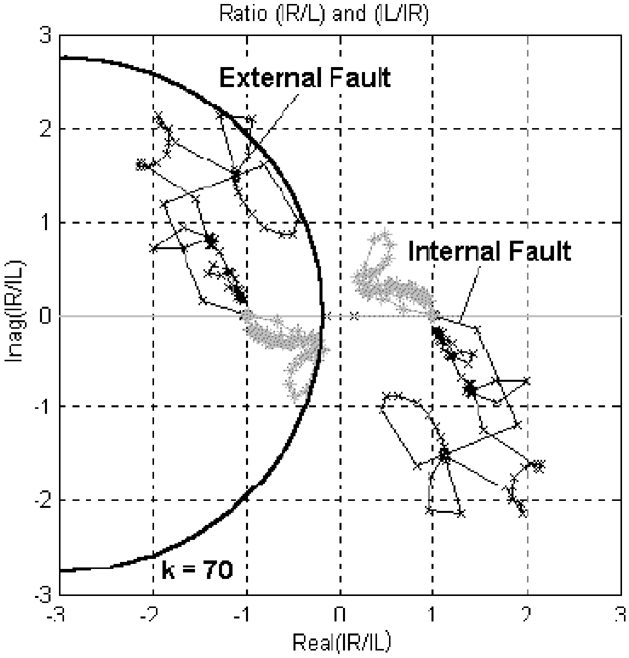
The most thorough method of determining the optimal secure slope setting for a given application would be a process such as given in [2], a simulation of the expected CT secondary currents for various cases of interest (both internal and external faults). The results of these simulations would then be used as inputs to an accurate model of the relay, including sampling rate, filtering methods, differential algorithm etc. and then finally, selecting a slope balancing sensitivity with security. Such analysis is application specific and may prove too time consuming or even impossible if some information such as the details of the relay's filtering methods or its differential algorithm aren't available. Thus, a more general rule for selecting a secure slope setting as a function of V_s, similar to equation (5) for total restraint relays, is desirable.

Using plots of trajectories of simulated operate vs. restraint current, this paper first confirms (5) for total restraint relays. Then a similar method is employed to find a new formula for selecting secure slope settings in maximum restraint style relays. This new formula provides relay engineers with a simplified method of selecting the secure slope as a function of saturation voltage, providing security while maintaining sensitivity.

II. CT MODEL VALIDATION / CONFIRM TOTAL RESTRAINT SLOPE REQUIREMENTS

This paper uses a computer model based on [3] and [4] to simulate the secondary current output of a saturated CT. Before studying the effects of saturation on maximum restraint differential relays, the model was verified by duplicating the results of [1]. Since the secure slope formula for total restraint relays given in equation (5) has been used successfully by relay engineers for years it may be considered valid. The same cases as in [1] were studied here; I=10677A, X/R=14, CT ratio=2000:5, 2Ω burden, voltage rating of 800, 400, 200 & 100V (corresponding to V_s=20, 40, 80 & 160V), simulation timestep ∼55μs, sampled at 16 samples/cycle then cosine filtered according to [5]. The filtered currents were then processed by a total restraint differential algorithm as defined by equations (1), (2) & (4) to determine the secure slope setting required to avoid misoperation for external faults due to the saturation of the CT next to the fault. The current waveforms obtained from simulation agree very closely with the reference results. This is seen by comparing Figure 2 and Figure 3 which display the saturated/unsaturated currents transformed into the alpha plane for one of the four cases simulated.

The case of $V_s = 20V$ does not result in any CT saturation so this case is not considered when determining the secure slope formula. Fitting a 2nd degree polynomial intersecting the origin to the results of the simulation cases detailed above gives the secure slope formula in (7). The similarity of equations (5) and (7) is demonstrated in Figure 4. The plots of the two equations lie nearly on top of one another over the range of interest and the difference between the slope settings prescribed by the two equations is always less than 3%. This strong agreement with an established result confirms the program used to model the output of a saturated CT is appropriate.



[1]

Fig. 2. Reference results for $V_s = 160V$, $k = 70\%$

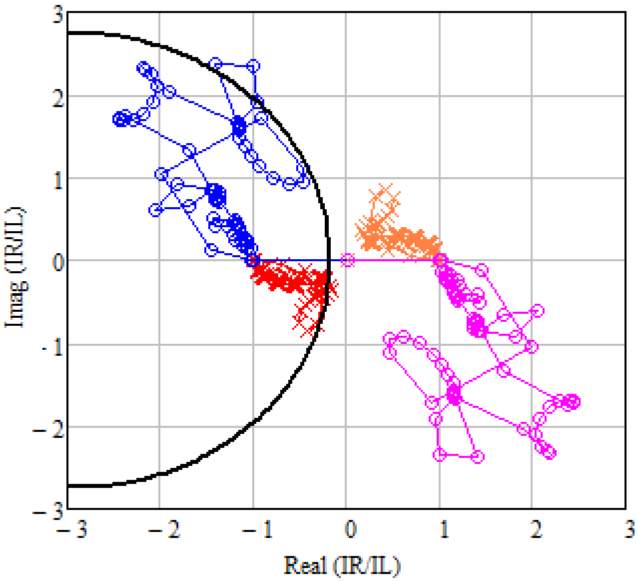


Fig. 3. Author's results for $V_s = 160V$, $k = 70\%$

$$k'_{total} = 0.852V_s - 0.00269V_s^2 \tag{7}$$

III. MAXIMUM RESTRAINT TYPE

A. Modelling & Simulation

Similar to the analysis conducted above for total restraint type relays, simulations performed when studying maximum

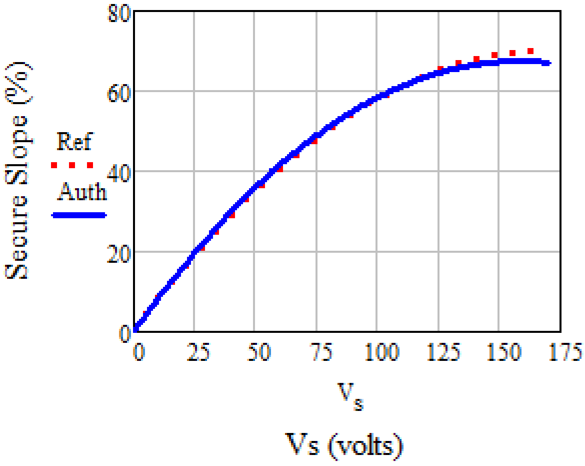


Fig. 4. Comparison of secure slope formulas, reference results vs. author's results

restraint type relays used the system shown in Figure 1. Faults were applied external to a protected zone with 2 CT sources. The simulation allows one CT to be saturated and takes the other to be not saturating at all (the secondary current is a perfect scaling of the primary current according to the turns ratio). Once the current waveforms have been obtained, they are processed by the relay model in order to determine the differential and operate currents calculated by the relay.

Maximum restraint differential relays were modelled using a sampling rate of 16 samples/cycle and a Fourier filter to extract the fundamental. A Fourier filter was selected since there are at least two major relay manufacturers producing maximum restraint type differential relays which use a Fourier filter as part of their filtering method. For each sample, the model calculates the differential and restraint currents according to equations (1) & (3). The secure slope setting required to prevent the differential element from operating was then calculated by dividing the differential current by the restraint current for each sample. A graphical representation of the method is shown in Figure 5.

Three sets of simulations were conducted. For each set of simulations, all inputs to the model were held constant except for one, which was varied to produce saturation voltages, V_s, on the saturated CT of 40 through 160V in steps of 20V. All cases used a turns ratio of 400 (2000:5), a secondary burden of 2Ω, and 0% magnetic remanence. The parameters varied in turn were primary fault current, system X/R ratio and the voltage rating of the CT.

Varying the level of remanence is equivalent to varying the CT's voltage rating so it isn't necessary to consider it in this study [3]. Holding all other parameters constant and varying the burden requires unlikely burdens (very large or very small) to achieve the full range of V_s values under consideration. Some tests with varied burdens were conducted which resulted in essentially the same secure slope requirements as the set of cases where the CT's voltage rating was varied. Thus, the burden was left at 2Ω and a set of simulations with varying burdens is not included in the results. Varying the turns ratio is equivalent to varying the fault primary current so this was also not considered.

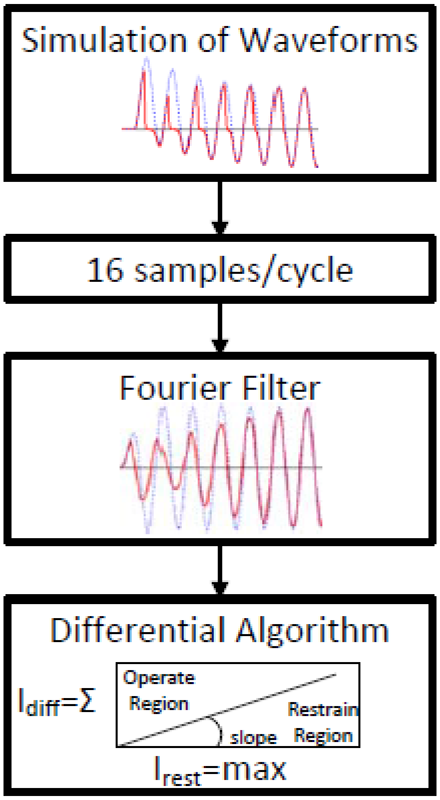


Fig. 5. Max. Restraint Differential Model

To investigate the effect different filtering methods might have on the results some of the same test cases as below were simulated with cosine filtering instead of Fourier. Some differences in the results were observed. Differences in the calculated secure slope settings were never more than 10% and were typically much less. Different relays may have different sampling rates. Sampling rates of 32 and 64 samples/cycle were confirmed to have negligible impact on the results.

B. Results

Table I contains the results of the simulations conducted. These results were plotted on a graph of secure slope vs. V_s and a curve was fitted to the data. The curve types considered included logarithmic as well as 2nd and 3rd degree polynomials. The curve selected is a 3rd degree polynomial intersecting the origin and fitting the maximum secure slope found for each value of V_s in Table I. This curve was chosen because its equation is reasonably simple and had the highest coefficient of determination of all the curve types considered ($R^2 = 0.99$ for the selected data). The fitted curve is given in equation (8) and the plot of results including the curve is seen in Figure 6.

TABLE I
SIMULATION RESULTS

	Vrated	V_s	slope (%)
Ipri=10667A, X/R=14	400	40	49
	266	60	74
	200	80	79
	160	100	81
	133	120	83
	114	140	85
	100	160	91
	Ipri	V_s	slope (%)
X/R=14, Vrated=100V	4000	40	47
	6000	60	64
	8000	80	70
	10000	100	81
	12000	120	91
	14000	140	93
	16000	160	96
	X/R	V_s	slope (%)
Ipri=16kA, Vrated=100V	9	40	59
	14	60	77
	19	80	84
	24	100	87
	29	120	89
	34	140	91
	39	160	92

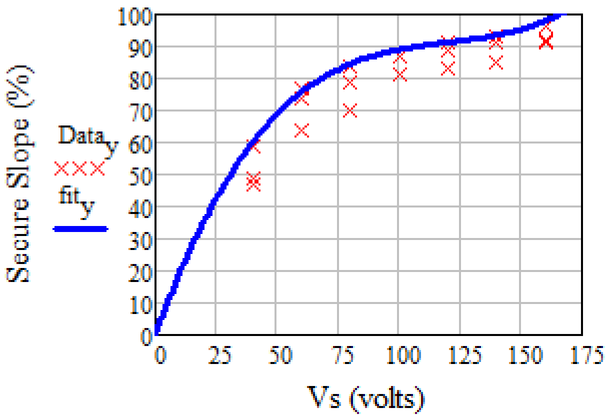


Fig. 6. Max. Restraint - Secure Slope vs. V_s

In a maximum restraint type differential relay, a bolted internal fault with a source of fault current on only one side of the protected zone will lie along the 100% slope line ($I_{diff} = I_{rest}$). Thus, it is not permissible to set the slope $\geq 100\%$ because one cannot permit the relay to restrain in this situation. However, manufacturers of maximum restraint differential relays do allow for very high slope settings, approaching 100%. To be in favour of security, [6], recommends a setting of 98%, noting this "implies that a large differential current is required for a differential operation". Considering this, along with the secure slope formula of equation (8) not exceeding 98% until $V_s > 160V$, the secure slope equation may be considered valid for values of $V_s < 160V$.

$$k_{max} = 0.000046V_s^3 - 0.0166V_s^2 + 2.09V_s \tag{8}$$

C. Application Specific Considerations

Users are advised to consider the specifics of the model used to develop the formula suggested in this paper before applying it in a particular application. The preceding analysis considers only two sources connected to the protected zone. One must consider the number/arrangement of sources connected to the protected zone in their application and may need to consider the specifics of the restraint calculations in the relay being used. For example, it may be possible to directly apply equation (8) to the fault shown in Figure 7a but not to the fault shown in Figure 7b.

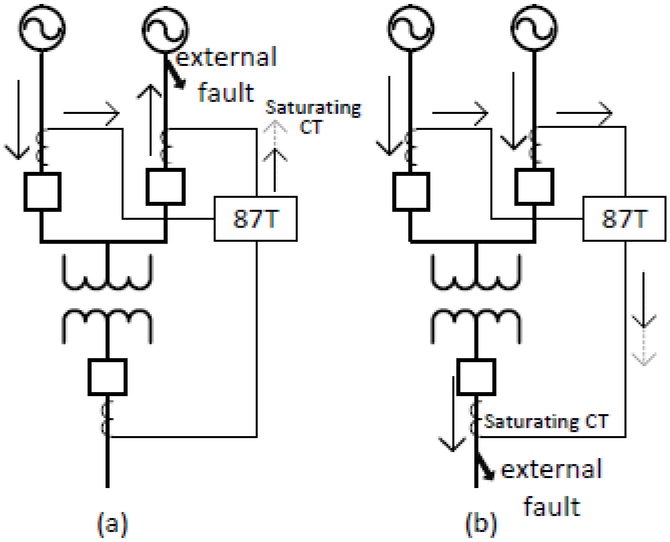


Fig. 7. High & low side external faults with high side bus CTs

If the 87T relay shown in Figure 7b only considers the individual source currents in the restraint calculation then, in the worst case, the restraint current calculated by the relay could be as little as half of the total fault current [7]. Some maximum restraint style transformer differential relays can be configured to consider the currents from each winding of the transformer in addition to the individual current sources themselves [8]. Such a relay's restraint calculation would be according to equation (9), where $|I_{Sx}|$=the magnitude of the current source x and $|I_{Wy}|$=the magnitude of the current flowing in/out of the protected transformer's winding y. If this type of maximum restraint type relay were used then one could directly apply equation (8) to both the scenarios shown in Figure 7 since this relay would calculate I_{rest} to be equal to the total fault current in both cases.

$$I'_{rest.max} = max(|I_{S1}|, |I_{S2}|, \ldots, |I_{Sn}|, |I_{W1}|, |I_{W2}|, \ldots, |I_{Wm}|) \tag{9}$$

IV. CONCLUSION

This paper confirmed the established formula for secure slope in total restraint differential relays by re-producing the results of [1]. Similar methods were used to find a formula for secure slope as a function of V_s appropriate for maximum restraint type differential relays. In many common application types, this formula may be used by relay engineers as an efficient tool for calculating secure slope settings for maximum restraint style differential relays using typically available data.

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