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Effect of the Impulse Phenomenon on the Differential Protection of the Power Transformer

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Abstract

Power transformer plays a vital role in our power system. Everybody is aware of the scenario consumers face once a power transformer goes out of order, particularly in our country. Owing to its demand, power transformer needs most up-to-date protection scheme. Overcurrent relay, gas relay and differential relay are the three important relay for power transformer protection. Faults are basically two types – through fault and external fault.

There are a number of papers by different researchers in the country advocating different philosophies to design a numerical relay or software relay which can discriminate between a inrush and fault.

This paper discusses the different types of inrush phenomenon in power transformer, except CT saturation, highlighting some of the methods to reduce it and detect it and simultaneously ventures to incorporate such a power transformer into the power system network and study fault pattern by the aid of world's most popular environment, that is MATLAB-SIMULINK and also discusses some of its advantages.

Keywords - *magnetizing inrush, numerical relay, power transformer protection, matlab-simulink, power system modelling.*

I. INTRODUCTION

Power transformer is a very vital and important Device in power system network. The unplanned outage of a power transformer is costly to power utilities hence the need to minimize the frequency and duration of unwanted outages. Transformers have three main functions in electronics; impedance conversion, voltage conversion and isolation. Because of these three applications, there are specialist types of transformers. For example, signal transformers are design to match impedances - for example, between a record cartridge and an amplifier. A power transformer is designed to handle large amounts of power (as the name implies) and usually converts voltages; they are used in power supplies and in electrical supply. Accordingly, high demands are imposed on power transformer protective relays. [26-35]The operating conditions of transformer protection, however, do not make the relaying task easy.

Protection of large power transformers is one of the most challenging problems in the area of power system relaying. Overcurrent, differential and gas accumulation are three types of protection that are normally applied to protect power transformers Magnetizing inrush inhibit is one the issues. Traditional second harmonic restraining technique may face security problems as the level of the second harmonic may drop below the reasonable threshold setting (around 20%) permanently or for several power system cycles during magnetizing inrush conditions. This is particularly true for modern transformers with magnetic cores built with improved materials, but it has a bearing upon old designs as well [1] Numerical relays capable of performing sophisticated signal processing functions enable the relay designer to re-visit the classical protection principles and enhance the relay performance, facilitating faster, more secure and dependable protection for power transformers [2,3]. Advanced digital signal processing techniques and recently introduced Artificial Intelligence (AI) approaches to power system protection provide the means to enhance the classical protection principles and facilitate faster, more secure and dependable protection for power transformers. Also it is anticipated that in the near future more measurements will be available to transformer relays owing to both substation integration and novel sensors installed on power transformers. All this will change the practice for power transformer protection. Inrush current refers to the large amount of current that sometimes occur upon energizing a transformer. Typically, for steady-state operation, transformer magnetization current is slightly less than 5% of the rated current [3]. However, at the time of energisation, this current may reach 20 times the normal rated current before quickly damping out and returning to steady state [3]. This damping effect typically takes less than twelve cycles. The practical inrush current magnitudes can range from 0.05 to 20 up, depending on the point on wave of energisation, as well as the residual flux in the transformer core.

II. MAGNETIZING INRUSH CURRENT

One of the main concerns in differential protection of this particular component of power systems lies in the accurate and rapid discrimination of magnetizing inrush current from different internal faults current. This is because the magnetizing inrush current, which occurs during the energizing of the transformer, generally results in several times full load current and therefore can cause mal-operation of the relays. Such mal-operation of differential relays can affect both the reliability and stability of the whole power system.

Initial magnetizing due to switching a transformer in is considered the most severe case of an inrush. When a transformer is de-energized (switched-off), the magnetizing voltage is taken away, the magnetizing current goes to zero while the flux follows the hysteresis loop of the core as shown in figure (1). This results in certain remnant flux left in the core. When, afterwards, the transformer is re-energized by an alternating sinusoidal voltage, the flux becomes also sinusoidal but biased by the reminisce. The residual flux may be as high as 80-90% of the rated flux, and therefore, it may shift the flux-current trajectories far above the knee-point of the characteristic resulting in both large peak values and heavy distortions of the magnetizing current.

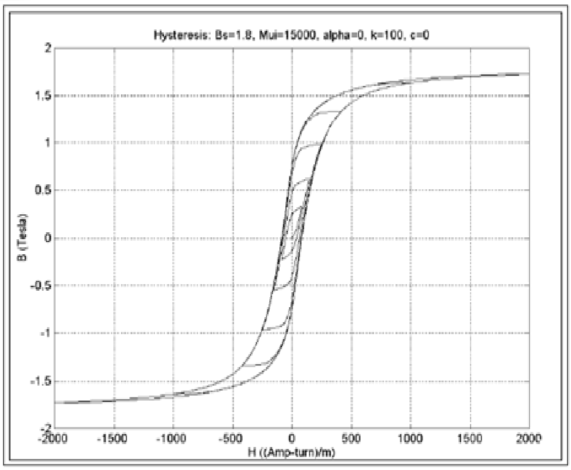

Fig1. The hysteresis loop of the core.

Magnetizing inrush occurs in a transformer whenever the polarity and magnitude of the residual flux do not agree with the polarity and magnitude of the steady state flux (Φss). Transformer energization is a typical cause of inrush currents. Inrush can occur when an adjacent transformer is energized. Recovery inrush occurs after a severe fault, (especially a three phase fault) which has depressed the voltage, is cleared.
These are the voltage, flux, and current signals during a magnetizing inrush. The transformer is energized at zero on the voltage wave with residual flux, ΦR=0. The value Φ is the total flux. The exciting current increases when the total flux reaches the saturation density point as shown in figure (2).

The waveform displays a large and long lasting dc component, is rich in harmonics, assumes large peak values at the beginning (up to 30 times the rated value), decays substantially after a few tenths of seconds, but its fully decay occurs only after several seconds (to the normal excitation level of 1-2% of the rated current).

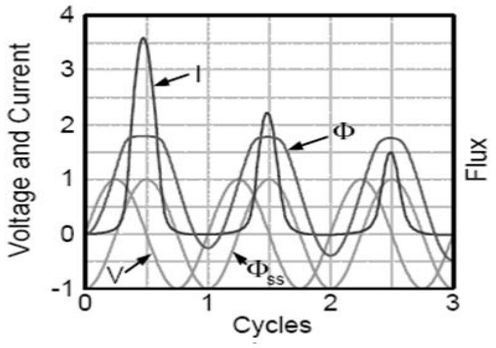

Fig 2. V, I, and Φ curves.

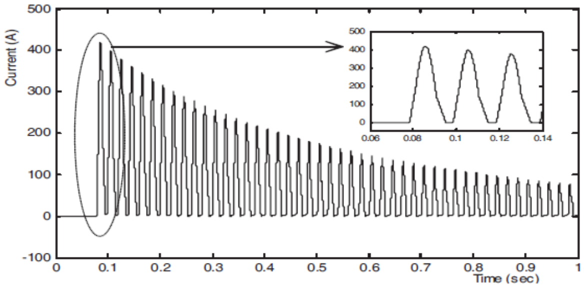

Fig 3. Typical inrush current.

There are several factors that control the magnitude and duration of the magnetizing inrush current:

- Size of the transformer.
- Strength of the power system to which the transformer is connected.
- Resistance in the system from the equivalent source to the transformer.
- Type of iron used in the transformer core.
- Prior history of the transformer and the existence of residual flux.
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Conditions surrounding the energization of the transformer:

- Initial energization.
- Recovery energization from protective action.
- Sympathetic inrush in parallel transformers.

However, the inductance is not linear and saturation can he expected to occur since transformers are usually designed to operate near the knee of the saturation curve under normal conditions. Taking the flux to twice its normal maximum will cause hard saturation, requiring very large exciting currents. Even this is not the worst case, suppose the transformer is energized at the zero point on the voltage wave with a residual flux of Φmax, In this case the saturation will be even greater. Exciting currents as great as 500 times normal are not unusual for such a condition Moreover the current wave will be fully offset from the time axis.

The way in which saturation causes severe exciting current build up is illustrated in figure (4), the saturation curve on the left shows the exciting current required in order to provide a given level of flux. For each point on the flux wave starting at the residual flux value, a value of current may be found from the saturation curve and plotted on the time axes.

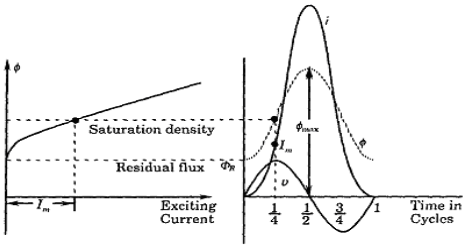

Fig 4. Derivation of the inrush current wave from the excitation saturation curve.

This is illustrated for one value of current, labelled Im Plotting many different points gives the fully offset current pulse shown. Note that the current waveform is not sinusoidal, but is a sharp pulse with the peak occurring at maximum flux.

The decay of the excitation current is rapid for the first few cycles, but then decays very slowly. Usually several seconds are required for the current to reach nominal levels. The time constant governing this decay is not a constant (L/R), since the inductance is varying due to saturation thus, the time constant is small at first, then increases as saturation is reduced. Moreover, the time constant is a function of the transformer size and may vary from 10 cycle for small transformers to 1 minute for large sizes The decay of exciting current also depends on the resistance seen looking into the power system. If the transformer is close to a generator this resistance will be very small and the exciting current will damp very slowly. Moreover, the current will still be distorted in its waveform for an extended period, as much as 30 minutes, after initial energization.

For three-phase transformer, each phase will have a different excitation current, since the point on the voltage wave at which excitation begins is different for all three phases. For example, if the transformer energized when the phase a voltage is at its peak, and with no residual flux, then phase A may not saturate at all, but phase B will probably saturate with a positive pulse not unlike that of figure (4), and phase C will experience a negative pulse of about the same magnitude as phase B.

Inrush currents also depend on the type of transformer core design, the type of three phase connection, and the type of steel, the type of steel may be very important, since it has been shown that the magnetizing ampere-turns required for cold-rolled steel of modern units are much greater than for older hot-rolled steel cores. The type of transformer connection is also important, with star and ***Δ*** windings giving different excitation results.

III. METHODS OF MINIMIZING THE EFFECT OF INRUSH CURRENTS

To minimize the effect of inrush current, we will use the following method:

1. We must use a biased differential relay and it setting (15-45) %.
2. The time delay for relay equal (45) ms approximately.
3. The relay supply by Filter to remove the effect of the harmonic (2nd and 3ed harmonics).

IV. RELAY SOLUTIONS TO THE INRUSH CURRENT PROBLEM

Since the inrush current exists only on the source side of the transformer, the inrush current will appear in the differential circuit and operate the relay. There are several solutions to this problem, all of which are somewhat complex and expensive:

1. Even Harmonic Cancellation.
2. Harmonic Restraint.
3. Harmonic Blocking.
4. Resonance Blocking.
5. D.C. Bias.
6. D.C Block.

The theory of magnetizing inrush current on C.T's is considered in detail as follow:

A. Harmonic cancellation

Owing to the saturated condition of the transformer iron, the wave-form of the inrush current is highly distorted; figure (5) shows a typical wave-form for maximum inrush.

The amplitudes of the harmonics, compared with the fundamental (100 %) are as follows**:**

Table (1): Amplitude of harmonics in a typical magnetizing inrush current wave-shape

Typical value	Component
55%	D.C
63%	2nd harmonic
26.8%	3rd harmonic
5.1%	4th harmonic
4.1%	5th harmonic
3.7%	6th harmonic
2.4%	7th harmonic

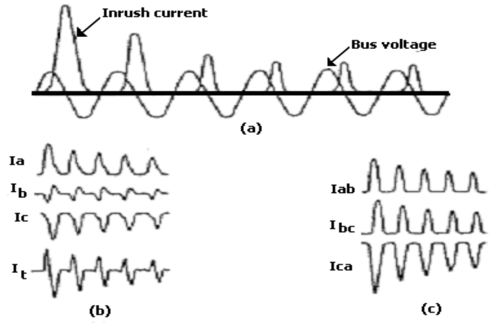

Fig 5. Typical wave-form of inrush current.
(a)Theoretical; (b) Actual currents in ⋋-connected windings;(c) Actual currents in ***Δ***-connected windings

The D.C component varies between 40% and 60%, the second harmonic 30% to 70%, the third harmonic 10% to 30%. The other harmonics are progressively less, the range depending upon the equipment in the circuit, e.g. tooth ripple from a generator. The third harmonic and its multiples do not appear in the CT's leads since the components circulate in the ***Δ*** winding of the transformer and the ***Δ*** connected CT`s. On the ⋋ side the D.C components and even harmonics can be cancelled out in the operating circuit of a rectifier bridge relay and added in the restraint. This leaves only the 5th, 7th, etc., which can either be ignored because of their small amplitude or blocked by a suitable filter.

Analysis of the waveform indicates that there is a significant amount of second harmonic in this wave form. Many transformer differential relays use this second harmonic signature to restrain the relay from operating. Figure (6) shows that as long as the ratio of second harmonic to fundamental exceeds a threshold, the relay will block tripping of its sensitive percentage differential element.

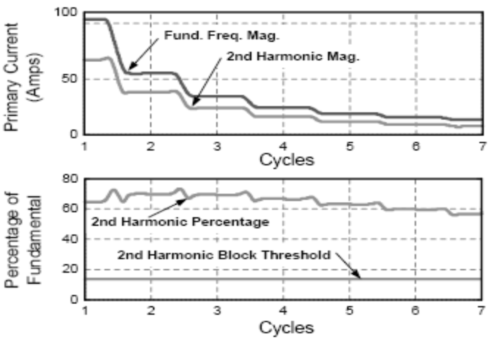

Fig 6. Second harmonic by analysis the wave form.

B. Harmonic Restraint

A popular method of making differential relays insensitive to magnetic inrush current is to filter out the harmonics from the differential current, rectify them and adds them to the percentage restraint as shown in figure (7).

Harmonic restraint is obtained from the tuned circuit XC, XL which permits only current of fundamental frequency to enter the operating circuit, D.C and harmonics being diverted into the harmonic restraining coil. The relay is adjusted so that it will not operate when the second harmonic (restraining) exceeds 15 % of the fundamental current (operating). The minimum pick-up is 15% of CT's rating and the minimum operating time is about two cycles.

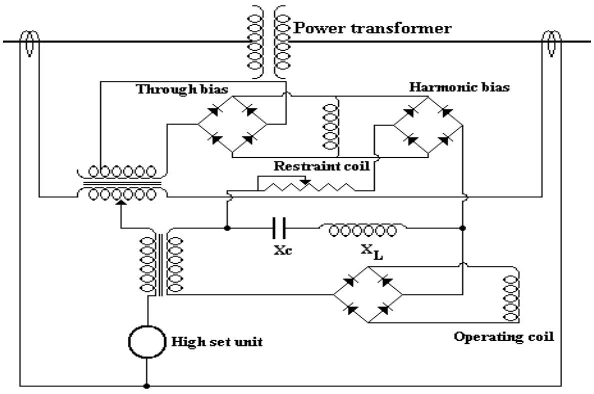

Fig 7. Basic circuit of harmonic restraint relay.

Owing to the fact that D.C offset and harmonic components may also be present in fault current, especially if the CT`s saturate, it is customary to provide an instantaneous over current unit in the differential circuit, which is set above the maximum inrush current but will operate in less than one cycle on heavy internal faults, in this way fast tripping is assured for all heavy faults.

C. Harmonic blocking

An alternative to harmonic restraint is to provide a separate blocking relay whose contacts are in series with those of a biased differential relay and which operates when the second harmonic is less than 15% of the fundamental, figure (8) is a simplified diagram showing the basic principle.

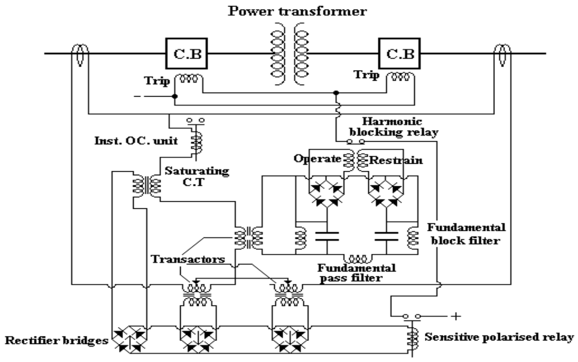

Fig 8. Basic circuit of harmonic blocking relay.

D. Resonance Blocking

This method is similar to the harmonic blocking except that the blocking relay is tuned to twice system frequency and is supplied by rectified current from the differential circuit. The magnetic inrush current of the power transformer when rectified, gives the number of

D.C pulses per second which correspond to system frequency and the relay blocks.

During a fault the current will have a large fundamental component which, when rectified, gives twice as many pulses per second and the relay operates, thereby permitting the differential relay to trip.

E. D.C. Bias Scheme

The characteristic feature of a shunt-loaded current- operated transudatory, in which the operating current increases linearly with increasing D.C in the control circuit for a constant voltage output, has been utilized in this relay, this feature gives a convenient way of obtaining percentage bias on through faults by rectifying the through current and using it to control linearly the output from the A.C primary winding carrying the differential current from the same phase.

The output from this transudatory goes to the second conductor which controls a tripping relay. The D.C component of the magnetizing inrush current has been used as "auto-bias" to the relay in the same transudatory element. When the magnetizing inrush current is symmetrical and does not contain a D.C component, the relay is made stable by a "cross-feed" bias from the D.C component of the inrush current in another phase. For this purpose another transudatory element has been incorporated, as shown in figure (9).

This type of protection is simpler and cheaper than harmonic restraint but has the possibility of undesirable tripping on inrush current which may occur in a three-phase transformer if the breaker is closed at the moment of voltage maximum on one phase. The resulting inrush current can have no D.C component to block the relay. This condition can be overcome at some sacrifice of speed and sensitivity when it is operation on offset internal fault current is demanded.

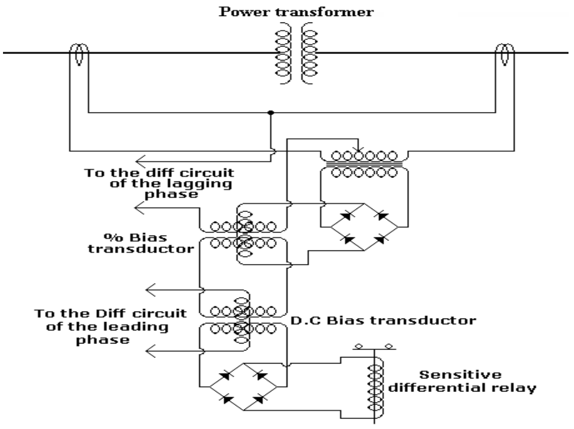

Fig 9. Percentage biased and D.C component biased transudatory relay for transformer protection.

F. D.C Blocking Method

A D.C blocking method using wave shape recognition splits the differential current into positive and negative semi-cycles. The sum is then calculated for both semi-cycles, S+ and S-. The ratio of the minimum sum to the maximum sum, DCR, is calculated. If the ratio, DCR, is less than 0.1, DCBL 1 asserts to block the differential element as shown in figure (10). Wave shapes that are severely offset will produce a blocking output. The presence of D.C offset in the inrush current is an additional indicator that can be used to guarantee relay security for inrush.

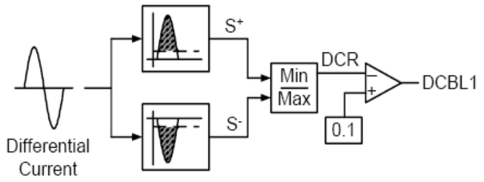

Fig 10. D.C blocking method.

D.C blocking asserts for severely offset wave shapes, characteristic of inrush currents, regardless of their harmonic content as shown in figure (11).

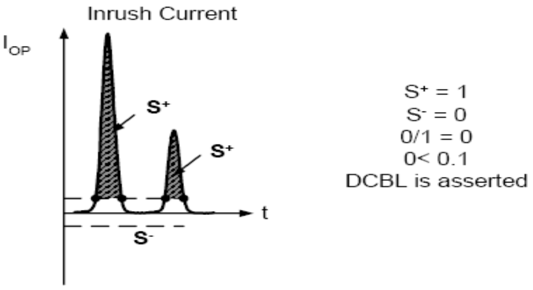

Fig 11. D.C blocking method (DCBL asserted).

D.C blocking does not assert for internal fault current that produces symmetrical half cycles of operate current as shown in figure (12). This includes wave shapes that may be distorted by symmetrical CT saturation.

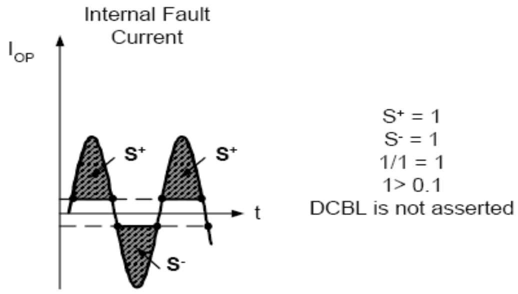

Fig 12. D.C blocking method (DCBL is not asserted).

V. POWER SYSTEM CASE REALISED IN MATLAB-SIMULINK ENVIRONMENTS

The following study has been realized in MATLAB-Simulink ,see figure (13). It consists of a 60 km transmission line connected to a 120 kV three-phase network feeding a 40 MVA inductive/resistive load supplied at 10 kV over a 40 MVA YgD11 transformer. The capacitors located at both sides of the transformer substitute the D-winding stray capacitance (secondary side) and the bus bar capacitance to the ground (primary side). A single-phase fault occurs at 1/3rd of the line at 0.044 sec (1 ms before the voltage peak in phase A). The fault is cleared by the protection at the supply side at 0.1 sec and at the remote end at 0.2 seconds.

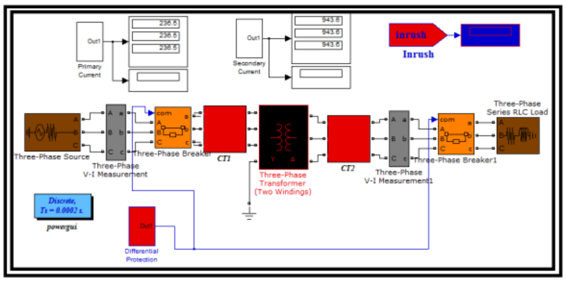

Fig 13. Model in MATLAB-Simulink.

Figure (14) shows the current flowing from the supply and remote network to the fault. The latter component has relatively small amplitude because it is the zero sequence return current of the Y/D transformer. It can be observed that the circuit breaker located at the left side opens at the first current zero after 0.1 sec, the right side breaker opens after 0.2 sec.

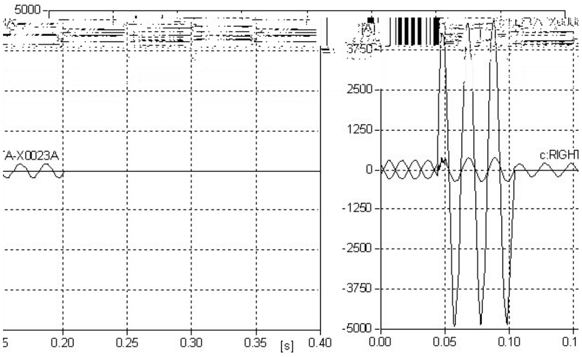

Fig 14.Components of the fault current (currents in phase A from the left and the right)

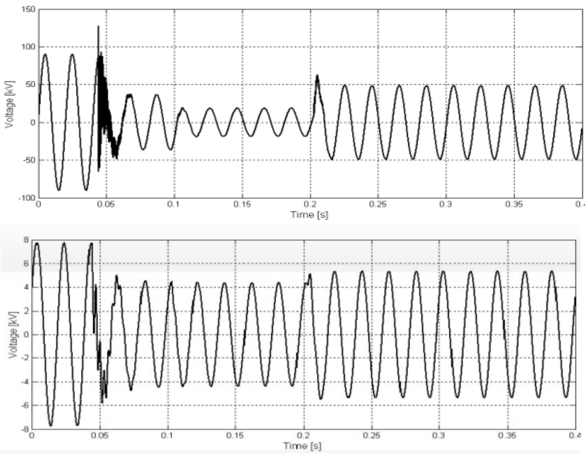

Fig 15. Voltages at the primary and the secondary side of the transformer (phase A).

VI. CONCLUSION

When a transformer is energized, there is large amount of inrush current generated in its primary winding. This current appears only on one side of the transformer and is not reflected on the other side of the transformer. This causes an imbalance of the currents appearing at the transformer differential relay. This imbalance will be seen as a differential current and will cause the differential relay to trip. Since an inrush condition is not a fault condition, the operation of a differential relay during an inrush condition must be prevented.

There are several ways of restraining the differential relay from operating during inrush. These include desensitizing of relays; wave shape recognition techniques and harmonic based methods. Desensitization method is no longer being practiced. Wave shape recognition methods are still relatively new and not widely practiced. Harmonic based methods are widely practiced. The inrush current has a large harmonic component which is not present in fault currents. Inrush currents generate harmonics with second harmonic amplitudes as high as 65% of the fundamental. This is used by harmonic restraint relays to distinguish between faults and inrush.

The harmonic restraint method adds the harmonic component of the operate current to the fundamental component of the restraint current, providing dynamic restraint during transformer inrush. Harmonic restraint methods ensure relay security for a very high percentage of transformer inrush currents. Properly setting and adjusting the second harmonic restraint percentage reduces the blocking time of differential protection during inrush. It also provides relay reliability to internal faults and stability to external faults.

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