

Power Transformer Protection Improvements With Numerical Relays

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1. ABSTRACT

This paper describes a new approach for transformer differential protection that ensures security for external faults, inrush, and overexcitation conditions and provides dependability for internal faults. This approach combines harmonic restraint and blocking methods with a wave shape recognition technique. Even harmonics of the differential current provide restraint, while the fifth harmonic and d.c. component block relay operation.

Keywords: Transformer Protection – Magnetizing Inrush – Harmonic Restraint – Harmonic Blocking

2. INTRODUCTION

Inrush or overexcitation conditions of a power transformer produce false differential currents that could cause differential relay misoperation. Both conditions produce distorted currents because they are related to transformer core saturation. One of the early solutions to prevent a differential relay misoperation during inrush conditions was to introduce an intentional time delay in the differential relay. Another approach was to desensitize the relay for a given time, to override the inrush condition. Others suggested adding a voltage signal to restrain or to supervise the differential relay. Researchers quickly recognized that the harmonic content of the differential current provides information that helps to discriminate internal faults from inrush and overexcitation conditions. However, this discrimination can be complicated by other sources of distortion such as CT saturation, nonlinear fault resistance, or system resonant conditions.

Kennedy and Hayward proposed a differential relay with only harmonic restraint for bus protection [1]. Hayward [2] and Mathews [3] further developed this method by adding percentage-differential restraint for transformer protection. These early relays used all the harmonics to restrain. With a relay that used only the second harmonic to block, Sharp and Glassburn introduced the idea of harmonic blocking instead of restraining [4].

Many modern transformer differential relays use either harmonic restraint or blocking methods. These methods ensure relay security for a very high percentage of inrush and overexcitation cases. However, these methods do not work in cases with very low harmonic content in the operating current. Common harmonic restraint or blocking, introduced by Einval and Linders [5], increases relay security for inrush, but could delay operation for internal faults combined with inrush in the nonfaulted phases. Transformer overexcitation may also cause differential relay misoperation. Einval and Linders proposed the use of an additional fifth-harmonic restraint to prevent such misoperations [5].

Wave shape recognition techniques represent another alternative for discriminating internal faults from inrush conditions. However, these techniques fail to identify transformer overexcitation conditions. Rockefeller [6] proposed to block relay operation if successive peaks of the differential current fail to occur at about 7.5–10 ms. Another well-known [7] principle recognizes the length of the time intervals during which the differential current is near zero. For inrush currents whose low current intervals are greater than one-quarter cycle, the relay is blocked. For internal faults, the low current intervals are less than one-quarter cycle, and the relay operates. The above method could fail to block in cases where the signal low current intervals last less than one-quarter cycle.

This paper describes a new approach for transformer differential protection using current-only inputs. The approach ensures security for external faults, inrush, and overexcitation conditions, and dependability for internal faults. It combines harmonic restraint and blocking methods with a wave shape recognition technique. The new method uses even harmonics for restraint, while the fifth harmonic and d.c. component block relay operation.

In the paper we first review the concept of transformer differential protection. We then analyze magnetizing inrush, overexcitation, and current transformer (CT) saturation phenomena as possible causes of relay misoperation. Next we propose a new approach for transformer differential protection and describe the relay that is based on this approach. Finally, we compare the behavior of different transformer differential methods for real cases of magnetizing inrush conditions.

3. TRANSFORMER DIFFERENTIAL PROTECTION

Percentage-restraint differential protective relays have been in service for many years. Figure 1 shows a typical differential relay connection diagram.

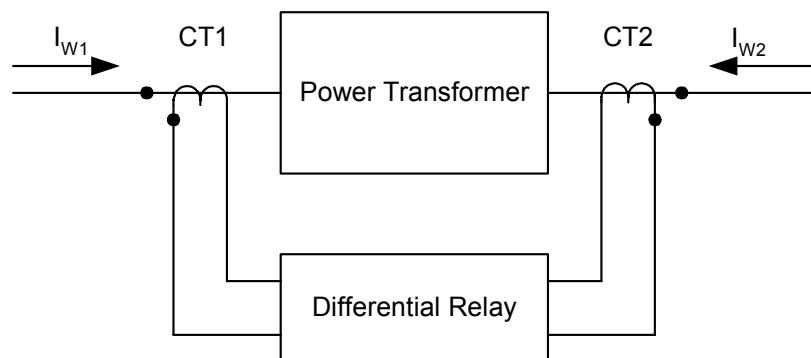


Figure 1 Typical Differential Relay Connection Diagram

Differential elements compare an operating current with a restraining current. The operating current (also called differential current), I_{op} , can be obtained as the phasor sum of the currents entering the protected element:

$$I_{OP} = |\vec{I}_{W1} + \vec{I}_{W2}| \quad [1]$$

I_{OP} is proportional to the fault current for internal faults and approaches zero for any other operating (ideal) conditions.

There are different alternatives for obtaining the restraining current. The most common ones include the following:

$$I_{RT} = k |\vec{I}_{W1} - \vec{I}_{W2}| \quad [2]$$

$$I_{RT} = k (|\vec{I}_{W1}| + |\vec{I}_{W2}|) \quad [3]$$

$$I_{RT} = \text{Max}(|\vec{I}_{W1}|, |\vec{I}_{W2}|) \quad [4]$$

Where k is a compensation factor, usually taken as 1 or 0.5.

Equation 3 and Equation 4 offer the advantage of being applicable to differential relays with more than two restraint elements.

The differential relay generates a tripping signal if the operating current, I_{OP} , is greater than a percentage of the restraining current, I_{RT} :

$$I_{OP} > SLP \cdot I_{RT} \quad [5]$$

Figure 2 shows a typical differential relay operating characteristic. This characteristic consists of a straight line having a slope equal to SLP and a horizontal straight line defining the relay minimum pickup current, I_{PU} . The relay operating region is located above the slope characteristic (Equation 5), and the restraining region is below the slope characteristic. In addition, the slope characteristic of the percentage-differential relay provides further security for external faults with CT saturation. A variable-percentage or dual-slope characteristic, originally proposed by Sharp and Glassburn, further increases relay security for heavy CT saturation. Figure 2 shows this characteristic as a dotted line.

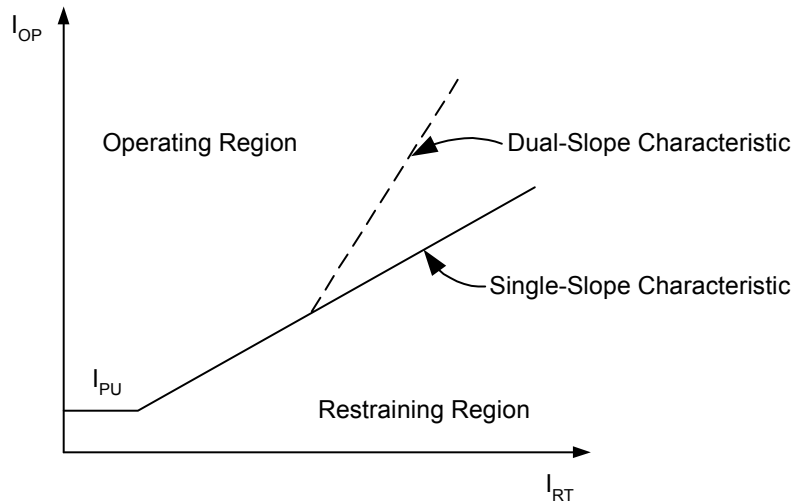


Figure 2 Differential Relay With Dual-Slope Characteristic

4. SOURCES OF FALSE DIFFERENTIAL CURRENTS

Inrush or overexcitation conditions of a power transformer produce false differential currents that could cause differential relay misoperation. Both conditions produce distorted differential currents because they are related to transformer core saturation. The distorted waveforms provide information that helps to discriminate inrush and overexcitation conditions from internal faults. However, this discrimination can be complicated by other sources of distortion such as CT saturation, nonlinear fault resistance, or system resonant conditions.

In the case of power transformer applications, possible sources of false differential currents are:

- Mismatch between the CT ratios and the power transformer ratio
- Variable ratio of the power transformer caused by a tap changer
- Phase shift between the power transformer primary and secondary currents for delta-wye connections
- Magnetizing inrush currents
- Transformer overexcitation
- Current transformer saturation

The relay percentage restraint characteristic typically solves the first two sources of error mentioned earlier. A proper connection of the CTs or emulation of such a connection in a digital relay addresses the phase shift problem. A very complex problem is that of discriminating internal fault currents from the false differential currents caused by magnetizing inrush and transformer overexcitation.

4.1. *Inrush Currents*

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 ideal instantaneous value of steady-state flux. Transformer energization is a typical cause of inrush currents, but any transient in the transformer circuit may generate these currents. Other causes include voltage recovery after the clearance of an external fault or the energization of a transformer in parallel with a transformer that is already in service. The magnitudes and waveforms of inrush currents depend on a multitude of factors, and are almost impossible to predict. The following summarizes the main characteristics of inrush currents:

- Generally contain d.c. offset, odd harmonics, and even harmonics.
- Typically composed of unipolar or bipolar pulses, separated by intervals of very low current values.
- Peak values of unipolar inrush current pulses decrease very slowly. Time constant is typically much greater than that of the exponentially decaying d.c. offset of fault currents.
- Second-harmonic content starts with a low value and increases as the inrush current decreases.

4.2. *Transformer Overexcitation*

The magnetic flux inside the transformer core is directly proportional to the applied voltage and inversely proportional to the system frequency. Overvoltage and/or underfrequency

conditions can produce flux levels that saturate the transformer core. These abnormal operating conditions can exist in any part of the power system, so any transformer may be exposed to overexcitation. Overexcitation of a power transformer is a typical case of a.c. saturation of the core that produces odd harmonics in the exciting current. The third harmonic is the most suitable for detecting overexcitation conditions, but either the delta connection of the CTs or the delta connection compensation of the differential relay filters out this harmonic. The fifth harmonic, however, is still a reliable quantity for detecting overexcitation conditions.

Transformer overexcitation causes transformer heating and increases exciting current, noise, and vibration. A severely overexcited transformer should be disconnected to avoid transformer damage. Because it is difficult, with differential protection, to control the amount of overexcitation that a transformer can tolerate, transformer differential protection tripping for an overexcitation condition is not desirable. A separate transformer overexcitation element, such as a V/Hz element, that responds to the voltage/frequency ratio could be used instead.

4.3. CT Saturation

The effect of CT saturation on transformer differential protection is double-edged. For external faults, the resulting false differential current may produce relay misoperation. In some cases, the percentage restraint in the relay addresses this false differential current. For internal faults, the harmonics resulting from CT saturation could delay the operation of differential relays having harmonic restraint or blocking.

The main characteristics of CT saturation are the following:

- CTs reproduce faithfully the primary current for a given time after fault inception. The time to CT saturation depends on several factors, but is typically one cycle or longer.
- The worst CT saturation is produced by the d.c. component of the primary current. During this d.c. saturation period, the secondary current may contain d.c. offset and odd and even harmonics.
- When the d.c. offset dies out, the CT has only a.c. saturation, characterized by the presence of odd harmonics in the secondary current

Differential relays perform well for external faults, as long as the CTs reproduce the primary currents correctly. When one of the CTs saturates, or if both CTs saturate at different levels, false operating current appears in the differential relay and could cause relay misoperation. Some differential relays use the harmonics caused by CT saturation for added restraint and to avoid misoperations.

5. NEW APPROACH FOR TRANSFORMER PROTECTION

The evaluation of existing harmonic restraint/blocking methods makes it clear that independent restraint/blocking methods may fail to ensure security for some real-life inrush conditions. Common harmonic restraint/blocking could provide solutions, but the behavior of these methods for internal faults combined with inrush currents requires further study.

Combining restraint and blocking into an independent restraint/blocking method provides a new approach to transformer differential protection. Even harmonics of the differential current provide restraint, while both the fifth harmonic and the d.c. component block relay operation.

5.1. Even-Harmonic Restraint

In contrast to the odd harmonics a.c. CT saturation generates, even harmonics are a clear indicator of magnetizing inrush. Even harmonics resulting from d.c. CT saturation is transient in nature. It is important to use even harmonics (and not only the second harmonic) to obtain better discrimination between inrush and internal fault currents.

The use of even harmonics (second and fourth) in a restraint scheme ensures security for inrush currents having very low second-harmonic current. The operation equation for second and fourth harmonic restraint differential element is:

$$I_{OP} > SLP \cdot I_{RT} + K_2 I_2 + K_4 I_4 \quad [6]$$

where I_{OP} is the relay operating current, I_{RT} is the restraining current, I_2 and I_4 are the second and fourth harmonics of the operating current, and K_2 and K_4 are constant coefficients equivalent to the traditional second and fourth harmonic restraining percentages.

5.2. Fifth-Harmonic Blocking

It is a common practice to use the fifth harmonic content of the operating current to avoid differential relay operation for transformer overexcitation conditions. In the proposed relay design, the fifth harmonic is independently compared with the operating current, which assures that a given relay setting, in terms of fifth-harmonic percentage, always represents the same overexcitation condition. In a fifth-harmonic restraint scheme, a given setting may represent different overexcitation conditions, depending on the other harmonics that may be present.

Relay tripping in this case requires fulfillment of (6) and not (7).

$$I_{OP} < K_5 I_5 \quad [7]$$

where I_5 is the fifth harmonic of the operating current, and K_5 is a constant coefficient.

5.3. DC Ratio Blocking

The proposed method of even-harmonic restraint and fifth-harmonic blocking provides very high relay security for inrush and overexcitation conditions. There are, however, some inrush cases in which the differential current is practically a pure sine wave. Any harmonic-based method could cause relay misoperation in such extreme inrush cases.

The d.c. component of inrush current typically has a greater time constant than that for internal faults. The presence of d.c. offset in the inrush current is an additional indicator that can be used to guarantee relay security for inrush. This wave shape recognition method is relatively easy to apply in a digital relay, because extraction of the d.c. component is a low-pass filtering process.

In the d.c. blocking method, the relay splits the differential current into its positive and negative semicycles and calculates one-cycle sums for both semicycles. Figure 3 shows a schematic diagram of the d.c. blocking method for relay element one. S+ is the one-cycle sum of the positive semicycle, and S- is the one-cycle sum of the negative semicycle. The minimum and the maximum of the absolute values of the two one-cycle sums are determined, and the d.c. ratio, DCR, is calculated by dividing the minimum one-cycle sum value by the maximum one-cycle sum value. When DCR is less than a threshold value of DCRF, the relay issues a blocking signal DCBL1.

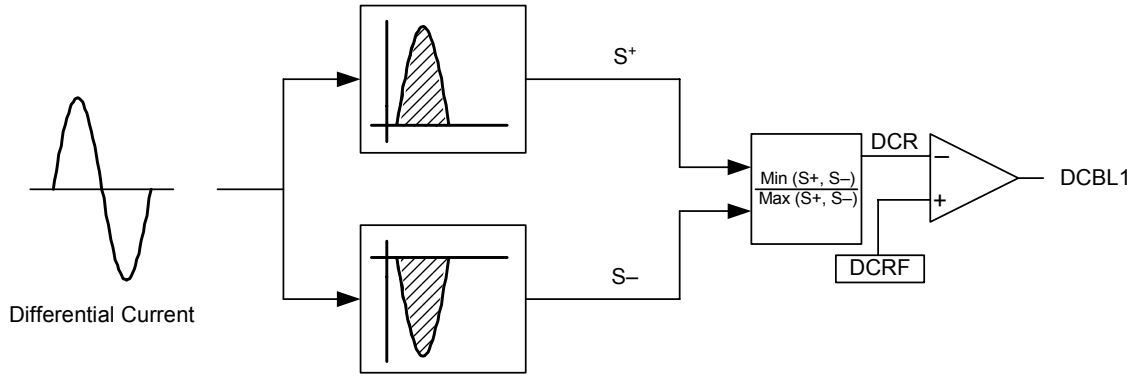


Figure 3 DC Blocking Logic

6. CURRENT DIFFERENTIAL RELAY

The relay consists of three differential elements. Each differential element provides percentage differential protection with independent even-harmonic restraint and fifth-harmonic and d.c. blocking. The user may select even-harmonic blocking instead of even-harmonic restraint. In such a case, two blocking modes are available: 1) independent harmonic and d.c. blocking, and 2) common harmonic and d.c. blocking.

6.1. Restraint Differential Element

Figure 4 shows a schematic diagram of one of the percentage differential elements with even-harmonic restraint. Inputs to the differential element are the operating current, I_{OP1} , the restraint current, I_{RT1} , and the second- and fourth-harmonic restraint currents (I_2 and I_4 , respectively).

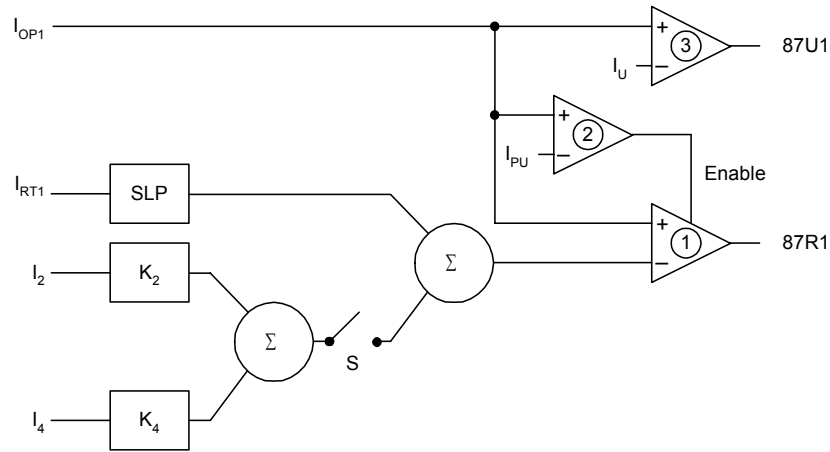


Figure 4 Restraint 87R1 and Unrestrained 87U1 Differential Elements

Restraint current, I_{RT1} , is scaled to form the restraint quantity $I_{RT1} \cdot f$ (SLP), which provides a dual-slope percentage characteristic. Harmonic restraint currents are scaled to form the second- and fourth-harmonic restraint quantities. The scaling factors are K_2 and K_4 , respectively.

Comparator 1 compares the operating current to the sum of the fundamental and even-harmonic restraint quantities. The comparator asserts for fulfillment of (6). Comparator 2 enables Comparator 1 if the operating current, I_{OP1} , is greater than a threshold value. Assertion of Comparator 2 provides the relay minimum pickup current, I_{PU} . Switch S permits enabling or disabling of even-harmonic restraint in the differential element.

The differential element includes an unrestrained instantaneous differential overcurrent function. Comparator 3, which compares the operating current, I_{OP1} , with a threshold value, I_U , provides the unrestrained differential overcurrent function.

6.2. Relay Blocking Logic

Figure 5 depicts the blocking logic of one of the differential elements. If the even-harmonic restraint is not in use, switch S1 closes to add even-harmonic blocking (2HB1, 4HB1) to the fifth-harmonic (5HB1) and d.c. blocking (DCBL1) functions. In this case, the differential elements operate in a blocking-only mode. Switches S2, S3, S4, and S5 permit enabling or disabling each of the blocking functions. The output (87BL1) of the differential element blocking logic asserts when any one of the enabled logic inputs asserts.

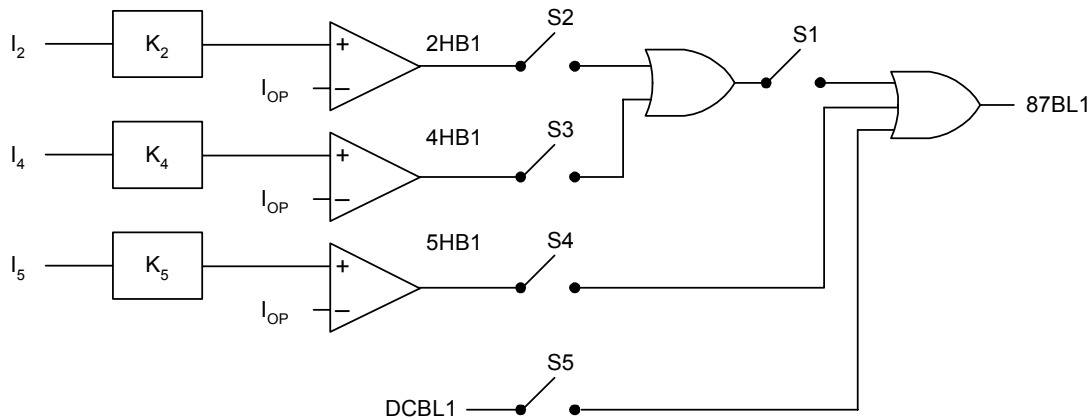


Figure 5 Differential Element Blocking Logic

Figure 6 shows the blocking logic of the differential relay. The user can set the relay to an independent harmonic blocking mode ($IHBL=Y$) or a common harmonic blocking mode ($IHBL=N$). If $IHBL$ is set to Y (Yes), blocking in a given element will only prevent tripping of that element. If $IHBL$ is set to N (No), blocking within any differential element will prevent tripping of all the restrained differential elements.

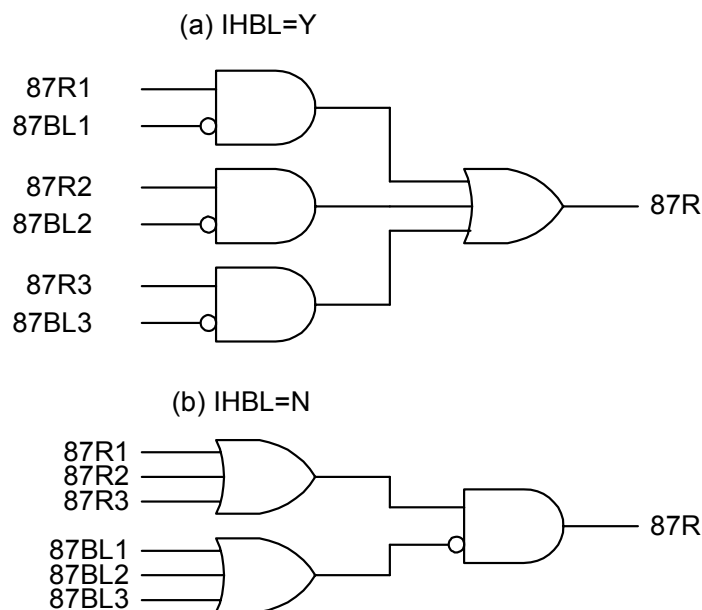


Figure 6 Differential Relay Blocking Logic

7. DIFFERENTIAL ELEMENT PERFORMANCE DURING INRUSH CONDITIONS

In this section, we present two field cases to demonstrate the new differential element performance. These cases are special because they cause some of the traditional differential elements to misoperate.

7.1. Case 1

The first case is from a transformer energization while A-phase is faulted on the high side and the transformer is not loaded. The transformer is a three-phase, delta-wye connected, distribution transformer; the CT connections are wye at both sides of the transformer.

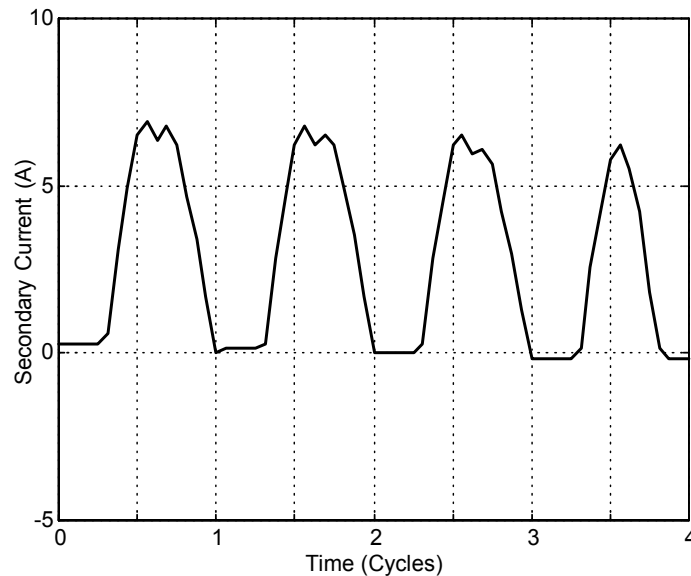


Figure 7 Element 1 High-Side Winding Current I_{AB}

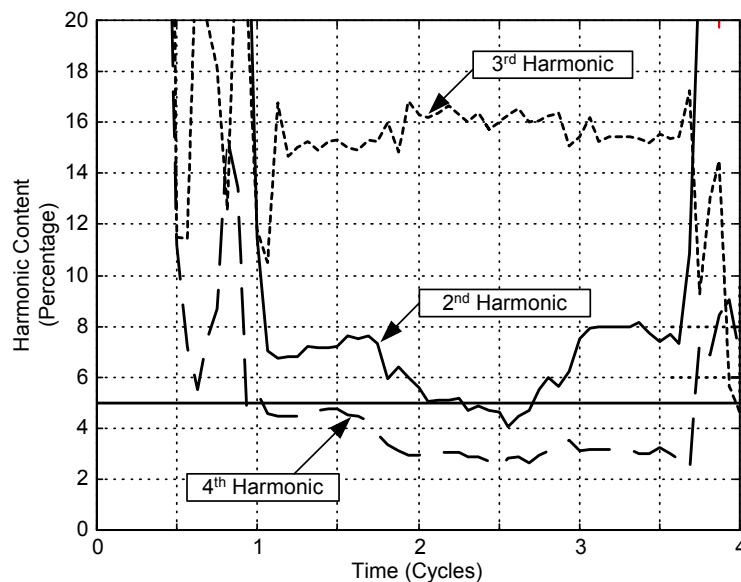


Figure 8 2nd, 3rd, and 4th Harmonics as Percentages of Fundamental of the Inrush Current

Figure 7 shows the differential Element 1 inrush current; this element uses I_{AB} current. This signal looks like a typical inrush current. Let us analyze the signal characteristics. The current signal has low second-harmonic content and high d.c. content compared to the fundamental.

Another interesting fact is that this signal also has high third-harmonic content. Figure 8 shows the second, third, and fourth harmonics as percentages of fundamental. Note that the second harmonic drops below five percent.

The different types of differential elements operate as follows:

1. Second- and Fourth-Harmonic Blocking: The low second- and fourth-harmonic content produces misoperation of the differential element that uses independent harmonic blocking.
2. All-Harmonic Restraint: The harmonic restraint relay that uses all harmonics maintains its security because of the high third-harmonic content of the inrush current.
3. Low Current Detection: The waveform has a low differential current section that lasts one-quarter of a cycle each cycle, the minimum time that the element requires for blocking; this element marginally maintains its security.
4. Even Harmonic Restraint: The low second- and fourth-harmonic content produces misoperation of the differential element that uses independent harmonic restraint.
5. DC Ratio Blocking: The ratio of the negative to the positive d.c. value is zero, so this element properly blocks the differential element that is based on even-harmonic restraint.

7.2. Case 2

This is a field case of energization during commissioning of a three-phase, 180 MVA, 230/138 kV autotransformer. The autotransformer connection is wye-wye; CTs at both sides of the autotransformer are connected in delta.

Figure 9 shows the secondary current from the autotransformer high side. This current results from autotransformer energization with the low-side breaker open. The current is a typical inrush wave with a relatively small magnitude. Note that the signal low current intervals last less than one-quarter cycle.

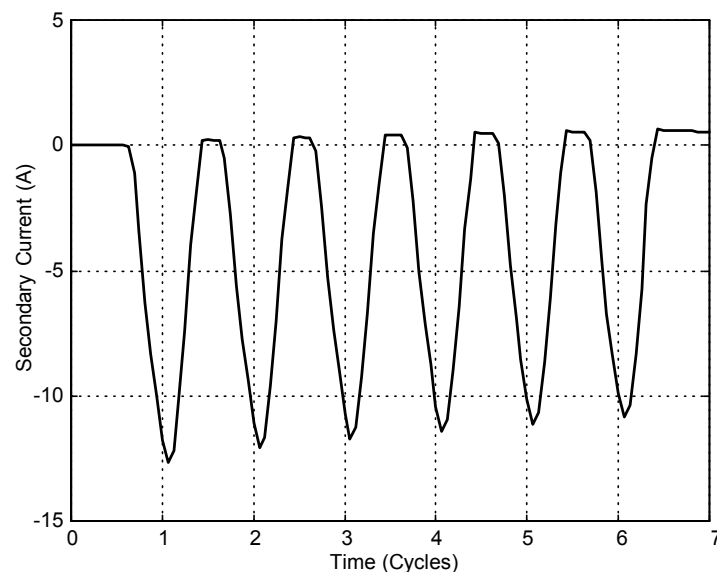


Figure 9 Inrush Current With Low Current Intervals of Less Than One Quarter Cycle

Figure 10 shows the harmonic content of the inrush current. Note that the inrush current has a relatively small second-harmonic percentage, which drops to about nine percent. All

differential elements except the low current detector operate correctly for this case. Notice that the even-harmonic blocking element requires a second harmonic threshold of eight percent to maintain its security. The low current zone in this case lasts less than the one-quarter cycle required to determine blocking conditions.

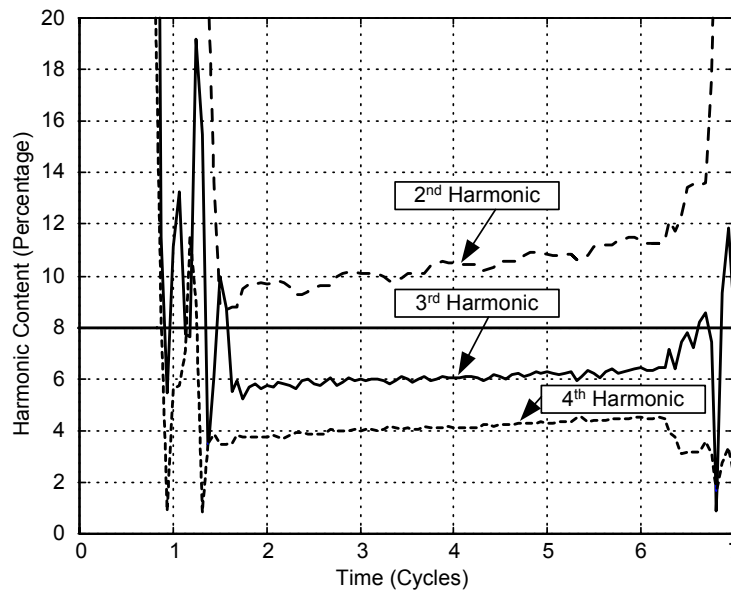


Figure 10 2nd, 3rd, and 4th Harmonic as Percentage of Fundamental for Case 2

8. CONCLUSIONS

1. Most transformer differential relays use the harmonics of the differential current to distinguish internal faults from magnetizing inrush or overexcitation conditions. The harmonics can be used to restrain or to block relay operation. Harmonic-restraint and blocking methods ensure relay security for a very high percentage of inrush and overexcitation conditions. However, these methods fail for cases with very low harmonic content in the operating current.
2. Common harmonic restraint or blocking increases differential relay security, but could delay relay operation for internal faults combined with inrush current in the non-faulted phases.
3. Wave shape recognition techniques represent another alternative for discriminating faults from inrush conditions. However, these techniques fail to identify transformer overexcitation conditions.
4. A new approach combining harmonic restraint and blocking methods with wave-shape recognition technique adds security to the independent harmonic restraint element without sacrificing dependability. This new method uses even harmonics for restraint, plus d.c. component and fifth harmonic for blocking.
5. Using even-harmonic restraint ensures security for inrush currents with low second-harmonic content and maintains dependability for internal faults with CT saturation. The use of fifth-harmonic blocking guarantees an invariant relay response to overexcitation. Using d.c. offset blocking ensures security for inrush conditions with very low total harmonic distortion.

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