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Using Transient Biasing to Reduce CT Requirements of Current Differential Protection

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KEYWORDS

Current differential protection, transient biasing, CT requirements, CT modelling.

1 INTRODUCTION

Even while such an advanced technology as “Non Conventional Instrument Transformers” is proliferating fast [1], the majority of protection devices are still connected to conventional electromagnetic current transformers (CT). Apparently, this situation isn't going to change for at least 5 to 10 more years. The reliability of any protection, and especially differential, is largely dependant on the correct CT dimensioning. Theoretically, it's possible to dimension a CT to completely prevent its saturation [2]. To achieve this it is necessary to comply with the condition:

$$V_x > \frac{I_s \cdot R_{\Sigma} \cdot (1 + X/R)}{1 - REM_{p.u.}}, \quad (1)$$

where

V_x is the saturation voltage,

I_s is the maximum expected fault current (the primary divided by the turns ratio),

R_{Σ} is the total secondary burden, with the internal CT resistance and the neutral lead burden.

X/R is the X/R ratio of the primary system,

$REM_{p.u.}$ is the maximum possible remanence of the CT in p.u.

The condition (1) essentially represents the equation 18 from [2] when the inductive burden can be neglected.

In most cases protective relays are connected to non-air-gapped CTs of IEC P, TPS, TPX class or ANSI C, K class. According to [2], remanent flux as high as 80% of saturation flux can be observed for these CT classes. It should be also noted that once remanent flux is established, it is dissipated very little under service conditions. To reduce the remanence to less than 10% of saturation flux density a voltage of about 60% of the knee-point voltage must be applied [2], which is extremely unlikely under service conditions.

If we assume X/R equal to 20 (quite a common value for transmission systems), then (1) transforms into the following equation:

$$V_x > \frac{I_s \cdot R_{\Sigma} \cdot 21}{1 - 0.8} = 105 \cdot I_s \cdot R_{\Sigma}.$$

It can be seen that taking into account the DC component and the remanence leads to rather high CT requirements. Compared with the simple calculation for a symmetrical AC current and a zero

remanence, the equation (1) defines a margin factor of 105. Moreover, in modern EHV systems the X/R ratio as high as 65 can be observed, which results in a margin factor of 330.

Therefore manufacturers of numerical protection relays have a difficult task in defining CT requirements for their devices. First of all these requirements must guarantee secure and dependant relay operation in all cases. On the other hand the requirements should be reasonably low, otherwise the choice of CT could become impossible or lead to unnecessary expenses. There are different techniques of reducing CT requirements, such as saturation detectors and waveform recovery algorithms [3]. Apart from these “real” techniques, a “virtual” one is used sometimes, namely adjustment of test methods for more favourable results. This situation is aggravated by the fact that there are no documents defining a common approach to CT dimensioning tests for manufacturers. An attempt to develop such a standard was made in report [4], though this document still has a “draft” status.

The Transient Biasing algorithm used in this paper is not a completely new principle. One can recall old electromechanical relays with fast-saturating transformers (FST), where FST saturation by a DC current component led to reduced sensitivity and therefore increased stability during primary CT saturation [5]. Saturating transformers were also employed sometimes in western-made differential relays to achieve a variable restrain characteristic. In this case DC-component shunting was considered an additional advantage [6].

2 CURRENT DIFFERENTIAL PROTECTION WITH TRANSIENT BIAS

2.1 Transient biasing algorithm

The initial idea of transient biasing was for any positive change (delta) of the bias current I_{BIAS} to increase the tripping threshold $I_{DIFF.THR.}$, and this additional biasing had to be accumulating. If, however, the bias current was not increasing, the transient bias value $I_{TR.BIAS}$ had to decay exponentially.

Unfortunately, testing this algorithm with models immediately showed that it had an essential drawback – the tripping time increased for internal faults. The reason is that an internal fault also leads to the positive change of the bias current, and the protection is effectively desensitized by the additional bias.

To avoid slowing the protection down an external fault detector was implemented. This detector is based on the ratio of the differential to the bias current deltas [7].

With this detector the positive delta of the bias current is only used to increase the additional biasing if this delta is caused by an external fault or a sudden surge of the load current.

The transient bias stops increasing during CT saturation because differential current occurs, but some value of $I_{TR.BIAS}$ must be already built up which provides sufficient stability until the next undistorted segment of the current waveform.

For a sample n in the current differential algorithm the following equation is applied given the additional transient bias $I_{TR.BIAS}$:

$$I_{DIFF.THR.}(n) = SLOPE(I_{BIAS}(n)) + I_{TR.BIAS}(n), \quad (2)$$

where

$I_{DIFF.THR.}(n)$ is the threshold of the differential protection,

$SLOPE(I_{BIAS}(n))$ is the bias characteristic with two slopes used in MiCOM P543-P546 relays (Fig. 1).

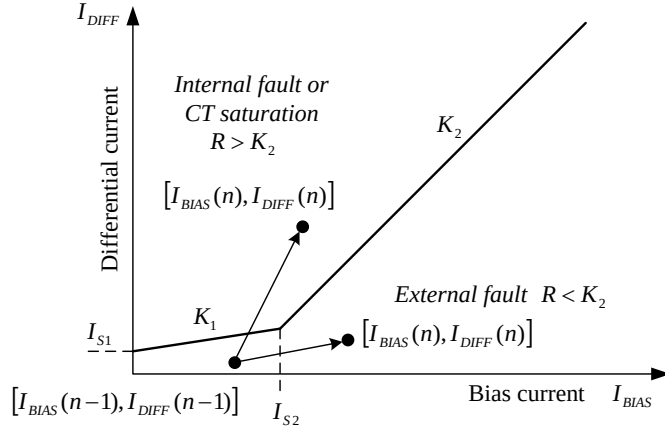


Fig. 1: The bias characteristic and the external fault detection principle.

To get the transient bias $I_{TR,BIAS}$, deltas of differential and bias currents are calculated, and also the ratio of these deltas R :

$$\Delta I_{DIFF}(n) = I_{DIFF}(n) - I_{DIFF}(n-1), \quad (3)$$

$$\Delta I_{BIAS}(n) = I_{BIAS}(n) - I_{BIAS}(n-1), \quad (4)$$

$$R = \Delta I_{DIFF}(n) / \Delta I_{BIAS}(n). \quad (5)$$

The transient bias is then calculated with the following algorithm:

$$\text{If } R < K_i \text{ and } \Delta I_{BIAS}(n) > 0 \quad (6)$$

$$I_{TR,BIAS}(n) = D \cdot I_{TR,BIAS}(n-1) + S \cdot \Delta I_{BIAS}(n), \quad (7)$$

otherwise

$$I_{TR,BIAS}(n) = D \cdot I_{TR,BIAS}(n-1), \quad (8)$$

where

K_i is the slope percentage (K_1 or K_2 depending on where the point $[I_{BIAS}(n), I_{DIFF}(n)]$ falls on the bias characteristic),
 S is the scaling coefficient,
 D is the decay coefficient, $D < 1$.

The differential algorithm in MiCOM P543-546 relays has a sampling frequency of 8 samples per cycle or 400 Hz (providing that the system frequency is 50 Hz).

Therefore after one cycle (20 ms) the transient bias will decay to D^8 of its initial value (if the condition (6) wasn't fulfilled during this time). In this paper the coefficient $D = 0.8$ is adopted, then after 20 ms $D^8 = 0.1678$ or about 17% of initial value. Such a fast decay helps to avoid delaying the trip in the case of a cross-country fault.

2.2 Testing of the transient biasing algorithm with SIMULINK models

While developing and testing the Transient Bias feature, a SIMULINK® model of CT was used extensively. This model is based on the Jiles-Atherton theory of hysteresis and constitutes a replica of a well-known CT implementation in the RTDS® and PSCAD® systems [8]. However, the SIMULINK® model is more flexible in use. External connections of the model can be found in Fig. 2 and the internal circuitry – in Fig. 3.

The CT model employed in the paper has the following parameters: the CT ratio $K_{ct} = 10/1$, the rated secondary current 1A, the knee-point voltage $V_K = 160V$.

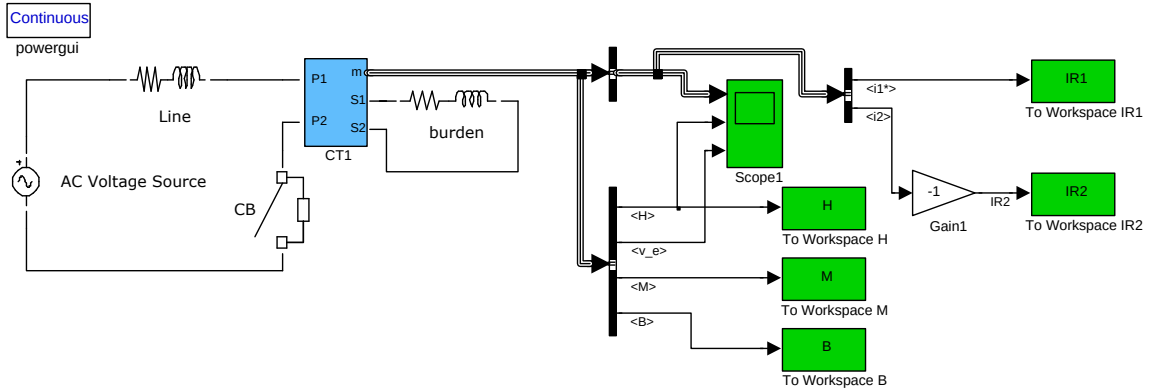


Fig. 2: External connections of the CT model.

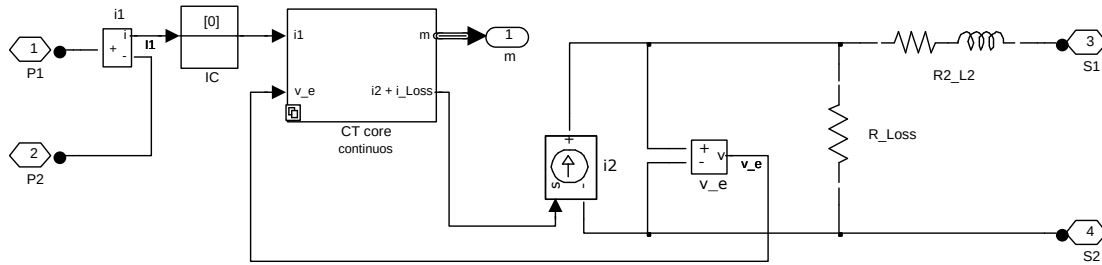


Fig. 3: The internal circuitry of the CT model.

Figure 4 illustrates the CT saturation, the spurious operation of the differential function without the transient bias and the stabilizing effect of the transient bias.

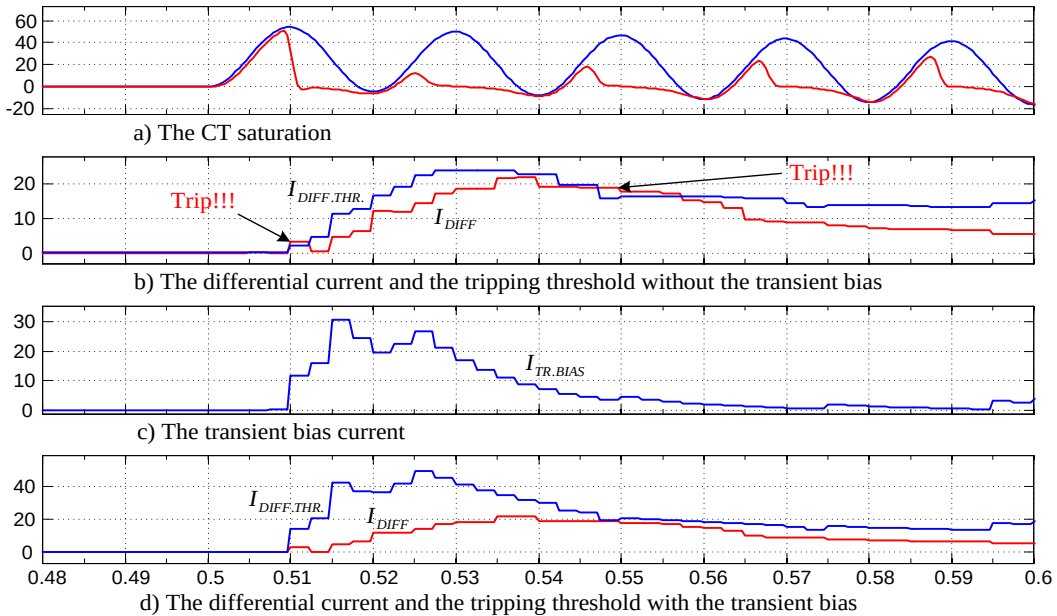


Fig. 4: The stabilizing effect of transient biasing.

The minor difference between the primary current and the relay current (Fig. 4.a) is due to an anti-aliasing filter employed in the relay model.

Once the tests in the Simulink® environment had demonstrated the merits of the transient bias algorithm, this feature was implemented in the software of MiCOM P543-P546 relays.

2.3 Testing relays with RTDS system and determining new CT requirements

The final tests of the differential relays with the transient biasing feature, and the determining of the new CT requirements, were carried out with the RTDS (Real Time Digital Simulation) system. The set-up involved the following:

1. A protected line with settable X/R ratio and fault current (for internal and external faults).
2. Two models of three-phase CT with settable knee-point voltage V_K and burden.
3. Several MiCOM P543-P546 relays connected to the CT models through digital-to-analogue converters and amplifiers.

The stability check for external faults is done by applying multiple faults with a pre-defined fault current and X/R ratio while incrementing the CT burden until one of the relays trips. The burden R_L (one-way) is increased step by step from 0.1 Ohm to 16 Ohms (38 steps in total).

The test stops once one of the relays trips, the RTDS system records a limiting burden R_{lim} equal to the burden one step before the trip occurred.

For internal faults the criteria to stop the test is the denial in operation or the unacceptable tripping time.

It is essential to test the protection with different CT remanence values. To achieve that, the initial remanence is set to zero and every fault is applied six times: three times with a positive DC component (the remanence grows from zero to its positive limit) and three times with a negative DC component (the remanence drops from the positive limit to its negative limit). The process is shown in Fig. 5 and Fig. 6.

To reduce the effect of different random factors every test was repeated three times, or three sets of Current Differential protection were connected in series (six MiCOM P543-P546 relays).

The following Current Differential settings were used (see Fig. 1):

Minimum pick-up level the relay	$I_{S1} = 0.2 \text{ o.e.}$
Knee-point bias current	$I_{S2} = 2 \text{ o.e.}$
First slope	$K_1 = 30\%$
Second slope	$K_2 = 100\% \text{ и } 150\%$

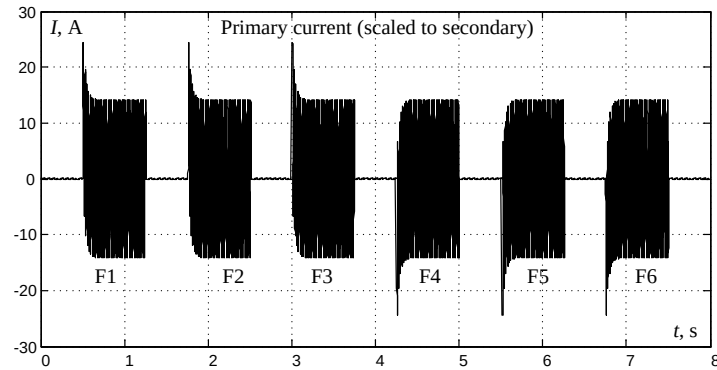


Fig. 5: Six-shot fault sequence.

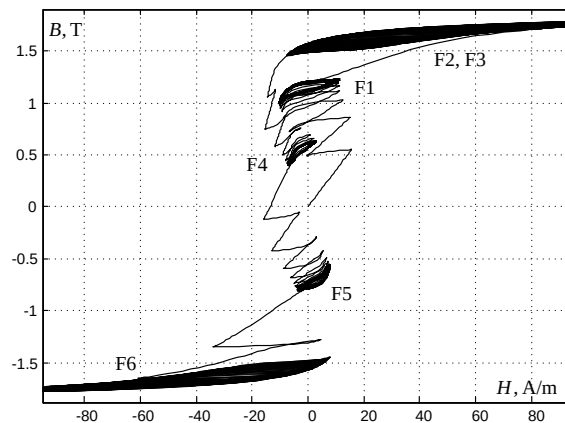


Fig. 6: Trajectory of B - H point movement.

The test results in the paper refer to the setting $K_2 = 150\%$.

After completing all the tests the RTDS system generates an array of limiting CT burdens R_{lim} for external and internal faults with different combinations of the following parameters:

1. Knee-point voltage of the CT V_K : 40-320 V
2. Fault current I_f : 2-50 A secondary
3. X/R ratio of the network: 5-120
4. Fault type: A-N, B-C, A-B-C
5. Point on wave (POW): 0° - 150°

For the second slope setting $K_2 = 150\%$ the number of tests totalled 3967 for external faults and 1915 – for internal, where a single test is the six-shot fault sequence as seen in Fig. 5.

2.4 Processing the results of the RTDS testing

The large amount of data produced by the RTDS system is processed in the MATLAB environment.

It should be noted that the limiting burden for internal faults is much higher than for external ones owing to the external fault detector and the fact that the transient biasing does not slow the relay down during internal faults.

A coefficient K is calculated from the limiting burden R_{lim} . This coefficient can be used as a dimensioning factor for an arbitrary CT.

$$K = \frac{V_K}{I_n \cdot (2 \cdot R_{lim} + 0.5)}, \quad (9)$$

where

V_K is the knee-point voltage of the CT used in the RTDS test,

I_n is the rated secondary current of the CT used in the RTDS test (1A),

$(2 \cdot R_{lim} + 0.5)$ - the total CT burden including both forward and return leads and the internal CT resistance (fixed at 0.5 Ohms).

In real applications the maximum fault current I_f and X/R ratio of the network are defined by calculation, while the fault type and POW are arbitrary factors for any fault. Therefore the highest K value for different fault types and POW (the worst case) must be chosen for each combination of the fault current and X/R ratio. The result of this procedure was a matrix of 56 values of K for every tested $[I_f, X/R]$ combination.

After applying a two-dimensional fitting procedure (from the MATLAB Optimization Toolbox) the following equation was derived (with 10% safety margin):

$$K = 1.1 \cdot A(I_f) \cdot B(X/R), \quad (10)$$

where $A(I_f)$ and $B(X/R)$ are defined by plots in Fig. 7 and Fig. 8.

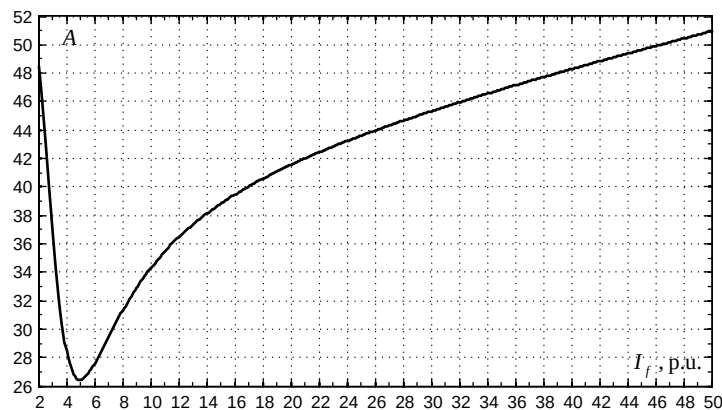


Fig. 7: Coefficient A plot.

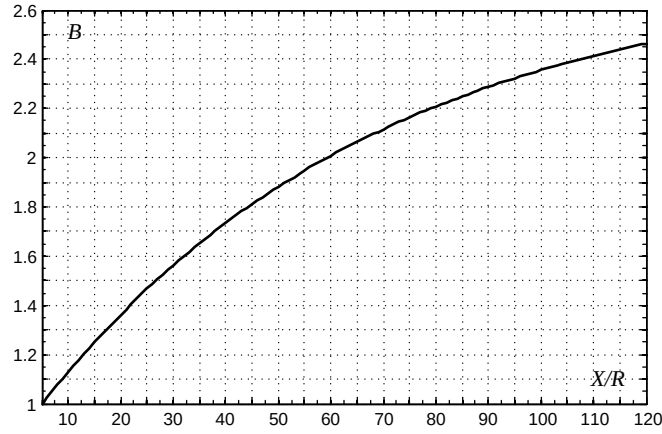


Fig. 8: Coefficient B plot.

An interesting phenomenon can be seen on Fig. 7 where relatively low fault current (< 5 p.u.) requires rather high A coefficient. This effect can be explained by the high sensitivity of the protection in the low fault current region. In practice this should not lead to CT over-dimensioning because low fault currents are typically accompanied by low X/R ratios.

The final equation for dimensioning an arbitrary CT with the knee-point voltage V_K is:

$$V_K \geq K \cdot I_n \cdot R_\Sigma. \quad (11)$$

CT dimensioning example:

The maximum fault current $I_f = 30$ kA, $X/R = 25$, $K_{CT} = 3000/5$, the total burden $R_\Sigma = 3$ Ohms. From plots on Fig. 7 and Fig. 8 the coefficients are $A = 34.5$, $B = 1.44$. Therefore the minimum allowed knee-point voltage is $1.1 \cdot 34.5 \cdot 1.44 \cdot 5 \cdot 3 = 820$ V

$$V_K \geq 820 \text{ V}.$$

2.5 Comparison with existing CT requirements

The existing CT requirements for MiCOM P543-546 relays are defined by the following equations:

If $(I_f \cdot X/R) \leq 1000$:

$$K = \max(65, 40 + 0.07 \cdot (I_f \cdot X/R)),$$

If $1000 < (I_f \cdot X/R) \leq 1600$:

$$K = 107.$$

The Table 1 shows the comparison between existing and new CT requirements for several combinations of the fault current and X/R ratio.

I_f , p.u.	X/R	K without transient bias	K with transient bias	Effect %
5	5	65	29	-55%
10	10	65	43	-34%
20	20	68	63	-7%
30	30	103	78	-24%
40	40	107	92	-14%
40	65	---	110	---

Table 1: Comparison between existing and new CT requirements for MiCOM P543-P546 relays.

3 CONCLUSION

The transient biasing algorithm is proposed in the paper which significantly increases the stability of Current Differential protection during external faults. The algorithm is first tested with CT and relay models in the MATLAB/SIMULINK® environment and then with the RTDS® system.

The paper also describes in detail a testing technique used by ALSTOM Grid to define CT requirements of Current Differential protection. The results of the CT requirements tests and benefits of using the Transient Bias feature are shown as well.

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