Analysis of Transformer Inrush Current and Comparison of Harmonic Restraint Methods in Transformer Protection

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I. Introduction

It is recommended that differential protection be used for the protection of transformers of 10MVA (self-cooled) and higher [1]. Differential protection generally is considered the best protection for transformers. However, inrush current due to transformer energization exists mostly only in one winding of the transformer; therefore, the relay sees the energization condition as a fault. To improve security while maintaining the required levels of dependability, many restraint methods have been proposed to block the operation of the differential element due to the inrush current.

Methods using harmonic restraint, wave-shape recognition, and artificial neural networks (ANN) have been proposed to discriminate magnetizing inrush and internal faults. The second harmonic restraint method is the most common one used by various relay manufacturers and application engineers. There are a few variations of harmonic restrained differential protection. This paper will analyze factors affecting the second harmonic ratio in inrush current, and describe various harmonic restraint methods and compare their performance.

II. Theoretical Background of Transformer Differential Protection

The well-known Kirchhoff's Current Law (KCL) specifies that the summation of the currents flowing into a single node will be zero. KCL applies to generator stator windings, bus, feeder, transmission line, etc.

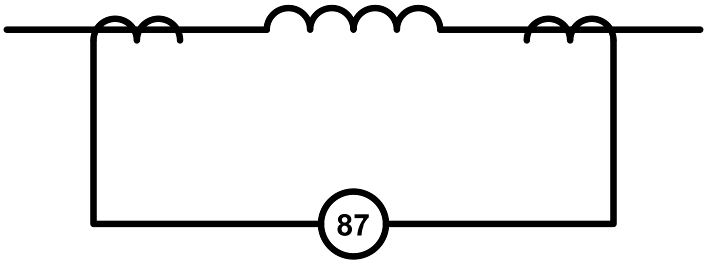

Fig. 1 Generator stator winding differential protection

For transformer differential protection, KCL cannot be directly applied. The transformer primary and secondary do not belong to a common node.

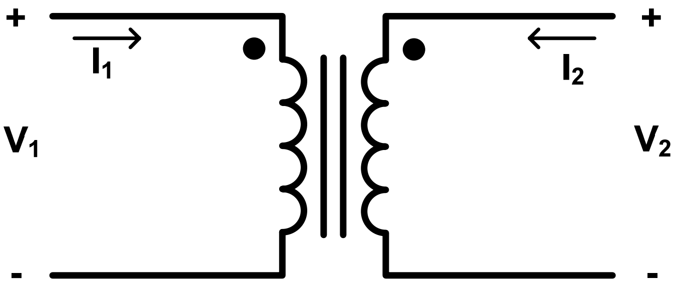

Fig. 2 Transformer differential protection

In an ideal two-winding single-phase transformer, the net power flowing in should be zero.

$$V_1 \cdot I_1^* + V_2 \cdot I_2^* = 0 \tag{1}$$

If

$$\frac{V_1}{V_2} = N$$

Then

$$I_1^* + \frac{I_2^*}{N} = 0 \tag{2}$$

We introduce the differential current or operating current to be

$$I_{op} = I_1 + \frac{I_2}{N} = 0 \tag{3}$$

Equation (3) is the fundamental of the transformer differential protection. It is based on power conservation. Since only currents are involved in equation (3), the protection is called current differential protection. Unlike differential protection based on the KCL, the transformer current differential protection needs to compensate for phase and amplitude based on the transformer configuration.

The concept of differential protection is illustrated in Fig. 3.

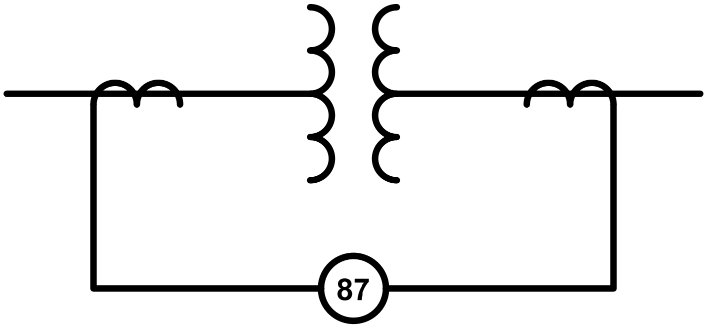

Fig. 3 The concept of transformer differential protection

Ideally, there is no power loss in a transformer, and there should be no operating current defined by equation (3). In reality, there are core losses, eddy current in the core and winding, errors from current transformers (CT) and load tap changers, the operating current will not be zero.

When calculating differential current, current in each winding needs to be compensated based on the transformer configuration and the winding turns ratio. Let $I_{comp\,i}$ be the compensated current in winding *i* of a multi-winding transformer.

The operating current is generally defined as

$$Iop = \quad \left| \sum_i I_{comp\,i} \right| \tag{4}$$

During a large through-fault, there may be some metering error in CT, which could result in a large operating current and cause a false trip. Percentage differential protection was proposed in the early twentieth century to improve the security of differential protection. The differential element will operate when the operating current (I_{op}) is above a certain ratio of the restraint current (I_R), i.e.,

$$I_{op} > Slope \cdot I_R \tag{5}$$

where $Slope$ represents the threshold ratio of the restraint current to the operating current.

The restraint current I_R may be commonly defined as the maximum, average, or minimum of the compensated currents.

$$I_R = Max \ \left(| I_{compi} | \right) \tag{6}$$

$$I_R = Average \ \left(\sum_i | I_{compi} | \right) \tag{7}$$

$$I_R = Min \ \left(| I_{compi} | \right) \tag{8}$$

It is necessary to understand which method is used in the calculation of the restraint current when setting the slope of the percentage differential relay.

III. Analysis of Transformer Inrush Current

It is very well known that a transformer will experience magnetizing inrush current during energization. Inrush current occurs in a transformer whenever the residual flux does not match the instantaneous value of the steady-state flux which would normally be required for the particular point on the voltage waveform at which the circuit is closed [2]. The residual flux is the flux in the core prior to energization of the transformer.

The residual flux is determined by several factors including:
a) the hysteresis loop of the core excitation curve
b) the point the current was interrupted
c) the circuit breaker capability
d) leading or lagging of the load power factor

The residual flux is generally 50% to 90% of the maximum operating flux. However, the residual flux could be at a higher level when the transformer is taken off line by an over-excitation relay, which may occur when protecting generator utility auxiliary transformers (UAT).

To understand the inrush current, a simplified transformer excitation curve is illustrated in Fig. 4.

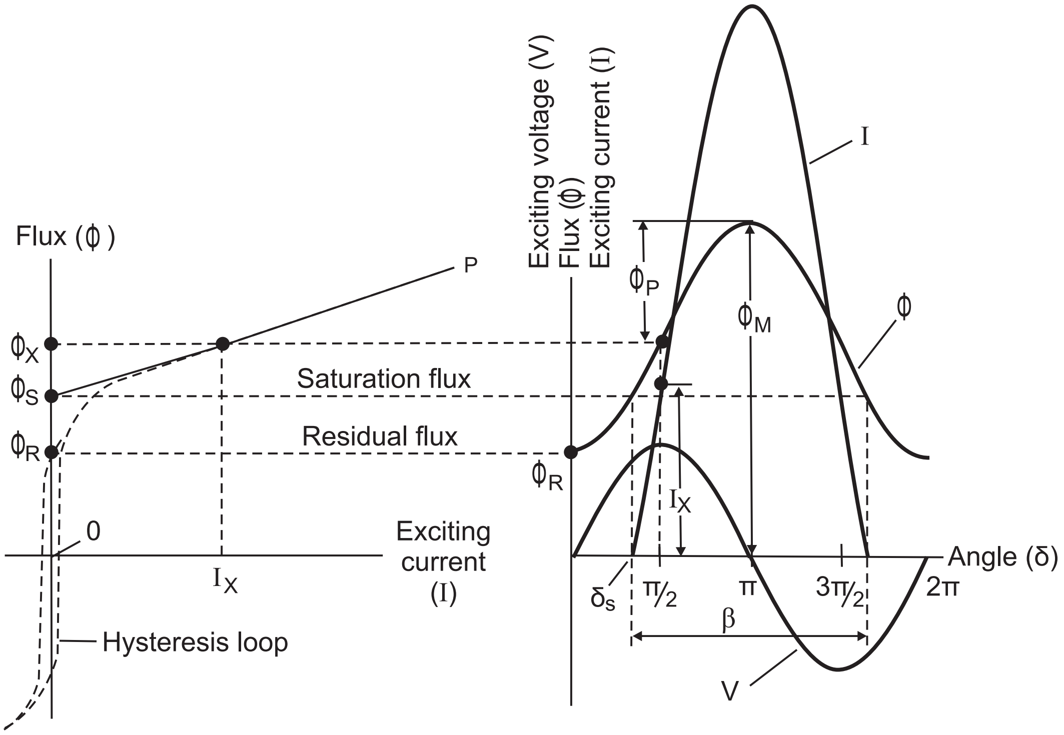

Fig. 4 Simplified transformer excitation curve

Fig. 4 illustrates the worst case of inrush current. A transformer with positive residual flux is energized at the zero voltage point of the rising edge of the energizing waveform. From Fig. 4, we see the base angle (β) is a function of residual flux ϕ_R, saturation flux ϕ_S, and rated flux ϕ_P.

Sonnemann [2] studied the relationship between percent second harmonic component and the base angle β of the inrush current. The study concluded that the second harmonic ratio will reach a minimum of approximately 17.1% when β equals 240°.

The minimum 17.1% of second harmonic component in inrush current is based on the following assumptions:

a) There is 90% residual flux in the transformer.
b) The transformer core saturation flux is at 140% of rated peak flux.

From the simplified excitation curve in Fig. 4, the inrush current starts to flow at the instant when the transformer core flux hits the saturation flux. The flux is a function of the voltage angle δ,

$$\phi(\delta) = (\phi_R + \phi_p) - \phi_p \cos\delta \qquad (9)$$

The inrush current starts to flow at angle δ when $\phi(\delta) = \phi_s$.

$$\delta_s = \cos^{-1}(\frac{\phi_R + \phi_p - \phi_s}{\phi_p}) \qquad (10)$$

The base angle β of the inrush current can be calculated,

$$\beta = 2\pi - 2\delta_s = 2(\pi - \cos^{-1}(\frac{\phi_R + \phi_p - \phi_s}{\phi_p}))$$

If we normalize the fluxes in terms of the rated flux ϕ_p, the above equation is simplified to be

$$\beta = 2(\pi - \cos^{-1}(\phi_R - \phi_s + 1)) \qquad (11)$$

The worst case base angle varies with the core residual and saturation flux, as is illustrated in Fig. 5.

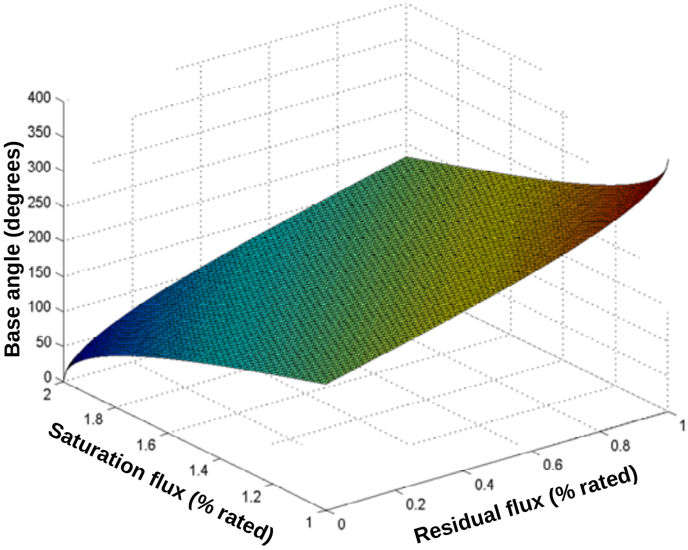

Fig. 5 Base angle changes with the residual and saturation flux

With the assumptions, $\phi_S = 1.4\phi_p$ and $\phi_R = 0.9\phi_p$,

$$\beta = 2(\pi - \cos^{-1}(0.5)) = 4\pi/3$$

The base angle of $4\pi/3$ (240°) was regarded as the maximum angle an inrush current can reach based on the assumptions made.

In order to analyze the harmonic component in the inrush current, an ideal inrush current is drawn separately in Fig. 6 for simplicity.

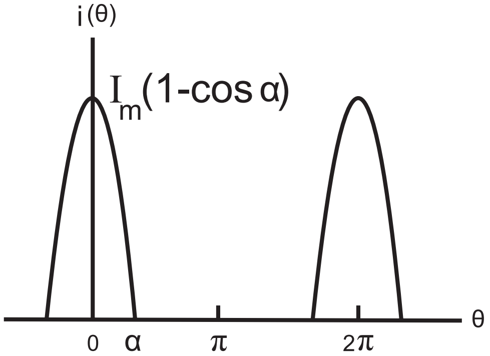

Fig. 6 Idealized inrush current waveform

One cycle of the idealized inrush current can be expressed as

$$i(\theta) = \begin{cases} I_m(\cos\theta - \cos\alpha), & \text{for } 0 \le \theta \le \alpha,\ (2\pi - \alpha) \le \theta \le 2\pi \\ 0, & \text{for } \alpha \le \theta \le (2\pi - \alpha) \end{cases} \tag{12}$$

Since the choice of origin gives a symmetric waveform about $\theta = 0$, the coefficients of sine Fourier series are zero. For mathematical simplicity, define

$$\alpha = \frac{1}{2}\beta \tag{13}$$

Fourier analysis gives the nth cosine Fourier series coefficient for (n ≥ 2) by

$$a_n = \frac{I_m}{\pi}[\frac{1}{n+1}\sin((n+1)\alpha) + \frac{1}{n-1}\sin((n-1)\alpha) - \frac{2}{n}\sin(n\alpha)\cos\alpha] \tag{14}$$

and the peak fundamental frequency component is given as

$$a_1 = \frac{I_m}{\pi}[\alpha - \frac{1}{2}\sin 2\alpha] \tag{15}$$

Horowitz [3] shows that, of all the harmonic components, the second is by far the greatest in magnitude.

When n=2, the second harmonic component expressed by equation (14) can further be simplified to

$$a_2 = \frac{I_m}{\pi}(-\frac{1}{6}\sin 3\alpha + \frac{1}{2}\sin\alpha) \tag{16}$$

The ratio of the second harmonic component to the fundamental component is

$$\frac{a_2}{a_1} = \frac{-\frac{1}{6}\sin 3\alpha + \frac{1}{2}\sin\alpha}{\alpha - \frac{1}{2}\sin 2\alpha} \tag{17}$$

Fig. 7 illustrates that the second harmonic ratio is a decreasing function of the base angle of inrush current.

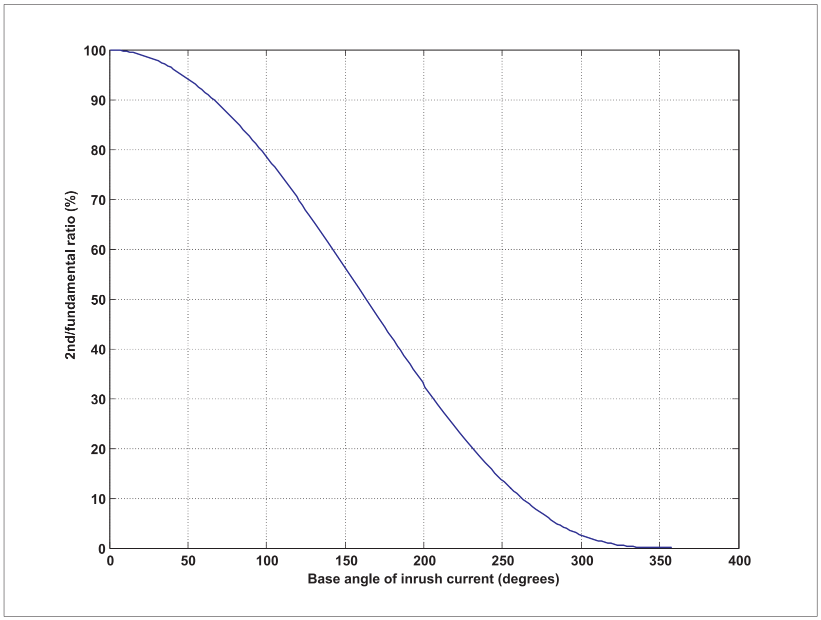

Fig. 7 Second harmonic ratio as a function of the base angle

When $\alpha = 4\pi/3$,

$$\frac{a_2}{a_1} = \frac{-\frac{1}{6}\sin(3\cdot 4\pi/3) + \frac{1}{2}\sin(4\pi/3)}{4\pi/3 - \frac{1}{2}\sin(2\cdot 4\pi/3)} = 0.1713 \text{ or } 17.13\%$$

This is why 17.1% of second harmonic ratio was considered as the minimum in transformer inrush current [2].

When $\alpha = 0$, equation (15) and (16) show that both the fundamental and the second harmonic components are zero. The differential protection is secure during a negligible amount of inrush current. It may be of academic interest to see how the second harmonic ratio changes when the angle approaches zero. Applying L'Hopital's rule three times on equation (17), we have

$$\lim_{\alpha\to 0} \frac{-\frac{1}{6}\sin 3\alpha + \frac{1}{2}\sin\alpha}{\alpha - \frac{1}{2}\sin 2\alpha} = \lim_{\alpha\to 0} \frac{-\frac{1}{2}\cos 3\alpha + \frac{1}{2}\cos\alpha}{1-\cos 2\alpha} = \lim_{\alpha\to 0} \frac{\frac{3}{2}\sin 3\alpha - \frac{1}{2}\sin\alpha}{2\sin 2\alpha}$$

$$= \lim_{\alpha\to 0} \frac{\frac{9}{2}\cos 3\alpha - \frac{1}{2}\cos\alpha}{4\cos 2\alpha} = 1$$

This result matches the curve in Fig. 7.

IV. Factors Affecting the Inrush Current

From equation (11), the base angle of the inrush current can be calculated based on the normal peak flux, the residual flux, and the saturated flux. With the base angle available, the second harmonic ratio can be calculated using equation (13) and (17).

4.1 Residual Flux

It is obvious that the peak inrush current increases with the residual flux level. Assuming saturation flux at 140% of rated peak flux, Fig. 8 can be drawn based on equations (13) and (17). It illustrates how the characteristics change with the residual flux. By inspecting Fig. 8, it can be concluded that the base angle of the inrush current is a monotonically increasing function of the residual flux, the second harmonic ratio is a monotonically decreasing function of the residual flux, and the fundamental component is a monotonically increasing function of the residual flux. If a transformer was tripped due to an over-excitation condition, it is likely that the residual flux is higher than usual. During transformer re-energization, if everything else stays the same, second harmonic ratio would be lower and the fundamental component of inrush current, i.e., the differential operating current, would be higher. This would reduce the security of a differential protection.

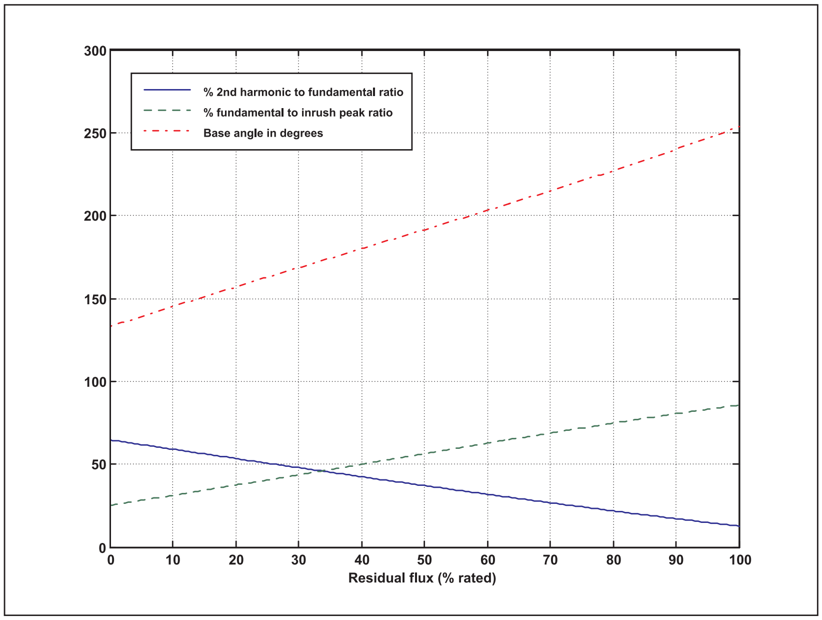

Fig. 8 Inrush characteristics as a function of residual flux

In a real system, the residual flux in the transformer will gradually die out due to the resistance in the system. This explains an interesting phenomenon that the second harmonic ratio will gradually increase when a transformer is being energized.

4.2 Saturation Flux

It can be seen from Fig. 4 that the peak inrush current decreases with the saturation flux level. Fig. 9 illustrates how the characteristics of the inrush current change with the level of saturation flux. The residual flux is maintained at 90% of the rated flux level. The base angle of the inrush current is a monotonically decreasing function of the residual flux. Accordingly, the second harmonic ratio increases with the saturation flux while the fundamental components of inrush current, i.e., the differential operating current, decrease with saturated flux. It is apparent that the increase of the saturation flux improves the security of harmonic restrained differential protection.

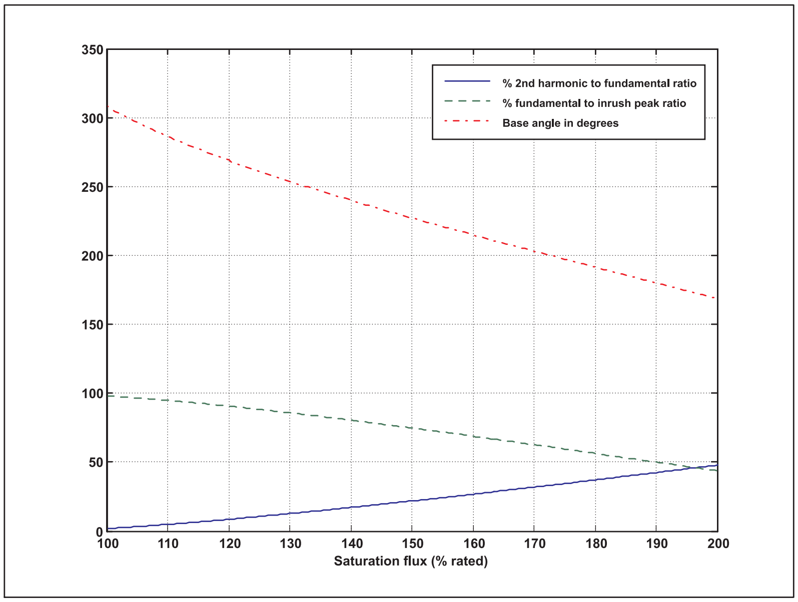

Fig. 9 Inrush characteristics as a function of saturation flux

4.3 Energization Voltage Angle

Fig. 4 illustrates the worst case transformer energization. The transformer with positive residual flux is energized at the positive going zero cross of the voltage waveform. When the energization instant is different from that of the worst case, i.e., the voltage waveform is skewed with a voltage angle γ and the base angle of the inrush current is smaller. A non-zero γ will reduce the peak flux level ϕ_M, the peak inrush current, and the base angle β of the inrush current. In order to use equation (11), the factor of the voltage angle can be integrated into the residual flux. The normalized residual flux ϕ_R in equation (11) should be replaced by $\phi_{Radj} = \phi_R - (1 - \cos(\gamma))$. The base angle of inrush current for energization with a general voltage angle γ can be expressed as

$$\beta = 2(\pi - \cos^{-1}(\phi_R - \phi_s + \cos(\gamma))) \tag{18}$$

where γ is the angle of the energizing voltage referenced to the worst case voltage.

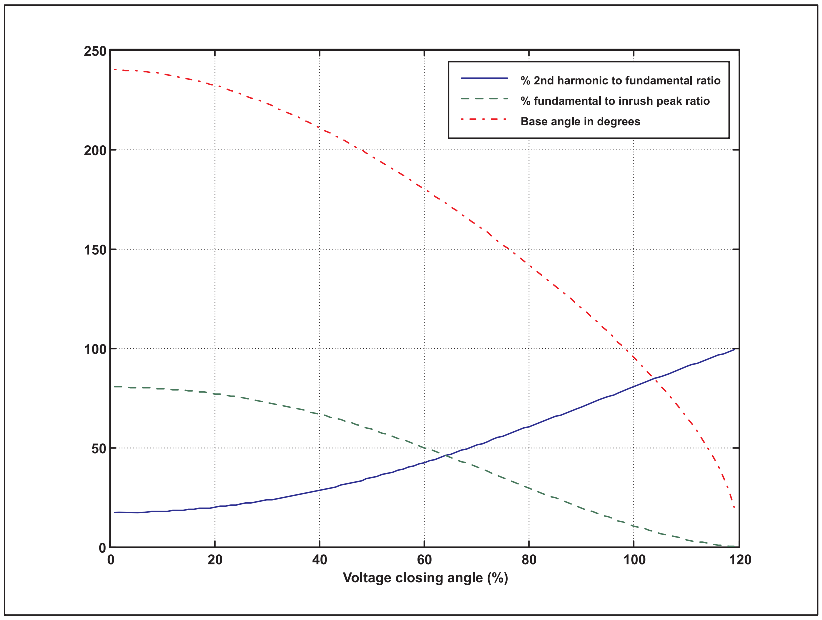

Fig. 10 Inrush characteristics as a function of voltage angle

Fig. 10 illustrates how the inrush characteristics change with the energizing voltage angle. For the worst case voltage waveform, i.e., when the energizing voltage angle is zero, the fundamental frequency component is at the maximum value, and the second harmonic ratio is at the lowest value. A differential protection element will see the maximum operating current with the lowest second harmonic ratio. It is apparent that the worst case energization is a most unfavorable situation for the security of differential protection. When the absolute of voltage angle is increased, the base angle of the inrush current will be reduced, the second harmonic ratio will be increased, and the fundamental inrush current, i.e., the differential operating current, will be reduced. However, the energizing voltage angle is generally not controllable, and a protection engineer has to estimate the worst case situation for a secure protection.

V. Analysis of Inrush Current in Modern Transformers

It is well known that modern transformers may experience very low harmonic inrush currents. Modern transformers generally use high flux density (Hi-B) steel materials that have higher rated flux, a larger linear portion of magnetization curve, and a lower remanent flux compared to regular grain oriented (RGO) type material [4]. Fig. 11 conceptually illustrates excitation B-H curves for both a modern transformer and a traditional transformer.

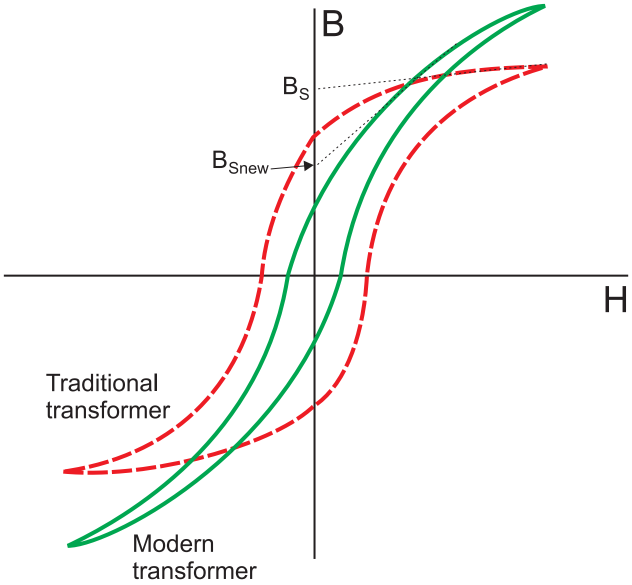

Fig. 11 Hysteresis loops for traditional and modern transformers

A B-H curve can be easily transformed into an Φ-I curve by the following relationships.

$$B = \phi / A \tag{19}$$

$$H = I \cdot N / d \tag{20}$$

Where

A = core cross-section area
N = number of turns in the coil
D = mean length of the coil

From Fig. 11, we can see that modern transformers can operate at higher flux. The saturation flux defined by Sonnemann [2] does not hold its original meaning for modern transformers. However, the definition is useful in the analysis of inrush current. From section 4.2, the lower level of saturation flux will cause larger base angle in the inrush current and, thus, lower second harmonic percentage in the inrush current. It can be seen from Fig. 7 that the harmonic ratio drops with the increase of the base angle and reaches approximately 5% when the base angle is 285º.

The existence of a significant amount of second harmonic component in the inrush current can be used to identify an energization event and avoid false tripping of differential protection. Generally, a second harmonic ratio setting of 20% is used to secure a differential circuit. However, modern transformers may experience a very low level of second harmonic in inrush current and require an improved harmonic restraint method.

VI. Harmonic Restraint Methods

The majority of relay manufacturers use the terms of harmonic restraint, harmonic inhibit, or harmonic blocking interchangeably. Although there are some variations in implementation, the differential relay will not operate when

$$\frac{|I_{Iop2nd}|}{|I_{op}|} > 2nd\ Harmonic\ Set\ Point \qquad (24)$$

In order to overcome the challenge of secure differential protection with low harmonic component in inrush current in new transformers, various harmonic restraint methods have been studied[5][6][7][8].

6.1 Per Phase Method

This is the earliest and simplest harmonic restraint method. Equation (24) applies to phase A, B and C separately. The restraint algorithm in each phase is independent and parallel. Per phase method is illustrated in Fig. 12.

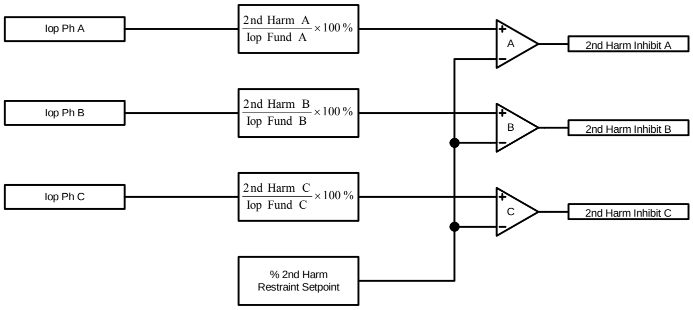

Fig.12 Per phase harmonic restraint method

Since each phase has different residual flux and is energized at a different angle, each phase most likely will have different harmonic levels. When the second harmonic ratio for a particular phase is above a preset level, the percent differential operation on that phase will be inhibited. Both experience and analysis show that it is possible to have low second harmonic ratio for one phase during transformer energization. Differential operation for a phase with small second harmonic ratio may cause an undesirable trip for a three-phase transformer. The differential protection with per-phase harmonic restraint method is very dependent but not secure.

6.2 Cross blocking Method

The harmonic detection for cross blocking method is the same as that of per phase method. The only difference is that the restraint signal from one phase will inhibit differential operation for all other phases. Cross blocking method is illustrated in Fig. 13.

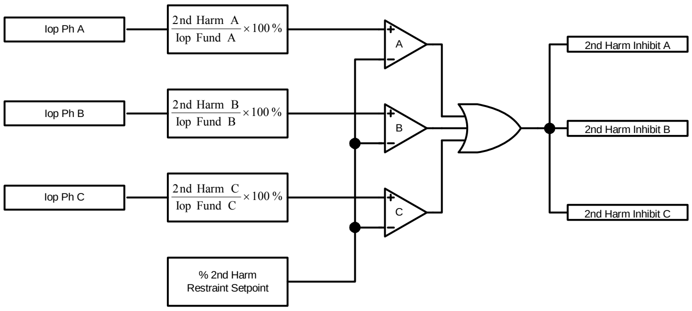

Fig.13 Cross blocking harmonic restraint method

It improves security by allowing the phase with the low harmonic ratio to be cross-blocked by a phase with a higher ratio preventing possible false trips. However, inrush current is generally several times the rated current, and the insulation bears the most severe mechanical stress during energization. If there is an internal fault in one phase or two phases, the high second harmonic ratio in a healthy phase may block the percent differential protection until the fault spreads to all three phases. The differential protection with cross blocking harmonic method is very secure but least dependable.

Two-out-of-three restraint method is a slight variation of the cross blocking method. The blocking of differential operation will need at least two phases to detect sufficient harmonic level. The disadvantage of this variation basically stays the same as that of cross blocking method.

6.3 Percent Average Blocking Method

The harmonic ratio for a percent average blocking method is the average of the second harmonic ratio of the three phases, i.e.,

$$2nd\ Ratio = \frac{1}{3}\left(\frac{|I_{op\,2ndA}|}{|I_{opA}|} + \frac{|I_{op\,2ndB}|}{|I_{opB}|} + \frac{|I_{op\,2ndC}|}{|I_{opC}|}\right) \tag{25}$$

Percent average blocking method is illustrated in Fig. 14.

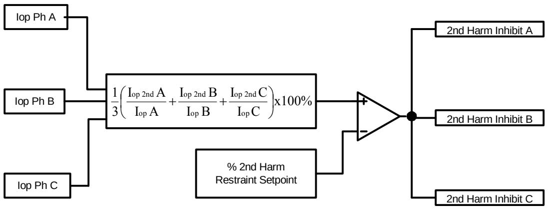

Fig.14 Percent average blocking harmonic restraint method

Compared to the cross blocking method and two-out-of-three method, this method improves the security of differential protection to a certain degree. The differential operation may be restrained when there is a true single phase fault during energization, provided that there are large harmonic ratios in the remaining healthy phases. This would cause a concern on the dependability in the differential protection.

6.4 Harmonic Sharing Method

A summing type harmonic sharing restraint method greatly improves the dependability of the differential protection during an internal fault. The shared second harmonic component is defined as

$$I_{2nd\ Sum} = |I_{op\ 2nd\ A}| + |I_{op\ 2nd\ B}| + |I_{op\ 2nd\ C}| \qquad (26)$$

The second harmonic ratios are then calculated per phase based on the shared $I_{2nd\ Sum}$ and the fundamental component of the operating current in each phase, i.e.,

$$2nd\ Ratio\ A = \frac{I_{op\ 2nd\ Sum}}{I_{op\ Fund\ A}},$$

$$2nd\ Ratio\ B = \frac{I_{op\ 2nd\ Sum}}{I_{op\ Fund\ B}},$$

$$2nd\ Ratio\ C = \frac{I_{op\ 2nd\ Sum}}{I_{op\ Fund\ C}} \qquad (27)$$

The harmonic restraint with summing type harmonic sharing is illustrated in Fig. 15.

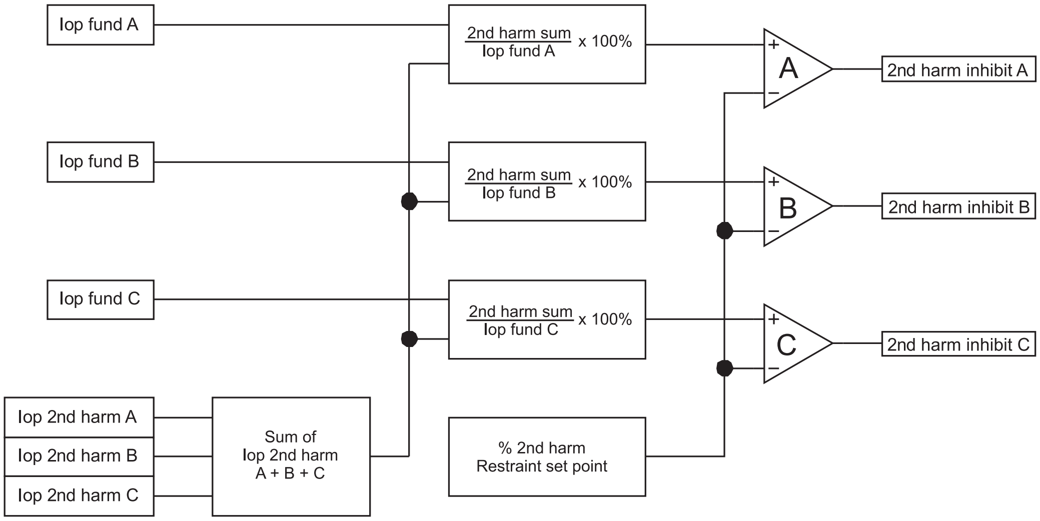

Fig.15 Restraint method with summing type harmonic sharing

In this method, the magnitudes of the second harmonic from three-phases are summed together to create a single harmonic signal, which is shared in the calculation of the second harmonic ratio in each phase. If there is an internal fault in one phase during energization, the large fundamental operating current would result in low harmonic ratio and, thus, no inhibit is generated from the faulted phase. Therefore, a three-phase transformer would be tripped during an internal fault. If one phase experiences a very low second harmonic ratio, the shared harmonic calculated from equation (26) will be large and the second harmonic ratios calculated from equation (27) will be large enough to restrain the differential protection from a false operation.

6.5 Second harmonic ratio and angle restraint method

Second harmonic ratio and angle restraint method uses both harmonic ratio and harmonic angle. The threshold of the preset harmonic ratio will be adjusted based on the angle of a derived signal,

$$\vec{I}_{21} = \frac{\vec{I}_2}{\vec{I}_1 \cdot e^{j\omega t}} = \frac{I_2}{I_1}(\angle\vec{I}_2 - 2\cdot\angle\vec{I}_1) \tag{28}$$

where:

$\vec{I}_2$ is the second harmonic phasor.

$\vec{I}_1$ is the fundamental phasor.

The multiplier of $e^{j\omega t}$ effectively doubles the angle from the fundamental DFT calculation.

To explore a bit further, an ideal inrush current waveform with 180° base angle ($\alpha = 90°$) and $I_m = 2$ was taken as an example. Fig. 17 illustrates the frequency spectrum up to 13th harmonic component. The frequency components can be derived by equation (14) and (15).

In Fig. 17, second harmonic = 0.4244, fourth harmonic = -0.0849, sixth harmonic = 0.0364 and other harmonic components can be ignored due to their relatively small amplitude.

Fig. 18 illustrates that waveform with only the direct, fundamental and second harmonic component, neglecting all other harmonic components shown in Fig.17. It can be seen that the approximate inrush current waveform is quite close to an ideal inrush.

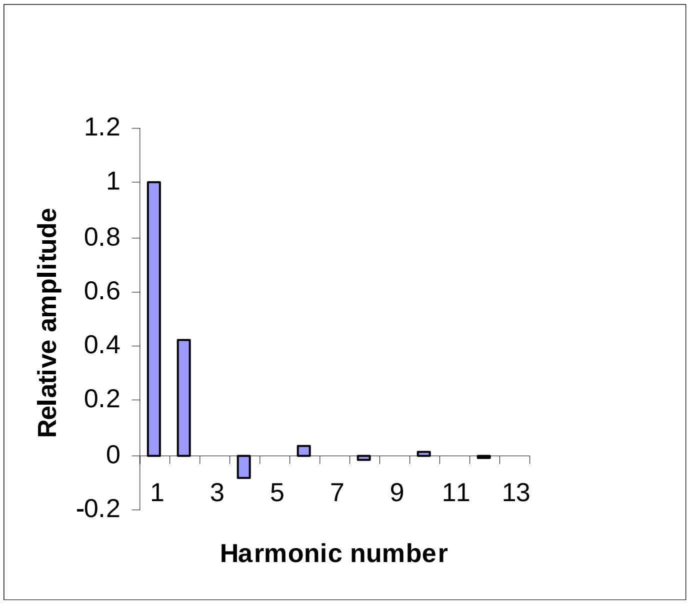

Fig. 17 Frequency spectrum of an ideal inrush current

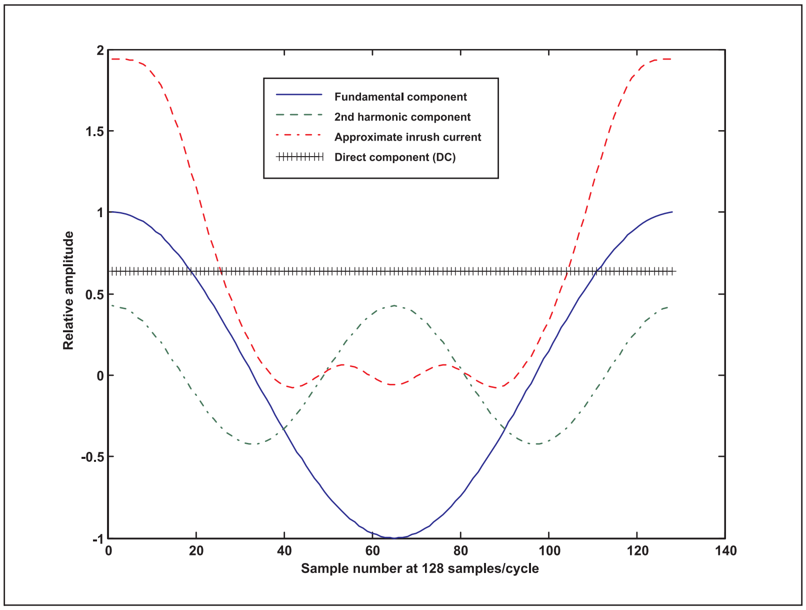

Fig. 18 Inrush waveform neglecting third and higher harmonic component

Fig. 18 also illustrates that the fundamental positive peak coincides with the positive peak of the inrush current. The second harmonic component also comes to its positive peak at the positive peak of the inrush current, except it comes twice as often. This conclusion matches the result in a classic reference [2].

It is obvious that the second harmonic phasor rotates at twice speed compared to that of fundamental frequency. It can be verified that the angle of phasor $\vec{I}_{21}$ defined in equation (28) is either 0º or 180º, depending on whether the inrush current is positive or negative.

The threshold second harmonic ratio may be adjusted based on the angle of $\vec{I}_{21}$. If the angle is at 0º or 180º, the threshold harmonic ratio may be adjusted to a lower percentage. If the angle is 90º or 270º, the threshold harmonic ratio may be adjusted to be a higher percentage. By dynamically lowering the harmonic restraint set point, security can be improved for normal energization with low harmonics.

The above analysis was based on an ideal inrush current based on a simplified transformer excitation curve. In reality, the measured inrush current may not be ideal due to a non-linear excitation curve, saturated sensing CTs or a delta connected windings. The angle of phasor $\vec{I}_{21}$ may be a bit random. When a fault occurs, the angle may also vary depending on the point of calculation and fault condition.

The application must be carefully considered to ensure the resulting angle calculation does not delay operation or cause false operation when automatically decreasing or increasing the 2nd harmonic ratio setting. This method may be less secure in applications where the possibility of angle randomness may occur.

VII. Analysis of Inrush Event Examples

7.1 A Low Second Harmonic Inrush Event

Fig. 19 illustrates a Δ/Y transformer connected to a radial distribution system. While this transformer is energized with load open, there is a station service transformer connected to the transformer secondary but outside the differential zone protection. When the main transformer is energized, the station service transformer also will be energized. This installation had problems with tripping during energization, and the user switched to a numeric relay. High voltage side CT is Y-connected and low voltage side CT is Δ-connected for external angle compensation. A set of COMTRADE data files was downloaded from an energization event, which is illustrated in Fig. 20 and Fig. 21.

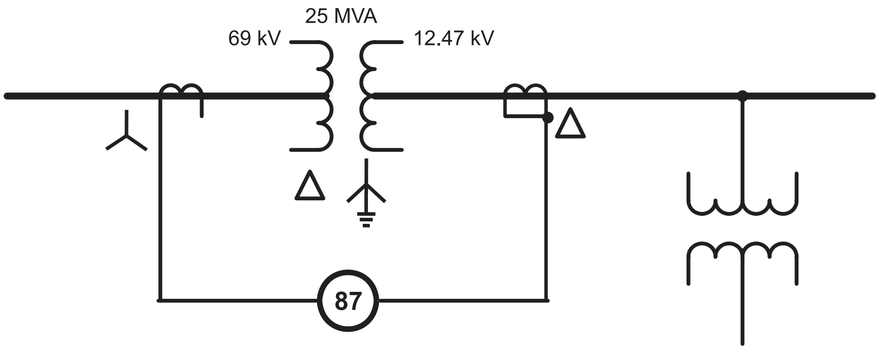

Fig. 19 A delta/Y transformer with low harmonic inrush current

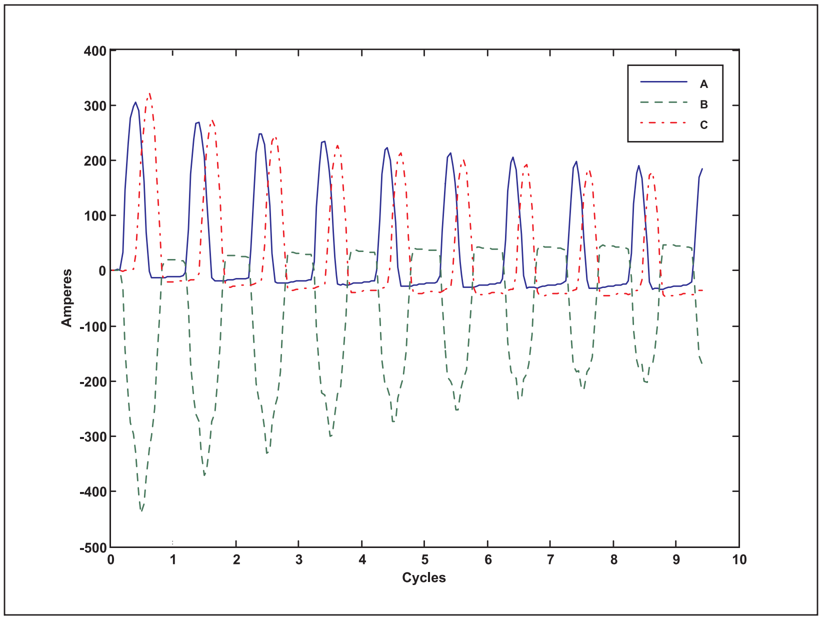

Fig. 20 Transformer inrush current, high voltage side (Example 1)

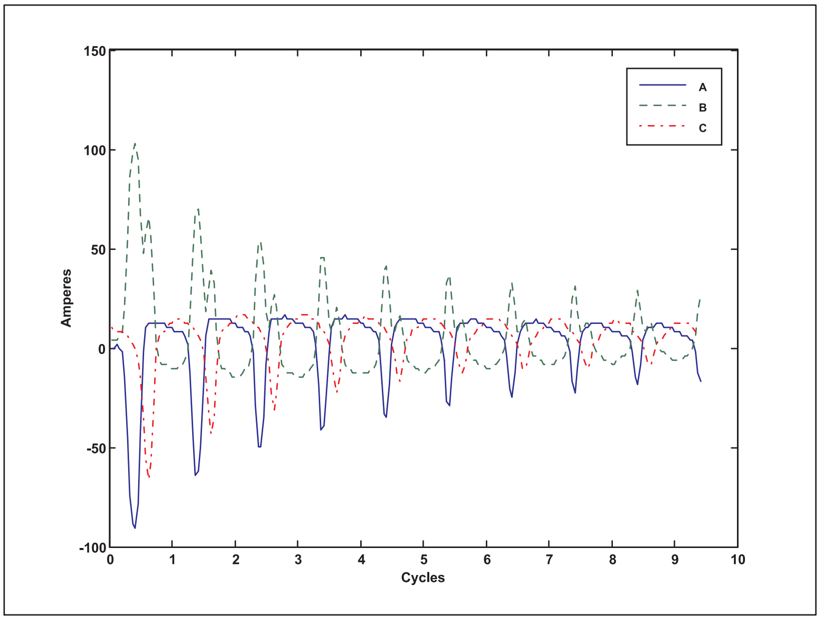

Fig. 21 Transformer inrush current, low voltage side (Example 1)

The secondary inrush currents are much smaller compared to those in the primary side. In the calculation of differential operating current, the contribution from the secondary inrush currents will be even smaller after tap compensation.

Fig. 22 illustrates the Root-Mean-Square (RMS) value of the fundamental component of the differential operating current. It can be seen that there is large operating current due to the inrush current, which could cause a false differential operation.

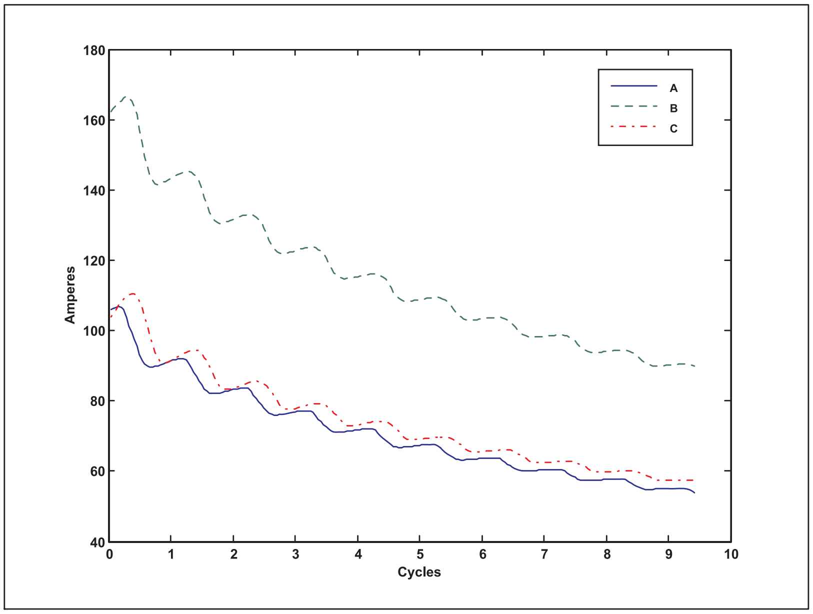

Fig. 22 Iop fundamental RMS value (Example 1)

The per-phase second harmonic ratios for all three phases are illustrated in Fig. 23. There is very low second harmonic ratio in phase B. For differential protection using per-phase harmonic restraint, security likely is a problem. The low second harmonic ratio in phase B was probably the reason this transformer had problems with tripping during energization.

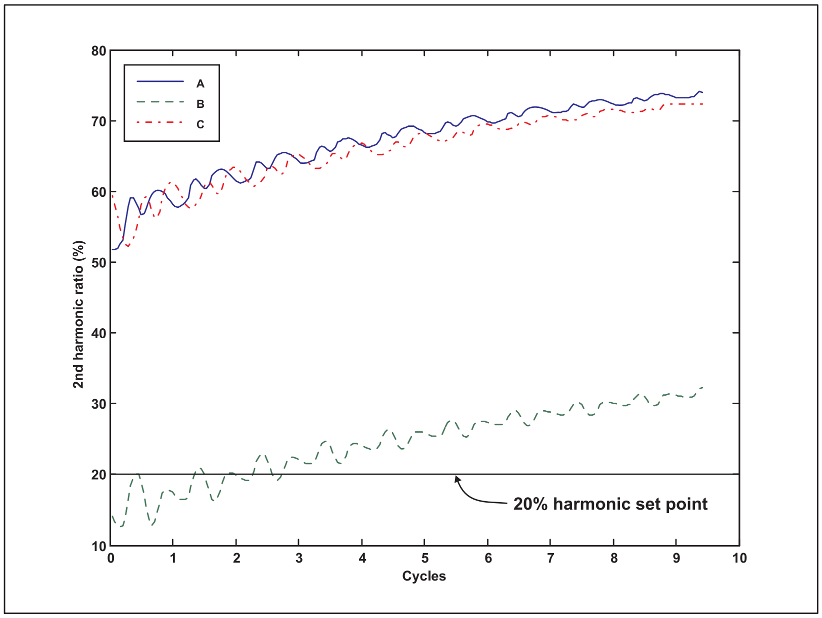

Fig. 23 Per-phase second harmonic ratio (Example 1)

When considering second harmonic cross blocking for this application, the second harmonic ratios in phase A and C are large, as seen from Fig 23, differential tripping of phase B will be cross blocked.

Figures 24 and 25 indicate the result of applying average second harmonic ratio and summing type harmonic sharing restraint methods. In both cases we observe the differential protection would be secure for this low harmonic energization.

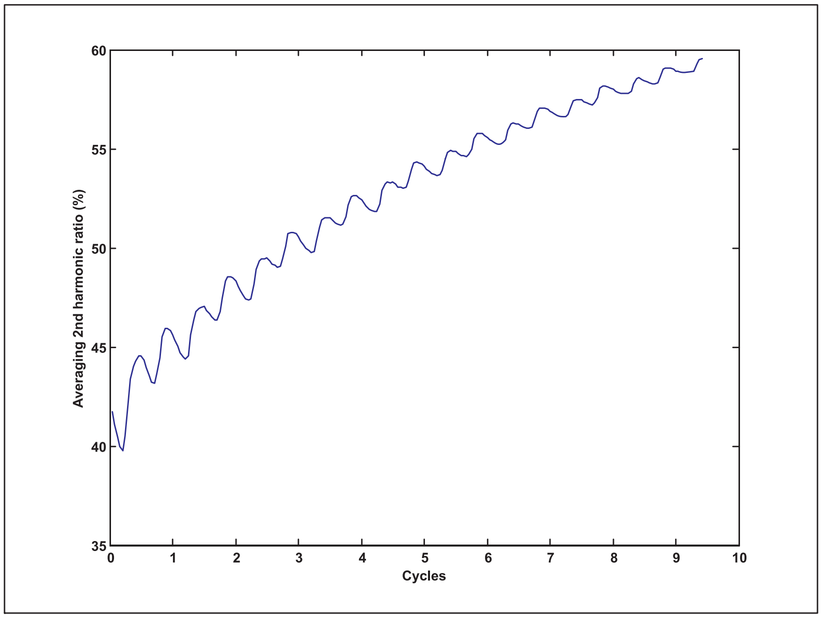

Fig. 24 Average second harmonic ratio (Example 1)

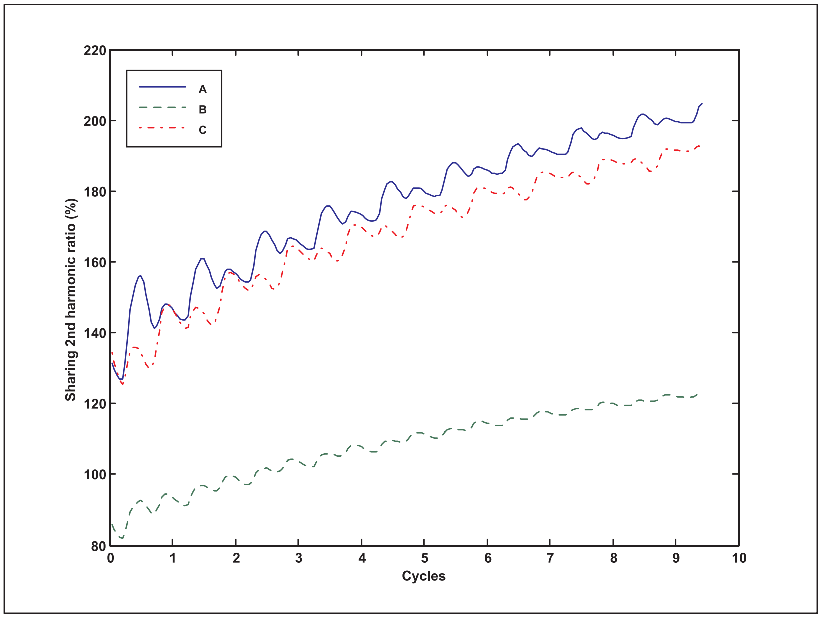

Fig. 25 Second harmonic ratio with summing type harmonic sharing

Fig. 26 illustrates the angles of phasor $\vec{I}_{21}$, which is defined in equation (28).

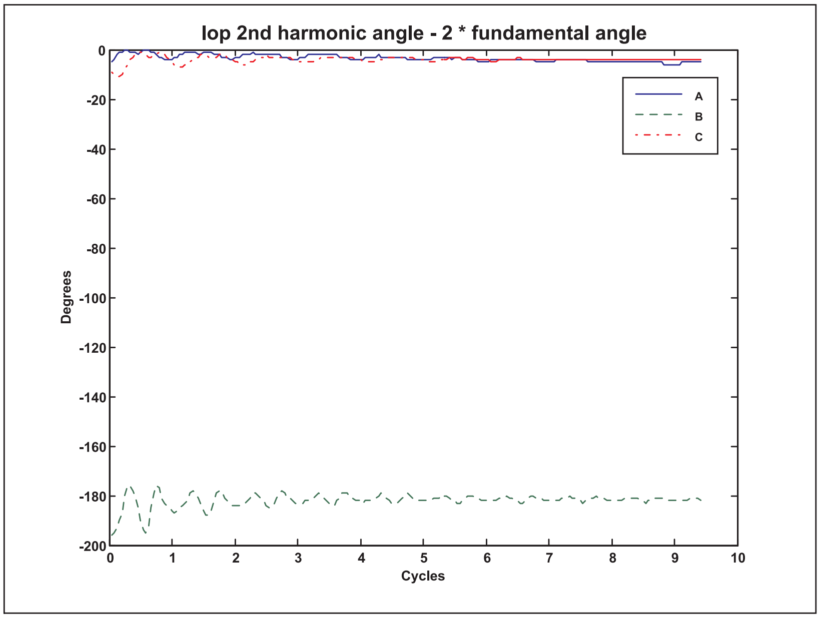

Fig. 26 Angles of $\vec{I}_{21}$ (Example 1)

From Fig. 26, the angles of $\vec{I}_{21}$ in phase A and C are near 0º, and the angle of $\vec{I}_{21}$ for phase B is near 180º. For these angles the second harmonic ratio setting is reduced and the lower threshold of harmonic ratio would help improve the security during the low harmonic energization.

7.2 An Inrush Event with an Internal Fault

To illustrate an inrush event with a true fault, a Matlab® Simulink® simulation was used. As shown in Fig. 27, a 450MVA, 500kV-230kV Yg/Yg transformer has experienced a phase C ground fault within the protection zone during energization.

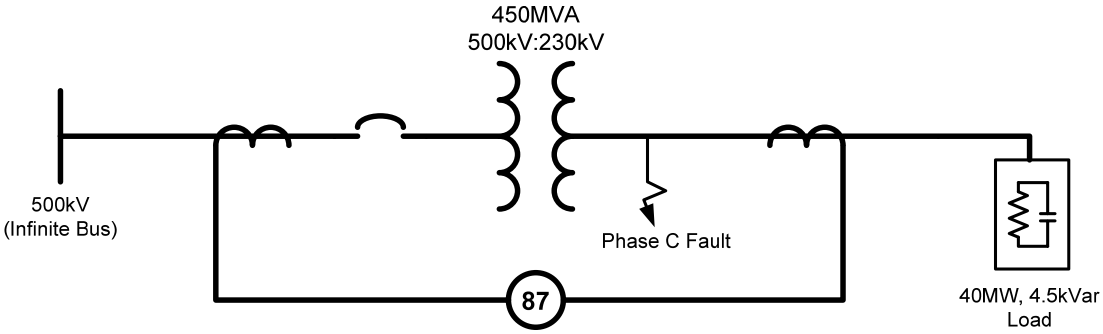

Fig. 27 Simulation of an inrush fault event

Fig. 28 and Fig. 29 illustrate the inrush waveforms for both the primary and secondary circuits as seen by the differential protection.

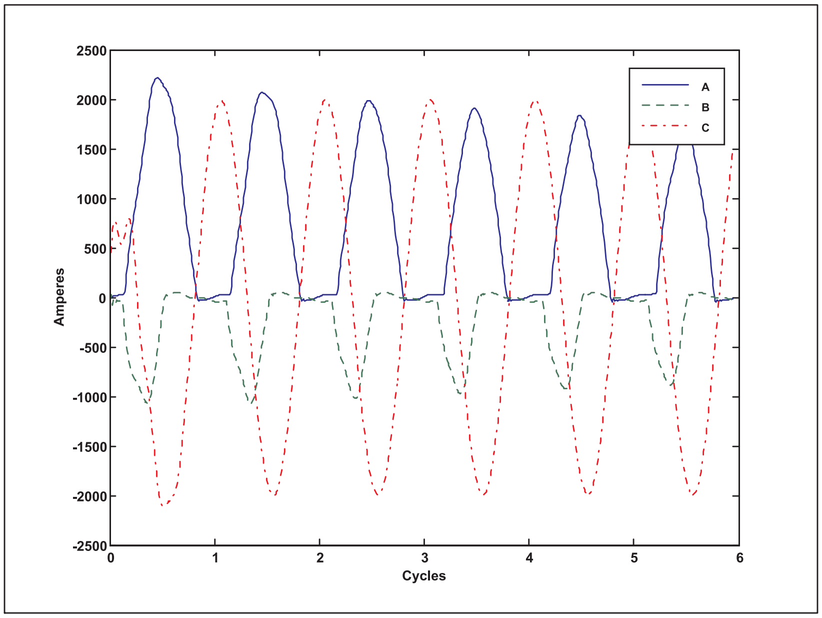

Fig. 28 Transformer inrush current, high voltage (Example 2)

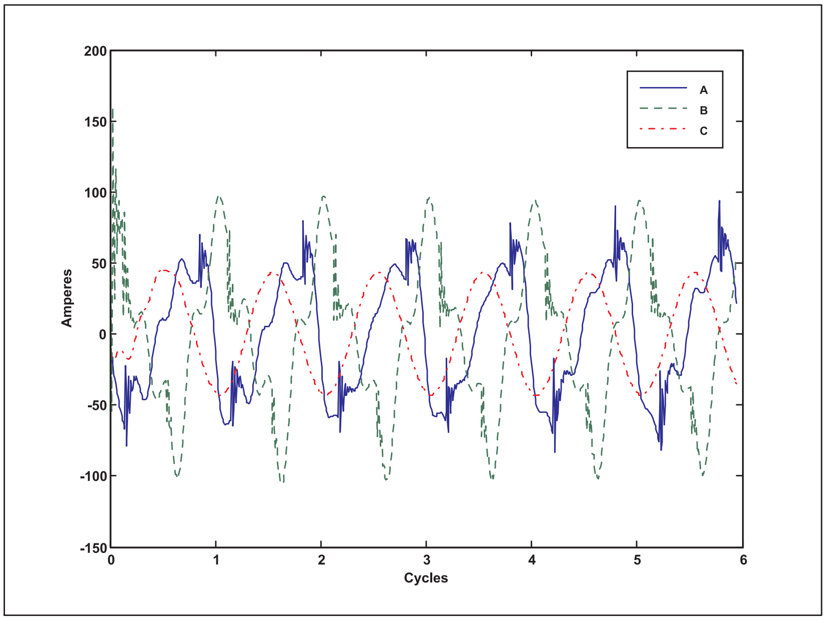

Fig. 29 Transformer inrush current, low voltage (Example 2)

Fig. 30 illustrates the differential operating current in each of the three phases. The high operating current is due to both magnetizing inrush and fault current. Without a proper restraint method, the differential protection could mis-operate during this event.

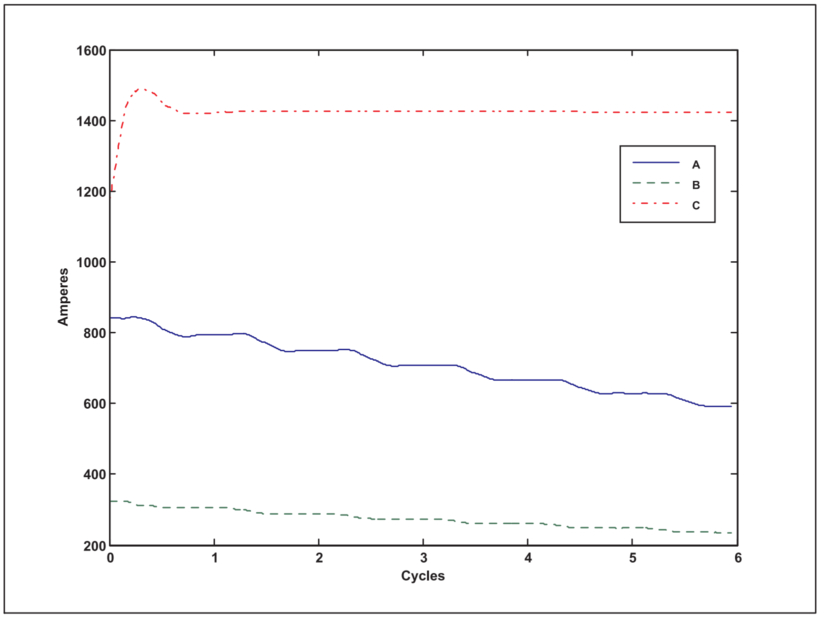

Fig. 30 Iop fundamental RMS value (Example 2)

Fig. 31 illustrates per-phase second harmonic ratio. Phase B has a very high second harmonic ratio. Phase C has a very low second harmonic ratio due to the large fault current. The second harmonic ratio of phase A is in the range of typical setting of harmonic ratio. A differential relay using per-phase harmonic restraint will have trip signal from phase C and the protection on the three-phase transformer is dependable.

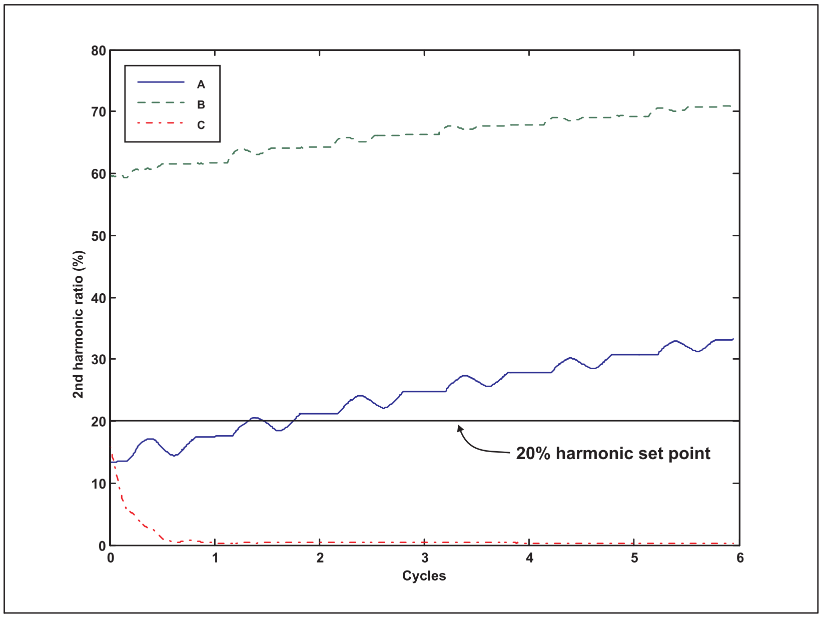

Fig. 31 Per-phase second harmonic ratio (Example 2)

Due to the high second harmonic ratio in phase B, a differential relay using cross blocking method will block the differential operation and the protection is not dependable to trip for this event. Depending on the setting of threshold harmonic ratio, phase A may or may not indicate an inrush event. Protection with two-out-of-three harmonic restraint may not protect this event reliably.

Fig. 32 illustrates how the average restraint harmonic ratio changes during the event of energizing a faulted transformer. With a second harmonic restraint set point of 28%, the differential protection with average percentage harmonic ratio restraint is unblocked for about a cycle. Out of this one-cycle window, the differential element is blocked and unable to correctly trip for this event.

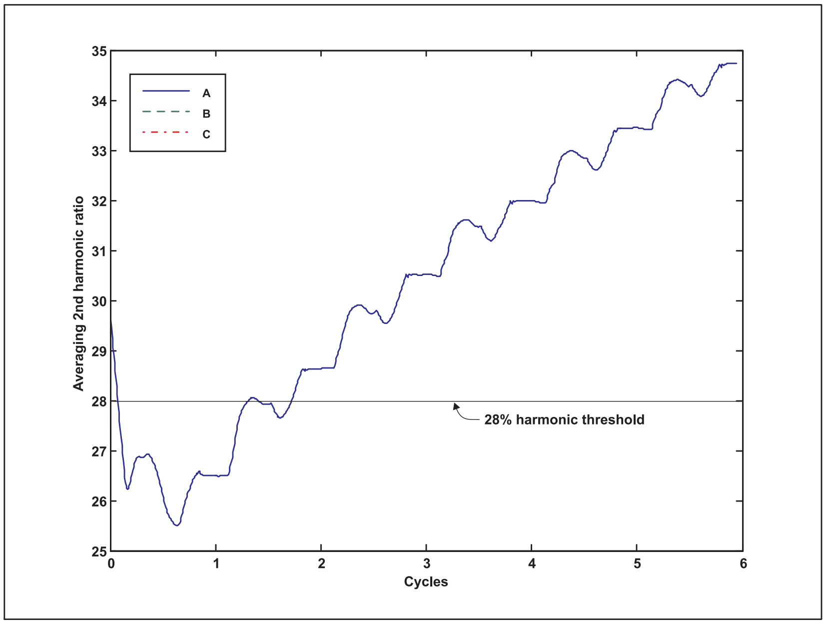

Fig. 32 Average second harmonic ratio (Example 2)

Fig. 33 illustrates the second harmonic ratio using summing type harmonic sharing method. By inspecting the curve of phase C harmonic ratio, the differential element will be able to trip for many cycles for a 28% harmonic restraint set point. A differential relay with harmonic sharing restraint is dependable to trip for this event.

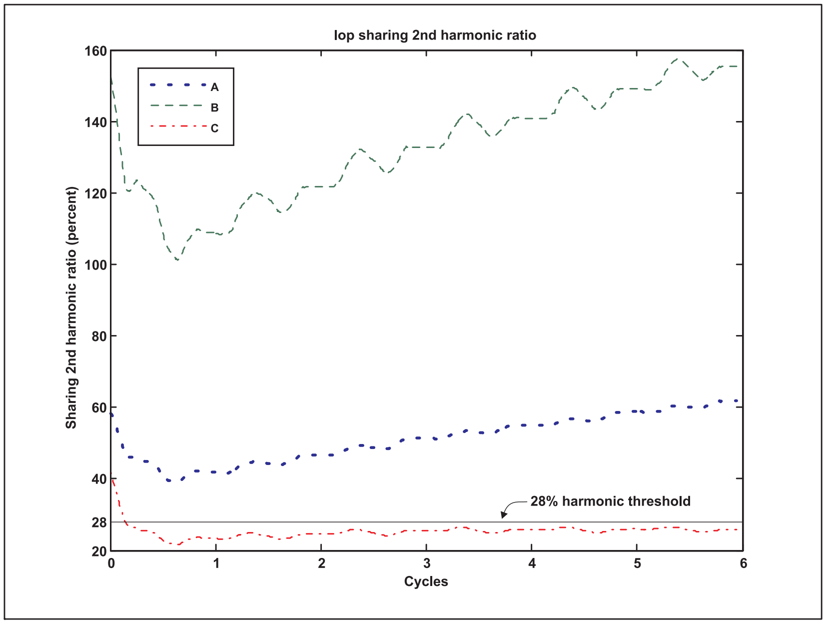

Fig. 33 Second harmonic ratio with summing type harmonic sharing (Example 2)

Fig. 34 illustrates that the phase angle of $\vec{I}_{21}$ is around 0º in phase A and 180º in phase B. The angle in phase C is a bit random due to a ground fault. The randomness of phase angle may delay a desired differential trip for a differential protection using the second harmonic ratio and angle restraint method. In this example, the harmonic ratio and angle method will not delay a differential trip due to very low 2nd harmonic ratio in the faulted phase C.

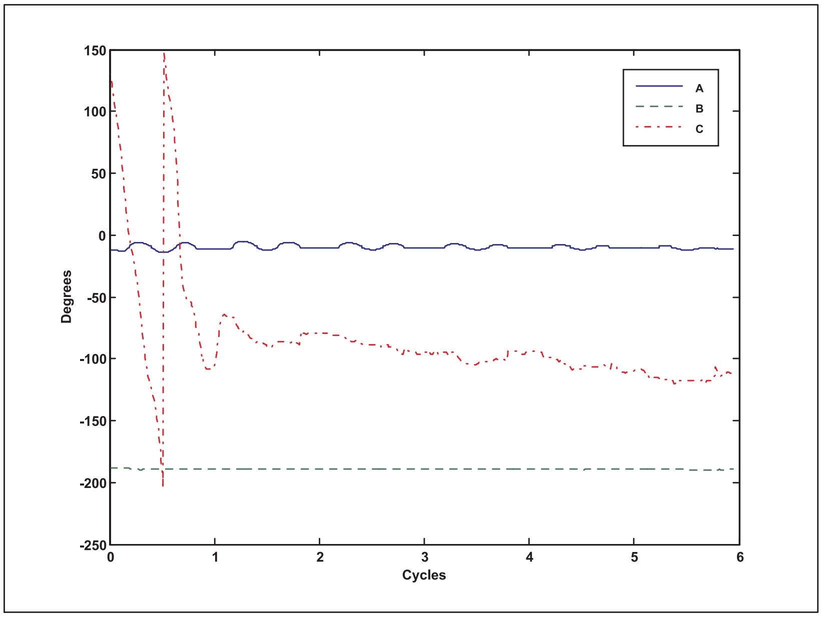

Fig. 34 Angles of $\vec{I}_{21}$ (Example 2)

VIII. Conclusion

Security is of concern in differential protection during transformer energization. Inrush current occurs mostly only in one side of the transformer and could cause a false differential trip. A common method is to use the second harmonic information in inrush current to secure differential protection when energizing transformers.

An analysis of factors like residual flux, saturation flux, and energizing angle on the second harmonic ratio in inrush current is provided in this paper. Higher residual flux and/or lower saturation flux in transformers may result in higher differential operating current and lower second harmonic ratio, which is likely to cause a security concern in differential protection during transformer energization.

It is well known that modern transformers may experience very low second harmonic ratios. Much research has been done to improve the security while maintaining the dependability. Per-phase harmonic restraint provides high dependability but low security for energization with low harmonics. Harmonic cross blocking provides better security but low dependability when energizing a faulted transformer. Average-percent harmonic restraint improves the security but may cause an unexpected blocking when energizing a faulted transformer with high harmonics in healthy phases. The restraint with summing type harmonic sharing provides very good dependability while maintaining the security for differential protection. The second harmonic ratio and angle restrained method improves security by dynamically lowering the harmonic restraint set point but may have dependability concerns due to inconsistency in the harmonic angle calculation during a true fault.

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Biographies

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