A Comparative Study for Current Transformer Dimensioning in Overcurrent Relay

A. H. Abu Bakar*, Non-member
S. M. Zali*, Non-member
Chia Kwang Tan*, Non-member
H. A. Illias**, Non-member
H. Mokhlis**, Non-member

Dimensioning a current transformer (CT) is one of the most important tasks during the substation planning process. The installation of a correctly specified CT will ensure the integrity of the protection scheme. However, some parameters required for dimensioning a CT can be obtained only after the CT is installed in the substation. Because of the conflicting requirements, utility companies commonly adopt a simplified approach in compensating for the missing parameters. Two other methods for dimensioning CT under the given constraint during the planning stage have also been proposed by several authors. In view of the availability of the three methods of approximating CT specifications, this paper will conduct a comparative study to evaluate their accuracies. The approximated specifications of the CT during the planning stage are compared against those measured from a practical substation. Based on the findings from the comparative studies, the most reliable approach for CT dimensioning during the planning stage is proposed. © 2016 Institute of Electrical Engineers of Japan. Published by John Wiley & Sons, Inc.

Keywords: current transformer, saturation factor, secondary time constant, knee point voltage

Received 4 August 2015; Revised 4 November 2015

1. Introduction

The design of medium- and high-voltage electrical networks is a complex process. A multitude of factors need to be taken into account such as the safety of personnel and equipment, continuity of supply, and costs of installation and operation. In the design of a protection system, several factors are of paramount importance, which include the selection of the correct earthing system, definition of the busway, calculation of fault current, and protection system definition. The scope of the protection system definition includes requirements of the protection scheme, choice of protection types, and the coordination and discrimination of protective relays. This paper will concentrate specifically on the design of the protection system, in particular current transformer (CT) dimensioning. In general, the protection plan must identify and verify both the operating and nonoperating conditions for all protection devices during both faulty and normal operation scenarios. However, given the complexity during the design stage, some factors are simplified or even ignored by the protection design engineers. The consequences of this include an over-rated or a noncompliant CT being installed, which leads to higher costs, unnecessary outages, or even severe consequences of personnel injuries and equipment damages.

In dimensioning a CT, it is important to determine the optimum value of the knee point voltage \( V_K \). Beyond this point, the CT will saturate and jeopardize the protection scheme. The three factors that influence \( V_K \) are the short-circuit factor \( K_{SSC} \), the remanence flux factor \( K_R \), and the saturation factor \( K_S \) [1]. In calculating the CT saturation factor \( K_S \), four parameters are required: the primary time constant \( T_P \), the secondary time constant \( T_S \), the time to saturation \( t \), and system angular frequency \( \omega \) [2–5].

Obtaining an accurate value for \( K_S \) is particularly important, as this will influence the value of knee point voltage \( V_K \).

The value for \( T_P \) depends on the system \( X/R \) ratio, whereas \( t \) is dependent on the protection relay operating time. All three values, i.e., \( T_P \), \( t \), and \( \omega \) can be approximated with a reasonably high accuracy. However, the value for \( T_S \) is difficult to obtain, as it varies from site to site [6]. This is because \( T_S \) depends on the site \( X/R \) from CT to relay circuitry. In fact, the accurate value for \( T_S \) can be obtained only through site measurements after the CT is installed. For the above reasons, in practice, \( T_S \) and \( K_S \) can only be approximated during the planning stage. The approximated \( T_S \) and \( K_S \) will eventually determine the specifications of the CT to be procured. However, very commonly the CT is found to be over- or underspecified after it is installed at the site. Corrective actions would then incur more time and cost in completing the project, and generally lead to delays. This issue has received particular attention in recent years due to the constant emphasis on cost-conscious decisions. There have also been reports that a number of wrongly specified CTs have caused maloperation of the relay. Most of these incidents have been traced to the incorrectly approximated \( T_S \) being used during the planning stage.

In view of the difficulties in obtaining an accurate value for \( T_S \) during the planning stage, various authors have proposed an estimated value for \( T_S \). Gangadharan et al. proposed the value for \( T_S = 3.0 \) s [1]. The value of 3.0 s was also suggested by Holst and Palki [7]. This value is said to be a good estimate for high-remanence CTs, as \( T_S \) is often a few or several seconds and the influence on \( K_S \) is relatively small and almost negligible during the first 100 ms [7]. However, there was no explanation as to why \( T_S \) was set to 3.0 s. Theoretically, \( T_S \) is in the order of few seconds.
For a TPX class CT, $T_S$ is 5.0 s or more, whereas for a TYP class CT, $T_S$ is between 0 and 10.0 s. For a TPZ class CT, the CT has a linear core with a secondary time constant of 60 ± 6 ms for 50 Hz and 50 ± 5 ms for 60 Hz applications [8].

In contrast, instead of suggesting a constant estimate for $T_S$, two simplified equations for the saturation factor $K_S$ had been proposed by several authors [9,10]. The common objective in both simplified equations is to eliminate $T_S$ from the equation of saturation factor $K_S$, based on certain assumptions.

Given that the accuracy of the various methods for approximating CT dimensioning is unknown until the CT is installed at site, the objective of this paper is to evaluate the accuracy for each of the proposed method. A comparative study will be performed for each of the proposed method with the data measured from a substation in Malaysia serving as the benchmark.

This paper is arranged such that the mathematical model for knee point voltage and its saturation factor are first presented. The three methods of approximating $K_S$ are also presented. The next section will present the Computer Aided Protection Engineering (CAPE) simulation that is practiced by the engineers to obtain the $X/R$ ratio and the primary time constant $T_P$ required in the mathematical model. Next, the results obtained from CAPE simulation is used to identify the three approximated saturation factors $K_S$. The following section will then present the data measured from a site in Malaysia. The subsequent section will then present a comparison between the data measured from the site and all three methods for estimating the saturation factor $K_S$. The findings of this comparative study are then discussed. The final section concludes the findings and results of this comparative study.

2. Mathematical Model

The knee point voltage $V_K$ is the most important parameter in dimensioning a CT. The mathematical model for $V_K$ is expressed in (1) [9]:

$$V_K = K_0.K_S.K_0.I_2.R_2$$  \hspace{1cm} (1)

where $V_K$ is the knee point voltage, $K_0$ s the effects of the offset present during faults,$K_S$ is the CT saturation factor, $K_0$ is the remanence flux factor, $I_2$ is the symmetrical fault current represented in the secondary (A), and $R_2$ is the total secondary resistance burden.

The value of $K_0$ depends on the faults inception angle; it has the maximum value at 0° angle and the minimum value at 90°. For fully offset fault currents, $K_0$ is equal to 1.0.

To obtain an accurate value for knee point voltage $V_K$, the saturation factor $K_S$ needs to be accurately determined. The mathematical model for $K_S$ is given by [9]

$$K_S = 1 + \left[ \frac{\omega.T_P.T_S}{T_S - T_P} \right]$$  \hspace{1cm} (2)

where $T_P$ is the primary system time constant, $T_S$ is the CT secondary time constant, $t$ is the time to saturate the CT, and $\omega$ is the angular frequency.

With the above mathematical model, the engineer is required to identify the CT specifications for procurement and installation at site. The time to saturation $t$ is the protection relay operating time and can only be obtained after a fault has taken place. Because of its unavailability, manufacturers have suggested the time to saturation $t$ as 30 ms. The value for the primary system time constant $T_P$ can be obtained through short-circuit simulation, while the angular frequency $\omega$ is computed as $2\pi f$ (frequency in hertz). However, protection engineers commonly face difficulties in obtaining the value for secondary time constant $T_S$ during the planning stage. Theoretically, $T_S$ is determined by the CT magnetizing inductance $L_m$ and the sum of resistances in the secondary circuit [6]. In effect, an accurate value for $T_S$ can only be obtained through site measurements after the CT is installed. Given that the CT specifications have to be identified for procurement, $T_S$ and $K_S$ can only be approximated during the planning stage. Any wrongly approximated $K_S$ will lead to incorrect CT being procured and installed. The utility risks longer project delivery time and higher cost if the wrongly specified CT were to be detected and replaced. The consequences would be far catastrophic if the wrongly specified CT is not detected. The consequences may include compromised protection scheme, power outages, personnel injuries, and equipment damage.

In view of the difficulties in obtaining $T_S$ during the planning stage and the risks of installing a wrongly specified CT, several authors have proposed a substitute for $T_S$. Three methods for approximating CT dimensioning have been proposed. The authors in Ref. [10] had proposed $K_S$ as follows:

$$K_S = 1 + \left[ \frac{X}{R} \right]$$  \hspace{1cm} (3)

In this method, a short-circuit simulation is required to be conducted to obtain the system’s $X/R$ ratio in order to compute the saturation factor $K_S$. Due to its simplicity, (3) is widely preferred by utility companies.

In contrast, the authors in Refs [1,7] had proposed to approximate $T_S$ as 3 s:

$$T_S = 3 \text{ s}$$  \hspace{1cm} (4)

Subsequently, the above $T_S$ and other parameters such as $T_P$, $t$, and $\omega$ can then be substituted into (2) to obtain $K_S$. In addition, several authors also proposed to simplify the saturation factor $K_S$ by eliminating $T_S$ from (2). The authors in Ref. [9] proposed to assume that the secondary time constant is much greater than the primary time constant ($T_S \gg T_P$) for the mathematical model in (2). As such, (2) will be simplified as

$$K_S = 1 + \omega.T_P \left[ 1 - e^{\frac{t}{T_P}} \right]$$  \hspace{1cm} (5)

In this method, the protection engineer has values for all the parameters in (5) except the value for $T_P$. Therefore, the next sections of this paper will present the methodology to obtain the $X/R$ ratio and consequently the primary time constant $T_P$ through short-circuit analysis.

3. Short-Circuit Analysis Using CAPE Software

A short-circuit analysis is conducted in this section to first obtain the $X/R$ ratio, which will then be used to determine the primary time constant $T_P$ that is required in calculating the saturation factor $K_S$. In this study, a short-circuit simulation was carried out by using the CAPE simulation software to obtain the $X/R$ ratio.

A 132/33 kV substation in Malaysia was chosen for this study. The substation is modeled as shown in Fig. 1. The application of the maximum symmetrical fault current is required to obtain the $X/R$ ratio. As such, a three-phase fault is simulated in CAPE with one transformer in service. The results of the simulation are shown in Table I. The simulation indicated that the fault current is 10 957 A and the $X/R$ ratio is 18.378.

Subsequently, the value of primary time constant $T_P$ was calculated using (6) as follows [10]:

$$T_P = \frac{L}{R}$$  \hspace{1cm} (6)

where

$$\frac{X}{R} = \frac{2\pi f L}{R}$$  \hspace{1cm} (7)

$$\therefore T_P = \frac{1}{2\pi f} \times \frac{X}{R} = \frac{1}{2\pi f} \times 18.378 = 0.0585 s$$

S44

IEEJ Trans 11(S1): S43–S48 (2016)
Table I. Data from CAPE simulation software

<table>
<thead>
<tr>
<th>$X/R$ ratio</th>
<th>$I_1$ (Amps)</th>
<th>$f$ (Hz)</th>
<th>$T_p$ (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.378</td>
<td>10 957</td>
<td>50</td>
<td>58.5</td>
</tr>
</tbody>
</table>

Therefore $T_p = 58.5$ ms has been computed from the $X/R$ ratio obtained from CAPE simulation software, as shown in Table I. In this study, the single line-to-earth fault was not simulated because the fault current value is too small to cause saturation of the CT. This is due to the neutral earthing resistor (NER).

4. Approximating Saturation Factor $K_S$ for CT Dimensioning

In this section, the parameters $X/R$, $T_p$, $t$, and $\omega$ will be identified and then be substituted into the three simplified mathematical models for approximating the saturation factor $K_S$.

The $X/R$ ratio and its resultant $T_p$ have been identified from the previous section as 18.378 and 58.5 ms, respectively. The angular frequency $\omega$ is computed as follows:

$$\omega = 2 \times \pi \times f = 2 \times \pi \times 50 \text{ Hz} = 314.2 \text{ rad/s}$$

Besides that, the time to saturation, $t$, is specified by the manufacturer as 30 ms. These parameters will now be substituted into the three simplified mathematical models for approximating the saturation factor $K_S$.

4.1. Method 1 In Method 1, the authors in Ref. [10] had proposed that $K_S = 1 + X/R$. The resultant computation is as follows:

$$K_S = 1 + \frac{X}{R} = 1 + 18.378 = 19.378$$

4.2. Method 2 In the second method, the authors in Refs [1,7] had proposed to substitute $T_S = 3$ s into (2). The resultant saturation factor $K_S$ is

$$K_S = 1 + \left[ e^{\frac{t}{T_p}} - e^{\frac{T_S}{T_p}} \right] \frac{\omega.T_p . T_S}{T_S - T_p}$$

$$= 1 + \left[ e^{-0.03} - e^{-0.0585} \right] \frac{314.2 \times 0.0585 \times 3}{3 - 0.0585} = 8.3334 \quad (8)$$

4.3. Method 3 In the third method, the authors in Ref. [9] had assumed that $T_S$ is much greater than $T_p$. This led to the following simplified mathematical computations for $K_S$:

$$K_S = 1 + \omega T_p \left[ 1 - e^{-\frac{t}{T_p}} \right] = 1 + 314.2 \times 0.0585 \left[ 1 - e^{-0.03} \right] = 8.3733$$
It can be observed that there is a vast difference in the results obtained in Method 1 when compared to Methods 2 and 3. The results obtained from Methods 2 and 3 are consistent. The next section will present the practical $K_S$ value measured at the 132/33 kV substation for comparison.

5. Site Measurement

The CT analyser test set from Omicron was used to measure the CT’s parameters at the 132/33 kV substation in Malaysia. The equivalent circuit for the CT and the connections of the CT analyser are shown in Fig. 2.

Three types of CTs were evaluated during the site measurements. The three CTs were of Class 5P20 for overcurrent earth fault (OC EF) protection with 600:1, 1600:1, and 2000:1 ratio, respectively. The excitation test of the CT generated results for the knee point voltage ($V_{K}$), secondary time constant ($T_S$), and remanence flux factor ($K_R$). In contrast, the resistance test generated the maximum secondary resistance burden ($R_s$), which was comprised of CT secondary wire loop resistance, lead resistance, and load resistance. The results from the site testing for the CTs with 600:1, 1600:1 and 2000:1 ratios are shown in Tables II–IV, respectively.

In the tables, $I_p$ is the primary current, $I_{CT}$ is the current over the secondary terminals, $I_{main}$ is the main inductance, $L_p$ is the leakage inductance of the primary winding, $L_s$ is the leakage inductance of the secondary windings, $N_p$, $N_s$ are the windings of the ideal transformer, $R_{CT}$ is the resistance of the secondary winding, $R_{Eddy}$ is the eddy current resistance, $R_H$ is the hysteresis resistance, $R_p$ is the resistance of the primary winding, $U_C$ is the voltage at the main inductance ($I_{main}$), $V_C$ is the rms value of the voltage at the main inductance, $U_{CT}$ is the voltage at the secondary terminals, and $Z_b$ is the external impedance at the rated frequency.

The measured secondary time constant $T_S$ from Tables II–IV, together with the primary time constant $T_p$ of 58.5 ms from CAPE and time to saturation $t$ of 30 ms from the manufacturers’ suggestion are then substituted into (2) to obtain the measured $K_S$ for each phase of both CTs, as shown in Table IV.

<table>
<thead>
<tr>
<th>Tested CTs</th>
<th>From site testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT ratio</td>
<td>$V_K$ (V)</td>
</tr>
<tr>
<td>600:1 Red</td>
<td>645.106</td>
</tr>
<tr>
<td>600:1 Yellow</td>
<td>643.806</td>
</tr>
<tr>
<td>600:1 Blue</td>
<td>641.056</td>
</tr>
</tbody>
</table>

6. Comparison Between Measured and Approximated $K_S$ Values

A comparison between the measured and approximated $K_S$ value is presented in this section. There are three values of approximated $K_S$ representing the three methods for estimating $K_S$, as presented in Section 4. These approximated values of $K_S$ are compared with the measured $K_S$ obtained by substituting the site-measured $T_S$ into (2). The result of the comparison is shown in Table V. Based on (1), it must be noted that the remanence ($K_R$) does not affect the saturation factor ($K_S$).

It can be observed that the commonly used method of approximating $K_S$ in Method 1 gives results with very high errors. The approximated $K_S$ exceeded the actual value by more than 100% for all three types of CTs and for all the three phases. In other words, the identified CT based on Method 1 will be over-dimensional. This commonly leads to problems in sourcing the CT within the given space constraint as well as incurring huge increase in project costs.

In contrast, the other two methods (Method 2 and Method 3) for approximating $K_S$ delivered results with high accuracies where the error is less than 1%. The installed CT specifications based on Method 2 and Method 3 will be very close to the original engineering design requirements. However, despite the high accuracies, the differences between Method 2 and Method 3 must be further examined. It can be observed from Table V that all the approximated $K_S$ from Method 2 are consistently lower than the measured $K_S$, while the approximated $K_S$ from Method 3 are consistently higher. In other words, a slightly underdimensioned...
CT is proposed by Method 2, while a slightly overdimensioned CT is proposed by Method 3. It has been pointed out that an underdimensioned CT will compromise the protection scheme and lead to severe consequences such as personnel injuries and equipment damage. In contrast, an overdimensioned CT will increase the project cost. Given the consequences, an overdimensioned CT will be a better option than an underdimensioned CT. Consequently, the $K_S$ proposed by Method 3 has been proven to be the preferred choice compared to Method 2. As a result, it is recommended that utility engineers adopt Method 3 for approximating $K_S$ in CT dimensioning.

The findings from this comparative study will ensure that a correct and reliable CT is procured and installed in the substation. This will save considerable cost and rectification time for the substation commissioning project. Besides, the risk of personnel injuries and equipment damage due to the wrongly specified CT will also be greatly reduced.

7. Conclusion

In this paper, we conducted a comparative study of the three methods for approximating the saturation factor $K_S$ during the planning stage. The approximated $K_S$ were compared against the $K_S$ measured from an actual substation. It was shown that the currently practised method for approximating $K_S$ leads to highly overdimensioned CT and will incur a much higher project costs. In contrast, the other two methods of approximating $K_S$ delivered results with very high accuracies. However, a closer examination for both methods of approximation gave vital information that will significantly impact the substation operation, particularly the protection scheme. It was concluded that approximating $K_S$ using the method proposed by General Electric [9] delivered the most reliable results and is the recommended for use during the planning stage.

Acknowledgments

The authors would like to thank the Ministry of Science, Technology and Innovation, Malaysia (eScience Fund: SP012-2014), and the Centre of Research Grant Management, University of Malaya (UMRG fund: RG299-14AFR), for providing financial support in the form of research grants for this project.

References


A.H.A. Bakar (Non-member) received the B.Sc. degree in electrical engineering from the University of Southampton, UK, in 1976 and the M.Eng. and Ph.D. degrees from the University of Technology, Malaysia, in 1996 and 2003, respectively. He has 30 years of utility experience in Malaysia before joining academia. Currently he is an Expert Consultant with the UMPEDAC, University of Malaya, Malaysia.

S. M. Zali (Non-member) received the B.Eng. degree in electrical and electronics engineering from the PETRONAS University of Technology, Malaysia, in 2009 and the M.Eng. degree in electrical engineering from the University of Malaya (UM), Malaysia, in 2014. She is currently pursuing the Ph.D. degree in electrical engineering at UM.

Chia Kwang Tan (Non-member) received the Ph.D. degree in electrical engineering from Universiti Tenaga Nasional, Malaysia, in 2013. He worked as a Researcher with TNB Research Sdn Bhd, the research arm of Malaysian Utility Company (TNB) for more than 2 years. He is currently a Senior Lecturer in the UM Power Energy Dedicated Advanced Centre (UMPEDAC), University of Malaya.

Table V. Comparison between measured and approximated $K_S$

<table>
<thead>
<tr>
<th>CT ratio</th>
<th>Phase</th>
<th>Measured $K_S$</th>
<th>Method 1 % difference</th>
<th>Method 2 % difference</th>
<th>Method 3 % difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>600:1</td>
<td>Red</td>
<td>8.3506</td>
<td>19.378</td>
<td>132.06</td>
<td>8.3334</td>
</tr>
<tr>
<td></td>
<td>Yellow</td>
<td>8.3507</td>
<td>19.378</td>
<td>132.05</td>
<td>8.3334</td>
</tr>
<tr>
<td></td>
<td>Blue</td>
<td>8.3499</td>
<td>19.378</td>
<td>132.07</td>
<td>8.3334</td>
</tr>
<tr>
<td>1600:1</td>
<td>Red</td>
<td>8.3622</td>
<td>19.378</td>
<td>131.73</td>
<td>8.3334</td>
</tr>
<tr>
<td></td>
<td>Yellow</td>
<td>8.3621</td>
<td>19.378</td>
<td>131.74</td>
<td>8.3334</td>
</tr>
<tr>
<td></td>
<td>Blue</td>
<td>8.3626</td>
<td>19.378</td>
<td>131.72</td>
<td>8.3334</td>
</tr>
<tr>
<td>2000:1</td>
<td>Red</td>
<td>8.3645</td>
<td>19.378</td>
<td>131.67</td>
<td>8.3334</td>
</tr>
<tr>
<td></td>
<td>Yellow</td>
<td>8.3647</td>
<td>19.378</td>
<td>131.66</td>
<td>8.3334</td>
</tr>
<tr>
<td></td>
<td>Blue</td>
<td>8.3646</td>
<td>19.378</td>
<td>131.67</td>
<td>8.3334</td>
</tr>
</tbody>
</table>
H. A. Illias (Non-member) received the B.Eng. degree in electrical engineering from the University of Malaya (UM), Malaysia, in 2006 and the Ph.D. degree in electrical engineering from the University of Southampton, UK, in 2011. He is currently a Senior Lecturer with UM. His main research interests include modeling and measurement of partial discharge phenomena in solid dielectric insulation and condition monitoring.

H. Mokhlis (Non-member) received the B.Eng. and M.Eng.Sc. degrees in electrical engineering from the University of Malaya (UM), Malaysia, in 1999 and 2002, respectively, and the Ph.D. degree in electrical engineering from the University of Manchester, UK, in 2009. He is currently an Associate Professor with the Department of Electrical Engineering, UM. His research interests include distribution automation and renewable energy.