CURRENT TRANSFORMER CONCEPTS

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ABSTRACT

This paper reviews the C and K bushing relay accuracy ratings for current transformers (cts) and their implications in relay application. The paper relates the concept of knee-point and the 10 ampere excitation voltage of a conventional excitation curve to the actual secondary waveforms produced at and above the ANSI voltage rating. The paper uses the volt-time area concept to introduce ct saturation and the voltage rating using an idealized B-H curve. Computer simulation using the actual shape of the B-H curve is then introduced and used to analyze specific ct applications in transformer and generator differential relays.

INTRODUCTION

A ct appears to be the simplest of electrical devices. For example, the bushing type ct is simply a winding on an insulated core which becomes a transformer only when placed over the primary conductor. The opening paragraph of Moreton's classic paper [1] states that the art of calculating current transformer characteristics from excitation curve data has been known for some time. Moreton wrote this paper in 1943 and referred to papers written two years earlier. Today, nearly 50 years later, there is still a vital interest in this seemingly simplest of electrical devices. For example, the IEEE/PES Instrument Transformer Subcommittee is voting on a revision of C57.13 (Project No. P546/D7a), which includes a K rating in addition to the C and T rating, and the Power System Relay Committee (PSRC) Working Group F7 is completing a publication titled: "Guide for the Application of Current Transformers for Relaying" (PC37.110/D9). PSRC Working Group F5 is also completing a paper dealing with the problems of applying low ratio cts and the adverse effect of saturation on relay performance due to extremely high fault currents. At the same time Electric Power Research Institute (EPRI) is funding a project to study models used to determine ct transient performance for relay testing using the Electromagnetics Transient Program (EMTP) [2].

Standard ratings and application guides deal with the steady-state sine wave behavior of a ct. The dilemma is that, despite the use of recommended rules applied to avoid it, transient saturation always occurs in certain critical relay applications. Consequently, the relay engineer needs an understanding of the non-linear characteristics of cts, ct accuracy ratings, and the transient behavior of cts. The purpose of this paper is to review ct concepts that provide these fundamentals.

CT EQUIVALENT CIRCUITS

A current transformer can be modeled as a constant current source where ratio current is injected into a magnetizing impedance in parallel with the burdens shown in Figure 1. Using a reactance to represent the magnetizing leg of a ct, as shown in Figure 1, is a useful visual concept. However, magnetization is a non-linear phenomenon, and different values of reactance must be used for each level of excitation. For example, the three B-H diagrams, shown in Figure 1, as flux ϕ versus magnetizing current I_M, represent low, medium and high levels of excitation.

At low excitation, the slope $d\phi/dI$ representing the inductance is low. This low slope indicates a disproportionate amount of magnetizing current compared to the burden current at low excitation. At medium excitation, the $d\phi/dI$ is relatively high and the magnetizing current is small compared to the current in the burden. At high excitation, the B-H curve exhibits the maximum slope in transition between saturated states. The fact that magnetizing current is so small compared to the ratio current during the transition suggests that it can be ignored. Consequently the core can be viewed simply as a volt-time switch as shown in Figure 1 which opens during a rate of flux change and closes during saturation.

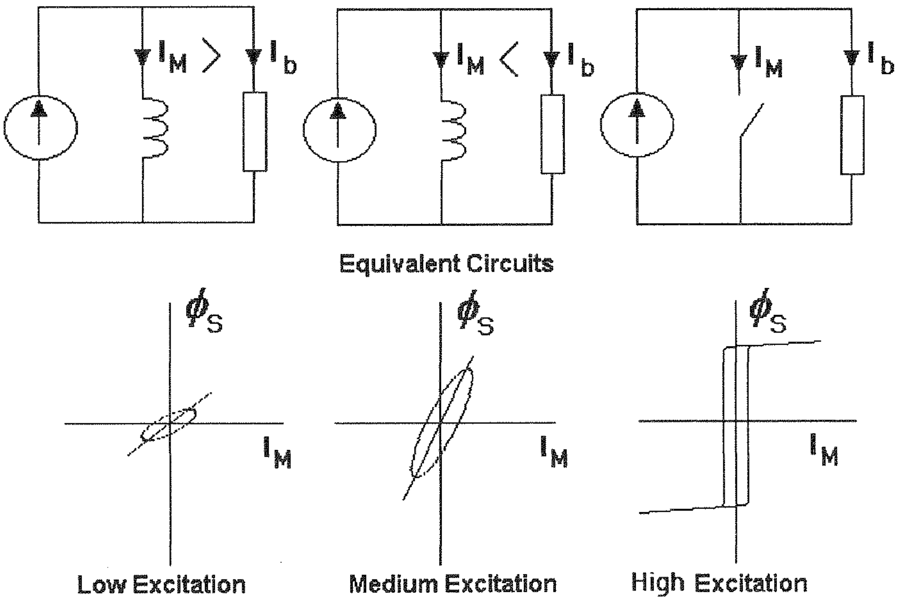

Figure 1: Ct equivalent circuits at various levels of excitation

VOLT-TIME AREA CONCEPT AND SATURATION WAVEFORMS

Relaying accuracy ratings are designated by a secondary terminal voltage rating. The concept of the voltage rating can be derived from the fundamental relation:

$$e = N\frac{d\phi}{dt} \tag{1}$$

Where e is a voltage induced by N turns and a rate of change of flux ϕ with respect to time t. Where the flux is limited to the transition from the saturation flux ϕ_S to $-\phi_S$ and $e = V \sin\theta$, then equation (1) gives:

$$2\phi_S N = \int e \, dt = V\int_0^{\theta_1} \sin(\theta) d\theta \tag{2}$$

Equation (2) shows that the area under the secondary voltage sine wave is limited by the saturation flux $2\phi_S$ and the number of turns N. The voltage rating of the ct is the rms value of the sine wave where the flux-limited volt-time area just fits under the half cycle of the sine wave. Furthermore, if the current is increased beyond this point, saturation occurs and the sine wave is cutoff at an angle less than 180°. The process of saturation can be shown by expressing the instantaneous value e as a function of the volt-time area. To do this, let $V_S = 2\phi_S N$. Making this substitution and integrating equation (2) gives:

$$1 - \left(\frac{V_S}{V}\right) = \cos\theta_1 \tag{3}$$

Expressing $\cos\theta_1$ in terms of $\sin\theta_1$ and noting that $\sin\theta_1 = (e / V)$ gives:

$$\left(\frac{V_S}{V}\right)^2 - 2\left(\frac{V_S}{V}\right) + 1 = 1 - \left(\frac{e}{V}\right)^2 \tag{4}$$

Solving (4) for the instantaneous voltage e during saturation gives:

$$e = \sqrt{2V_S\left(V - \frac{V_S}{2}\right)} \tag{5}$$

Equation 5 can be expressed in multiples of a ct rated current by letting $V = MV_1$ and $V_S = M_S V_1$ where V_1 is the peak secondary voltage when rated current is applied to the transformer. With these substitutions, equation (5) becomes:

$$\frac{e}{V_1} = N = \sqrt{2M_S\left(M - \frac{M_S}{2}\right)} \tag{6}$$

Equation (6) is plotted in Figure 2 along with the resulting voltage waveforms at various multiples of rated current. As shown in Figure 2 , an input of $(M_S / 2)$ produces a sine wave output with a volt-time area equal to that of the transformer core. When the input is M_S, the output exists for 90° of the sine wave and the last linear peak occurs. When the input exceeds M_S, the volt-time area occurs in less than 90° and the peak output follows the parabola described by equation (6).

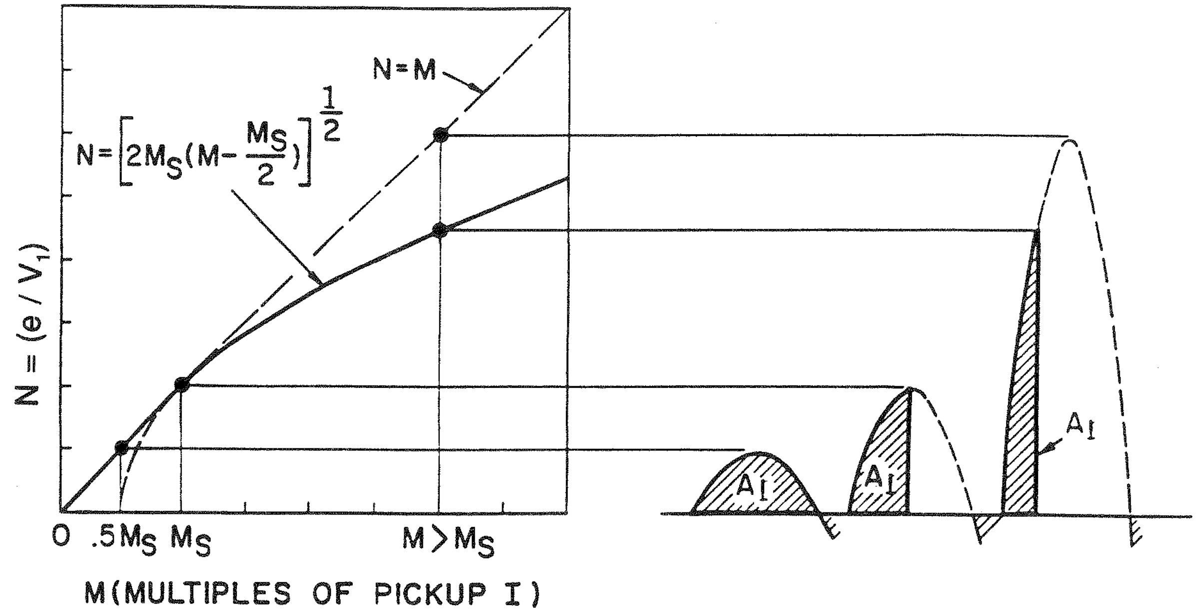

Figure 2: Ct secondary current waveforms for various levels of excitation using a resistive burden

The volt-time area concept gives a clear illustration of the voltage rating and the limit of sine wave operation of a ct. It also provides an uncluttered view of the saturation process and the waveforms produced. The simple BASIC PC program listed in Appendix A implements the volt-time concept for demonstration purposes. Figure 3 shows a program output plot for a ct which has a 20-per unit rating but is subjected to a 10-per unit current with a dc component from a 0.009 second time constant (75° impedance) primary circuit. The plot shows the saturation during the dc offset.

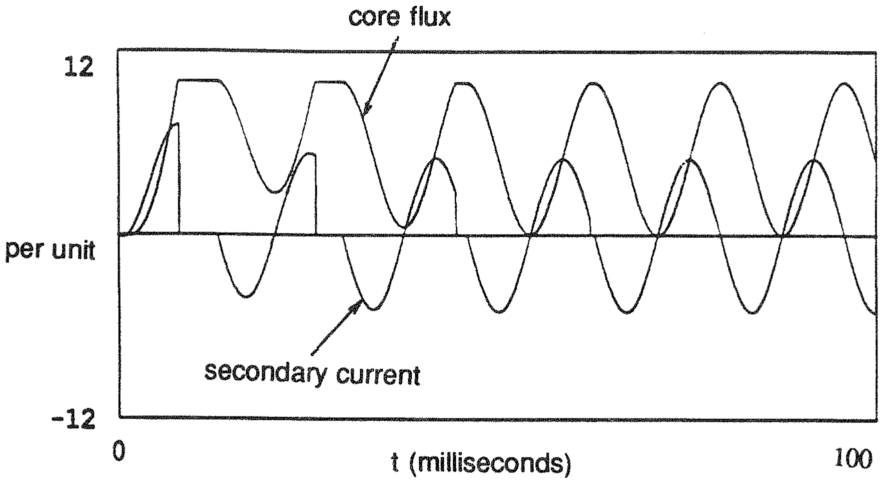

Figure 3: Core flux and secondary current in a ct with a 20 per unit symmetrical rating carrying 10 per unit current with the offset due to 0.009 second primary time constant (75° impedance angle)

The Excitation Curve

The volt-time concept assumes the magnetic core is a volt-time switch. This concept assumes no magnetizing current when there is rate of change of flux and all the ratio current flows to the burden. When saturation flux is reached, as indicated by volt-time area, and there is no longer a change of flux, the switch closes shunting all the ratio current away from the burden until a reversal of current and integration becomes negative to reduce the flux. Here saturation occurs at a well defined point indicated by a specific value flux and turns.

However, finite ampere-turns are required to establish flux in the core, which can be expressed as magnetizing current measured at the secondary terminals. The excitation current, which is subtracted from the ratio current, has definite values for each voltage as shown by the excitation curve in Figure 4. This figure depicts steady-state voltage versus excitation current where voltage is measured with an average reading voltmeter calibrated in rms. It is actually a plot of flux versus magnetizing current since the average voltage is the volt-time integral averaged over the period of the sine wave.

The excitation curve shown in Figure 4 represents a C400, 2000:5 multi-ratio bushing ct and is a measure of ct performance that can be used to determine ratio correction factors at various levels of steady-state excitation. Where it has a well-defined knee-point, it has no discernable point of saturation. For this reason relaying accuracy ratings are based on a ratio correction not exceeding 10% and ratings are designated by classification and secondary voltage.

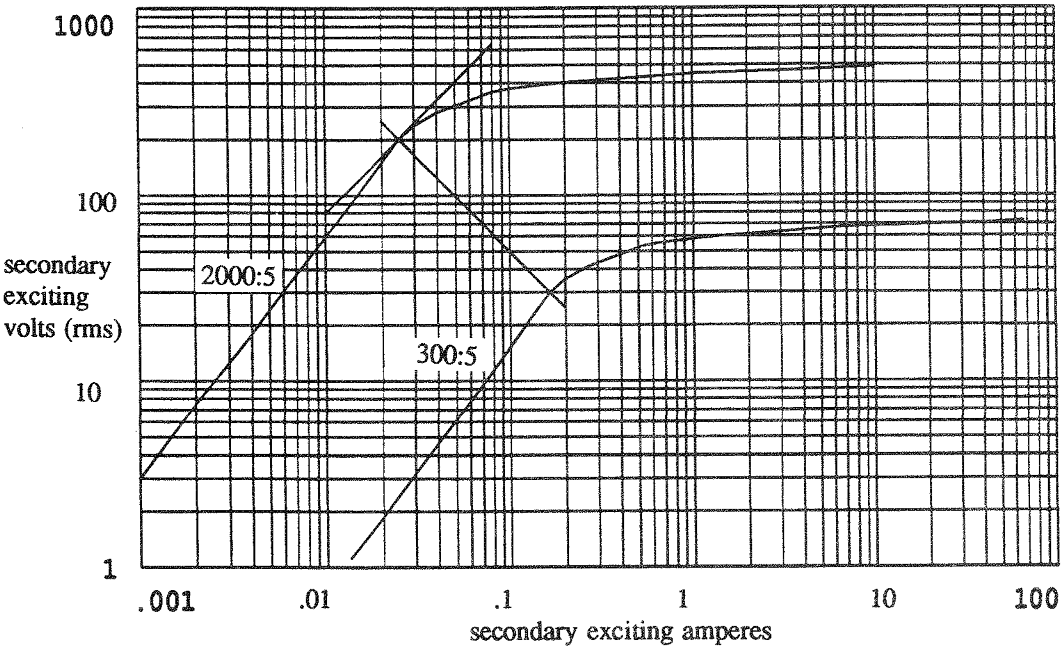

Figure 4: 2000:5 ct excitation curve and its 300:5 tap both with knee-point tangents and normal lines

The C and K classifications cover toroidal cts with distributed windings so that leakage flux can be neglected and the ratio can be calculated using a standard burden to determine the excitation voltage. The excitation current can then be read from the curve. The K rating is a proposed rating where the knee-point is at least 70% of the secondary voltage rating. The secondary voltage rating is the voltage the ct will deliver to a standard burden at 20 times rated secondary current without exceeding 10% ratio correction. The standard burden values for relaying are 1.0, 2.0, 4.0, and 8.0 ohms all with an impedance angle of 60°. Consequently, at 20 times the rated current of 5 amperes the standard voltage ratings are 100, 200, 400, and 800 volts. Standard burden values of 0.1, 0.2 and 0.5, with a 25.8° impedance angle, are used for rating metering cts which are of insufficient accuracy for relaying.

A multi-ratio ct is voltage rated using the maximum turns ratio. The voltage read from the upper curve at 10 amps excitation current is 486 volts. This is less than the standard rating of C800 but above C400. Accordingly, the ct is rated C400. The magnetizing impedance of the ct can be obtained by dividing each value of voltage read from the curve by the corresponding excitation current. The results are shown in Table 1. The magnetizing impedance is non-linear, increasing from 3000 ohms at 0.001 amps excitation current to a maximum of 8000 ohms at 0.0248 amperes of excitation. This is the point of maximum permeability and is located by the 45° tangent to the curve. The impedance values decrease from this point as the excitation is increased reaching 49 ohms at 10 amperes of excitation current.

Table 1: Excitation Curve Values

V(volts)	Ie(amperes)	Ze(ohms)
3.0	.001	3000
7.5	.002	3750
12.5	.003	4167
18	.004	4500
60	.010	6000
150	.020	7500
200	.025	8065
235	.030	7833
276	.040	6900
300	.050	6000
356	.080	4450
372	.100	3720
400	.200	2000
447	1.0	447
466	4.0	117
472	6.0	79
486	10	49

Any point on the maximum ratio curve can be referred to a lower ratio tap by using a constant volts per turn relation for the voltage and a constant ampere turn relation for the current.

Consequently:

$$V_2 = \frac{N_2}{N_1} V_1 \qquad I_2 = \frac{N_1}{N_2} I_1 \tag{7}$$

so that the knee-point of each curve lies along the normal line to the 45° tangent drawn in Figure 4. Figure 4 also shows the curve for the 300:5 ampere minimum tap.

COMPUTER SIMULATION

Because cts are subject to saturation during the dc transient of fault current, there is a growing interest in computer simulations like the EMTP program which produce detailed plots of current corresponding to an oscillograph obtained from a full-scale system test. A primary aim of the simulation is to obtain digitized records which can be reconstituted as secondary analog signals using D/A conversion and amplification for the purpose of relay testing.

The simple equivalent circuit for the simulation is shown in Figure 5. In Figure 5 the primary current referred to the secondary is a constant current feeding a non-linear magnetizing inductance and the resistance and inductance of the burden.

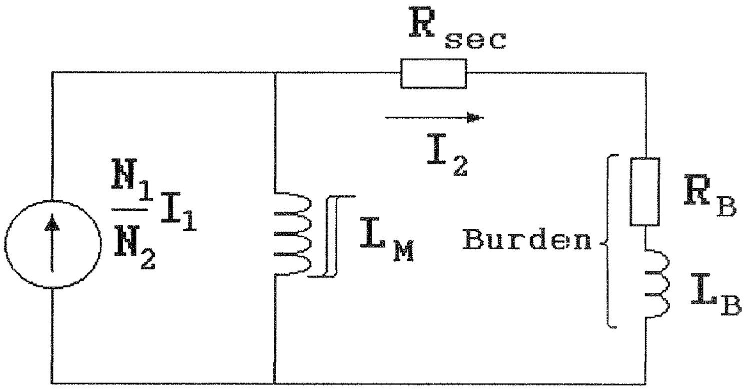

Figure 5: Equivalent circuit of a current transformer

The equivalent circuit in Figure 6 is needed to simulate the interaction between the two cts and the restraint and operating windings of a differential relay. In Figure 6, the side A and side B cts are represented by the ratio currents I_A and I_B and non-linear magnetizing inductances L_A and L_B. Linear elements R_1, L_1, R_2, and L_2 represent resistance and inductance of the leads and include the resistance of the ct secondary windings. R_3 and L_3 represent the linear elements of the relay operate winding. L_{3wdg} is the non-linear inductance of a saturable reactor, a necessary element in the representation of machine differential relays.

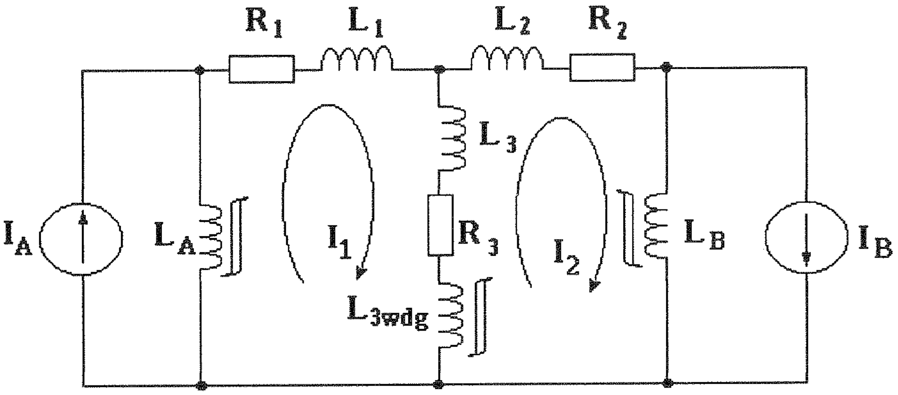

Figure 6: Equivalent circuit for the differential connection of two cts

The simulation is the time discrete solution of the differential equation of the voltage drops caused by the loop currents. A recursive solution using a finite time increment is used because the magnetizing inductance, L_M, changes continually as a function of the voltage. Thus the output of the program is an increment-by-increment time plot of the current, voltage and flux density.

Some programs like the EMTP program use a piece-wise linear representation of the saturation curve of the cts which the user must enter as a series of points. Other programs [3] use an equation to emulate the B-H curve of the ct. The characteristic S-shaped curve of the Fröhlich equation is made to fit the B-H curve for oriented grain steel by equating the slope of the curve at the origin to the maximum incremental permeability (of order of 5000), and the slope during saturation to the permeability of free space ($4\pi \times 10^{-7}$). The inductance L_M, is then calculated using an incremental permeability equal to the slope of the B-H curve as emulated by the Fröhlich equation:

$$L_M = \frac{N^2 u_0 u_r A}{l} \tag{8}$$

where:

L_M = magnetizing inductance in Henries
N = number of turns
A = core cross sectional area (sq. meters)
u_0 = permeability of free space
u_r = core material incremental relative permeability
l = mean length of the core (meters)

The plot of the B-H curve emulated by the Fröhlich equation is shown in Figure 7. The permeability is taken to be the slope of the curve through the center of the hysteresis loop. The curve of the slope of the B-H curve in Figure 7 emphasizes that the magnetizing inductance has no single value but changes for every value of instantaneous excitation during a cycle. In addition, the excitation curve indicates that the slope of the B-H loop varies with the level of excitation. Since simulations are used to analyze high excitation involving saturation, the slope at the origin is set equal to the maximum permeability of the core. The maximum relative permeability for the C400, 2000:5 ct was found to be 6300 calculated using the 8065 ohm maximum reactance from Table 1 and using typical core dimensions.

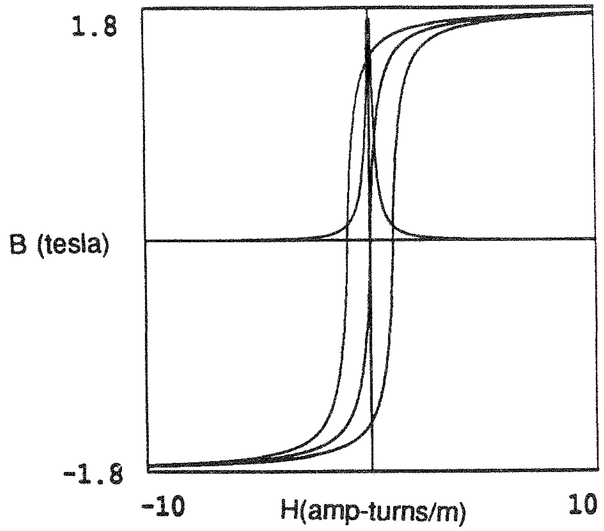

Figure 7: B-H loop and the slope of the mean curve

CT APPLICATION RULES

Generally, protective relays are designed for sine wave operation and their performance is not specified for other waveforms. Therefore, in a protective relay application, the voltage and burden of the ct should be specified to ensure undistorted secondary current for the maximum fault condition.

IEEE/ANSI Standard C57.13 suggests that cts for relaying be applied on the basis that the maximum symmetrical fault current not exceed 20 times the ct current rating and that its burden voltage not exceed the accuracy class voltage of the ct. Applying cts for relaying is an art rather than a science because the engineer is left to choose the specific operating point on the excitation curve. However, there is a rationale for choosing a ct to produce the knee-point excitation at the maximum symmetrical fault current since the magnetizing reactance is at a maximum. Observe that the knee-point of a typical excitation curve is about 46% of excitation voltage corresponding to 10 amperes excitation current. A popular rule-of-thumb suggests that the C-rating be twice the excitation voltage developed by the maximum fault current. By good planning or dumb luck, the rule-of-thumb guarantees operation near the knee-point of the excitation curve for the maximum symmetrical fault.

Preventing saturation due to the exponential component of fault current requires a C-rating exceeding the symmetrical rating by a factor equal to the X/R ratio of the faulted primary system plus one. The dilemma is that it is routinely impossible to achieve such ratings despite the fact that saturation affects the performance of high-speed relays. It is in these cases that simulations are used to assess the effects of transient saturation on relay performance.

Transformer Differential Application

Figure 8 shows a 4160 volt power plant auxiliary bus supplied by a 5000 kVA delta-wye resistance grounded transformer. The transformer has a 4.95% impedance on a 5 MVA base and is fed by a standby and an emergency bus. The bus is protected by phase and ground directional overcurrent relays and the transformer protected by percentage differential relays with harmonic restraint and a ground overcurrent relay fed by a ct in the transformer neutral.

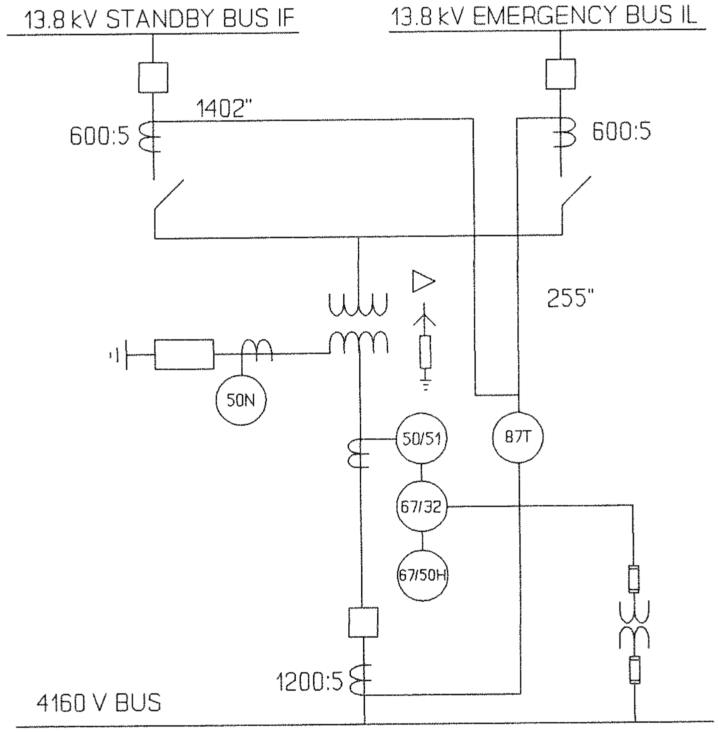

Figure 8: Power Plant Auxiliary

A rating C-200, 1200:5 was selected for the low side cts and a C-200, 600:5 rating for the high-side cts. The taps for the 87T relay were set at 2.9 amps for the high side winding and at 8.7 amps for the low-side winding leaving a ratio mismatch of 4.4%. The percentage differential for tripping was set at 25%.

The complication in this application is in the fact that the 600:5 cts are located 1400 feet from the switchgear, requiring at least 2800 feet of leads. Only 25 feet of leads were required for the 1200:5 cts mounted in the switchgear with the relay. The long run was installed with paralleled No. 10 gauge wire which has a calculated resistance of 3.36 ohms, including the totally resistive relay burden. The 1200:5 ct was installed with a calculated total burden of 0.365 ohms. The maximum through fault current was calculated as 12,312 amperes on the 4160 bus (3711 amperes at 13.8 kV) with an X/R ratio of 11.

In the low side 1200:5 ct, the maximum symmetrical secondary fault current of 51.3 amperes flowing in the total burden of 0.365 produces 18.72 volts. This voltage multiplied by $(X/R+1)=12$ gives 225 volts. Consequently, the low-side ct can support undistorted asymmetrical ratio current in the secondary. In the 600:5 cts, a maximum symmetrical fault current of 30.9 amperes flowing in the total circuit burden of 3.4 ohms produces 105 volts or about half the 200 volt accuracy rating. These cts, therefore, are adequately rated by the accepted rules. However, their core will saturate with asymmetrical fault current. Since only one set of cts will saturate, relay operating current will persist for asymmetrical faults.

The implications of this arch-typical application are shown by the computer simulation of Figure 9. The upper graph shows the time plot of saturated 600:5 ct secondary current with the unsaturated 1200:5 ct secondary current. This lower plot shows the large difference current which decays with the dc transient. The plot is literally the magnetizing current during saturation caused by the asymmetry. It has the same wave shape and is caused by the same phenomenon as the inrush current of the power transformer itself. Figure 10 is a plot of the harmonic content obtained from a Fast Fourier analysis of the difference current. The magnitudes of the harmonics are plotted in per unit of the fundamental. The analysis shows typical values of 173% dc component, 49% second harmonic, 62% fifth harmonic, and 153% sixth harmonic. As it turns out, the second and fifth harmonics are high enough during the offset that a differential relay with harmonic restraint units will restrain the relay from operating. Thus, the two times knee-point voltage rule-of-thumb is adequate for this application.

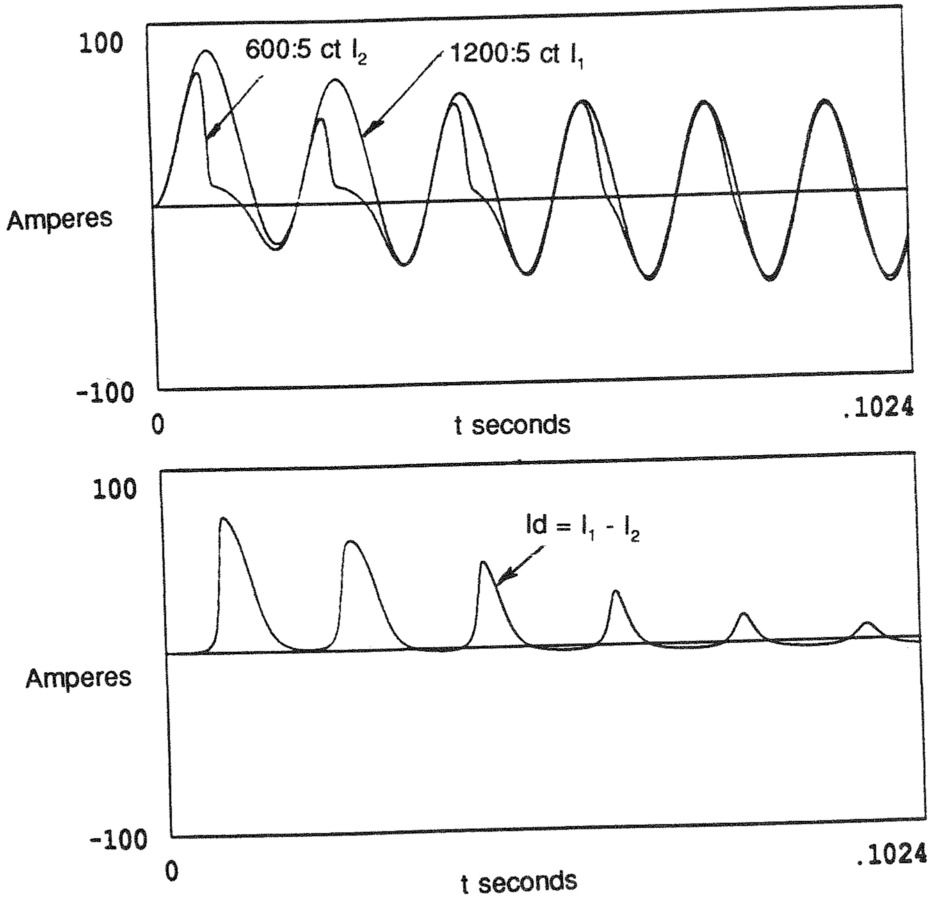

Figure 9: Differential relay restraint currents I1 and I2 with high-side ct saturation. Id is the differential current plotted in the lower graph

$\frac{\lvert c_i \rvert}{\lvert c_1 \rvert}$
1.73
1
0.489
0.288
0.242
0.616
1.533
0.596
0.343
0.227
0.103

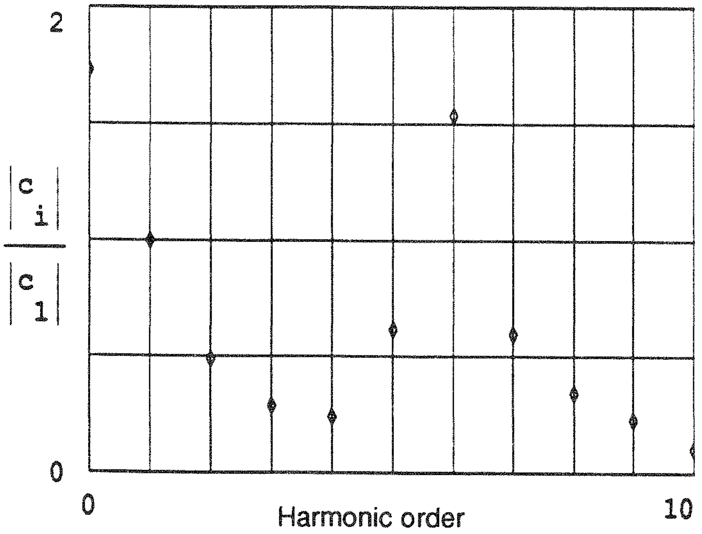

Figure 10: Harmonic content of the differential current in Figure 9 plotted in per unit of the fundamental frequency

Generator Differential Relay Application

It is impractical to size cts to avoid transient saturation in a generator differential because of the high X/R ratios encountered. The rule is to select the largest practical rating and match the terminal and neutral-side cts. The pitfall is that the highest ct accuracy class is the C800 and that any ct with an excitation voltage exceeding 800 volts is classified C800 no matter how high the voltage. For example, one 6000:5 ct may have an excitation voltage of 1500 volts at 10 amperes of excitation current and be classified C800. A second 6000:5 ct of a different manufacture may have 978 volts at 10 amperes of excitation and also be classified C800. The generator cts must have the same excitation curve with matching knee-point voltage and the same excitation voltage at 10 amps excitation current.

Consider the application of a generator differential relay for a 111 MVA, 13.8 kV generator. The machine has an X/R ratio of 52 and can contribute 58800 amperes to an external bus fault. All the cts are classified 6000:5, C800. However, the set of generator terminal cts has a 700 volt knee-point voltage while the set of neutral-side cts has a 500 volt knee-point voltage. We have observed that the knee-point voltage is generally 46% of the excitation voltage occurring at 10 amperes of excitation. The actual rating can be considered 700/0.46 = 1522 and 500/0.46 = 1086 volts, respectively. The table of input data for the maximum fault case is as follows:

SIDE A CT DATA:		SIDE B CT DATA:	
C-rating (actual)	1522	C-rating (actual)	1086
Ratio	1200	Ratio	1200
Core mean length (m)	1.02	Core mean length (m)	1.02

SIDE A LEAD & WDG DATA:	
Lead Resistance	2.6
Restraint Wdg. Resistance	0.01
Restraint Wdg. Reactance	0.01

SIDE B LEAD & WDG DATA:	
Lead Resistance	2.3
Restraint Wdg. Resistance	0.01
Restraint Wdg. Reactance	0.01

OPER. WDG, & EXT REACTOR DATA:	
Operating Wdg. Resistance	0.52
Operating Wdg. Reactance	0.01
Reactor Knee-point Volts	12
Ext. Ohms Reactance	170
Ext. Reactor Core Length	0.229

PRIMARY CURRENT:	
Primary current	58800
Primary time constant	0.15
Incident angle (max offset)	0.0

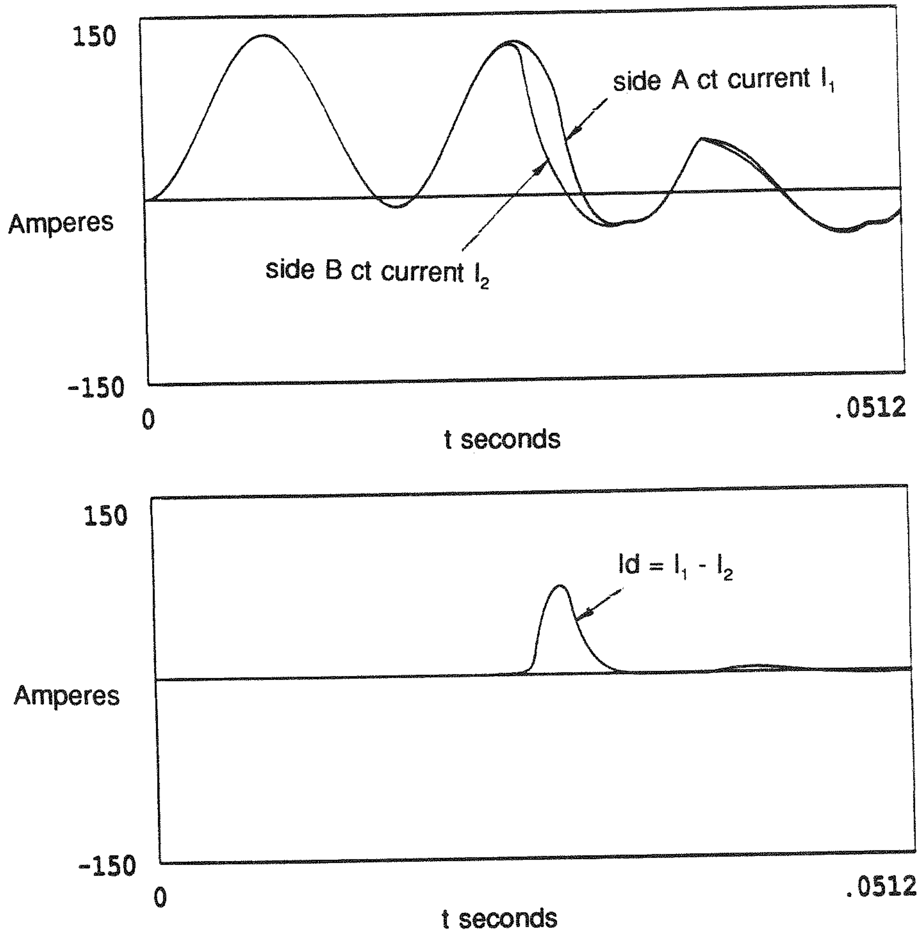

Figure 11: Secondary currents I1 and I2 due to a 58800 amperes through fault current with offset. The differential current Id is plotted below. 6000:5 cts have knee-point volts of 700 and 500. X/R = 52

Figure 11 is a plot of the restraint currents for the maximum asymmetrical fault case with the difference current plotted below. In this application, the ct voltage rating exceeds the burden voltage produced by the maximum symmetrical fault by a factor of 11.8 in the side A ct and by a factor of 8.8 in the lesser rated ct. These conservative ratings delayed saturation for nearly two cycles allowing time for a subsequent instantaneous trip. Figure 12 shows the effect of adding 0.4 ohms to the side A burden to even the time to saturate. In this case, the pulse of difference current is virtually eliminated. This study shows the margin for ct mismatch.

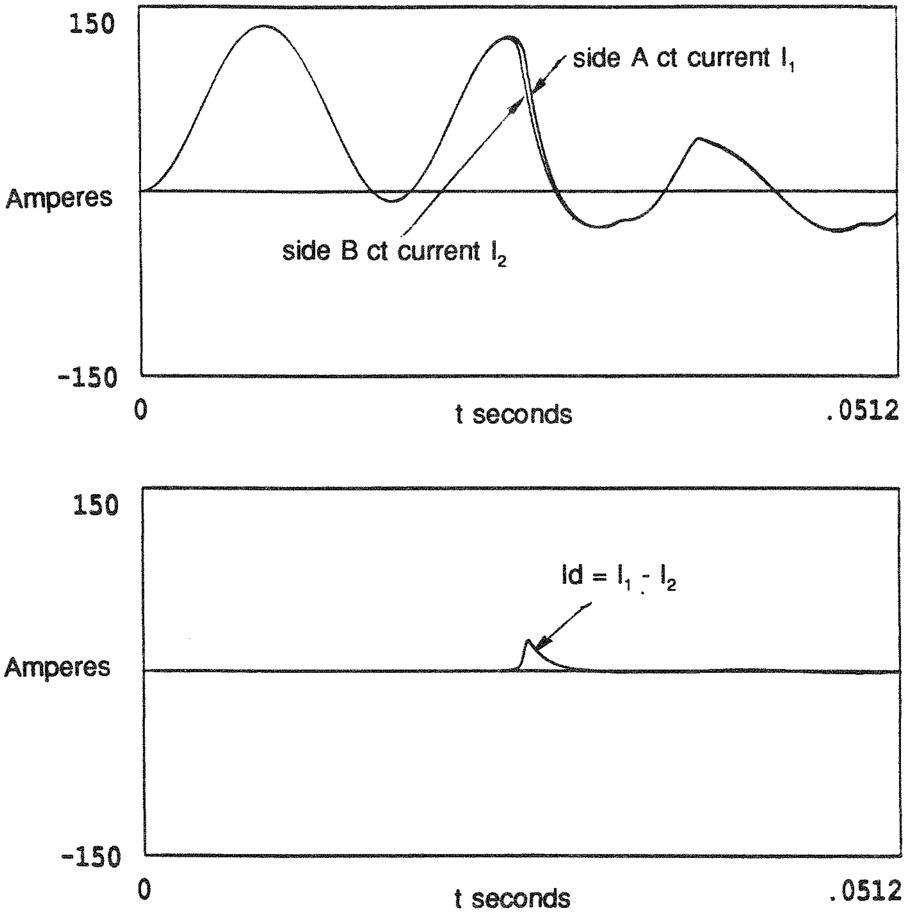

Figure 12: Secondary currents I_1 and I_2 due to a 58800 ampere through fault with offset. Differential current Id (lower plot) is decreased by adding burden resistance. 6000:5 cts. Knee-point voltages of 700 and 500. X/R = 52

CONCLUSIONS

1. The process of ct saturation can be understood using the volt-time concept. The concept defines a threshold of saturation using an idealized B-H curve and establishes the relation of the accuracy class voltage to the saturation flux.

2. A ct excitation curve provides a measure of the steady-state performance. Excitation curves have a knee-point voltage defined by the 45° line drawn tangent to the curve.

However, it is important to note that the knee-point is the point of maximum permeability and not the point of saturation.

3. The saturation point of a ct is defined as the excitation voltage at 10 amperes of excitation current which produces no more than a 10% ratio correction at 20 rated times current using a standard burden. The 10% error defines the threshold of significant wave distortion due to saturation.

4. Ct models were discussed to show how computer simulations can be used to verify the transient performance of cts which are applied using symmetrical current and rating factors. The computer runs for both transformer and generator differential relay applications were shown. Both examples show the limit of transient operating current due to dc saturation that can be tolerated for a through fault condition.

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[5] S. E. Zocholl, W. C. Kotheimer, and F. Y. Tajaddodi, "An Analytic Approach to the Application of Current Transformers for Protective Relaying," Proceedings of the 15th Annual Western Protective Relay Conference, Spokane, WA. October 1988

APPENDIX A: VOLT-TIME AREA COMPUTER SIMULATION OF CT PERFORMANCE

1. The BASIC program shown below is for use with an IBM-compatible PC with CGA graphics.

2. To run the program using EGA or VGA graphics remove the comment symbol (') in lines 15, 155, and 505.

3. In the program listing all 0s in the variables are zeros.

4. Load GRAPHICS.COM before loading the program so that the PRINT SCREEN command can be used to produce a hard copy of the plots.

5. As shown, the program plots Flux and secondary current. To get the additional plots of primary and the difference current, remove the comment symbol (’) from the statements 470 and 487.

```
10 SCREEN 2: KEY OFF: CLS
15 'SCREEN 9 :COLOR 11, 9: CLS
20 T$ = "*** SATCT ***"
30 LOCATE 1, (80 - LEN(T$)) / 2
40 PRINT T$
50 L$ = "a simplified program to analyze the ct waveform resulting from a"
60 L1$ = "specified saturation level relative to a specified current"
70 LOCATE 2, (80 - LEN(L$)) / 2: PRINT L$
80 LOCATE 3, (80 - LEN(L1$)) / 2: PRINT L1$
90 LOCATE 6, 1: INPUT "No. of cycles-----------"; TP
100 LOCATE 7, 1: INPUT "Per unit current--------"; M
110 LOCATE 8, 1: INPUT "closing angle----------"; CA
120 LOCATE 9, 1: INPUT "ckt impedance angle----"; ZA
130 LOCATE 10, 1: INPUT "per unit to saturate----"; Q
140 LOCATE 11, 1: INPUT "per unit residual flux--"; A0
145 LOCATE 12, 1: INPUT "plot vert. scale factor"; G
150 CLS
155 'COLOR 7, 9
160 WINDOW (-TP / 100, -20)-(TP, 20)
170 LINE (-TP / 10, 0)-(TP, 0)
180 LINE (0, -20)-(0, 20)
190 FOR N = 1 TO TP
200 LINE (N, -.5)-(N, .5)
210 NEXT N
220 FOR N = -20 TO 20
230 LINE (0, N)-(.01 * TP, N)
240 NEXT N
250 S = 0: J0 = 0: U0 = 0
260 T = .0001: W = 377: RAD = ATN(1) / 45
270 B = CA * RAD
280 T0 = TAN(ZA * RAD) / W
290 FOR K = 0 TO TP / .006
300 J = J0 + T
320 U = M * (EXP(-(J / T0)) * COS(B) - COS(W * J + B)): U1 = U
330 D = ((U - U0) / 2 + U0) * W * T
340 A = D + A0
350 IF S = 1 THEN 370
360 IF A >= Q THEN 370 ELSE 410
370 IF U >= 0 THEN 380 ELSE 400
380 A = A0: U = 0: S = 1
390 GOTO 470
400 S = 0
410 IF S = 2 THEN 430 ELSE 420
420 IF A <= -Q THEN 430 ELSE 470
430 IF U <= 0 THEN 440 ELSE 460
```

```
440 A = A0: U = 0: S = 2
450 GOTO 470
460 S = 0
470 'LINE (J0 * 60, U10 * G / M)-(J * 60, U1 * G / M), 1  'Ratio current plot
480 LINE (J0 * 60, A0 * G / M)-(J * 60, A * G / M), 12    'Flux plot
485 LINE (J0 * 60, U0 * G / M)-(J * 60, U * G / M), 11    'Secondary current plot
487 'LINE (J0 * 60, (U10 - U0) * G / M)-(J * 60, (U1 - U) * G / M), 13 'difference current plot
490 A0 = A: U0 = U: J0 = J: U10 = U1
500 NEXT K
505 'COLOR 14, 9
510 LOCATE 21, 35: PRINT "per unit current     ="; M
520 LOCATE 22, 35: PRINT "per unit to saturate="; Q
530 LOCATE 23, 35: PRINT "Ckt Impedance angle="; ZA; CHR$(248)
540 A$ = INPUT$(1)
550 END
```

BIOGRAPHICAL SKETCHES

Donald W. Smaha has a BSEE degree from Auburn University and a MSEE from the University of Alabama. He is a senior member of IEEE, an author of several technical papers, a member of the Georgia Tech Relay Conference Planning Committee, a member of the Power System Relay Committee, and a professional Engineer in the states of Alabama, Georgia, Florida, and Mississippi. In 1982 he received the Power System Relay Committee prize winning paper award.

He joined Georgia Power Company as a Distribution Engineer after receiving his Bachelor's degree in 1965. He soon volunteered in the US Navy Seabees and served two years in South Vietnam. In 1968 he transferred to Southern Company Services where he progressed through various disciplines in System Planning and Engineering. He is presently Principal Engineer 1 in the Electrical and Controls Department of Power and System Engineering at Southern Company Services in Birmingham, Alabama. In this position Mr. Smaha is responsible for all activities and studies performed at Southern Company Services for the Southern Electric System.

Stanley E. Zocholl has a BSEE and MSEE from Drexel University. He is a IEEE fellow and a member of the Power Engineering Society and the Industrial Applications Society of IEEE. He is a member of the Power System Relay Committee and chairman of the Relay Input Sources Subcommittee. He is also a member of the Planning committees of the Georgia Tech and Western Protective Relay Conferences.

He joined Schweitzer Engineering Laboratories in 1991 in the position of Distinguished Engineer. He was with ABB Power T&D Company-Allentown (formerly ITE, Gould, BBC, Westinghouse ABB) since 1947 where he held various engineering positions including Director of Protection Technology.

His biography appears in Who's Who in America. He holds over a dozen patents associated with power system protection using solid state and microprocessor technology and is the author of numerous IEEE and Protective Relay Conference papers. He received the best paper award of the 1988 Petroleum and Chemical Industry Conference. In 1991 he was recognized by Power System Relay Committee for Distinguished Service to the committee.