

**STUDY OF CURRENT TRANSFORMER
PERFORMANCE DURING TRANSIENT CONDITIONS
AND DEVELOPMENT OF A SELECTION CRITERION
IN PROTECTION APPLICATIONS**

Raneraja Rajakaruna Thilakarathna Wasala Mudiyanse Ralahamillage
Anurudda Indranath Madawala

Index No: 118678 G



University of Moratuwa, Sri Lanka.
Degree of Master of Science
Electronic Theses & Dissertations
www.lib.mrt.ac.lk

Department of Electrical Engineering

University of Moratuwa
Sri Lanka

July 2015

DECLARATION

“I declare that this is my own work and this dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my dissertation, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books)”.

.....
Signature of the candidate  University of Moratuwa, Sri Lanka. Date:
Electronic Theses & Dissertations
(R. R. T. W. M. R. A. I. Madawala) www.lib.mtu.ac.lk

The above candidate has carried out research for the Masters Dissertation under my supervision.

Signature of the supervisors
..... Date:
(Eng: W. D. A. S. Wijayapala)

..... Date:
(Eng: J. Karunanayake)

ACKNOWLEDGEMENT

First, I pay my sincere gratitude to Eng. Anura Wijayapala and Eng. Jayasiri Karunanayake who encouraged and guided me to perform this research and on preparation of final dissertation.

I extend my sincere gratitude to Prof. J.P. Karunadasa, the former Head of the Department of Electrical Engineering, Dr. Prinath Dias, present Head of the Department, and all the lecturers and visiting lecturers of the Department of Electrical Engineering for the support extended during the study period.

I would like to thank Mr. D. N. Nawarathne, Chief Engineer, Asset Management (Generation Hydro Electrical) Branch, and Ceylon Electricity Board who gave me the initiative to study of current transformer performance during transient conditions and developing selection criteria for current transformers for protection application.

I would also like to take this opportunity to extend my sincere thanks to Dr A.P.Tennakoon, Chief Engineer Protection (CEB, Asset Management - Hydro), Mr. D.Wedamasinghe, Electrical Engineer (CEB, Kelanitissa Power Station) Mr. Saliya Liyanage, Project Manager (CEB, Norochholei Coal Power Project), Mr. Sisira Dissanayake, Electrical Engineer & Mr. Krishantha Hemarathna Electrical Engineer (CEB, Asset Management - Thermal Electrical), Mr. Kushan Dinusha Bandara - Electrical Engineer & Mr. Waruna Rasanjana - Electrical Engineer (CEB, Asset Management - Hydro Electrical), Mr. Keerthi Samarasinghe - Electrical Engineer (CEB, Samanala Power Station), Mr. T.D Guluwita - Electrical Engineer, Mr. Ajith Peliarachchi - Electrical Engineer, Mr. Harsha Viraj - Electrical Engineer, Mr. H. D. Dharmasena - Engineering Assistant, Mr. N. Fernando - Electrical Superintendent (CEB, Kelanitissa Power Station) and all the Staff of Kelanitissa Power Station of Ceylon Electricity Board who gave their co-operation to do my research successfully.

It is a great pleasure to remember the kind co-operation extended by the colleagues in the post graduate program, friends, my mother, specially my wife Narmada and two kids Anuda and Isuru who helped me to continue the studies from start to end.

ABSTRACT

The optimum selection of current transformers is one of the most crucial requirements of correct protection functioning of power systems. In the case of CT selection, protection engineer has to pay attention on transient behavior as well as steady state performance of current of transformers. Transient performance of current transformers varies with system parameters and current transformer parameters. System parameters vary with fault level and inductance to resistance ratio (L/R) at fault location. In Sri Lankan power system, these parameters rapidly vary due to network development. Type of selected protection relay, type of protection function and switchgear arrangement make huge influence on current transformer selection. This dissertation focuses on developing a current transformer selection criterion with analysis of current transformer transient performance and protection application. The developed selection criterion is mainly focused on protection relay based selection and generalized CT selection.

In addition to analysis of the current transformer transient performance, PSCAD software is used for current transformer performance simulation on fault conditions and a case study is used to validate the developed selection criteria.

TABLE OF CONTENTS

DECLARATION	I
ACKNOWLEDGEMENT	II
ABSTRACT.....	III
TABLE OF CONTENTS.....	IV
LIST OF FIGURES	X
LIST OF TABLES	XIII
LIST OF ABBREVIATION	XIV
CHAPTER 1	1
INTRODUCTION	1
1.1 Background	1
1.2 Objective	1
CHAPTER 2	4
GENERAL THEORY AND THE ANALYSIS OF CURRENT TRANSFORMER BEHAVIOR UNDER TRANSIENT CONDITIONS.....	4
2.1 Parameters that govern CT performance under-transient conditions.....	4
2.2 Fault current variation with system parameters	4
2.2.1 Fault inception angle and fault loop impedance	4
2.2.2 Fault current variation with primary time constant (T_P)	5
2.3 CT Flux requirement under transient condition	6
2.3.1 CT Flux requirement under transient conditions with a fully resistive burden	9
CHAPTER 3	10
CURRENT TRANSFORMER DIMENSIONING.....	10

3.1	Introduction	10
3.2	Transient factor (K_{tf})	10
3.3	Transient dimensioning factor (K_{td})	10
3.3.1.1	1 st time zone ($0 \leq T_{al} \leq T_{al1}$)	11
3.3.1.2	2 nd time zone ($T_{al1} \leq T_{al} \leq T_{al @ B \max}$)	12
3.3.1.3	3 rd time zone ($T_{al} \geq T_{al @ B \max}$)	13
3.4	CT secondary current	15
CHAPTER 4		17
PROTECTION CT CLASSES, THEIR REQUIREMENTS AND A COMPARISON		17
4.1	Introduction	17
4.2	Protection transformer classes	17
4.2.1	Protection transformer – Steady state performance	17
4.2.1.1	Protection transformer – Class P	17
4.2.1.2	Protection transformer – Class PR	18
4.2.1.3	Protection transformer – Class PX and class PXR	18
4.2.2	Protection CT classes – Based on transient performance	19
4.2.2.1	Class TPX	19
4.2.2.2	Class TPY	19
4.2.2.3	Class TPZ	20
4.3	Comparison of B-H Loop in different type of CT cores	20
4.4	Comparison between composite error and instantaneous error	21
4.4.1	Composite error (ϵ_c)	21

4.4.2 Instantaneous error current (i_{ϵ})	22
4.4.2.1 Peak instantaneous error (ϵ^{\wedge})	22
4.5 Excitation characteristic of a CT	24
4.5.1 Under steady state conditions	24
4.5.2 CT Operation under transient conditions	25
4.6 Accuracy Limit Factor (ALF)	26
4.6.1 ALF variation with the connected burden	27
CHAPTER 5	28
CURRENT TRANSFORMER SELECTION.....	28
5.1 Introduction	28
5.2 CT selection criteria	28
5.2.1 CT class	28
5.2.1.1 Protection functions	29
5.2.1.1.2 Selection of CT classes - Different types of protection relays.....	33
5.2.1.1.3 Electromagnetic relays.....	34
5.2.1.1.4 Static relays	35
5.2.1.1.5 Numerical relays	36
5.2.2 Core construction	41
5.2.2.1 Closed core CTs	41
5.2.2.2 Gapped core CTs.....	42
5.2.2.3 CT core selection	43



University of Moratuwa, Sri Lanka.
 Electronic Theses & Dissertations
www.lib.mrt.ac.lk

CHAPTER 6	45
SELECTION OF OPTIMUM CT SIZE	45
6.1 Introduction	45
6.2 Sizing parameters	45
6.2.1 Maximum possible fault level of the location	45
6.3 Primary time constant or network time constant (T_p) at the location.....	46
6.3.1 Secondary time constant (T_s).....	46
6.3.2 Required saturation free time (T_{al}).....	46
6.3.2.1 T_{al} for numerical relays	47
6.4 CT sizing for different protection applications	48
6.4.1 Differential protection relay.....	48
6.4.1.1 Determination of primary time constant (T_N).....	51
6.4.1.2 Determination of secondary time constant (T_s).....	51
6.4.1.3 K_{td} for electro-magnetic and static relays	51
6.4.1.4 Selection of CT ratio.....	51
6.4.1.5 Required ALF with numerical relay	52
6.4.1.6 Required ALF with static relay.....	52
6.4.2 Bus bar differential protection	52
6.4.3 CT sizing for distance protection.....	53
6.5 Sample calculation - 220kV GIS Kelanitissa.....	56
6.5.1 Line parameters	56
6.5.2 Sizing for closed core CTs.....	57



6.5.2.1 Calculation of over dimension factor for close in fault with ARC application.....	57
6.5.2.2 Fault in zone limit with ARC application.....	62
6.5.2.3 Size comparison between closed core and gaped core CTs.....	64
6.6 CT size comparison with and without numerical relay.....	65
6.6.1 Case 1: Closed core	65
6.6.2 Case 2: Gapped core	65
CHAPTER 7	67
CASE STUDY	67
7.1 Events of incident.....	67
7.2 Conclusion and discussion	68
7.2.1 Inadequate CT size.....	69
7.2.1.1 Existing CT data.....	69
7.3 Problems that have to be answered	70
CHAPTER 8	73
DEVELOPMENT OF CT SELECTION CRITERIA.....	73
8.1 Network and CT parameters based CT selection criteria.....	73
8.2 Relay based CT selection	77
CHAPTER 9	78
PSCAD SIMULATION.....	78
9.1 Core cross section and CT saturation.....	78
9.2 Turns ratio and CT saturation.....	79
9.3 Burden and CT saturation	80
9.4 Remanence flux and CT saturation	81



CHAPTER 10	83
CONCLUSION AND RECOMMENDATIONS	83
10.1 Conclusion.....	83
10.2 Recommendation.....	83
REFERENCE LIST	84



University of Moratuwa, Sri Lanka.
Electronic Theses & Dissertations
www.lib.mrt.ac.lk

LIST OF FIGURES

Figure 2-1: Primary Current Variation with T_p	6
Figure 2-2: Equivalent circuit of a CT.....	6
Figure 2-3: Development of CT core flux with different T_p and constant T_s (1000ms)	8
Figure 2-4: Variation of core flux with low T_s	8
Figure 2-5: Variation of core flux with secondary power factor of burden.....	9
Figure 3-1: CT core flux development in the initial stages of a short circuit	11
Figure 3-2: Variation of time K_{td} with primary and secondary time constants	13
Figure 3-3: Variation of time taken reach maximum flux with primary time constant	14
Figure 3-4: Variation of over dimensioning factor (maximum) with primary and secondary time constant.....	15
Figure 3-5: Variation of secondary DC current component with secondary time constant	16
Figure 3-6: Variation of secondary current with secondary time constant	16
Figure 4-1: BH loop of different type of CT cores	21
Figure 4-2: DC current components and its decay.....	23
Figure 4-3: Knee point voltage in accordance with ANSI.....	24
Figure 4-4: Equivalent circuit of a CT with burden.....	25
Figure 5-1: Biased characteristic in differential protection	30
Figure 5-2: Distance relay arrangement.....	32
Figure 5-3: Comparison of static and numerical protection relays operation region.	34

Figure 5-4: Schematic diagram of static relay	36
Figure 5-5: CT current wave comparison in differential protection	38
Figure 5-6: Adjusted biased curve	39
Figure 5-7: Trip logic of numerical relay SIEMENS 7SS5 with saturation detection	39
Figure 5-8: Remanence flux variation with secondary time constant.....	43
Figure 6-1: Determination of K_{tf} in time zone 1 (IEC 61869-2).....	48
Figure 6-2: Single line diagram of GT7.....	49
Figure 6-3: Switchyard arrangement of 220kV GIS Kelanitissa.....	56
Figure 7-1: Wimalasurendra generator arrangement	67
Figure 7-2: Disturbance records from protection relay (REG316*4).....	71
Figure 7-3: Disturbance records from protection relay (REG316*4).....	72
Figure 8-1: Network and CT parameters based CT selection criteria-Page 1	73
Figure 8-2: Network and CT parameters based CT selection criteria-Page 2	74
Figure 8-3: Network and CT parameters based CT selection criteria-Page 3	75
Figure 8-4: Network and CT parameters based CT selection criteria-Page 4	76
Figure 8-5: Relay based CT selection	77
Figure 9-1: Fault Simulated Network	78
Figure 9-2: Unsaturated secondary current wave with lager cross section ($0.5 \times 10^{-3} \text{ m}^2$)	79
Figure 9-3: Saturated secondary current wave with smaller cross section ($0.1 \times 10^{-3} \text{ m}^2$)	79

Figure 9-4: Unsaturated secondary current wave with higher secondary turns (200)	80
Figure 9-5: Saturated secondary current wave with lower secondary turns (100).....	80
Figure 9-6: Unsaturated secondary current wave with lower secondary burden (0.5Ω)	81
Figure 9-7: Saturated secondary current wave with higher secondary burden (2.5Ω)	81
Figure 9-8: Unsaturated secondary current wave with lower remanence flux (0.1T)	82
Figure 9-9: Saturated secondary current wave with higher secondary remanence flux (1.5 T)	82



University of Moratuwa, Sri Lanka.
 Electronic Theses & Dissertations
www.lib.mrt.ac.lk

LIST OF TABLES

Table 4-1: Error limits of transient class CTs.....	22
Table 5-1: Comparison on the suitability of the steady state and transient state based CTs for Differential protection	30
Table 5-2: Comparison of differential relay operating time	34
Table 6-1: Generator and transformer manufacturers' data.....	49
Table 6-2: Line parameters	56
Table 7-1: Existing CT data	69



University of Moratuwa, Sri Lanka.
Electronic Theses & Dissertations
www.lib.mrt.ac.lk

LIST OF ABBREVIATION

AIS	Air Insulated Switchgear
ALF	Accuracy Limit Factor
CT	Current Transformer
CVT	Capacitive Voltage Transformer
E_{al}	Rated Equivalent Limiting Secondary e.m.f.
E_{ALF}	Secondary Limiting e.m.f. for Class P and PR Protective Current Transformers
E_{FS}	Secondary Limiting e.m.f for Measuring Current Transformers
E_k	Rated Knee Point e.m.f.
F	Mechanical Load
F_c	Factor of Construction
f_R	Rated Frequency
F_{rel}	Relative Leakage Rate
FS	Instrument Security Factor
GIS	Gas-Insulated Switchgear
\hat{I}_{al}	Peak Value of the Exciting Secondary Current at E_{al}
I_{cth}	Rated Continuous Thermal Current
I_{dyn}	Rated Dynamic Current
I_e	Exciting Current
I_{PL}	Rated Instrument Limit Primary Current
I_{pr}	Rated Primary Current
I_{psc}	Rated Primary Short-Circuit Current
I_{sr}	Rated Secondary Current
IT	Instrument Transformer
I_{th}	Rated Short-Time Thermal Current
I_e	Instantaneous Error Current
K	Actual Transformation Ratio
k_r	Rated transformation ratio
K_R	Remanence Factor
K_{ss}	Rated Symmetrical Short-Circuit Current Factor

K_{td}	Transient Dimensioning Factor
K_{tf}	Transient Factor
K_x	Dimensioning Factor
L_m	Magnetizing Inductance
R_b	Rated Resistive Burden
R_{ct}	Secondary Winding Resistance
R_s	Secondary Loop Resistance
S_r	Rated output
t'	Duration of the First Fault
t''	Duration of the Second Fault
t'_{al}	Specified Time to Accuracy Limit in the First Fault
t''_{al}	Specified Time to Accuracy Limit in the Second Fault
t_{fr}	Fault Repetition Time
T_P, T_N	Specified Primary Time Constant
T_S	Secondary Loop Time constant
U_m	Highest Voltage for Equipment
U_{sys}	Highest Voltage for System
VT	Voltage Transformer
Δ_ϕ	Phase Displacement
ε	Ratio Error
ε_c	Composite Error
$\hat{\varepsilon}$	Peak Value of Instantaneous Error
$ac\hat{\varepsilon}$	Peak Value of Alternating Error Component
Ψ_r	Remanent Flux
Ψ_{sat}	Saturation Flux