ONTARIO HYDRO
RESEARCH DIVISION REPORT

To Mr. J.H. Waghorne
Director of Research

PARALLELING OF CURRENT TRANSFORMERS FOR METERING APPLICATIONS

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The paralleling of current transformers results in a reduced accuracy because of the increase of the effective burden on the current transformers. The report outlines pitfalls of installations using current summation, and presents a method for assessing the accuracy of such installations. The report recommends the use of summation current transformers exhibiting high metering accuracy.

The summation of currents is often required when the load current from two or more pieces of equipment is to be measured by one instrument. Current summation with current transformers can be effected by either paralleling the secondaries or using auxiliary summating current transformers. The purpose of this report is to discuss the problems associated with installations using current summation for metering purposes, and to provide a guide that can be used for assessing the metering performance of an installation using either parallel-connected current transformers or auxiliary summating current transformers.

Introduction

Assuming that a current transformer provides a given accuracy when loaded with a particular burden, then one could argue that an improvement in accuracy should be possible when the burden is supplied from two transformers, each supplying half the required volt-amperes. Unfortunately, when two equal currents are added by paralleling the secondary windings of two current transformers, the burden (in volt-amperes) increases by a factor of 4, and as a result each current transformer is asked to supply double, not one half, the original burden. Loss of accuracy usually results.

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To obtain an improvement in accuracy by having two current transformers each supply half the burden, a two-to-one ratio change in the secondary current is required. Similar arguments apply to situations where n current transformers are paralleled, and therefore an n-to-1 ratio change in the secondary current is required if each of the transformers is to supply 1/n of the burden.

The multiplying effect of the burden has been the reason for claims of undesirable performance of some current summation installations. Similarly, improved performance because of the sharing of the burden by a number of transformers has been claimed for other installations. The facts are that current summation is practical and can be designed to be accurate if certain rules are observed.

This report analyzes the performance of installations involving parallel-connected current transformers, provides a step-by-step procedure for determining the accuracy of such installations, gives some points on designing current summating systems, and gives data on some available current summating transformers.

The report assumes that the currents to be summed are all in phase for addition, and 180° out of phase for subtraction. In practice there will always be a departure from this ideal condition. To simplify many of the calculations, it is assumed that all the burdens (Z) are in phase and can, therefore, be added directly. In practice, the resistive (R) and the inductive (X) components of burdens should be added separately and combined vectorially if highest accuracy in calculations is desired.

The report considers the current circuits of a polyphase installation as separate single-phase circuits and with the leads having only resistance. In practice, the burden of the common lead in a 2-element installation should be considered to have a 60° phase angle (leading for one phase and lagging for the other) in order to account for the summation of current in that lead. Similarly, the resistance of the neutral lead in a 3-element installation is eliminated, if the currents are considered to be balanced, and no current flows in the neutral lead. The multiplication of the white-phase burden by $\sqrt{3}$ must not be forgotten when dealing with 2-1/2-element installations using delta-connected CTs.

Performance of Parallel-Connected Current Transformers*

Considering the equivalent circuit of a current transformer, one finds that the errors of the transformer are caused by the magnetizing current (I_M). The magnetizing current is related

*Refer to Appendix C for definition of terms and symbols.

to the flux in the core, or to the voltage induced in the winding, according to the magnetizing characteristics for that transformer. The voltage induced in the winding (V_I) is equal to the current times the total impedance of the secondary circuit.

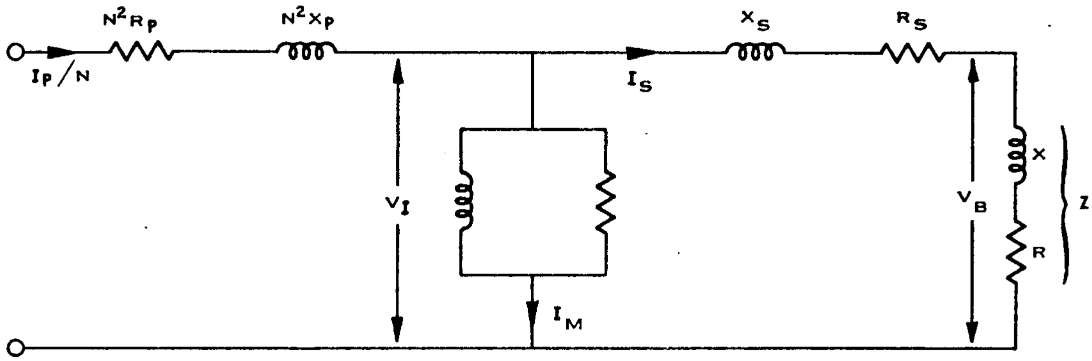

Figure 1

The effective burden (Z_E) in the above example is equal to the external connected burden $Z = R + jX$. The error of the installation is proportional to the magnetizing current I_M and may be expressed as $E = NI_M/I_P$

or $E = I_M/I_S$, if I_M is small compared to I_S. (1)

When two current transformers of equal ratio and rating are connected to supply rated current to a common burden, and with each transformer supplying the same current (amplitude and phase), and assuming the internal burdens of the transformers to be negligible, then the effective burden as seen by each CT is twice the common burden.

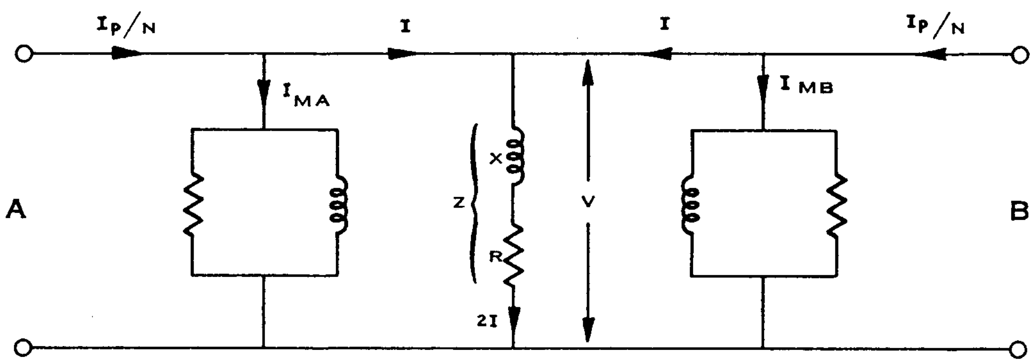

Figure 2

In the above example, the burden on transformer A is equal to the burden on transformer B, which is equal to the effective burden Z_E

where $Z_E = V/I = Z \cdot 2I/I = 2Z$

Similarly when three CTs of equal ratio and rating are connected in parallel, the burden as seen by each CT is three times the common burden, based on the same assumptions.

It is therefore important to remember that the effective burden,

$$Z_E = n\ Z \qquad (2)$$

where n = number of CTs connected in parallel
Z = common burden.

Returning to the two parallel-connected transformers, the overall error of this connection,

$$E = N(I_{MA} + I_{MB})/2I_P \qquad (3)$$

or $E = (I_{MA} + I_{MB})/2I_S$

if I_{MA} and I_{MB} are small compared to I_S.

Generalizing, the overall error in a single-phase network employing a number of parallel-connected current transformers is equal to the average error of the current transformers, each operating at the calculated effective burden and at rated current. The above accuracy calculations apply to installations where the transformers are of equal ratio or rating, and where the common burden is the only burden on the transformers. It can be shown that, under the above condition, this accuracy is maintained regardless of the manner in which the total load (nI_{PR}) is split between the current transformers.

In practical installations, where the transformers are not of equal ratio or rating, and where the common burden is only a portion of the total burden, the accuracy of the installation at the rated current for the installation may vary depending on the split of the current among the transformers, and on the accuracy of the individual transformers. The overall accuracy, however, is between that of the least accurate transformer and that of the most accurate transformer in the installation.

<u>Summating Current Transformers</u>

Summating current transformers are often used in place of simple paralleling of current transformers. Example 3 in Appendix B is an example of an installation using a summating current transformer. The transformers exhibit the following desirable characteristics:

(a) allow for isolation between the current-transformer secondary circuits whose currents are to be added.

(b) allow for isolation of the metering equipment from the secondary circuit of the primary current transformer.

(c) allow for a ratio change between the primary and the secondary of the summating transformer.

(d) allow for currents from primary current transformers of different ratios to be summed without the use of an auxiliary ratio-matching transformer.

The undesirable characteristics of the summating transformer include:

(a) additional metering error due to the transformer error.

(b) additional circuit impedance which adds to the burden of the primary current transformers.

Good summating transformers will exhibit high accuracy, and low short-circuit impedance.

Data on readily available summating current transformers are given in Appendix A. The accuracy of these CTs is not very high at 0.3 B0.9 or 0.6 B0.9, and the resistance of the secondary winding is rather high at about 0.3 ohm. It should be pointed out that the errors of a summating transformer add directly to the errors of the primary transformer and may easily reach or exceed acceptable limits. For example, the accuracy class of an installation can be 1.2 per cent when the primary transformer and the summating transformer each operate at the 0.6 per cent accuracy class.

Summating current transformers exhibiting higher metering accuracy, such as 0.3 B1.8, can be obtained when nickel-steel, rather than grain-oriented silicon steel, is used for the core material. The use of these higher accuracy transformers should be considered for applications on summation applications involving revenue metering of large loads.

Burden and Accuracy Calculations

The procedure for determining the rated accuracy of a current summating installation is given below.

The accuracy class of a current summating installation is equal to the weighted average of the accuracy class of all the current transformers employed. The accuracy class of each transformer is determined from the accuracy specifications for that transformer, or from accuracy tests when the transformer is loaded with its effective burden. The effective burden, for the purpose of this report, is defined as the voltage across the terminals of the transformers divided by the current supplied by the transformer. The effective burden must be obtained for the condition where all primary transformers are carrying their rated current.

For small installations, where two or three transformers of the same ratio and rating are paralleled:

(1) Determine the current transformation ratio for the installation. It is equal to the current transformation ratio of one of the transformers.

(2) Determine the rated primary current for the installation. It is equal to the rated primary current of one of the transformers multiplied by the number of transformers used.

(3) Determine the effective burden for each transformer by multiplying the common burden by the number of transformers used, and adding to this value any individual burdens applied solely to that transformer.

(4) Determine the accuracy class of each transformer when operating at its effective burden.

(5) Determine the accuracy class of the installation by averaging the accuracies of the transformers used in the installation.

For more complex installations, involving auxiliary current transformers or the subtraction of current:

(1) Draw a diagram of the complete current circuit for the installation.

(2) Calculate the rated primary current for the installation. It is equal to the arithmetic sum of the rated primary currents for the transformers used in the installation.

(3) Mark down all the known quantities, these are rated currents and impedances.

(4) Calculate voltages and effective burdens for all the primary and auxiliary transformers.

(5) Determine the accuracy class of each transformer when operating at its effective burden.

(6) Determine the weighted accuracy for each transformer by multiplying its accuracy class by the ratio of the rated transformer current to the rated current for the installation.

(7) Determine the accuracy class of the installation by summing all the weighted accuracies for all the transformers used in the installation.

Example 1, in Appendix B, is an example of a calculation for a small installation. Examples 2 and 3 illustrate calculations of more complex installations. Example 4 illustrates calculations of an installation involving addition as well as subtraction of currents. This example (No 4) uses the circuit of example 3, with two of the currents subtracting, rather than adding.

There are a number of points that should be brought out regarding example 4. These are:

(1) The current transformation ratio has not changed from that in example 3.

(2) The rated primary current for the installation has been reduced from that in example 3.

(3) The effective burdens on the transformers have been reduced from those in example 3.

(4) The accuracy class of the transformers, operating at the reduced burdens, has been improved.

(5) The accuracy class of the installation has been reduced from that in example 3.

Item 5, above, is of special interest. It indicates that a low accuracy class results when subtraction is used in summation circuits, even though the individual transformers operate at high accuracy (item 4). In practice, accuracies that are higher than those calculated may be obtained when the errors of the subtracting transformers cancel all or a portion of the errors of the adding transformers.

Design Hints

Whenever designing a current summation system for metering applications, one should apply the following guidelines:

(1) Unless the primary transformers are of high-accuracy and high-burden rating, there should be a current step down ratio-change used ahead of the common burden. The recommended ratio change is equal to the number of primary current transformers used in the system.

(2) Summating transformers, if used, should be of highest accuracy available and should exhibit a low short-circuit impedance.

(3) Step down auto-current transformers exhibit a very low short-circuit impedance and should, therefore, be considered for application where isolation between current transformer circuits is not required.

(4) The preferred method of summating currents from current transformers of different ratio is to use a multiple primary current transformer. The use of auxiliary ratio matching current transformers is not recommended.

Conclusions and Recommendations

Due care must be exercised whenever designing current summation schemes for metering applications. The simple paralleling of current transformers may easily result in unacceptably large errors, unless the accuracy of the transformers is high, and the connected burden is low. It is recommended that the accuracy of current summation schemes be calculated according to the procedure contained in this report.

Since current summation schemes usually require a ratio change, the use of summating current transformers is indicated. The accuracy of available summating current transformers is not very high, and their use may result in large errors under certain connections and burden conditions. It is suggested that summating current transformers of high accuracy and low short-circuit impedance be procured and used for revenue metering installations requiring high accuracy.

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Reference

1. A. Hobson. Current Summations with Current Transformers. Proceedings of IEE, Vol 102, Pt A. p 581.

APPENDIX A

SUMMATION CURRENT TRANSFORMER DATA

1. Ontario Hydro Type MP8
Central Stores No 663-1064

Primary Windings	:	8 primary windings each rated at 5 amperes maximum and having resistances between 0.14 ohm (P_1) and 0.22 ohm (P_8).
Ratio	:	4-to-1 each primary to secondary.
Secondary Winding	:	Rated at 10 amperes maximum, typical resistance 0.33 ohm.
Accuracy	:	0.6 B0.9, 25/60 Hz on nameplate 0.3 B0.5, 0.6 B0.9, 0.6 B1.8 at 60 Hz according to tests.
Insulation	:	0.6 kV
Notice of Approval	:	SD-EA170

2. Sangamo Type 1A Form 6-W5

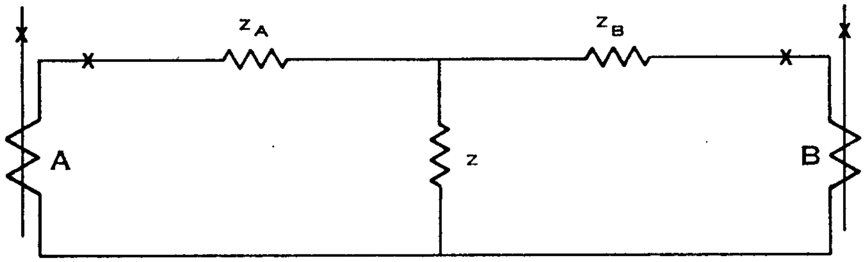
Primary Windings	:	4 primary windings each rated at 5 amperes maximum and having typical resistances in the range of 0.2 to 0.3 ohm.
Ratio	:	2-to-1 each primary to secondary.
Secondary Winding	:	Rated at 10 amperes maximum, typical resistance 0.28 ohm.
Accuracy	:	0.3 B0.9 on nameplate. 0.3 B0.9, 0.6 B1.8 according to tests.
Insulation	:	0.6 kV
Notice of Approval	:	T-69.

APPENDIX B

EXAMPLES OF BURDEN AND ACCURACY CALCULATIONS

EXAMPLE 1

A. CIRCUIT



B. DATA

Current Transformer A - Ratio : 1200-to-5 amperes
Accuracy: 0.3 B0.5, 0.6 B0.9, 1.2 B1.8.

Current Transformer B - Ratio : 1200-to-5 amperes
Accuracy: 0.3 B0.9, 0.6 B1.8

Burdens - $Z_A = 0.3\,\Omega$, $Z_B = 0.4\,\Omega$, $Z = 0.5\,\Omega$

C. CALCULATIONS

(1) Transformation ratio - 1200:5 or 240-to-1.

(2) Rated primary current - 1200 x 2 = 2400 amperes.

(3) Effective burden for transformer A:

$$Z_{EA} = Z \times 2 + Z_A = 0.5 \times 2 + 0.3 = 1.3$$

Effective burden for transformer B:

$$Z_{EB} = Z \times 2 + Z_B = 0.5 \times 2 + 0.4 = 1.4$$

(4) Accuracy class of transformers operating at their effective burdens:

A_A - 1.2%
A_B - 0.6%

(5) Accuracy class of the installation:

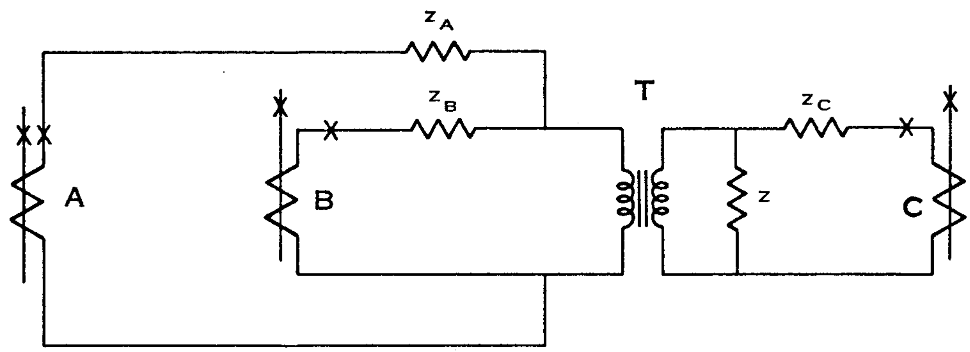
$$A = \frac{1}{2}(A_A + A_B) = \frac{1}{2}(1.2 + 0.6) = 0.9\%.$$

D. COMMENTS

Since the transformers are not identical, and are loaded with individual as well as common burdens, the accuracy of the installation will vary as the ratio of current in A to the current in B varies. The accuracy will be somewhat higher when B carries most of the current, or somewhat lower when A carries most of the current.

EXAMPLE 2

A. CIRCUIT



B. DATA

Current Transformer A - Ratio : 1200-to-5
Accuracy: 0.3 B0.9, 0.6 B1.8

Current Transformer B - Ratio : 1200-to-5
Accuracy: 0.3 B0.9, 0.6 B1.8

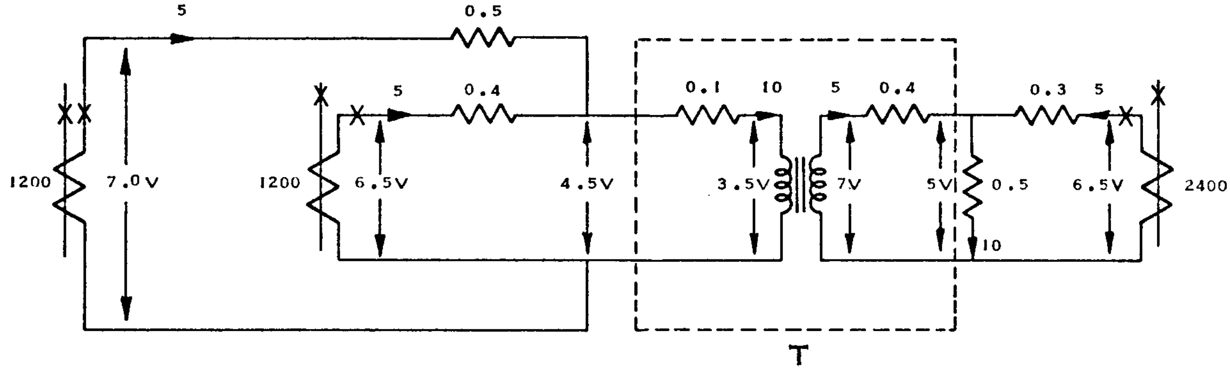
Current Transformer C - Ratio : 2400-to-5
Accuracy: 0.3 B1.8

Current Transformer T - Ratio : 10-to-5
Accuracy: 0.3 B0.9, 0.6 B1.8

Burdens: $Z_A = 0.5\Omega$, $Z_B = 0.4\Omega$, $Z_C = 0.3\Omega$
$Z = 0.5\Omega$, $Z_{PT} = 0.1\Omega$, $Z_{ST} = 0.4\Omega$

C. CALCULATIONS

(1) Diagram



(2) Rated primary current - 1200 + 1200 + 2400 = 4800 amperes.

(3) Effective burdens:

Z_{EA} = 7/5 = 1.4 Ω Z_{EB} = 6.5/5 = 1.3 Ω
Z_{EC} = 6.5/5 = 1.3 Ω Z_{ET} = 5/5 = 1.0 Ω

(4) Accuracy class of transformers:

A_A = 0.6% A_B = 0.6%
A_C = 0.3% A_T = 0.6%

(5) Weighted accuracy of transformers:

A - 0.6 x 1200/4800 = 0.15
B - 0.6 x 1200/4800 = 0.15
C - 0.3 x 2400/4800 = 0.15
T - 0.6 x 5/10 = 0.30
Total = 0.75%

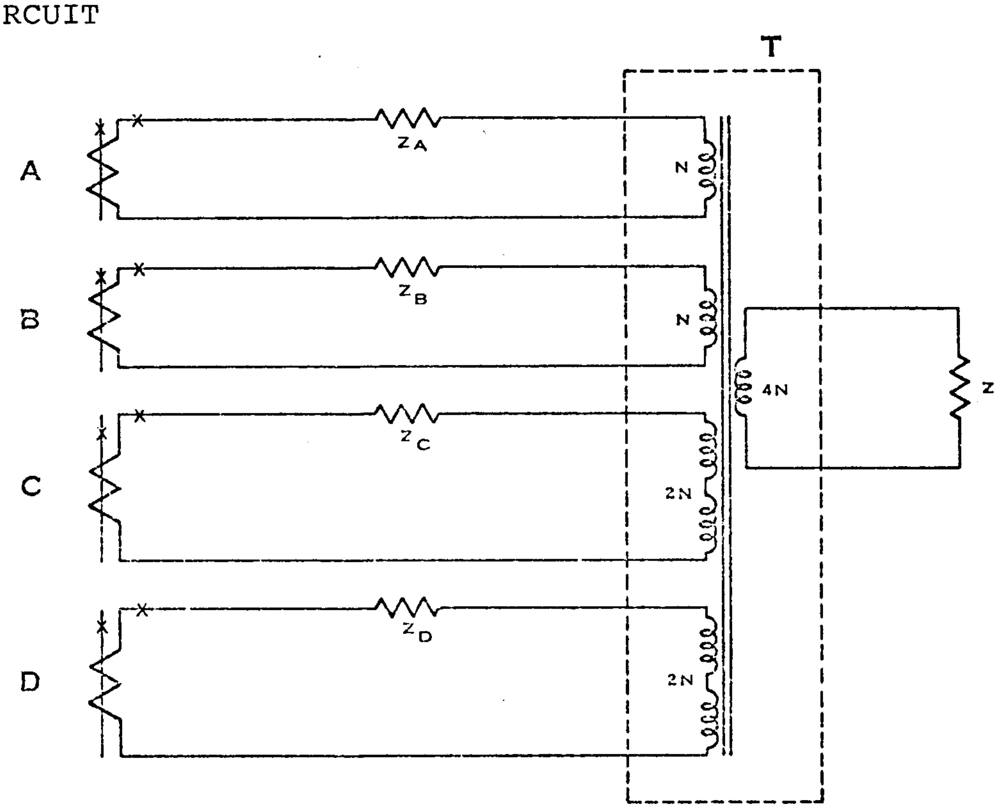
(6) Accuracy class of installation: A = 0.75%.

D. COMMENTS

The accuracy class of the auxiliary transformer (T) is weighted according to the ratio of the current it carries in the secondary (5 A) to the total current in the common burden (10 A).

EXAMPLE 3

A. CIRCUIT



B. DATA

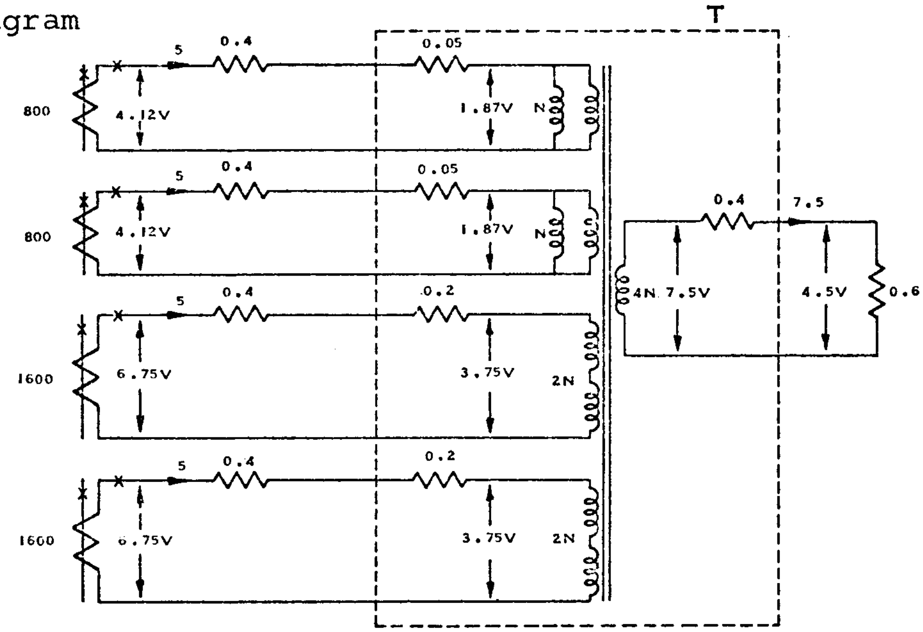
Current Transformers A and B	- Ratio :	800-to-5
	Accuracy:	0.3 B0.5, 0.6 B0.9
Current Transformers C and D	- Ratio :	1600-to-5
	Accuracy:	0.3 B0.9, 0.6 B1.8
Current Transformer T	- Ratio :	20-to-5 on each of 8 primary windings.
	Accuracy:	0.3 B0.5, 0.6 B0.9

Burdens - $Z_A = Z_B = 0.4\,\Omega$, $Z_C = Z_D = 0.4\,\Omega$

$Z = 0.6\,\Omega$, $Z_S = 0.4\,\Omega$, $Z_P = 0.1\,\Omega$ each

C. CALCULATIONS

(1) Diagram



(2) Rated primary current: 800 x 2 + 1600 x 2 = 4800 amperes.

(3) Effective burdens:

$Z_{EA} = Z_{EB} = 4.12/5 = 0.82\,\Omega$

$Z_{EC} = Z_{ED} = 6.75/5 = 1.35\,\Omega$

$Z_{ET} = 4.5/7.5 = 0.6\,\Omega$

(4) Accuracy class of transformers:

A_A - 0.6% A_B - 0.6%

A_C - 0.6% A_D - 0.6%

A_T - 0.6%

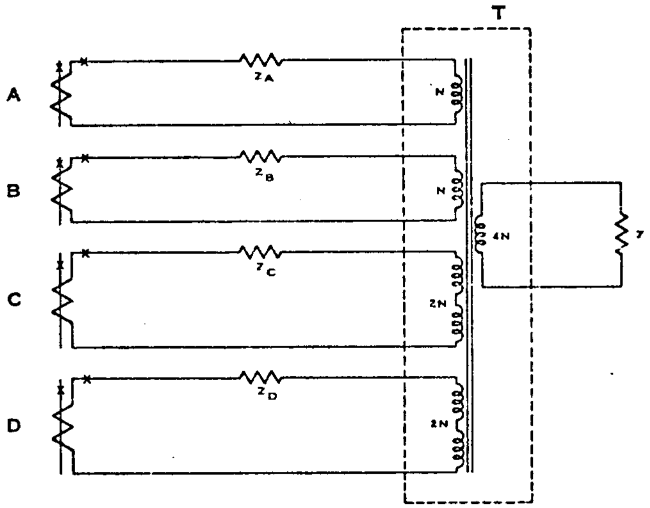
(5) Weighted accuracy of transformers:

A - 0.6	x	800/4800	=	0.1
B - 0.6	x	800/4800	=	0.1
C - 0.6	x	1600/4800	=	0.2
D - 0.6	x	1600/4800	=	0.2
T - 0.6			=	0.6
		Total	=	1.2%

(6) Accuracy class of installation: A = 1.2%.

EXAMPLE 4

A. CIRCUIT



B. DATA

Current Transformers A and B - Ratio : 800-to-5
Accuracy: 0.3 B0.5, 0.6 B0.9

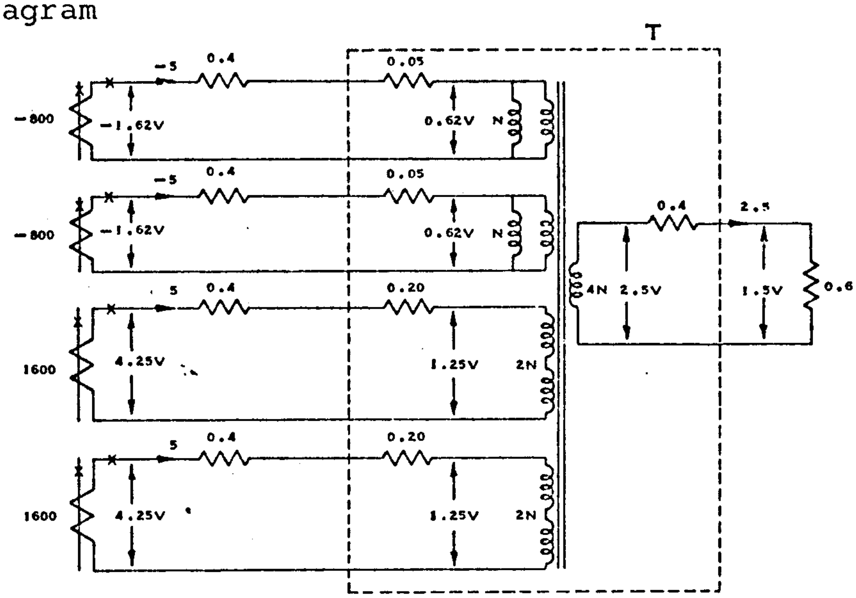
Current Transformers C and D - Ratio : 1600-to-5
Accuracy: 0.3 B0.9, 0.6 B1.8

Current Transformer T - Ratio : 20-to-5 on each of 8 primary windings
Accuracy: 0.3 B0.5, 0.6 B0.9

Burdens - $Z_A = Z_B = 0.4\,\Omega$, $Z_C = Z_D = 0.4\,\Omega$
$Z = 0.6\,\Omega$, $Z_{ST} = 0.4\,\Omega$, $Z_{PT} = 0.1\,\Omega$ each.

C. CALCULATIONS

(1) Diagram



(2) Rated Primary Current: 1600 x 2 - 800 x 2 = 1600 amperes.

(3) Effective burdens:

$Z_{EA} = Z_{EB} = -1.62/-5 = 0.32\ \Omega$

$Z_{EC} = Z_{ED} = 4.25/5 = 0.85\ \Omega$

$Z_{ET} = 1.5/2.5 = 0.6\ \Omega$

(4) Accuracy class of transformers:

A_A - 0.3% A_B - 0.3%

A_C - 0.3% A_D - 0.3%

A_T - 0.6%

(5) Weighted accuracy of transformers:

A - 0.3 x 800/1600 = 0.15
B - 0.3 x 800/1600 = 0.15
C - 0.3 x 1600/1600 = 0.30
D - 0.3 x 1600/1600 = 0.30
T - 0.6 = 0.60

Total = 1.5%

(6) Accuracy class of installation: A = 1.5%.

D. COMMENTS

In practice, the errors of the transformers whose current is subtracted may cancel some of the errors of the remaining transformers. Partial cancellation of errors will occur if the errors of current transformers used in an installation are due to magnetizing losses only, and not to turns compensation. Assuming no turns compensation in the example, the weighted accuracy of transformers A and B can be made negative. The accuracy class of the installation will then become 0.9%.

It should be pointed out that the current in the secondary circuit of the summating transformer in examples 3 and 4 is other than rated (5 amperes). The calculated accuracy class for the installations, however, applies over the secondary current range of 5 to 0.5 amperes. The errors of the installation are expected to be double the accuracy class at 10% rated current (0.5 ampere), as is allowed for current transformers by CSA Standard C13-1970.

It is possible to obtain negative burdens on some transformers in installations involving subtraction of current. The error at zero burden for that transformer should be used in the calculations.

APPENDIX C

DEFINITION OF TERMS AND SYMBOLS

TERMS

Effective burden on a transformer is equal to the voltage on the secondary terminals of the transformer (V) divided by the current supplied by the transformer (I), when all circuits in the installation carry rated current-transformer current.

Rated current (primary, secondary) for an installation is the algebraic sum of the rated currents of all the current transformers (ΣI_R). The rated primary current (ΣI_{PR}) is equal to the rated secondary current (ΣI_{SR}) multiplied by the current transformation ratio for the installation.

Accuracy class is the limit of error under a specified range of operating conditions. The accuracy classes are not restricted to those recognized by standard specifications (eg, CSA Standard C13-1970).

Overall error of an installation is the overall departure from truth, for that installation, at a particular operating condition.

SYMBOLS

A - Accuracy class of an installation (per cent).
With subscripts (A, B...) - accuracy class of transformer.

E - Error (per unit composite error).

I - Current (amperes).
Subscripts: P - primary; S - secondary; R - rated; M - magnetizing.

N - Nominal transformer ratio.

n - Number of parallel connected transformers.

R - Resistance (ohms).
Subscripts: P - primary winding; S - secondary winding.

V - Voltage (volts) on the terminals of a transformer.
Subscripts: I - refers to voltage induced in the winding of a transformer.

X - Reactance (ohms).

Z - Impedance (ohms).
Subscript: E - for effective burden (impedance) on a transformer.