Digital Protection Of Power Transformer

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ABSTRACT

Electric Power utilities traditionally use electromechanical or solid state differential relay to detect winding faults in power transformer. These relays use harmonic component to restrain the relay from operating during non-fault case. Existing electromechanical & static relay use analog filters to obtain trip & restraint signals. But these relays don't have features like self-checking and flexibility. Also, the electromechanical and analog relays are not suitable for implementation in sub station automation and distribution automation schemes, as they lack capability to communicate. In this paper, a laboratory prototype of a numeric relay for protection of power transformer has been developed. The relay implementation use differential protection with second harmonic restraint for magnetizing inrush and fifth harmonic restraint for over-excitation.

1. Introduction

In order to generate electric power and transmit it to customers, millions of rupees are spent on power system equipment. This equipment is designed to work under specified normal conditions. However a short circuit may occur due to failure of insulation caused by

1) Over-voltages due to switching.

2) Over-voltages due to direct or indirect lighting strokes.

3) Bridging of conductors by birds.

4) Breakdown of insulation due to decrease of its dielectric strength.

5) Mechanical damage to the equipment.

This short circuit current may cause heavy damage to equipment and would also cause intolerable interruption of service of consumers.

In modern power system, to minimize damage to equipment two alternatives are open to the designer, one is to design the system so that faults can not occur and the other is to accept the possibility of faults and take steps to guard against the effect of these faults. Although it is possible to eliminate faults to a large degree by careful systems design, careful insulation co-ordination, current operation and maintenance, it is obviously not possible to ensure cent percent reliability and therefore the possibility of faults must be accepted.

2. Transformer Protection

Small transformers are usually protected by fuses or over current relays. Larger transformers are usually protected by percentage current differential relays. Consider a two-winding single-phase transformer as shown in Figure 1. Where i_1 and i_2 are primary and secondary current respectively, N_1 and N_2 are the nominal turns of two windings, and T is the ratio of tape changer When the transformer is without a fault within the zone defined by two CT's. $i_1 N_1 = i_2 N_2 T$ ----------------- 1

Equation 1, where i_1, and i_2, are primary and secondary current respectively, is an approximation because it does not take into account the magnetizing current. If the two current transformers have turn ratios of 1:n and 1:n, respectively, then CT secondary currents I, and I_2

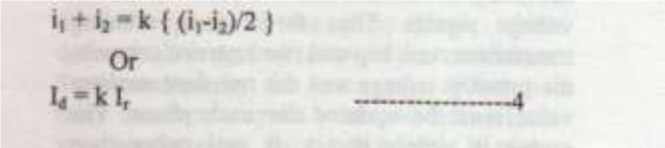
$I_1 = i_1/n_1$ & $I_2 = i_2/n_2$ ------------------------------ 2

When the tape changer is at the neutral tap setting (i.e. when T-1), the CT secondary currents may be made equal in magnitude by choosing n l and n2 such that

$N_1 n_1 = N_2 n_2$ -------------------------------3

Since the current transformers are selected from available standard ratio CT's in general $N_1n_1 \neq N_2n_2$, and $i_1 - i_2 \neq 0$ for a

transformer without a fault. The tap changer creates an additional disparity between i, and i_2 In general then



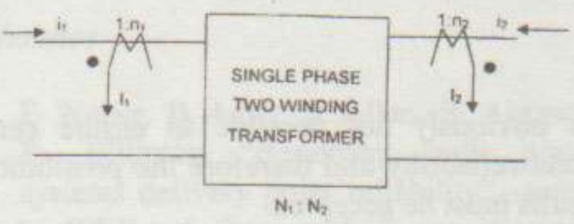
$i_1 + i_2 = k \{ (i_1 - i_2)/2 \}$

Or

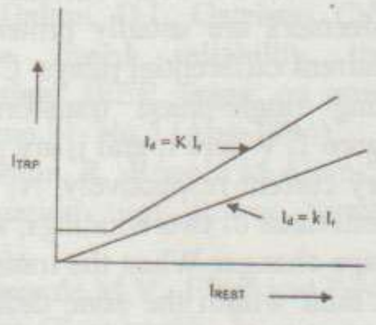
$I_d = k I_r$ ------------------4

3. Voltage Restrained Relay

It is possible to integrate a protection system by assuming that the bus voltage measurement would be available for transformer protection. While the requirement of additional voltage measurements would increase the cost of a stand-alone transformer protection unit, such voltage measurement may be obtained quite inexpensively in an integrated system. In fact, an early solution to the inrush problem used voltage measurement to restrain a percentage differential. The so-called "tripping suppressor" used a voltage relay to suppress the tripping if the voltage was high. In its early analog form the "tripping suppressor" was found to be slower than harmonic restraint devices. Since the harmonic restraint algorithm is essentially a one cycle relay and since the short window line protection algorithms can compute voltage phasors in as little as a quarter



Single phase two winding transformer



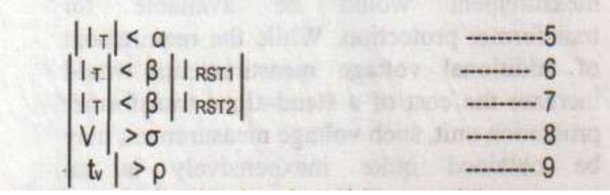
Slope of the percentage differential characteristic.

FIGURE 1&2

of a cycle, it has been suggested that a digital "tripping suppressor" may be faster than the digital harmonic restraint algorithm.

The proposed algorithm used a one-half cycle window for the calculation of fundamental frequency components of trip and restraint currents and the primary voltage for the each phase It was determined that it was necessary to include a transient monitor for the voltage signals. Thus for a three winding transformer, one trip and two restraint currents, the primary voltage and the transient monitor value must be updated for each phase. The saving is simply that t is real rather than complex.

The relay is restrained for a given phase if



$$|I_T| < \alpha \quad \text{----------}5$$
$$|I_T| < \beta\, |I_{RST1}| \quad \text{----------}6$$
$$|I_T| < \beta\, |I_{RST2}| \quad \text{----------}7$$
$$|V| > \sigma \quad \text{----------}8$$
$$|t_v| > \rho \quad \text{----------}9$$

where, I is trip signal, and IRSTI and IRST2 are restraining signal

The quantities in the above equations are half cycle phasor results rather then the full cycle quantities. The first three inequalities in the above equations produce the percentage differential characteristic while the last two restrain if the voltage is high or the transient monitor indicates that the voltage phasor is unreliable. The transient monitor is necessary since the voltage waveform can be so distorted that the half cycle phasor for the voltage fails to be large enough. The voltage quantities for phase c for an inrush case are shown in Figure 3. The serious voltage distortion is due to the inrush The m rush is sufficient to produce a current differential trip In phases 'a' and 'c'. For samples 17-23 only the transient monitor restrains phase 'a' while at sample 27 the monitor drops but the high voltage restrains phase 'c'.

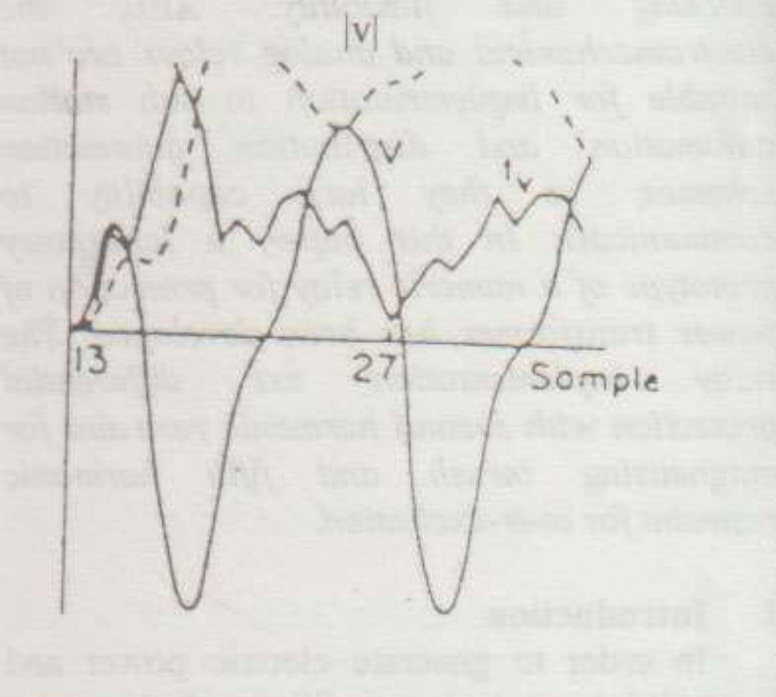


Figure 3: Phase voltage quantities for the voltage restrain algorithm.

4. Flux Restrained Differential Relay

Figure 1 and 2 is a schematic representation of a two winding transformer, and the characteristics of its percent differential relay. The trip current is the differential current (I_1+I_2) and the restraint current (I_1-I_2) / 2 I_1 and I_2 are CT secondary currents of the main transformer primary and secondary winding respectively. The slope of the percent differential characteristic is adjusted to make the relay insensitive to relay and CT inaccuracies as well as to off-nominal tap positions of the tap changer.

It is well known that the current differential relay may trip due to magnetizing inrush currents or due to magnetizing currents during over-excitation of the transformer. A digital computer based harmonic restraint was presented, since saturation of current transformers also leads to harmonics in the current waveform, the algorithm presented In [2] used a combination of 2nd and 5th harmonics to identify a condition of over- excitation or magnetizing inrush. The harmonics were computed using the Discrete Fourier Transform (DFT) which is particularly easy to implement when a sampling frequency of 12 sample per cycle is used. At the sampling rate of 12 times per cycle of the fundamental frequency, only one irrational number ($\sqrt{3}/2$) is involved in the recursive calculation of the DFT. Since the development of the fundamental frequency lags the development of the harmonic components during the onset of a transient, the relay has a restraining signal developed before a trip signal (which is a fundamental frequency component) is obtained. This leads to a very secure relaying principle, with a speed of response about equal to about one cycle. A second computer based relay for transformer protection was presented in [3]. For a three winding- three phase power transformer, the harmonic restraint relay calls for recursive DFT computation of 9 frequency components of currents, requiring a fairly sophisticated microcomputer for its implementation. The voltage restraint relay, although requiring few computations, does depend on the availability of a voltage magnitude window that would securely distinguish between external and internal faults and transient voltage reductions during severe inrush conditions. If it could be estimated correctly, then in would provide sound discriminate for over-excitation as well as magnetizing inrush conditions. Although the voltage at transformer terminal shows severe distortion (Primarily a reduction for fraction of a cycle), the flux levels during these periods are high. Consequently the uncertainties associated with the windows of the voltage. magnitude for restraining function no longer exists when the flux is used as a restraining quantity. The voltage at the terminals of a transformer winding, the current entering that winding i(t) and the mutual flux linkage A(t) of the transformer are related by (Neglecting the resistance of the winding)

$$e - L\,di/dt = d\Lambda/dt \qquad \text{------------10}$$

Where, L. is the leakage inductance of the winding. Integrating between instants of time t, and t

$$\Lambda(t_2) - \Lambda(t_1) = \int_{t_1}^{t_2} e.dt - L\{i(t_2) - i(t_1)\} \qquad \text{--11}$$

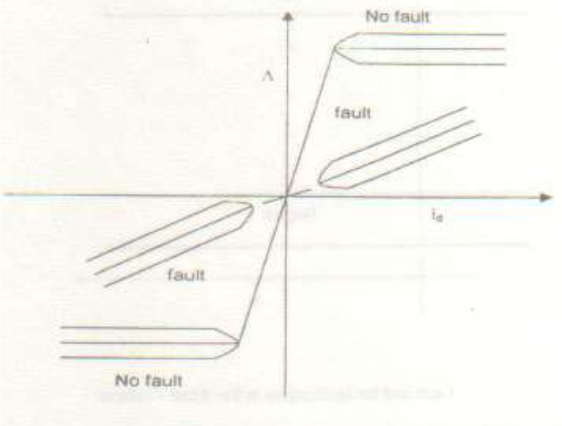
Applying the trapezoidal rule of integration to the integral in equation (11),

$$\Lambda(t_2) = \Lambda(t_1) + (t_2-t_1)/2\ \{e(t_2)-e(t_1)\} - L\{i(t_2)-i(t_1)\} \qquad \text{----------12}$$

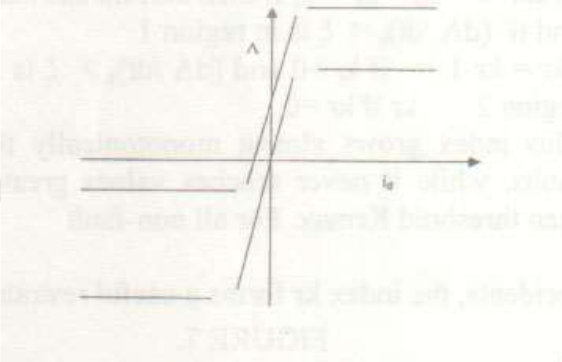
If the voltage and currents are sampled at instants of time At apart then in general for samples obtained at instants (k) and (k-1).

$$\Lambda_k = \Lambda_{k-1}\,\Delta t/2\ \{(e_k - e_{k-1}) - L\,(i_k - i_k)\} \qquad \text{--------------- 13}$$

Equation (13) describes a procedure for computing the mutual flux linkages of a transformer from its past history and the measured currents & voltage samples at its terminals. The differential current $i_d = (i_1 + i_2)$ is equal to the magnetizing current of transformer. (In case of three winding transformer, this current would be $i_d = i_1 + i_2 + i_3$



Open circuit characteristic of transformer



Effect of residual flux on magnetization curve

FIG 4 & 5

Figure 4 shows the open circuit magnetizing characteristics of the transformer and the (i_{dk}, Λ_k) relationship for an internal fault of the transformer. With a fault terminal voltage (and hence A_1) is much smaller than in case of inrush phenomenon. There are thus distinct regions in the (i-A) plane, which define fault or no fault states of the transformer Supplemented by the percentage differential relay the flux restraint principle makes for a very secure relay. In the (dA/dt - i) plane, there is a region which corresponds to a fault or saturated operation. Another region, sufficiently removed from the first, designates operation on the magnetizing curve in the unsaturated region. During an internal fault, the current samples and (dA/dt) samples remain in region (1) fault region of Figure 6 continuously .On the other hand during inrush phenomena, they alternate between the two regions. An index of restraint kr can thus be defined which is increased each time the sample pair lies in the region 1, and the differential current indicates a trip condition and decreased wht

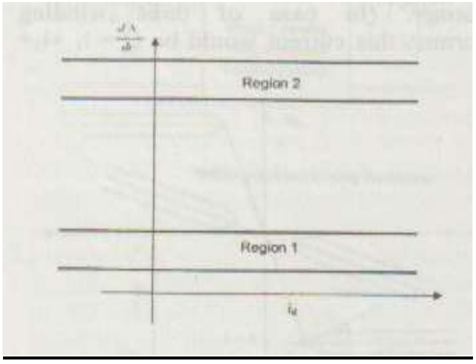
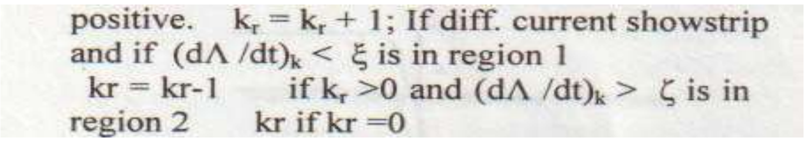


FIG6

Fault and No-fault region in the dA/di-i plane.

The index is also constrained always to remain



positive. $k_r = k_r + 1$; If diff. current showstrip
and if $(d\Lambda/dt)_k < \xi$ is in region 1
kr = kr-1 if $k_r > 0$ and $(d\Lambda/dt)_k > \zeta$ is in
region 2 kr if kr =0

This index grows almost monotonically for faults, while it never reaches values greater than threshold Krmax. For all non-fault

incidents, the index kr forms a useful restraint

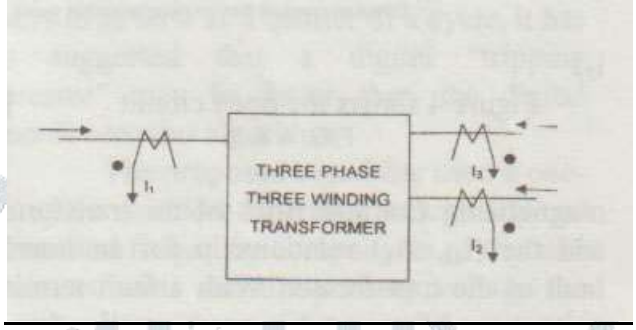


FIGURE 7.
One phase of three phase three winding transformer

function. The threshold Krmax must be determined experimentally. Among other things, it depends on the sampling rate chosen.

5. Harmonic Current Restrained Relay

Principles of transformer protection have been discussed in relaying literature for many years [4]. Consider the power transformer shown in Figure 7. The protection under consideration is the percent differential protection of the transformer. The slope of percent differential characteristic shown in Figure 2 is adjusted to make the differential relay insensitive to CT and relay inaccuracies, as well as the off-nominal tap positions of the transformer. The harmonic content of the inrush current depends upon many factors: residual magnetization of the core and the instant of switching are two of the more important factors. These are other phenomena, which also contribute to the harmonic, and their effect on the behavior of the harmonic restraint function must also be considered. Three major sources of harmonics are as follows:

1. Magnetization inrush due to nonlinearities of transformer core.
2. Saturation of current transformers.
3. Over-excitation of the transformers due to a dynamic over voltage condition.
6. Calculation of Harmonics

The 12 sample per cycle sampling rate makes the calculation of harmonics as straightforward as the fundamental frequency calculations used in line relaying [5]. If the signal f(t) is assumed, for simplicity in presentation, to be periodic with a fundamental frequency of 50 Hz and limited to the fifth harmonic by the antaliasing filter then the relation between the samples

$$F_k = f(k\Delta t),\ \Delta t = 1/600\ s \qquad \text{-------------13}$$

and the harmonics

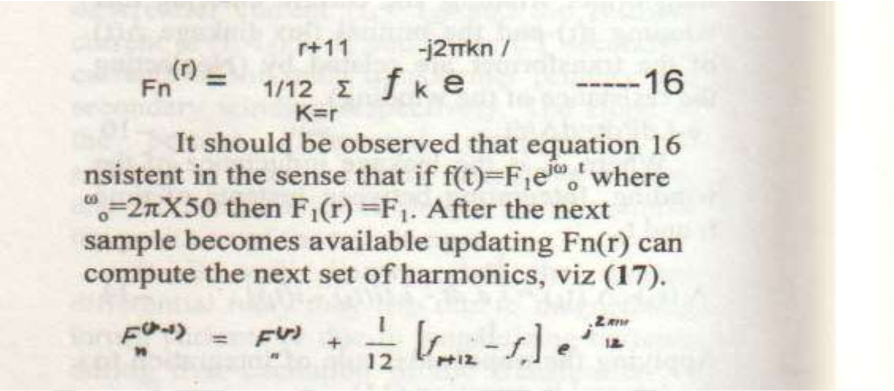
Fn, n=0, ±1, ±2, ±3, ±4, ±5

$$F_n = 1/12 \sum_{K=0}^{11} f_K \, e^{-j2\pi kn/12} \qquad ----14$$

The phasor Fn associated with the nth harmonic is given by.

$$F_n = \frac{j\,(F_n + F_{-n}\ )}{2} \qquad ----15$$

The expression in equation (15) only uses the first 12 sample values beginning at t = 0 Let Fn(r) represent the nth harmonic beginning at the rth sample, ie.,



$$F_n^{(r)} = 1/12 \sum_{K=r}^{r+11} f_K \, e^{-j2\pi kn/} \qquad -----16$$

It should be observed that equation 16 nsistent in the sense that if $f(t)=F_1e^{j\omega_o t}$ where $\omega_o=2\pi X50$ then $F_1(r)=F_1$. After the next sample becomes available updating Fn(r) can compute the next set of harmonics, viz (17).

$$F_n^{(r+1)} = F_n^{(r)} + \frac{1}{12}\left[f_{r+12} - f_r\right] e^{j\frac{2\pi n}{12}}$$

7. Conclusion:

In order to examine the computation beyond the harmonic calculation, a typical algorithm was programmed. Fundamental frequency currents must be used for trip and restraint functions to guard against tripping due to a through fault. It should also be realized that in the case of a multi winding transformer, more than one fundamental frequency-restraining signal must be examined to allow for different types of through faults that are possible. In determining the relay response these multiple restraint signals must be checked and the appropriate signal selected based upon the prevailing currents in the transformer winding.

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