



PS1 – Poster-06



Improvements to Transformer Differential Protection – Design and Test Experience

Tony H. YIP, Mariela MOSCOSO, Graeme J. LLOYD, Kevin LIU, Zheng WANG
ALSTOM Grid
UK
tony.yip@alstom.com

KEYWORDS

New algorithms, transformer differential protection, CT saturation, magnetising inrush.

1 INTRODUCTION

Percentage Bias characteristics have been commonly applied for transformer differential protection. Traditional protection schemes use dual slope or multiple slope characteristics to provide stability during CT saturation, together with second harmonic as a restraining or blocking quantity for inrush conditions. However, studies have shown that there is a limitation with the dual slope characteristic for stability, to avoid requiring excessive over-dimensioning of the CTs. The second harmonic blocking has also been shown to slow down the protection for internal faults if CT saturation occurs [1], [2]. This is because CT saturated waveforms can also contain a high second harmonic component. Early studies on magnetizing inrush indicates that the second harmonic content might be 15% or more of the fundamental current [3]. Recent studies indicate that improvements in the transformer design and core steel result in low content of second harmonic (as low as 7%) [3].

This paper presents new algorithms that have been developed to improve the performance of transformer biased differential protection. A transient bias algorithm has been implemented which increases the operating threshold momentarily when there is a sudden increase in the bias current, thus enhancing stability during external faults. This approach will not affect the performance during internal faults, since the differential current will rise much faster than the bias currents. A novel CT saturation detection algorithm has been developed. It is based on the fact that magnetising inrush and saturated current waveforms are distorted and discontinuity patterns can be observed on both waveforms. This new technique emphasizes the discontinuity pattern by differentiating the differential current making it possible to distinguish magnetising inrush from CT saturation within a cycle. A no gap detection algorithm has been applied to complement the CT saturation detection. It considers the number of samples above a dynamic threshold within the last “N” executions. The assertion of CT saturation or no gap detection unblocks the differential protection from the second harmonic blocking. As a result, the restrained differential element is allowed to trip even during CT saturation, giving faster tripping times for internal faults.

2 TRANSIENT BIAS TECHNIQUE

To provide further stability for external faults, additional measures are considered on the calculation of the bias current: delayed bias, maximum bias and transient bias.

The delayed bias is calculated on a per phase basis and it is the maximum of the fundamental bias quantities calculated within the last cycle. The delayed bias provides added stability when an external fault is cleared and the fault currents drop off.

$$I_{bias_A_delayed} = \text{Maximum} [I_{bias,A}(n), I_{bias,A}(n-1), \dots, I_{bias,A}(n-(k-1))] \quad \text{Equation 1}$$

$$I_{bias_B_delayed} = \text{Maximum} [I_{bias,B}(n), I_{bias,B}(n-1), \dots, I_{bias,B}(n-(k-1))] \quad \text{Equation 2}$$

$$I_{bias_C_delayed} = \text{Maximum} [I_{bias,C}(n), I_{bias,C}(n-1), \dots, I_{bias,C}(n-(k-1))] \quad \text{Equation 3}$$

The maximum bias is the maximum of the delayed bias currents from all three phases. The maximum bias is used to prevent mal-operation under external faults conditions, when spill current could flow into a healthy phase the CT of which is partially saturated.

$$I_{bias,max} = \text{Maximum} [I_{biasA_delayed}, I_{biasB_delayed}, I_{biasC_delayed}] \quad \text{Equation 4}$$

The maximum bias is used to calculate the differential operating current I_{op} , using the following equations by considering the multiple slope characteristic shown in 0:

$$\text{Characteristic equation for the range: } 0 \leq I_{bias,max} \leq \frac{I_{s1}}{K_1} \quad \text{Equation 5}$$

$$I_{op} = I_{s1} \quad \text{Equation 6}$$

$$\text{Characteristic equation for the range: } \frac{I_{s1}}{K_1} \leq I_{bias,max} \leq I_{s2} \quad \text{Equation 7}$$

$$I_{op} = K_1 \cdot I_{bias,max} \quad \text{Equation 8}$$

$$\text{Characteristic equation for the range: } I_{bias} \geq I_{s2} \quad \text{Equation 9}$$

$$I_{op} = K_1 \cdot I_{s2} + K_2 (I_{bias,max} - I_{s2}) \quad \text{Equation 10}$$

$$K_1: \quad \text{characteristic slope in range} \quad \frac{I_{s1}}{K_1} \leq I_{bias,max} \leq I_{s2} \quad \text{Equation 11}$$

$$K_2: \quad \text{characteristic slope in range} \quad I_{bias,max} \geq I_{s2} \quad \text{Equation 12}$$

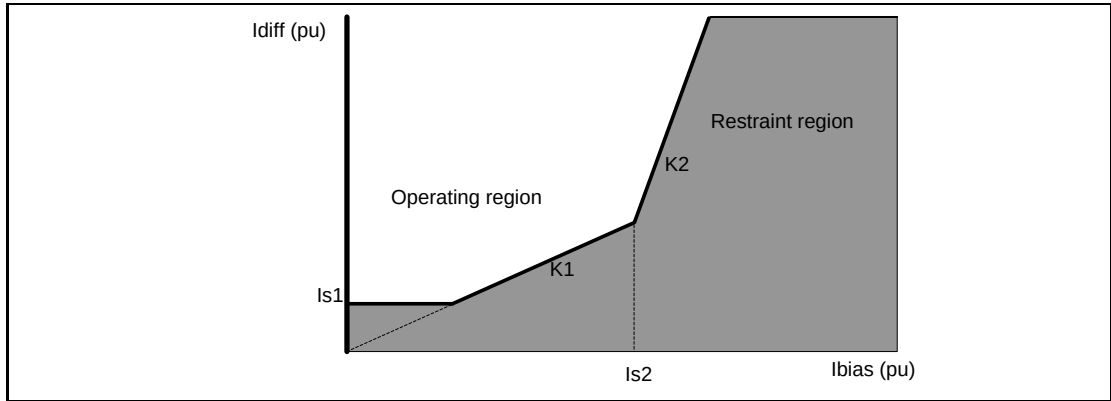


Fig. 1: Tripping characteristic of differential protection

The transient bias is introduced when there is a sudden increase in the mean bias measurement. The transient bias decays exponentially and it resets to zero once the relay trips, or if the mean bias quantity is below the restrained element setting. The operating current threshold is calculated at the maximum bias current. The transient bias is calculated on a per phase basis and it is added to the operating current calculated at the maximum bias. Therefore, the following differential current thresholds are available:

$$\text{Diff threshold phase A} = I_{op} \text{ at max bias} + \text{transient bias_phase A} \quad \text{Equation 13}$$

$$\text{Diff threshold phase B} = I_{op} \text{ at max bias} + \text{transient bias_phase B} \quad \text{Equation 14}$$

Diff threshold phase C = I_{op} at max bias + transient bias_{phase C}

Equation 15

The differential current is compared against the differential current threshold given above on a per phase basis. If the differential current is above the threshold, then the biased differential element might trip as long as the second harmonic and fifth harmonic blockings are not asserted.

The transient bias technique considers a time decay constant, stability coefficients and the differential function settings to provide a dynamic bias characteristic. 0 shows the differential thresholds calculated by the relay on a per phase basis for a AN external fault on the star side of a Ynd11 transformer. It can be observed that the transient bias has enhanced relay stability. For the relay to trip, the differential current should be above the operating current at max bias + transient bias.

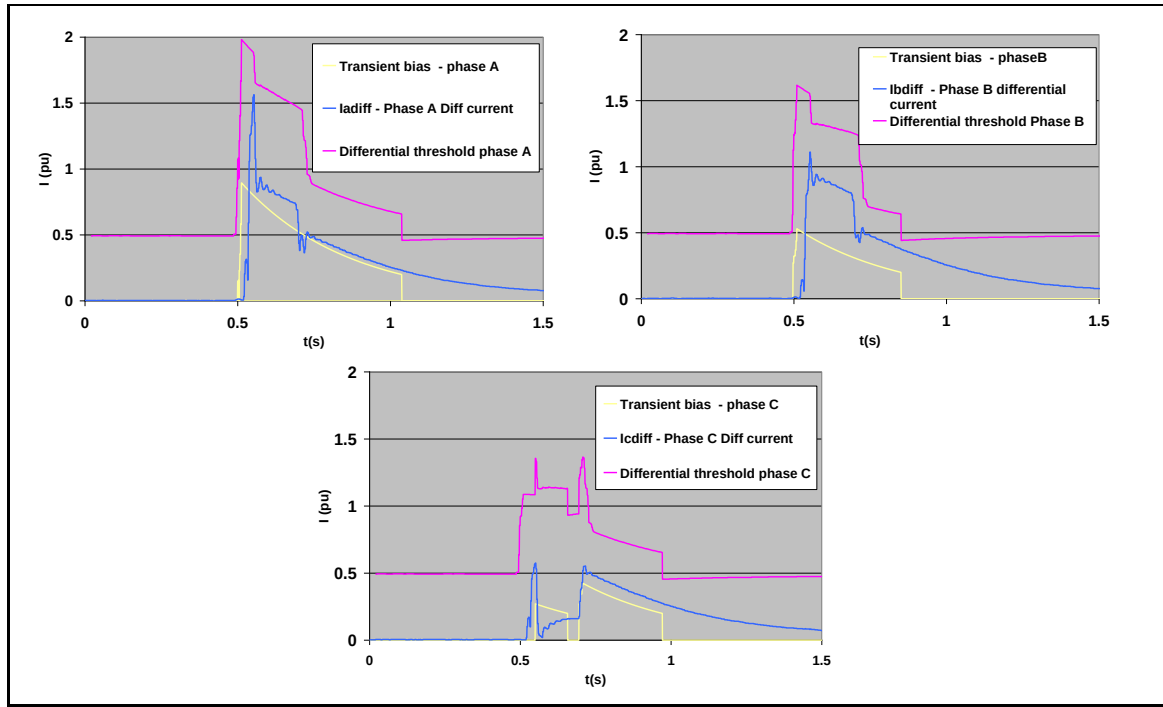


Fig. 2: Transient bias – external fault

0 shows the nominal biased characteristic, the dynamic threshold and the differential current loci. The differential currents increment from A to B, meanwhile the differential current thresholds also increase from A' to B'. It can be observed that considering the nominal characteristic for phases A and B results in a mal-operation because I_{adiff} and I_{bdiff} are above the nominal characteristic. Taking into account the transient bias quantities prevents an unwanted trip because I_{adiff} and I_{bdiff} are below the dynamic threshold. From B to C the differential currents are below the dynamic threshold from B' to C'.

The transient bias enhances the stability of the differential element during external faults and allows for the time delay in CT saturation caused by small external fault currents and high X/R ratios. For single-end or double-end fed faults the differential current is dominant and the transient bias has no effect.

0 shows the differential thresholds calculated by the relay on a per phase basis for a BN internal fault on the delta side of a Ynd11 transformer. The transient bias does not prevent the operation of the differential element as the differential current is above the operating current at max bias + transient bias.

0 shows that the dynamic threshold coincides with the nominal characteristic because the transient bias for phase A is zero. For phases B and C the operating currents have been increased due to the transient bias, but since this is an internal fault the dynamic thresholds are well below the differential current loci.

No transient bias is produced under load switching conditions. Also, no transient bias is generated when the CT comes out of saturation.

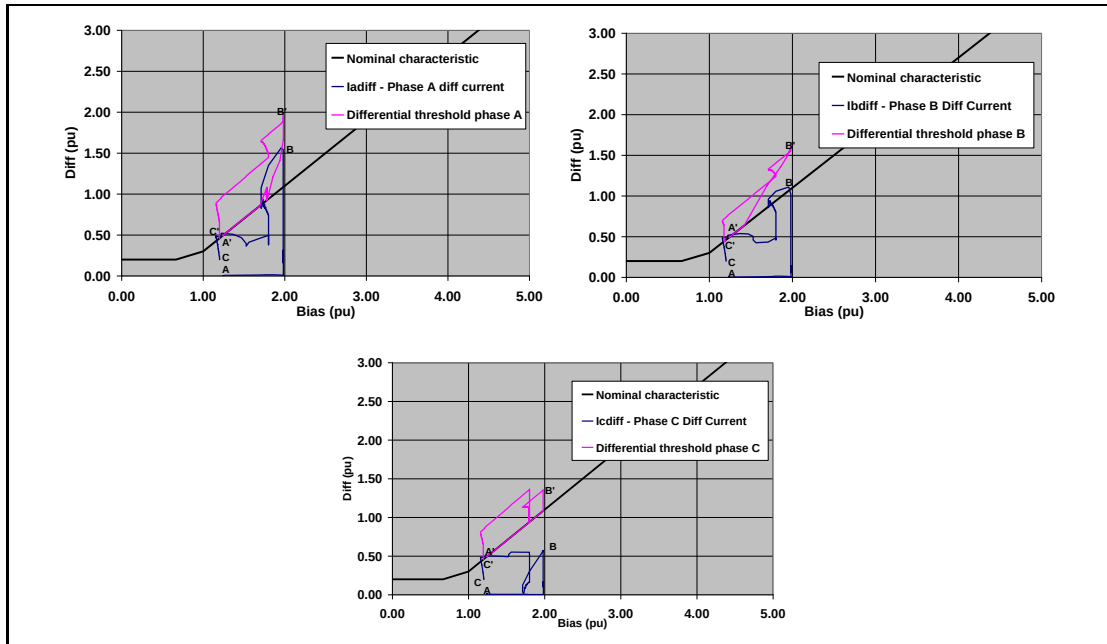


Fig. 3: Differential characteristic with transient bias – external fault

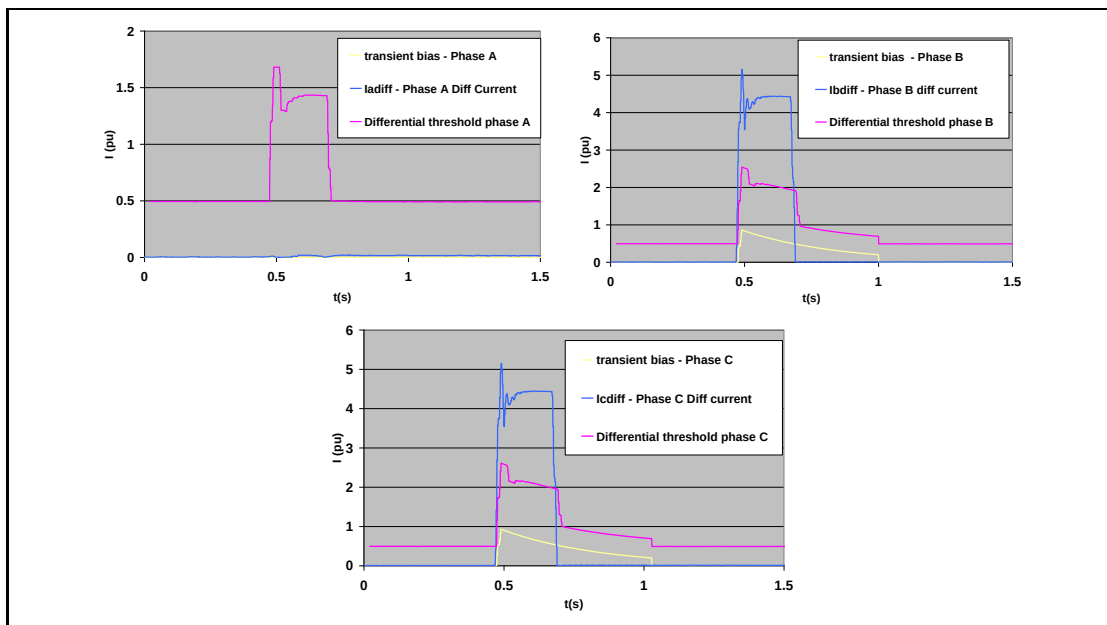


Fig. 4: Transient bias – internal fault

3 CT SATURATION AND NO GAP DETECTION TECHNIQUES

When second harmonic blocking is used to stabilize the restrained differential element during inrush conditions, the CT saturation detection technique can be used to enhance the restrained differential element operating time during internal faults with CT saturation. The content of second harmonic may be above the second harmonic threshold during internal faults with CT saturation. As a result, the biased differential element may be blocked during an internal fault. If the fault level is not high enough, then the unrestrained differential element will not be asserted; thus a fast trip cannot be achieved. When the CT comes out of saturation, the biased differential element would be operative. The result is a delayed differential trip [1], [2]. The delayed trip can be avoided either by unblocking the biased differential element during internal faults or by using a CT with a sufficiently high knee point voltage to avoid CT saturation (which might not be possible).

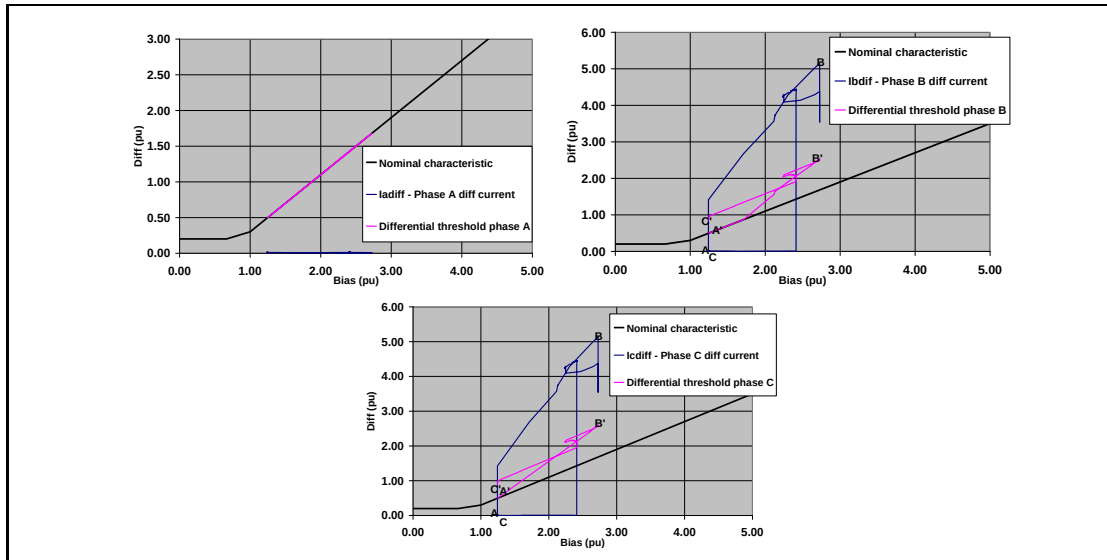


Fig. 5: Transient bias – differential characteristic – internal fault

The CT saturation detection technique distinguishes between magnetising inrush and saturation; therefore, the relay stability is maintained during inrush conditions. To detect a CT saturation condition the differential current samples on a per phase basis are considered. The relay analyzes the differential current waveforms considering their derivatives and dynamic and fixed thresholds that were determined by RTDS (real time digital simulator) tests. The CT saturation detection logic unblocks the low set differential element during CT saturation to allow the biased differential element operation.

The no gap detection technique compliments the CT saturation technique. It considers the number of samples on a per phase basis above a dynamic threshold within the last N executions. This threshold is a function of the second harmonic content. If the summation of the number of samples above the dynamic threshold is above or equal to a fixed threshold (determined by RTDS tests) then there is no gap, and the blocking of low set differential element is prevented.

The differential biased trip is affected by the CT saturation and no gap detection techniques. If the second harmonic blocking is asserted and either the CT saturation detection or no gap detection technique is asserted, then the biased differential trip is unblocked. A biased differential trip will occur if the fifth harmonic blocking is not asserted and the bias differential start signal is asserted. The differential biased trip logic is described in 0.

Extensive real time simulation testing has been done to evaluate these techniques. 0(a) is the disturbance record for a AN internal fault from a relay with CT saturation and No gap detection enabled, the operating time of the low set differential element is 28 ms. It can be observed that both the CT saturation logic and the no gap detection logic are asserted. The CT saturation and No gap detection logics complement each other. 0(b) is the disturbance record for a AN internal fault from a relay with CT saturation and No gap detection disabled. The operating time is 57 ms. Hence, the relay is 29 ms faster if the CT saturation and No gap detection is enabled.

4 CT REQUIREMENTS

To determine the CT requirements for the differential function through fault injection tests were performed under different X/R ratios, CT burdens, fault currents, fault types and point on wave fault inception. The fault current waveforms considered a six fault sequence, where the second set of three faults was controlled to generate the opposite flux movement in the CT than the first set [4].

To establish the CT requirements the burden was incremented and the six fault sequence repeated, until either the burden limit had been reached, or the relay mal-operated.

0 shows the CT requirements when the transient bias technique is applied and when it is not. It can be observed that when the transient bias technique is not included the K factor is more than 5 times the K factor when the transient bias technique is included.

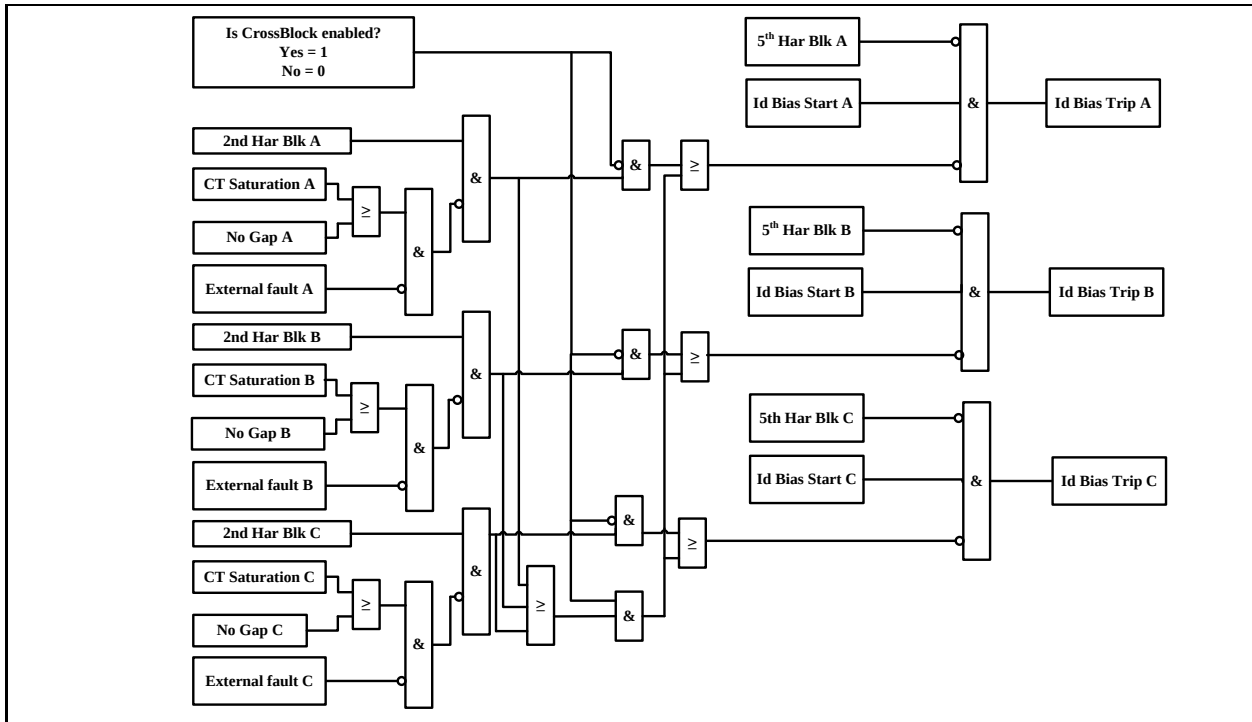


Fig. 6: Differential biased trip logic

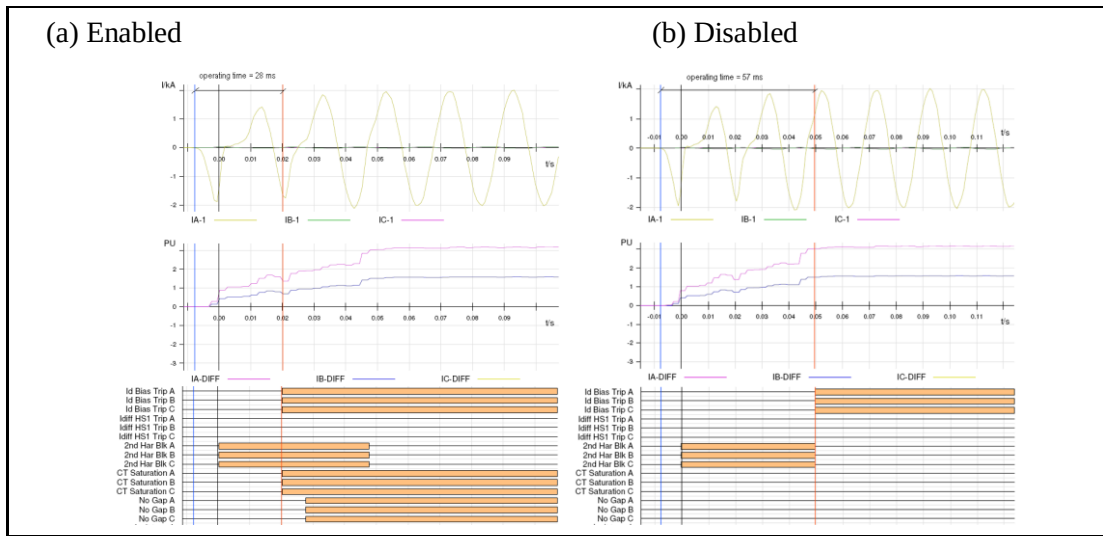


Fig. 7: (a) CT saturation and no gap detection enabled (b) CT saturation and no gap detection disabled

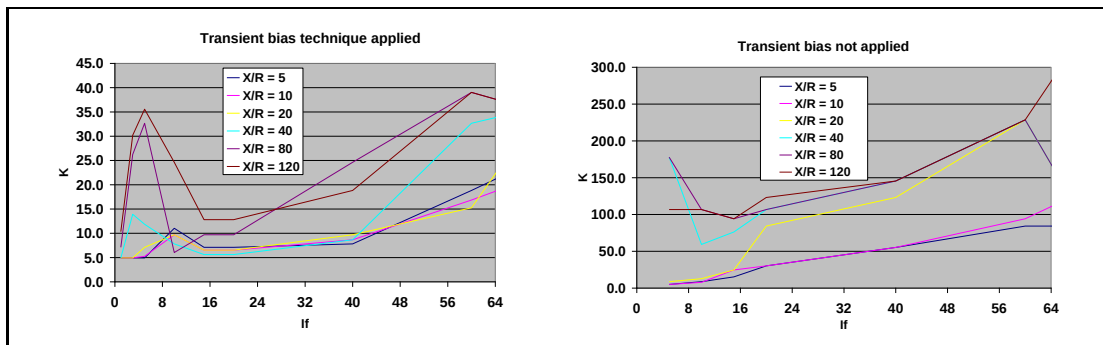


Fig. 8: CT Requirements with and without transient bias

Considering the results shown in 0 when the transient bias technique is applied the CT requirements might be quoted as follows:

System conditions	K (CT dimensioning factor)	Knee point voltage
$I_n < I_F \leq 64I_n$ $5 \leq X/R \leq 20$	$K = 25$	$V_K \geq 25 \times I_n \times (R_{CT} + 2R_L + R_r)^{(1)}$ $V_K \geq 25 \times I_n \times (R_{CT} + R_L + R_r)^{(2)}$
$I_n < I_F \leq 64I_n$ $20 < X/R \leq 120$	$K = 40$	$V_K \geq 40 \times I_n \times (R_{CT} + 2R_L + R_r)^{(1)}$ $V_K \geq 40 \times I_n \times (R_{CT} + R_L + R_r)^{(2)}$

Table 1: CT requirements

Where:

K = CT dimensioning factor

I_F = maximum external fault current

X/R = primary system X/R ratio

I_n = Relay rated current

R_r = resistance of any other protective relays sharing the current transformer (Ω)

⁽¹⁾ = single phase fault or phase-phase-ground fault

⁽²⁾ = three phase fault or phase-phase fault

To ensure that through fault stability is achieved the following ratios:

$$V_{k-HV} / R_{tot-HV} : V_{k-LV} / R_{tot-LV}$$

$$V_{k-HV} / R_{tot-HV} : V_{k-TV} / R_{tot-TV}$$

$$V_{k-LV} / R_{tot-LV} : V_{k-TV} / R_{tot-TV}$$

should not exceed a maximum disparity of 4:1. Fulfilling the disparity ratios ensures that during a through fault condition the flux density in the current transformers is not greatly different [5].

Where:

V_{k-HV} = Knee point voltage of CT at HV side

R_{tot-HV} = Total burden connected to CT at HV side = $(R_{CT} + 2R_L + R_r)$ or $(R_{CT} + R_L + R_r)$

V_{k-LV} = Knee point voltage of CT at LV side

R_{tot-LV} = Total burden connected to CT at LV side = $(R_{CT} + 2R_L + R_r)$ or $(R_{CT} + R_L + R_r)$

V_{k-TV} = Knee point voltage of CT at TV side

R_{tot-TV} = Total burden connected to CT at TV side = $(R_{CT} + 2R_L + R_r)$ or $(R_{CT} + R_L + R_r)$

5 CONCLUSION

It has been demonstrated that the transient bias algorithm improves the stability of the biased differential element because the biased characteristic varies dynamically taking into consideration the increase in bias current as well as the differential settings. In addition, the CT requirements for a biased differential element are much lower when the transient bias technique is included.

The CT saturation and no gap detection techniques improve the operating times as the biased differential element is not longer blocked during internal faults with CT saturation.

REFERENCES

- [1] IEEE Std C37.91-2000 Guide for Protective Relay Application to Power Transformers.
- [2] ALSTOM Transformer Differential Protection Relay MBCH publication R6070L.
- [3] BLACKBURN J. L., 1997. Protective Relaying Principles and Applications. 2nd ed. New York: New York.
- [4] NGTS 3.24.18 Issue 1 – 2000 Unit Feeder Main Protection.
- [5] ALSTOM KBCH Manual KBCH/EN-M-G11.