International Journal of Electrical Engineering.
ISSN 0974-2158 Volume 4, Number 1 (2011), pp.83-102

http://www.irphouse.com

A Discussion on Power Transformer Magnetizing Inrush, Remedy, Fault Detection in Matlab–Simulink Environment

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Abstract

Power transformer plays a vital role in our power system. Every body 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 uptodate protection scheme. Overcurrent relay, gas relay and differential relay are the three important relay for power trandformer protection. Faults are basically two types – through fault and external fault. Inrush is not a 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 like probanilistic neural network (PNN), fuzzy logic (FZL), support vector machines (SVM), HS-transform, wavelet transform (WT), back – propagation neural network (BPNN), discrete wavelet transform(DWT) etc.

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 modeling.

Introduction

Power transformer is a very very vital and important Device in power system network. many transformers of our country is of british era. 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; impedence conversion, voltage conversion and isolation. Because of these three applications, there are specialist types of transformers. For example, signal transformers are design to match impedences - 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 pu, depending on the point on wave of energisation, as well as the residual flux in the transformer core.

Continuous development of appropriate software packages makes simulation of power engineering problems more and more effective. However, these analysis tools differ from each other considerably from the point of view of the applicability to a special problem. The author demonstrate a widespread environment: MATLAB-SIMULINK, which can be used to simulate a wide spectrum of dynamic systems.. An example is presented which demonstrate the capabilities and underline the advantages of matlab-simulink environment to a power system problem incorporating power transformer to study fault pattern, which can be subsequently be used for designing suitable numerical relay. The paper as such discusses the inrush behaviour, its remedy in power transformer.

Inrush Detection and Trip Blocking

Transformer inrush refers to the transient exciting current resulting from a sudden change in the exciting voltage. This occurs at the instant of energization, after the clearing of an external fault (recovery inrush), or during the inrush period of another nearby transformer (sympathetic inrush) [7]. Inrush current appears as operate current to a differential relay so the relay must either a) have sufficient time delay and insensitivity to the distorted wave so as to not see the event (of course, this is the undesirable answer) or b) take advantage of the inrush's distinctive waveform to sense the event and block tripping. The most common means to sense inrush is via the use of harmonic content in the operate quantity. The second harmonic predominates in inrush currents [7] and is used in most transformer differential relays, either alone or in combination with other non-fundamental components, though there are other waveshape monitoring schemes in a couple relays in the market. The harmonic sensing relays most commonly block operation if the harmonic(s) in the operate leg exceed(s) a give percentage of the fundamental component, though some relays on the market use the harmonic to increase the restraint current. Some relays use a scheme that uses total harmonic current in all three phases in the analysis of every phase, and some use a cross blocking scheme, where if one phase is blocked, all phases are blocked.

Energizing Inrush

Energization inrush is caused by remanence (residual flux) in the core and the point in the voltage waveform when a transformer breaker closes. If the instantaneous voltage at energization calls for flux of the same polarity as the remanence, the core is driven into saturation, creating peak exciting currents that can exceed ten times rated exciting current. As a comparison, normal steady-state excitation current is about 0.01 to 0.03 times rated. In Fig. A the steady-state flux at the instant of energization matches the residual flux, so no transient current flows.

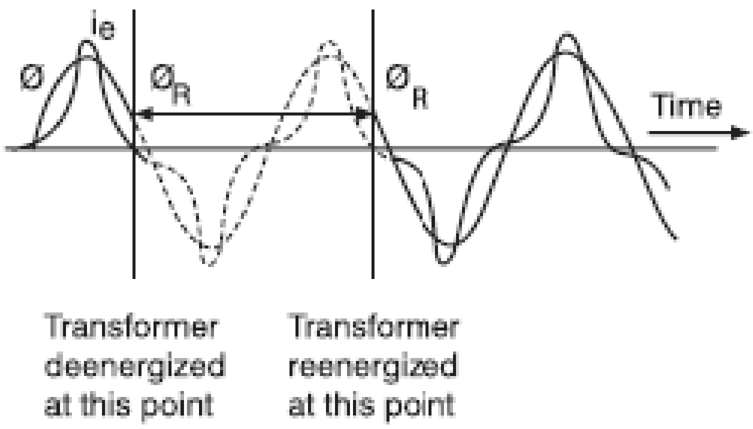


Figure A: trafo is energized without inrush pattern.

In contrast, in Fig. B, the steady-state flux at energization is at its negative peak. Combined with a positive remanence, this condition produces the maximum level of transient current The inrush current is actually much larger in relation to steady-state current than indicated by Fig. C, in order to keep the figure to a reasonable size.

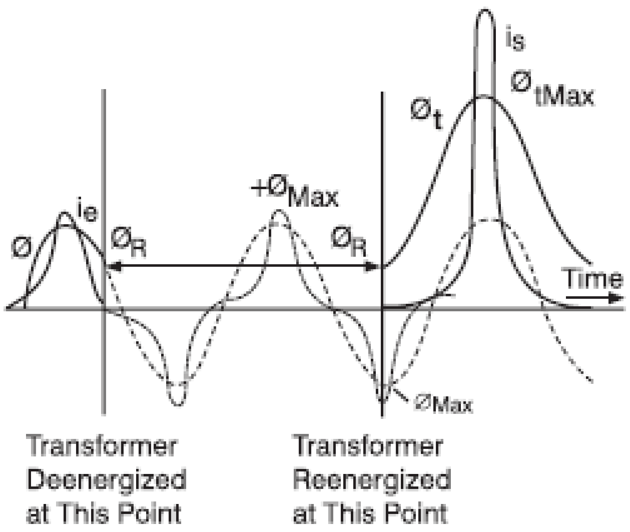


Figure B: the inrush pattern when the power trafo is energised.

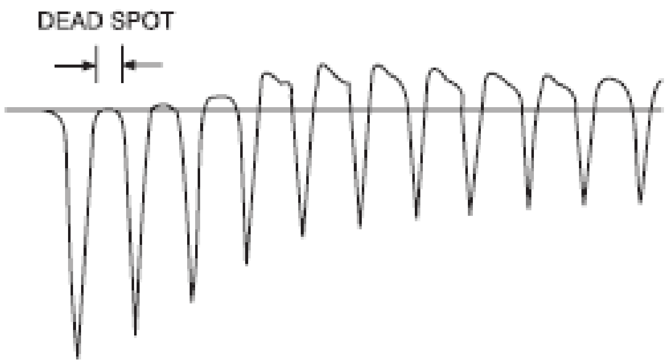


Figure C: waveform pattern when the power trafo is energized.

Figure C shows a typical inrush waveform. Note the dead/flat spot where almost no current is flowing as the core exits and then re-enters the saturated region. The alternating flat to high peak current contains the second harmonic that a relay uses to recognize the existence of an inrush condition. Note in the first two to three cycles of Fig. C's waveform, there is an effective DC component of the waveform. This DC is causing a flux buildup in the CT steel and a partial saturation of the core.

After about 3 cycles, the flat/dead spot rises above the 0 current axis, and the component of current above the 0 current axis is roughly equal to current below the axis, indicating the CT is no longer producing any DC offset (even though DC may exist on the primary), but it is still reproducing at least some of the AC components, though in a possibly distorted fashion. In extreme cases, the CT can saturate during the first cycle, so the flat spot in the current waveform never remains at the 0 current level for any duration. The decay rate of successive primary-current peaks depends upon the amount of resistance in the source and the nonlinear inductance of the transformer. In three phase transformer differential relays, the differential relay has the ability to monitor harmonic levels in all three phase differential comparators at the same time; hence, it makes a decision that an inrush condition exists on a three phase basis, rather than on a per phase basis.

Recovery Inrush

A recovery inrush occurs at the clearing of an external fault as a result of the sudden increase in voltage from the depressed and unbalanced level that exists during the fault. This voltage transient causes a flux transient, with accompanying abnormally high exciting current. The current level is less than that seen during transformer energization.

Sympathetic Inrush

The current Ip in Fig. D shows sympathetic inrush current in transformer T1, resulting from the energization of an adjacent transformer T2. The decaying DC component of current Ie flowing in T2 develops a drop in the source impedance Rs and Xs, producing pulses of inrush current Ip on the alternate half cycles. Note the delayed buildup of Ip. The severity of the sympathetic inrush is a function of the level of DC voltage drop across the source impedance. A common set of differential relays should not be used to protect both T1 and T2 transformers in Fig. D if they can be switched separately. The sum of the two transformer currents, Is, may not contain sufficient harmonics to restrain the relays once transformer T1 saturates severely.

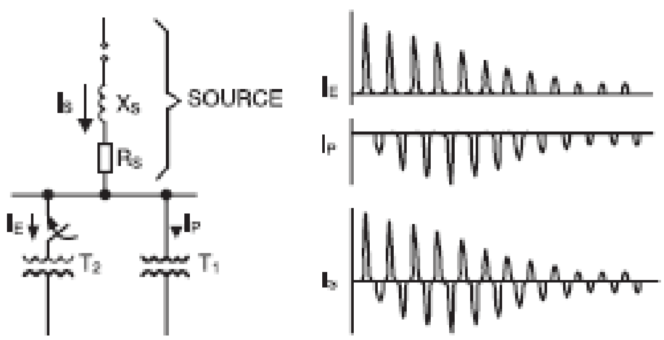


Figure D: concept of sympathetic inrush.

Causes of Magnetizing Inrush

Magnetizing inrush currents in power transformers results from any abrupt change of the magnetizing voltage. Although usually considered a result of energizing a transformer, the magnetizing inrush may be also caused by:

a. occurrence of an external fault,
b. voltage recovery after clearing an external fault,
c. change of the character of an external fault, and
d. out-of-phase synchronizing of a near-by generator.

Since the magnetizing branch representing the core appears as a shunt element in the transformer equivalent circuit, the magnetizing current upsets the balance between the currents at the transformer terminals, and is therefore experienced by the differential relay as a "false" differential current.

Inrush due to switching-on

Initial magnetizing due to switching a transformer on is considered the most severe case of an inrush. When a transformer is de-energized, the magnetizing voltage is taken away, the magnetizing current goes to zero while the flux follows the hysteresis loop of the core. This results in certain remanent flux left in the core. When, afterwards, the transformer is re-energized by an alternating sinusoidal voltage the flux gets biased by the remanence. The residual flux may be as high as 80-90% of the rated value [1], 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. Figure E shows a sample inrush current.

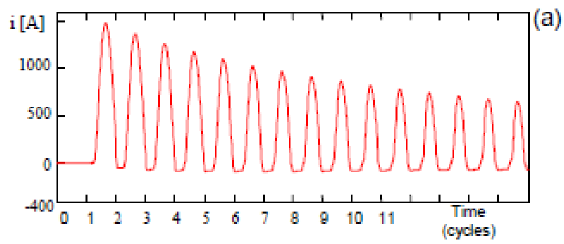


Figure E: sample inrush current.

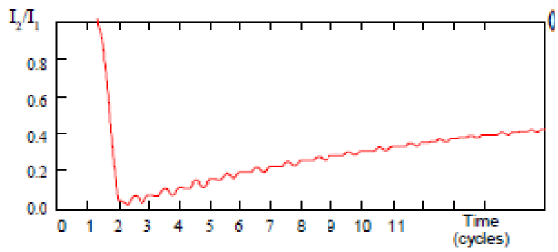


Figure F: its 2nd harmonic ratio

The waveform displays a large and long lasting dc component, is rich in harmonics, assumes large peak values at the beginning, decays substantially after a few tenths of a second, but its full decay occurs only after several seconds. The shape, magnitude and duration of the inrush current depend on several factors. They are [1]:

a. Size of a transformer.
b. Impedance of the energizing system.
c. Magnetic properties and remanence of the core.
d. Point-on-wave (phase angle) and way (inner, outer winding, type of switchgear) the transformer is switched on.

Inrush Explained in Detail

When a transformer is initially energized, there is a substantial amount of current through the primary winding called inrush currents. The rate of change of instantaneous flux in a transformer core is proportional to instantaneous voltage drop across the primary winding. The voltage of the transformer is a derivative of the flux, and the flux is the integral of the voltage. In a normal operation, the voltage and the flux are phase-shifted by 90 as shown in figure F

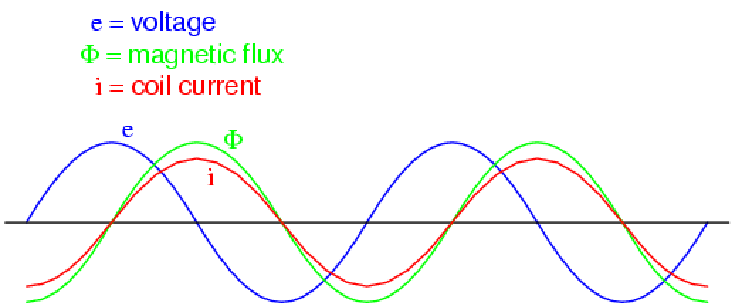


Figure F: Voltage, Magnetic Flux, Current Wave Forms.

When the transformer is energized at the moment in time when the instantaneous voltage is at zero, the flux and current build up to their maximum level as shown in figure G

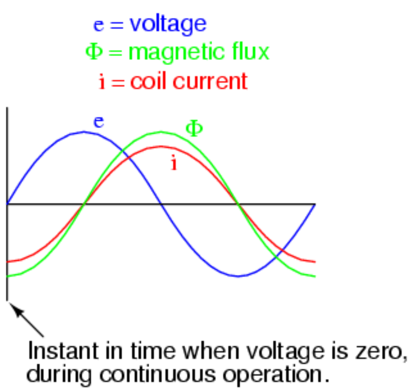


Figure G: Transformer Enerzised When Voltage at Zero.

In a transformer that has been sitting idle, both the magnetic flux and the winding current should start at zero. When the magnetic flux increases in response to a rising voltage, it will increase from zero upwards. Thus, in a transformer that is energized, the flux will reach approximately twice its normal peak magnitude as shown in figure H

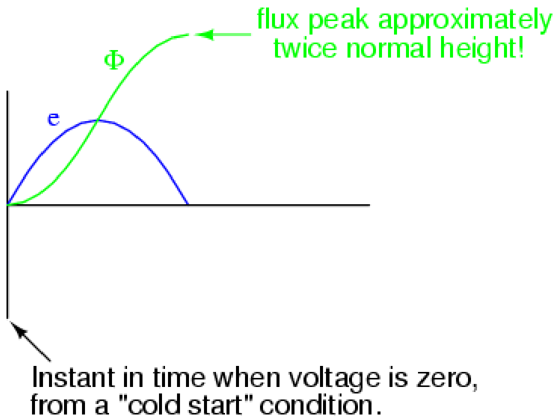


Figure H: Transformer Enersised When Flux At Zero.

In an ideal transformer, the magnetizing current would rise to approximately twice its normal peak value [8]. However, most transformers are not designed with enough margins between normal flux peaks and the saturation limits. During saturation, disproportionate amounts of mmf are needed to generate magnetic flux. This means that the winding current, which generates the mmf to cause flux in the core, will disproportionately rise to a value exceeding twice its normal peak as shown in figure I. This is what causes inrush currents in a transformer's primary winding when energized.

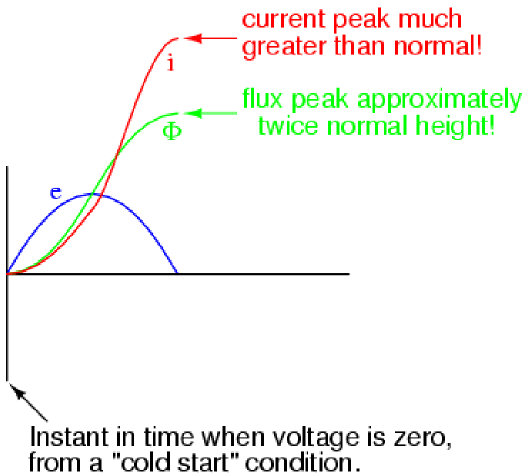


Figure I: Transformer Enerzised When Voltage At Zero.

The magnitude of the inrush current strongly depends on the exact time that electrical connection to the source is made [8]. If the transformer happens to have some residual flux in its core at the moment of energisation, the inrush could even be more severe as shown in Figure J

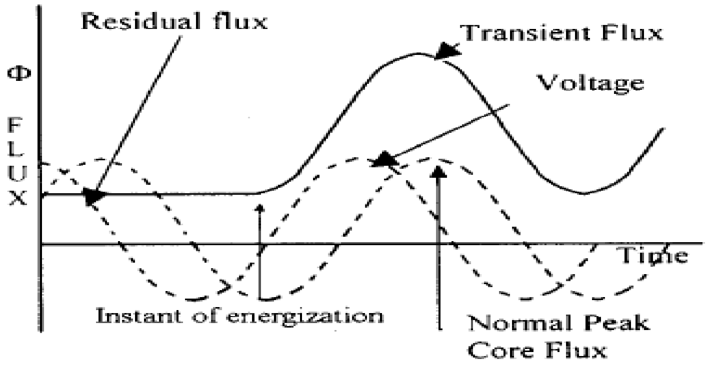


Figure J: Transformer energisation with residual flux [2].

The magnitude of this inrush current can be several times the load current and flows only on one side of the differential relay, which tends to operate if some form of restraint is not provided [14]. Typical second harmonic content of inrush current due to the energisation of a power transformer simulated using Matlab/Simulink is shown in Figure K.

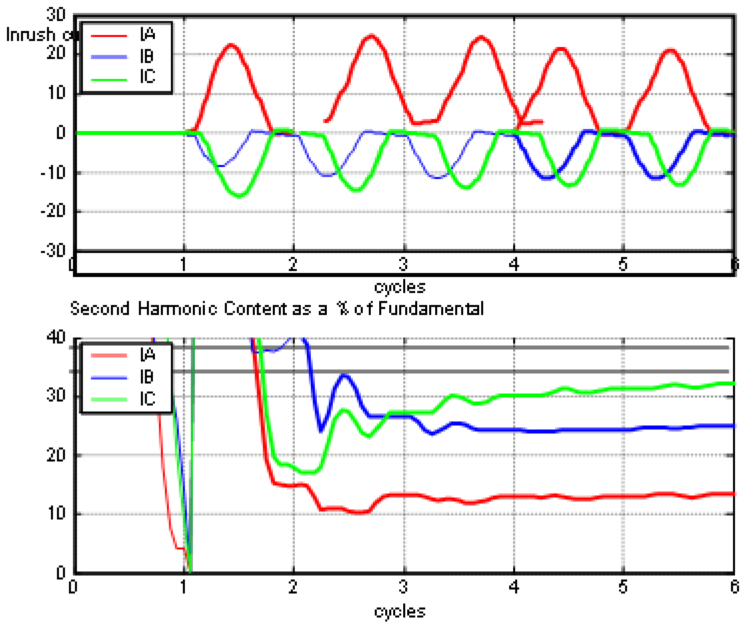


Figure K: 2^{nd} Harmonic In Inrush.

Transformer Inrush Magnitude.

The voltage incidence angle and the residual flux are the main factors that determine the first peak of the inrush current. The results also showed that the greatest inrush currents occur when the transformer is switched at 0°. The least amplitude occurs when the voltage is at 90° and 270°. The system time constant (L/R) determines how fast the inrush current diminishes. The time constant for the decaying current is in the range of 0.1 seconds for small transformers, 100kVA and below and in the range of 1 second for larger units. The other factor that affects magnetizing inrush is the magnetic properties of the core material. The magnetizing inrush is more severe when the saturation flux density of the core is low. Most transformer core material have flux densities of 1.5 to 1.75 Tesla. Transformers operating closer to the latter value display lower inrush currents [21]. In general, however, the magnitude of the inrush current is a random factor and depends on the point of the voltage waveform at which the switchgear closes, as well as on the sign and value of the residual flux. It is approximated that every 5^{th} or 6^{th} energization of a power transformer results in considerably high values of the inrush current [21]

Effect of Inrush Currents on Differential Protection

The inrush current of a transformer can be as high as between 5-10 times of the rated transformer current. 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 on the currents appearing on 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 from an inrush condition should be avoided.

Gapping the Core as Remedy

Most power transformers are built with high permeability steel cores [16]. The problem of using high permeability core materials is that inrush currents are increased. To solve the inrush problems, transformer manufacturers resort to gaps in the core. Gapping is an expensive production methodology and is difficult to control and test. In addition, gapped transformers become acoustically noisy. Most suppliers have proprietary technology (gapless) that produce toroidal transformer that have reduced inrush currents.. It is important that the second harmonic peak of transformers is known for setting of second harmonic restraint threshold

Other Approaches as Remedy

Other approaches include

- Waveform-based algorithms [2].
- Model methods [4,5].
- Differential power method [6].
- Flux-based method [7].

They do not address the problem entirely

Differential protection restraint to magnetizing inrush current as remedy
Early transformer differential relay designs used time delay, or a temporary desensitization of the relay to overcome the inrush current [15]. This technique increased the time to operate. Other designs used an additional voltage signal to restrain or to block the differential relay operation. However, for a stand-alone differential relay the additional voltage signal is not always available.

The methods presently used to differentiate between inrush currents and internal faults fall in two groups: those using harmonics to restrain or block relay operation, and those based on wave shape identification.

Harmonic-based methods as remedy
The magnetizing inrush currents have high component of even and odd harmonics. Table B shows typical amplitudes of the harmonics, compared with the fundamental (100%) [8]. Given that harmonic content of the short circuit currents is negligible, the harmonic based methods are used for either restraining or blocking the relay from operation during initial current inrush. Harmonic-based methods allow the differential relay to remain sensitive to fault currents while keeping the relay from operating due to magnetizing currents.

Table B: Percentage of harmonics in typical magnetizing inrush current.

Harmonic components in Magnetizing Inrush Current	Amplitude (% of Fundamental)
DC	55
2nd Harmonic	63
3rd Harmonic	26.8
4th Harmonic	5.1
5th Harmonic	4.1
6th Harmonic	3.7
7th Harmonic	2.4

Harmonic restraint techniques as remedy
The original harmonic-restrained differential relay used all the harmonics to provide the restraint function [11], [12], [13]. The resulting high level of harmonic restraint provided security for inrush conditions at the expense of operating speed for internal faults with current transformer saturation. As a result, the harmonic-restrained differential relay compares the fundamental component of the operating current with a restraint signal consisting of the unfiltered restraint current plus the harmonics of the operating current.

The differential relay operation condition can be expressed as;

$$I_{op} \geq SLP_i . I_{rt} + k_2 I_{2h} + k_3 I_{3h} + ..., \qquad \text{Equation A1}$$

where,

I_{op}	is the fundamental component of the operating current
I_{2h}, I_{3h}	are higher harmonics of the operating current
I_{rt}	is the unfiltered restraint current
k_1, k_2	are the constant coefficients

A more recent set of techniques use only the second harmonic to identify currents and the fifth harmonic to avoid maloperation for transformers due to over-excitation [9]. The basic operating equation for one phase can be expressed as follows:

$$I_{op} \geq SLP_i.I_{rt} + k_2 I_{2h} + k_5 I_5 \qquad \text{Equation A2}$$

Common harmonic restraint for three-phase transformer differential protection is a technique where the harmonic restraint quantity is proportional to the sum of the second and the fifth-harmonic components of the three relay elements. The relay operation is of the following form:

$$I_{op} \geq SLP_i.I_{rt} + \sum_{n=1}^{3}(k_2 I_{2hn} + k_5 I_{5hm}) \qquad \text{Equation A3}$$

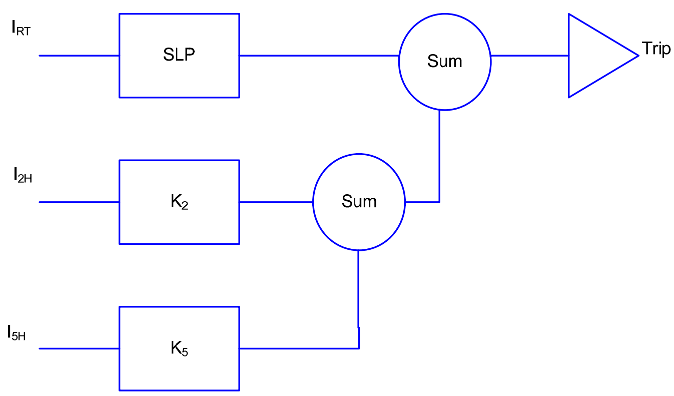
Harmonic-Restrain Techniques as further remedy
Typically, numerical transformer differential relays use second and fifth-harmonic locking logic [9]. A tripping signal requires that the following conditions are satisfied

$$I_{op} \geq SLP_i.I_{rt} \qquad \text{Equation A4}$$

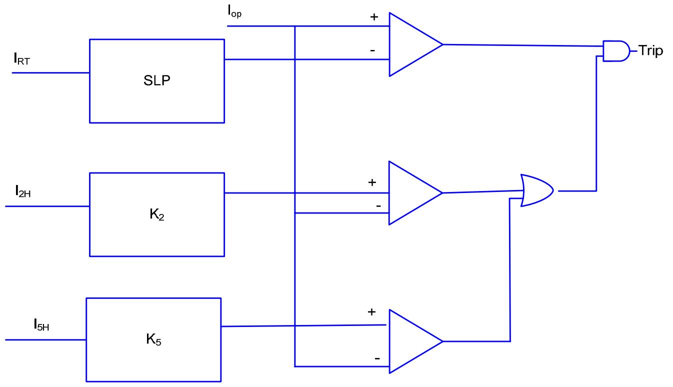
$$I_{op} \leq k_2 I_{2h} \qquad \text{Equation A5}$$

$$I_{op} \leq k_5 I_{5h} \qquad \text{Equation A6}$$

In Figure L (A& B) are shown the logic diagrams of harmonic restraint and harmonic blocking differential elements.



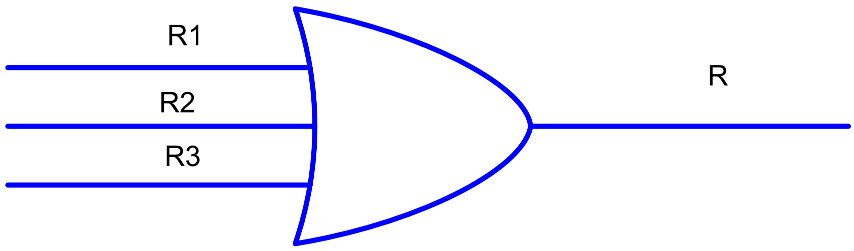
(a) Harmonic restraint



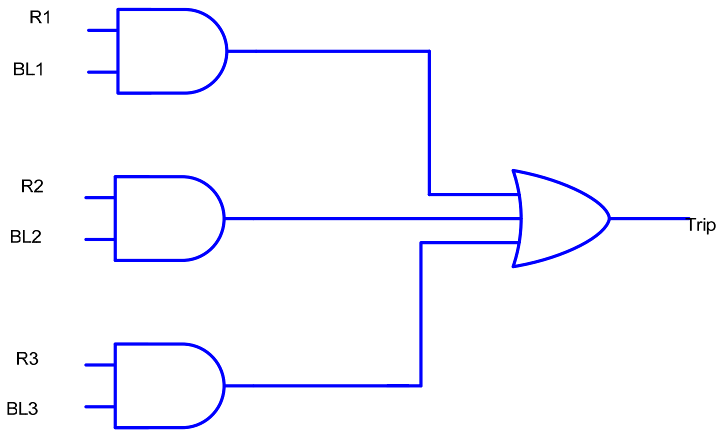
(b) Harmonic blocking

Figure L: Logic diagrams of differential elements employing harmonic-based methods.

In Figure M (A&B), the three-phase version of the logic diagrams of independent harmonic blocking differential element and independent harmonic restrain are shown [9]. The relay consists of three differential elements of the types shown in Figure M. In both cases, a tripping signal results when any one of the relay elements asserts.



(A) Independent harmonic restraint



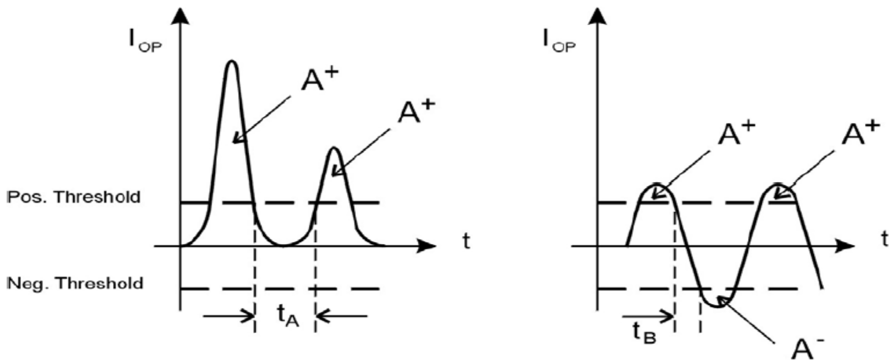
(B) Independent harmonic blocking

Figure M: Logic diagrams of three-phase differential elements employing harmonic based methods.

Wave shape recognition methods as remedy

Other methods for differentiating between internal faults and inrush conditions are based on analysis of the waveform of the differential current [25]. Wave shape recognition methods are divided between those methods that are based on the identification of the separation of different current peaks [16], [17], [18], [19], [20] and those methods that use DC offset or asymmetry in the differential current [21], [22], [23], [24].

A well-known principle [18], [19] recognizes the length of the time intervals during which the differential current is near zero. In Figure N is depicted the basic concept behind this low current differential method.



(a) Inrush (b) Internal Fault Current

Figure N: Differential relay blocking based on recognition of low-currents intervals.

Matlab-Simulink Environment

There are numerous widespread commercial software tools used by power engineers for electrical circuit simulation purposes. It is, however, a challenging and time consuming task to get acquainted with all the details and specialities of such a program, that's why the majority of the users is not inclined to keep tabs on the evolution of similar products or does not even know them. This paper also aims to model a power system, incorporating our much discussed power transformer using MATLAB-SIMULINK and finding results on creating faults. The same result can be taken use of in some other powerful algorithm like s-transform, gauss- Newtonian algorithim, probabilistic neural network and fuzzy logic to devise numerical protection scheme for power transformer. This is beyond the scope of this paper. The SIMULINK was created to model general dynamic systems using MATLAB simulation engine.

In matlab sources can be DC voltage source, AC voltage or current source, External controlled voltage or current source (controlled by an arbitrary signal), 3-phase programmable control source (time variation of amplitude, phase and frequency by step, ramp or modulation, 2 harmonics in addition). Sources driven by arbitrary signals can be realised in matlab programs., In MATLAB harmonics and symmetrical components can be easily generated. In matlab switches are Single and three-phase logical controlled (opens at next current zero-crossing) ideal switch (parallel to an RC snubbercircuit). MATLAB offers a much wider range of measuring devices, which makes it simpler to process the simulated signals. The dominance of MATLAB in the signal processing area is visible. The values of the "Sinks" of MATLAB can be seen on-line during the simulation, and the values of most elements can be changed on-line (by "pausing" the simulation and entering another value).. MATLAB offers widespread and numerous built-in functions. Matlab have components that can be developed by the user either in Matlab's programming language or C or Fortran.. Matlab have Controller blocks: PID, fuzzy, neural networks, etc. Optimal control toolbox _ DSP blockset_ Fixed point blockset Data acquisition and system identification toolboxes. With certain restrictions a C code can be generated from the models and this code can be compiled to an executable file. MATLAB models can communicate with other Windows programs over DDE or ActiveX protocol.

POWER SYSTEM CASE realised in MATLAB-SIMULINK environments
The following study has been realized in MATLAB-Simulink (see Fig O.).. 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.

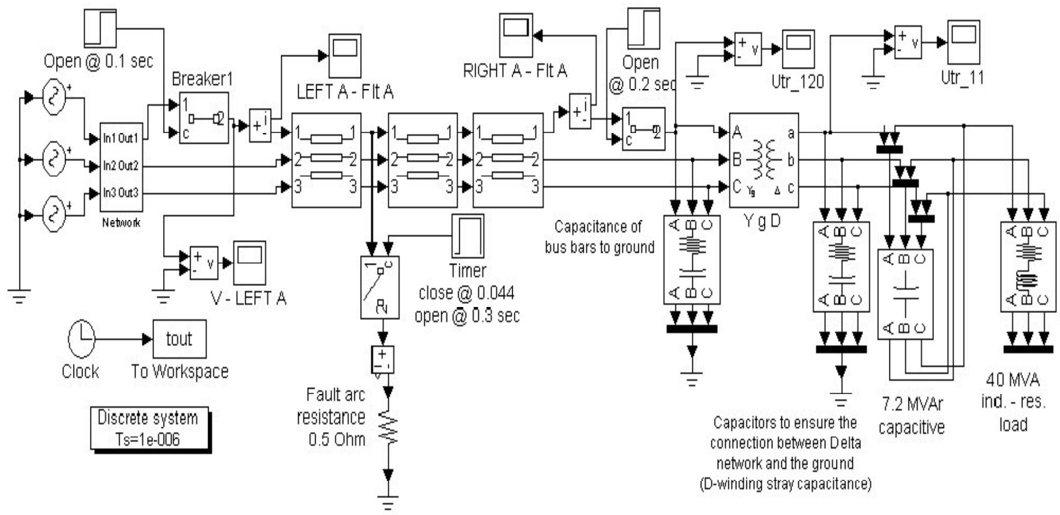


Figure O: Model in MATLAB-Simulink.

Fig P downwards 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/Δ 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.

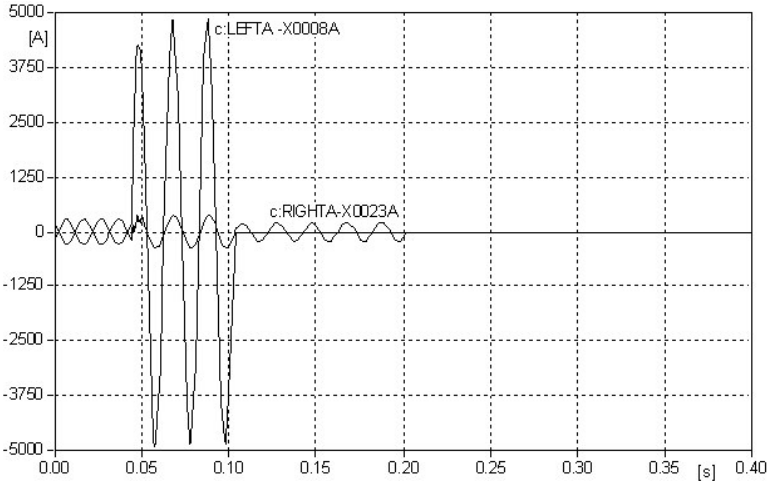


Figure P: Components of the fault current (currents in phase A from the left and the right)

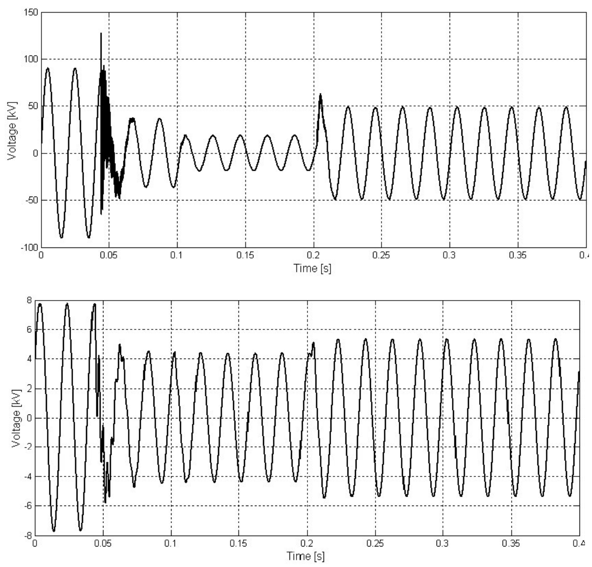


Figure Q: Voltages at the primary and the secondary side of the transformer (phase A).

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 practised. Wave shape recognition methods are still relatively new and not widely practised. Harmonic based methods are widely practised. 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.

Harmonic restraint methods may not be adequate to prevent differential element operation for unique cases with very low harmonic content in the operating current. Modern methods for differentiating inrush current from fault current may be required to ensure security without sacrificing fast and dependable operations when energising a faulted transformer. Further research is required in methods such as wavelet-based techniques, s-transform, adaline pso fuzzy, fast gauss Newtonian methods, 2^{nd} harmonic phase angle algorithm etc for discrimination of internal faults from magnetizing inrush currents in power transformers. MATLAB offers more possibilities in power electronics, signal processing and control. The paper also presents an example that demonstrate the mainstays of MATLAB-SIMULINK software superiority.

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