PD IEC/TR 61869-100:2017

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Instrument transformers

Part 100: Guidance for application of current transformers in power system protection

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The UK participation in its preparation was entrusted to Technical Committee PEL/38, Instrument transformers.

A list of organizations represented on this committee can be obtained on request to its secretary.

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Published by BSI Standards Limited 2017

ISBN 978 0 580 84959 6
ICS 17.220.20

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This Published Document was published under the authority of the Standards Policy and Strategy Committee on 28 February 2017.

Amendments/corrigenda issued since publication

Date	Text affected

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Full document details: PD IEC/TR 61869-100:2017

IEC TR 61869-100

Edition 1.0 2017-01

TECHNICAL REPORT

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Instrument transformers –
Part 100: Guidance for application of current transformers in power system protection

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 17.220.20

ISBN 978-2-8322-3808-0

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INSTRUMENT TRANSFORMERS –

Part 100: Guidance for application of current transformers in power system protection

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IEC TR 61869-100, which is a technical report, has been prepared by IEC technical committee 38: Instrument transformers.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
38/469/DTR	38/475A/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

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This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all the parts in the IEC 61869 series, published under the general title *Instrument transformers*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

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INTRODUCTION

Since the publication of IEC 60044-6:1992[1], *Requirements for protective current transformers for transient performance*, the area of application of this kind of current transformers has been extended. As a consequence, the theoretical background for the dimensioning according to electrical requirements has become much more complex. For IEC 61869-2 to remain as user-friendly as possible, the explanation of the background information has been transferred to this part of IEC 61869.

[1] Withdrawn and replaced by IEC 61869-2:2012.

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INSTRUMENT TRANSFORMERS –

Part 100: Guidance for application of current transformers in power system protection

1 Scope

This part of IEC 61869 is applicable to inductive protective current transformers meeting the requirements of the IEC 61869-2 standard.

It may help relay manufacturers, CT manufacturers and project engineers to understand how a CT responds to simplified or standardized short circuit signals. Therefore, it supplies advanced information to comprehend the definition of inductive current transformers as well as their requirements.

The document aims to provide information for the casual user as well as for the specialist. Where necessary, the level of abstraction is mentioned in the document. It also discusses the question about the responsibilities in the design process for current transformers.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60255 (all parts), *Measuring relays and protection equipment*

IEC 60909-0:2016, *Short circuit currents in three-phase a.c. systems – Calculation of currents*

IEC 61869-1:2007, *Instrument transformers – General requirements*

IEC 61869-2:2012, *Instrument transformers – Additional requirements for current transformers*

3 Terms and definitions and abbreviations

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 61869-1:2007 and IEC 61869-2:2012 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1.1
rated primary short circuit current
I_{psc}
r.m.s. value of the a.c. component of a transient primary short-circuit current on which the accuracy performance of a current transformer is based

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[SOURCE: IEC 61869-2:2012, 3.3.206]

3.1.2
rated short-time thermal current
I_{th}
maximum value of the primary current which a transformer will withstand for a specified short time without suffering harmful effects, the secondary winding being short-circuited

[SOURCE: IEC 60050-321:1986, 321-02-22; IEC 61869-2:2012, 3.3.203]

3.1.3
initial symmetrical short circuit current
I''_k
r.m.s. value of the a.c. symmetrical component of a prospective (available) short-circuit current, applicable at the instant of short circuit if the impedance remains at zero-time value

[SOURCE: IEC 60909-0:2001, 1.3.5]

Note 1 to entry: While I_{th} is a basic parameter of a plant and of its components, I_{psc} is an accuracy requirement, and has a determining influence on the saturation behaviour of a current transformer. The protection system will ensure tripping at a current I''_k, which is usually lower than I_{th}. Depending on the protection requirement, a current transformer may saturate much before reaching I''_k. Therefore, in certain cases, I_{psc} may be much lower than I''_k.

3.1.4
primary current
I_p
current flowing through the primary winding of a current transformer

3.1.5
secondary current
I_s
current flowing through the secondary winding of a current transformer

3.1.6
angular frequency
ω
angular frequency of the primary current

3.1.7
time
t
time

3.1.8
phase angle of the system short circuit impedance
φ
phase angle of the system short circuit impedance

3.1.9
fault inception angle
γ
inception angle of the primary short circuit, being 180° at voltage maximum (see Figure 1)

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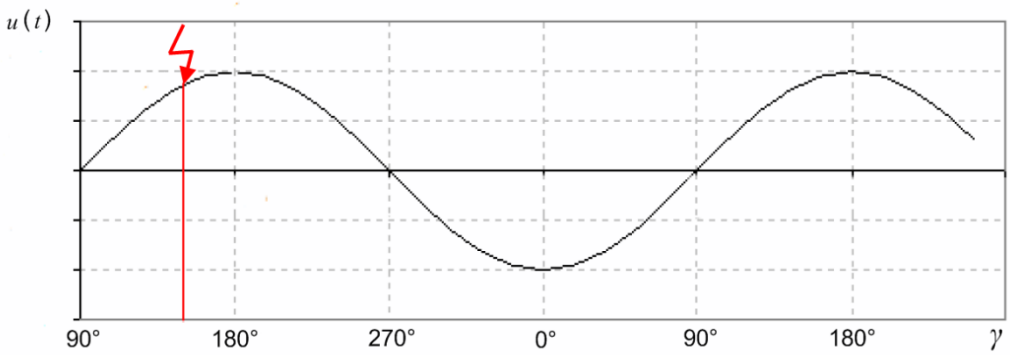

Key

u primary voltage

γ fault inception angle

Figure 1 – Definition of the fault inception angle γ

3.1.10
minimum fault inception angle
γ_m
lowest value of fault inception angle γ to be considered in the design of a current transformer

3.1.11
alternative definition of fault inception angle
θ
inception angle of the primary short circuit, defined as $\gamma - \varphi$

3.2 Index of abbreviations

This table comprises Table 3.7 of IEC 61869-2:2012, complemented with the terms and definitions given in 3.1.1 to 3.1.11.

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	frequency
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
I''_k	Initial symmetrical short circuit current
$\hat{I}_{al}$	peak value of the exciting secondary current at E_{al}
I_{cth}	rated continuous thermal current

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I_{dyn}	rated dynamic current
I_e	exciting current
I_{PL}	rated instrument limit primary current
I_p	primary current
I_{pr}	rated primary current
I_{psc}	rated primary short circuit current
I_s	secondary current
I_{sr}	rated secondary current
IT	Instrument Transformer
I_{th}	rated short-time thermal current
i_ε	instantaneous error current
k	actual transformation ratio
k_r	rated transformation ratio
K_R	remanence factor
K_{ssc}	rated symmetrical short circuit current factor
K_{td}	transient dimensioning factor
K_{tf}	transient factor
K_x	dimensioning factor
L_{ct}	non-linear inductance of a current transformer
L_m	linearized magnetizing inductance of a current transformer
L1,L2,L3	designation of the phases in the electrical three-phase system
n_s	number of secondary turns
R_b	rated resistive burden
R_{ct}	secondary winding resistance
R_s	secondary loop resistance
S_r	rated output
t	time
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	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
$\Delta\varphi$	phase displacement
ε	ratio error
ε_c	composite error
$\hat{\varepsilon}$	peak value of instananeous error

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$\hat{\varepsilon}_{ac}$	peak value of alternating error component
φ	phase angle of the system short circuit impedance
γ	fault inception angle
γ_{m}	minimum fault inception angle
θ	alternative definition of fault inception angle
ψ	secondary linked magnetic flux in the current transformer core
ψ_{r}	remanent flux
ψ_{sat}	saturation flux
ω	angular frequency

4 Responsibilities in the current transformer design process

4.1 History

The IEC 60044-6 standard “Instrument transformers – Part 6: Requirements for protective current transformers for transient performance" was introduced in 1992 (at that time as IEC 44-6). It was the first standard that considered the transient performance of protective CT.

In the well-known P-class, the usually indispensable over-dimensioning due to the primary DC component has to be “hidden” in the accuracy limit factor or in the burden.

The definition of the new classes TPX, TPY, and TPZ was strongly “cycle-oriented”, defining all necessary parameters of a C-O and of a C-O-C-O cycle. These classes allowed the shifting of responsibility for the calculation of the over-dimensioning due to the primary DC component (represented by the “transient factor” K_{td}, nowadays called “transient dimensioning factor”) to the CT manufacturer.

The transient performance classes never became widely accepted by different reasons:

– Their specification by duty cycles (and time to accuracy limit if necessary) is much more complex than the conventional classes 5P and 10P, which were originally foreseen for electromechanical relays.
– The duty cycle definition does no longer reflect the actual criteria for defining the overdimensioning factors.

Nowadays, it is common practice that the relay developers stipulate the required overdimensioning of the protection current transformers, taking into account the wave form of the primary signal as well as their own protection requirements.

When IEC 60044-6 was integrated in IEC 61869-2, it was taken into account that the cycle definition plays a declining role, as the aspects explained above have to be considered. Therefore, the definition of transient performance was extended by allowing the direct definition of the transient dimensioning factor K_{td} instead of the cycle parameters. This new way of specification is easy and similar to that of the well-known P-classes. One intention of this technical report is to explain such possible alternative specifications for several critical applications.

4.2 Subdivision of the current transformer design process

In modern digital relays, the decision-making time has decreased continuously as a result of increasing sampling rates and by refining the protection algorithms. As a consequence, the required saturation-free time of the current transformers has been reduced correspondingly.

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This leads to smaller CT cores, what is in line with the development of modern compact gas-insulated switchgears. Furthermore, some of the algorithms apply Fourier and r.m.s. filtering of the dynamic CT current signal. As a consequence, the relays react more 'smoothly' to high currents with possible saturation. For these reasons, the required CT performance and final core size cannot be expressed solely by the initial saturation time and one simple analytical formula.

Therefore, it is recommended that the relay developers first use analytical formulae for an initial consideration. In a second step, they may test their algorithms with a simulation model of the CT core and publish the requirements in terms of simple parameters (e.g. over-dimensioning factor, transient dimensioning factor, etc.) for significant worst case fault scenarios in the protection relay manual (or other documents). During the project engineering phase, the published requirements are applied to concrete cases and the hereby verified class parameters are communicated to the CT manufacturer.

For backward compatibility to IEC 60044-6, the transient factor K_{tf} – analytically calculated from parameters such as time to accuracy limit t'_{al}, duty cycle, etc. – may be applied directly as transient dimensioning factor K_{td} without further protection relay test. This way is not recommended, but may be chosen in situations where the design responsibility is not delegated entirely to the relay manufacturer.

The procedures used to determine the transient dimensioning factor K_{td} on the basis of protection rules can be considered to be the specific know-how of relay specialists, and are not part of this technical report.

In a complementary manner, this report highlights the path from the cycle definition, which still has certain significance, to the definition of a transient dimensioning factor. The analytical formulae in this technical report are extended and diversified. As a consequence, they look much more complex than in IEC 60044-6. But the intention is that they are only applied by a few protection relay developers who then provide the project engineers and the CT manufacturers with design parameters which permit a simpler CT sizing procedure to be applied.

5 Basic theoretical equations for transient designing

5.1 Electrical circuit

5.1.1 General

As an introduction, Figure 2 presents a simplified interaction chain between the main components of the protection circuit: network currents are measured by current transformers, and the values are transmitted to the protection devices.

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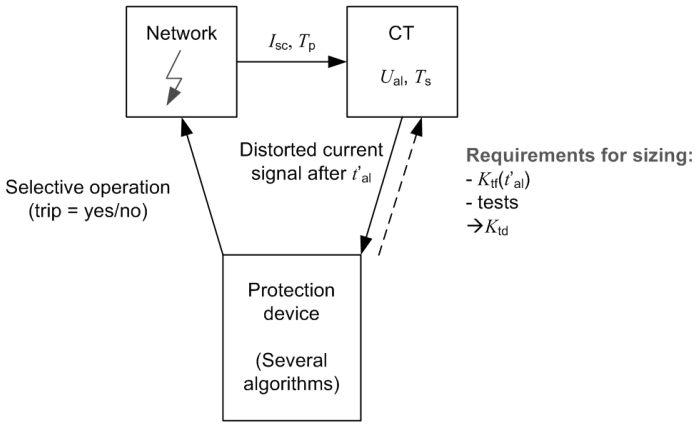

Key

I_{sc}	primary short circuit current
K_{td}	transient dimensioning factor
K_{tf}	transient factor
T_p	specified primary time constant
T_s	secondary loop time constant
t'_{al}	specified time to accuracy limit in the first fault
U_{al}	rated equivalent limiting secondary voltage

Figure 2 – Components of protection circuit

Protection relay development:

– Find out worst case scenarios in typical networks for short circuit currents with I_{sc}, T_p.
– Define needed K_{ssc} and start with analytical calculation of $K_{tf}(t'_{al}, t''_{al}, t', t_{fr}, T_p, T_s)$.
– Verify first results by tests: Numerical CT simulation (software) and protection relay (hardware). If necessary, correct K_{ssc} and K_{tf} and include safety factors.
– Publish results in protection relay manual for the significant worst case scenario(s).
Now the transient factor K_{tf} (from protection point of view) becomes the transient dimensioning factor K_{td} (for CT sizing and construction point of view), where K_{td} includes safety margins M: $K_{td} = K_{tf} * M$.
After the tests, K_{td} does not need to have correlations with the original K_{tf} if tests show different behaviour.

NOTE Protection relay manufacturers normally perform tests with complete protection IEDs (software and hardware) to decide and publish the CT requirements as a total transient dimensioning factor K_{tot}. Depending on the protection function and the application, this factor considers the minimum necessary time to saturation, the remanence factor and also others. In these tests, the fault inception angle covers the complete defined range and is not limited to only the theoretical worst case. For more information, refer to 8.2.

Project engineering:

– Consider the protection relay manual for CT requirements.
– Find the worst case scenarios in the projected network with short circuit currents with I_{sc}, T_p. Find out if these worst case scenarios are considered in the manual.
– Calculate the rated primary currents I_{pr}, K_{ssc}, burdens R_b, etc. and specify the needed CT parameters, applying the K_{td} from protection relay manual.
– The CT manufacturer applies the specified parameters without considering t'_{al}, t''_{al}, t', t_{fr}, T_p, etc.

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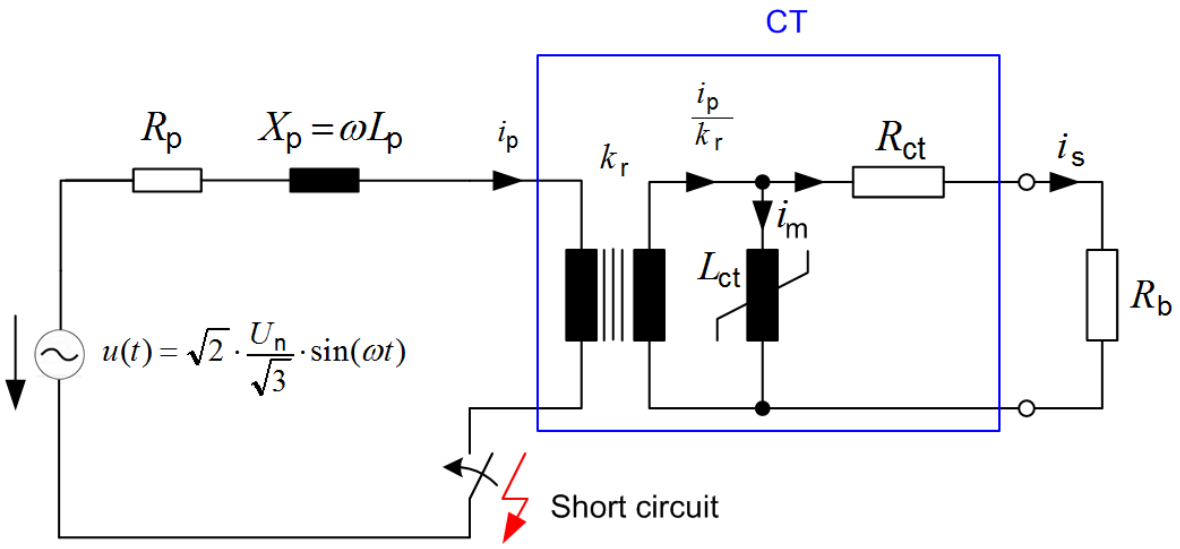
Backward compatibility to IEC 60044-6:

Alternatively, K_{tf} (t'_{al}, t''_{al}, t', t_{fr}, T_p, T_s) can be calculated and applied directly as K_{td} without tests, where the responsibility lies with the involved project parties.

– Calculate rated primary currents I_{pr}, K_{ssc}, burdens R_b, etc., and specify the needed CT parameters (class, t'_{al}, t''_{al}, t', t_{fr}, T_p).
– The CT manufacturer may calculate K_{td} = K_{tf} as a function of t'_{al}, t''_{al}, t', t_{fr}, T_p.

The more detailed electrical circuit (Figure 3), which has to be considered for current transformer designing, contains

– the primary network represented by the equivalent short circuit diagram;
– the current transformer (CT);
– the protection device as burden.



Time constant of d.c. component of primary short circuit current: $T_p = \frac{L_p}{R_p} = \frac{X_p}{\omega R_p}$

Key

i_p primary current
i_m excitation current
i_s secondary current
k_r rated transformation ratio
L_{ct} nonlinear inductance of the current transformer
L_p inductance of the primary circuit
R_b rated resistive burden
R_{ct} secondary winding resistance
R_p resistive part of the impedance of the primary circuit
u primary voltage
U_n phase-to-phase operating voltage
T_p specified primary time constant
X_p inductive part of the impedance of the primary circuit
ω angular frequency

Figure 3 – Entire electrical circuit

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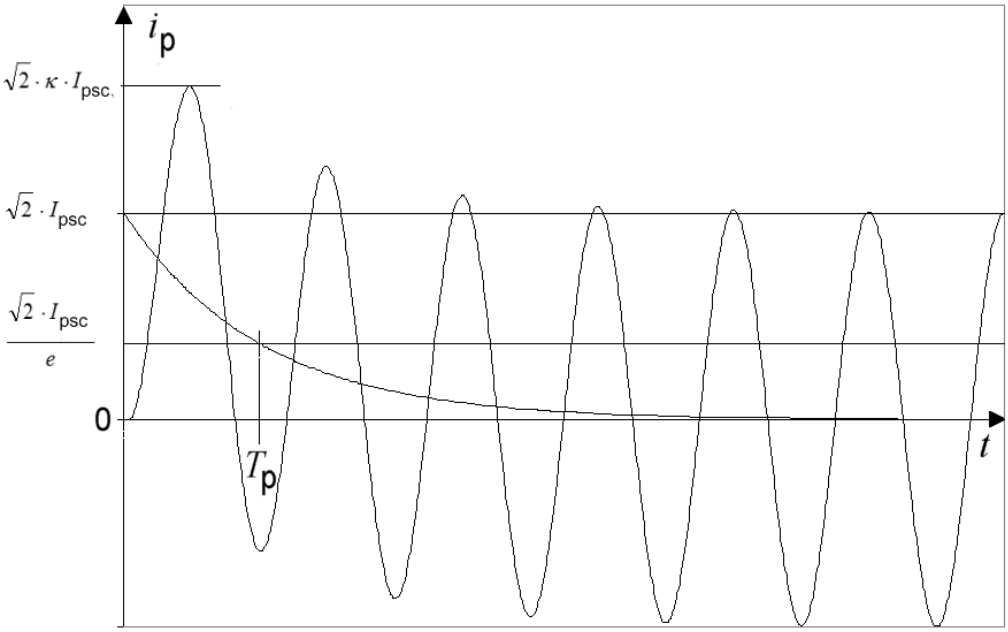
The primary equivalent short circuit diagram represents the whole primary circuit according to IEC 60909-0:2001 and introduces the primary short circuit current $i_p(t)$, composed of an AC component and a DC component, which is declining exponentially with a primary time constant T_p (see Figure 4). For simplification, only the far-from-generator short circuit is treated here.



Key

i_p primary current

I_{psc} rated primary short circuit current

e base of natural logarithm

t time

T_p specified primary time constant

κ factor for the calculation of the peak short circuit current according to IEC 60909-0:2001. It attains its maximum value $\kappa = 2$ if T_p tends towards ∞.

Figure 4 – Primary short circuit current

In IEC 61869-2, the standard value for I_{dyn} is defined as 2,5 I_{th}. This value does not correspond strictly to the worst-case value of $\sqrt{2} \cdot \kappa \cdot I_{psc}$, which is 2,83 $\cdot I_{psc}$.

EXAMPLE At 50 Hz, the factor κ = 2,5 / √2 = 1,77 corresponds to an X_p / R_p value of 11 and a T_p value of 35 ms only.

5.1.2 Current transformer

The current transformer is represented by the current ratio k_r, the non-linear inductance L_{ct} with magnetizing curve and winding resistance R_{ct}.

Figure 5 shows the time dependent magnetizing curve of a typical CT core as flux $\psi(t)$ in the non-linear inductance L_{ct} versus magnetizing current $i_m(t)$ (see Figure 3) gained by measurement with an indirect test (primary side with open terminals, excitation and measurement from secondary terminals). If a voltage of rated frequency (e.g. 50 Hz) is applied, the grey curves are the result for steady-state excitations with different magnitudes. If the excitation is performed with DC voltage (see DC method in IEC 61869-2) starting with a demagnetised CT core, the red curve is the result. If the excitation with DC voltage starts with positive remanence, the blue initial curve is the result (see also Figure 51). The main

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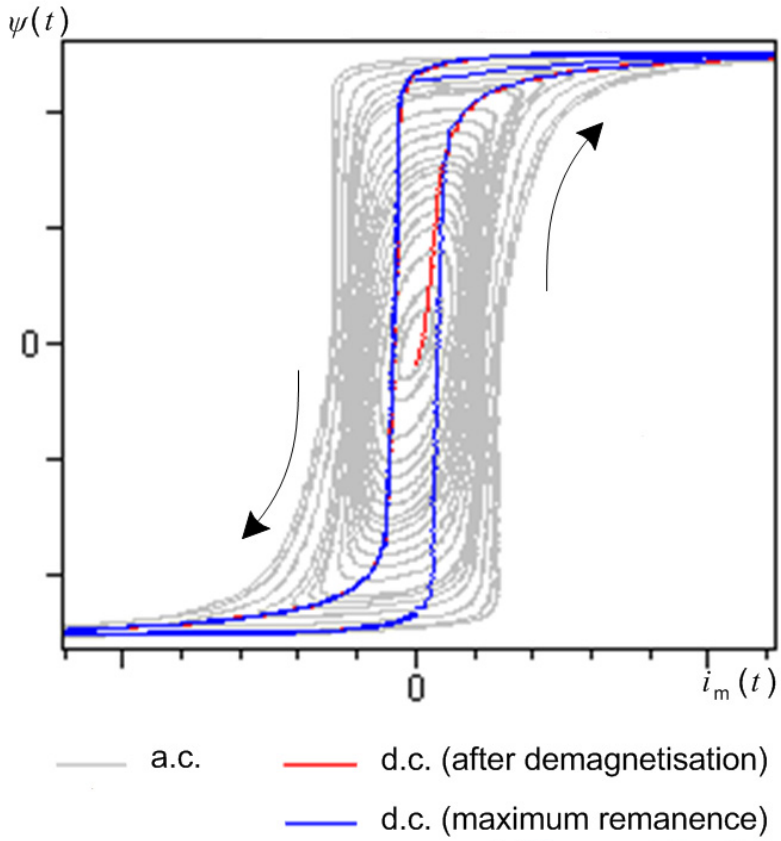
difference between the DC and the AC curve is mainly caused by higher eddy currents in the AC case.

Such measurements show the magnetizing curve:

- with a steep linear part which is limited by magnetic saturation,
- with ascending and descending curves which are shifted because of hysteresis.

The result is an ambiguous curve, which depends on frequency and antecedence.



Key

ψ magnetic flux in the current transformer core

i_m magnetizing current

t time

Figure 5 – Non-linear flux of L_{ct}

Such a non-linear physical behaviour is very difficult to describe, so simplifications are necessary. Therefore, at first the hysteresis is neglected and the magnetizing characteristic is simplified to an origin curve with its saturation (dotted line in Figure 6).

In a second step, this curve can be typically represented by a simplified model with one single constant inductance L_m as the slope of the linear part of the magnetizing curve (Figure 6), so the saturation is neglected too (solid red line in Figure 6).

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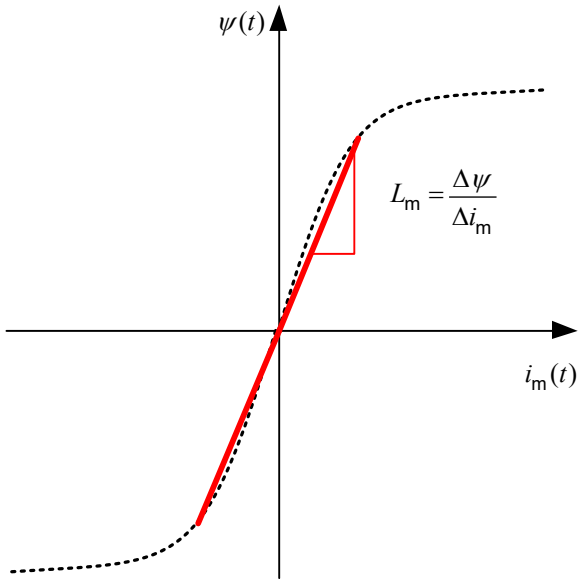

Key

ψ magnetic flux in the current transformer core

i_m magnetizing current

L_m linearized inductance

t time

Figure 6 – Linearized magnetizing inductance of a current transformer

With such a simplified linear analytical theory, the magnetic behaviour is only described correctly

– for CT demagnetised cores (no remanence), or gapped cores where remanence is significantly reduced,

– up to the time of the first saturation or up to the accuracy limit t'_{al}.

Two simplification steps are therefore needed:

– neglecting the hysteresis phenomena,

– neglecting saturation.

5.2 Transient behaviour

5.2.1 General

As an example, in Figure 7, the short circuit behaviour is simulated with a non-linear model, considering the following configuration:

Current transformer: 500/1 A, 2,5 VA, 5P20, R_{ct} = 2 Ω
real burden = rated burden

Short circuit: I_{psc} = 10 kA = 20 × I_{pr}, T_p = 50 ms

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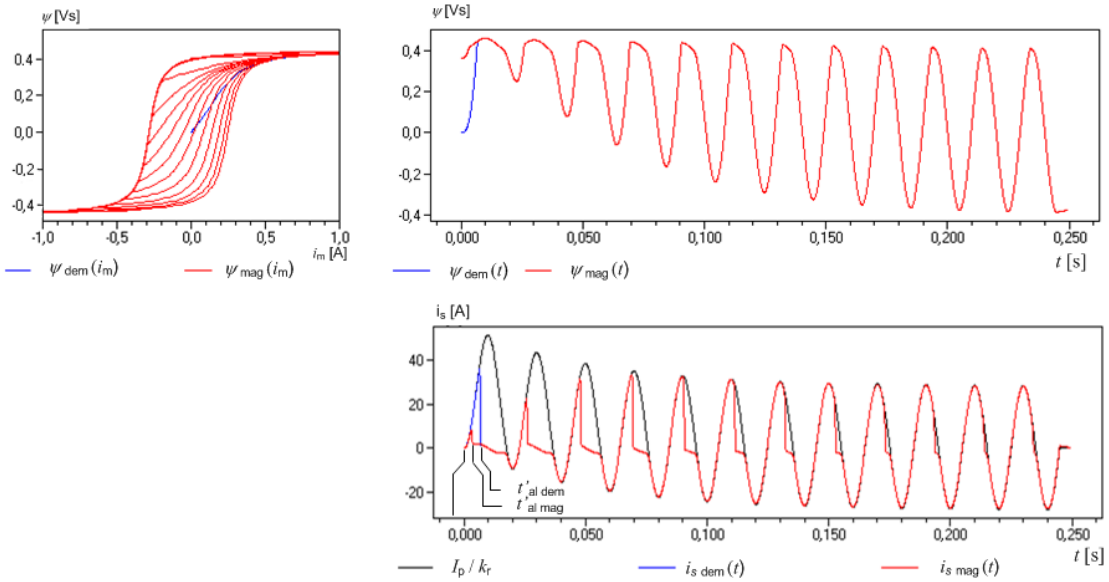

Key

I_p	primary current
$i_{s\ dem}$	secondary current in an initially demagnetized core
$i_{s\ mag}$	secondary current in an initially magnetized core
k_r	rated transformation ratio
t	time
$t'_{al\ dem}$	maximum possible t'_{al} value in an initially demagnetized core
$t'_{al\ mag}$	maximum possible t'_{al} value in an initially magnetized core
ψ	magnetic flux in the current transformer core
ψ_{dem}	magnetic flux in an initially demagnetized core
ψ_{mag}	magnetic flux in an initially magnetized core

Figure 7 – Simulated short circuit behaviour with non-linear model

The simulation in Figure 7 is performed in phase L1 with a maximum DC component and with an AC component I''_k of 20 times the rated primary current I_{pr}. This CT core with protection class 5P20 is correctly dimensioned for the symmetrical steady state case, when the DC component has declined. Saturation occurs, however, shortly after fault inception due to the DC component, regardless of whether the core is demagnetised or not. Therefore the transient performance CT classes TPX, TPY, TPZ with an additional transient dimensioning factor K_{td} were created.

The simulation starts with a demagnetized CT core (blue lines) as well as with a saturated core (90 % remanence, red lines). The left image shows the magnetic flux $\psi(t)$ versus magnetizing current $i_m(t)$. It shows hysteresis and saturation. The magnetic flux can only alternate between the positive and negative limits due to saturation. Starting without remanence (demagnetised case), the first saturation is reached at $t'_{al,dem}$ = 6,5 ms. With remanence, the first saturation is reached much earlier at $t'_{al,mag}$ = 3 ms. In some cases, this could lead to maltrips by some protection relays, e.g. differential protection function. In other cases, e.g. overcurrent protection, it does not result in a maltrip. It may however result in a slower reaction of the protection system.

Negative effects for certain protection functions due to remanence can be avoided easily by application of gapped CT cores. In this case, hysteresis is neglected for simplification purposes (first simplification step).

From the point of view of protection functions, the requirement for the signal quality of the CT secondary current is given by the time to accuracy limit t'_{al}. This value is defined as the

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minimum saturation-free time interval, beginning at the first fault inception. Within this time span, the magnetic flux shall be in the linear range of the magnetizing curve, and the protection function shall decide whether to trip or not. The time after the first saturation is then out of the scope in this consideration. With the required time t'_{al}, the transient factor K_{tf} and the transient dimensioning factor K_{td} are calculated and/or determined by testing with the protection relay respectively (see Clause 9). Therefore, for such purposes, only the linear range of the magnetizing curve is interested. The physical problem can be further reduced and simplified to a linear one by neglecting the saturation too (second simplification step). With the constant inductance L_{ct} in the linear problem, the differential Equation (1) can be solved with acceptable mathematical complexity.

5.2.2 Fault inception angle

In the simulation of Figure 7 with a single phase and demagnetised core, a switching angle is chosen to achieve the highest DC component. Under this understanding, a time to accuracy limit t'_{al} of approximately 6,5 ms is obtained.

It shall be kept in mind that this t'_{al} value is valid for one phase only. In cases of multi-phase short circuits, other phases shall also be considered. The above simulation was complemented correspondingly, applying the same preconditions.

In Figure 8, the DC component of phase L1 is at its highest value, while the DC component of other phases L2, L3 is considerably lower. Despite this fact, one can observe that saturation occurs earlier in phase L2 ($t'_{al} \cong 5$ ms) than in phase L1. Therefore, further detailed considerations of the variation of the fault inception or switching angle are necessary.

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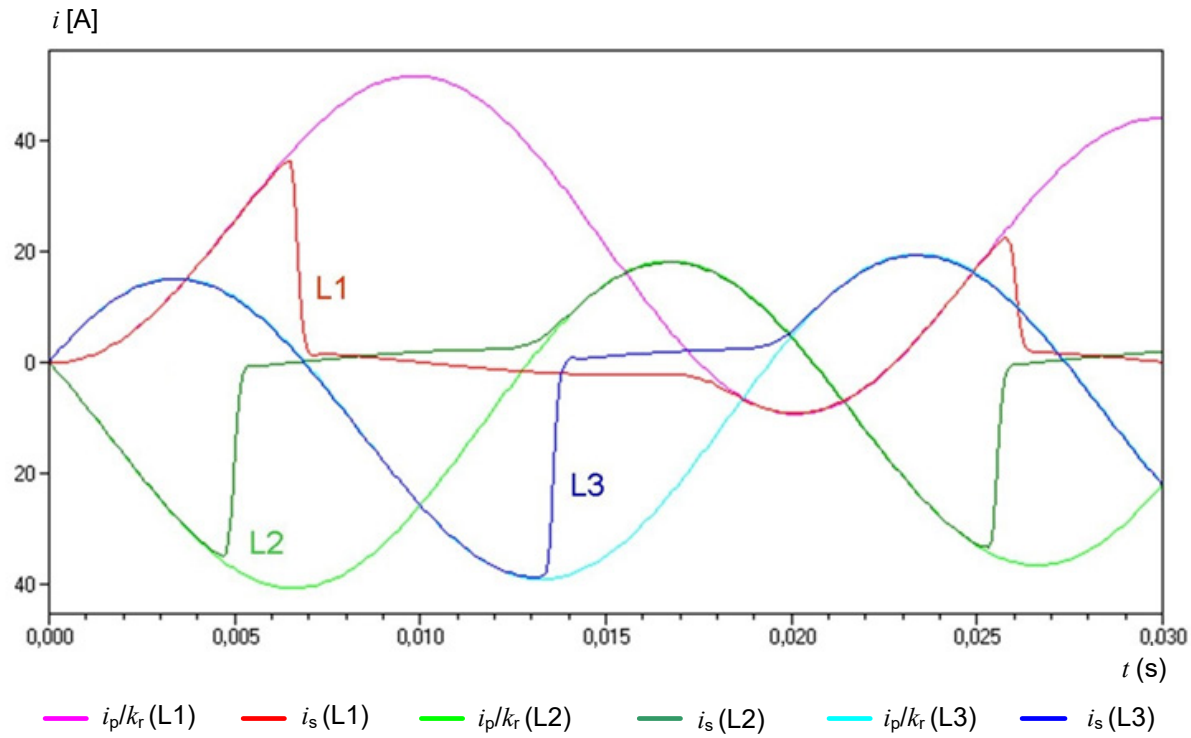

Key

i	current
i_p	primary current
i_s	secondary current
k_r	rated transformation ratio
t	time

Figure 8 – Three-phase short circuit behaviour

5.2.3 Differential equation

Based on the two simplifications above, with the constant inductance L_{ct} in the linear physical problem, the linear differential equation of the first order is formulated for the magnetizing current i_m and the primary current $i_p(t)$ (see Figure 3):

$$T_s \frac{di_m(t)}{dt} + i_m(t) = i_p(t) \qquad i_m(0) = 0 \tag{1}$$

The magnetic behaviour can then be described by the analytical formula for the secondary linked flux:

$$\psi(t) = L_{ct}\, i_m(t) \tag{2}$$

The flux contains a transient part (due to the DC component of the primary short circuit current), and a steady state AC part. Figure 9 presents these parts in a simplified form.

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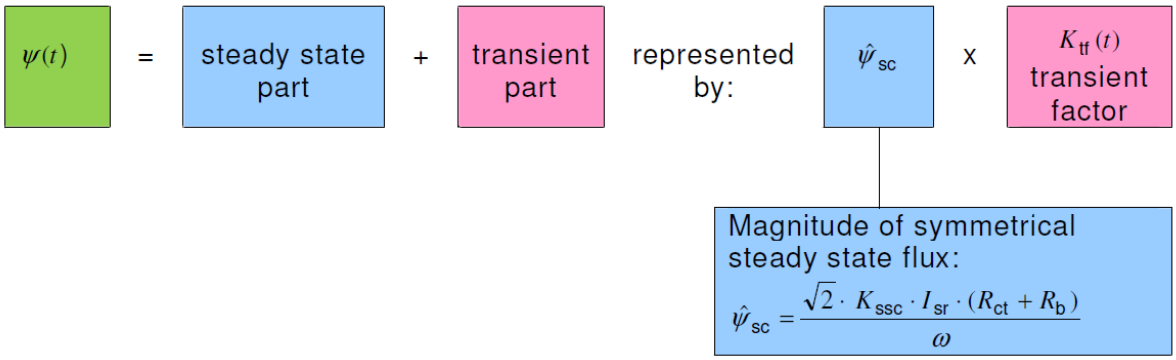

Key

I_{sr}	rated secondary current
K_{tf}	transient factor
K_{ssc}	rated symmetrical short circuit current factor
R_b	rated resistive burden
R_{ct}	secondary winding resistance
t	time
ψ	secondary linked flux
$\hat{\psi}_{sc}$	peak value of the secondary linked flux in the current transformer core at symmetrical short circuit condition
ω	angular frequency

Figure 9 – Composition of flux

The transient part with two time constants T_p and T_s is represented by the time-dependent transient factor $K_{tf}(t)$. This factor scales up the magnitude $\hat{\psi}_{sc}$ from the peak value of the AC component to the peak value of the transient curve.

As it will be shown below, $K_{tf}(t)$ is expressed by several formulae and represents only the magnetic linear theory. For transient performance, the physical requirement for the CT, resulting from the protection algorithms, can be expressed by the single parameter t'_{al} (time to accuracy limit). t'_{al} again is used to calculate K_{tf}, which defines the flux limit, up to which the CT core shall not saturate.

For the algorithms of modern protection devices, it is not sufficient just to provide the CT requirements as the only parameters, such as t'_{al}. In some cases, this value is not constant. It can be a function of further parameters, e.g. the magnitude of the fault current, its inception angle γ (determining the DC component, decaying with the primary time constant T_p) and the protection settings. Therefore it is recommended to test the protection relays with different CT sizes and significant worst-case conditions with a numerical non-linear CT model also containing hysteresis. The analytically calculated transient factor K_{tf} and the additional relay tests lead to the final transient dimensioning factor K_{td} of the CT, which leads to the rated equivalent limiting secondary e.m.f. E_{al} according to the definition in IEC 61869-2:2012, 3.4.237:

$$E_{al} = K_{ssc} \times K_{td} \times (R_{ct} + R_b) \times I_{sr} \tag{3}$$

In this regard, K_{td} differs from the definition in the previous standard: IEC 60044-6: The formulae in IEC 61869-2:2012 consider also very small time to accuracy limit values t'_{al}, as well as the worst-case fault inception angles resulting from the requirements of modern protection relays.

They provide a basis for the relay tests, which should be performed by protection manufacturers in order to provide simpler CT requirements in the relay manuals. These simpler requirements have to be applied by end users in projects and CT designing. In this regard, the technical responsibility for CT requirements is shifted somewhat away from the

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end users toward the relay manufacturers and thus the requirements become simpler for the end user.

The protection device as the burden of the CT measures low operational currents as well as higher overcurrents at the highest desirable accuracy. The input signal of the protection device is the CT secondary current, which should correspond to the primary current. In modern protection devices, multiple measuring and protection algorithms are implemented, which require different accuracy classes and transient performances from the CT, where a compromise has to be found between CT size, maximum accuracy and the best performance.

6 Duty cycles

6.1 Duty cycle C – O

6.1.1 General

The following equations refer to a C – O duty cycle. The general expression for the instantaneous value of a primary short circuit current may be defined as:

$$i_{sc}(t) = \sqrt{2}\ I_{psc}\left[e^{-t/T_p}\cos(\gamma-\varphi) - \cos(\omega\, t + \gamma - \varphi)\right] \tag{4}$$

with the equivalent voltage source of the primary short circuit

$$u(t) = -U_{max}\cos(\omega\, t + \gamma) \tag{5}$$

where

I_{psc} is the r.m.s. value of primary symmetrical short circuit current $I_{psc} = K_{ssc} \cdot I_{pr}$;

$T_p = \dfrac{L_p}{R_p}$ is the primary time constant;

γ is the switching angle or fault inception angle (see 3.1.9);

$= \arctan\dfrac{X_p}{R_p} = \arctan(\omega\, T_p)$ is the phase angle of the system short circuit impedance.

For simplification purposes, the fault inception angle and system short circuit impedance angle can be summed up into one single angle θ, which makes the calculation easier to understand:

$$\theta = \gamma - \varphi \tag{6}$$

$$i_{sc}(t) = \sqrt{2}\ I_{psc}\left[\mathrm{e}^{-t/T_p}\cos(\theta) - \cos(\omega\, t + \theta)\right] \tag{7}$$

The angles θ and γ both describe the possibility of varying the fault inception angle and therefore can be applied alternatively, but according to their definition.

Figure 10 shows two typical primary short circuit currents:

a) The red one occurs with a fault inception angle of $\gamma = 90°$ which leads to the highest peak current and the highest peak of secondary linked flux for long t'_{al} (Figure 11).

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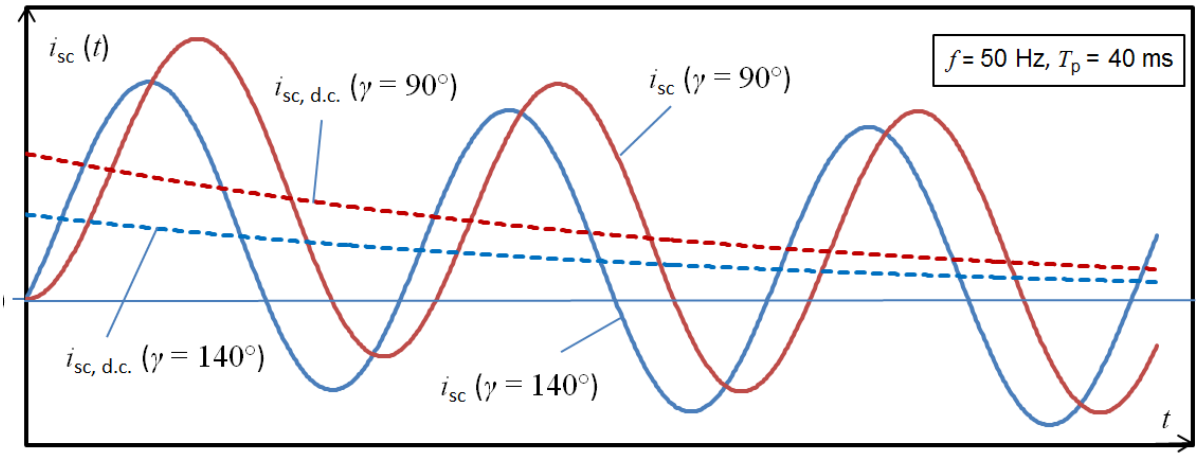
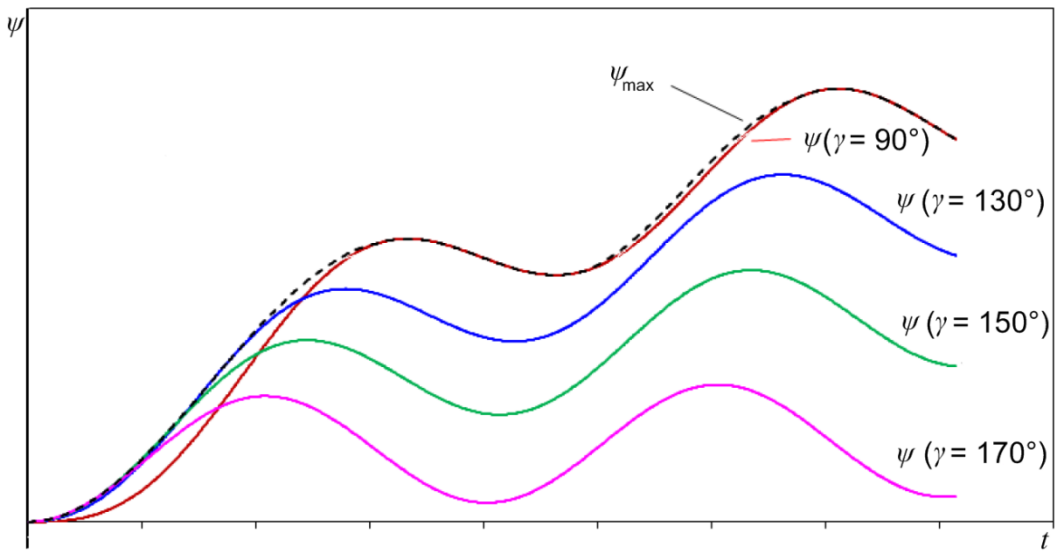
b) The blue one occurs with γ = 140° which leads to a lower asymmetry. These cases are important for short t'_{al}, because, during the first half cycle, the current and flux are temporarily higher than in the case of γ = 90°.



Key

f	frequency
T_p	specified primary time constant
γ	fault inception angle
i_{sc}	instantaneous value of a primary short circuit current
$i_{sc,,d.c.}$	DC component of the instantaneous value of a primary short circuit current
t	time

Figure 10 – Short circuit current for two different fault inception angles



Key

t	time
γ	fault inception angle
ψ	secondary linked flux
ψ_{max}	highest possible flux value at a given time point, considering all fault inception angles γ in a defined range

Figure 11 – ψ_{max} as the curve of the highest flux values

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It is easier to evaluate and plot the formulae in the calculations described in 6.1.2 and 6.1.3 with a software tool. For the more complex formulae, the programming code is given in Annex A.

6.1.2 Fault inception angle

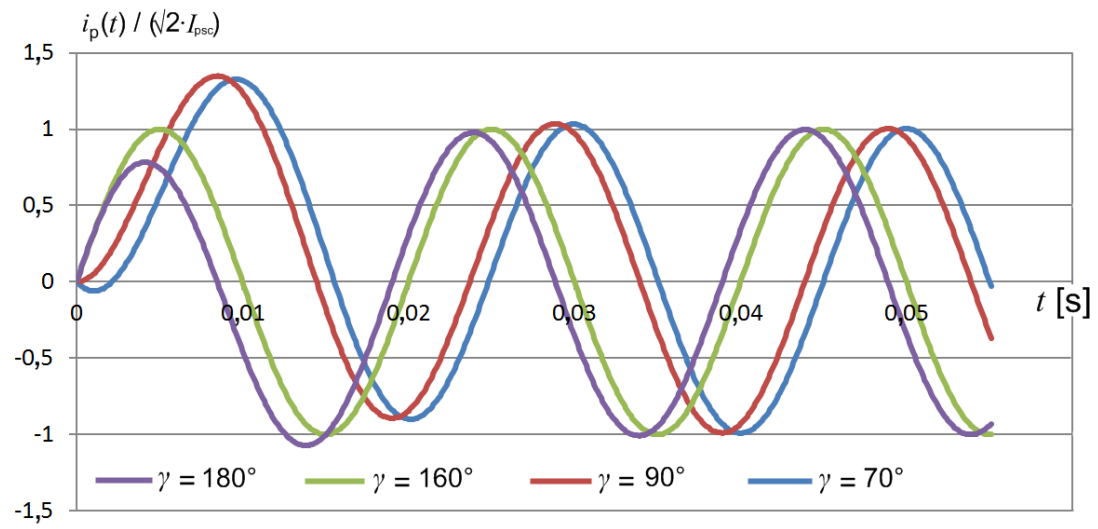
Table 1 shows the four significant cases of short circuit current inception angles (here described for positive current polarity only. The negative polarity occurs by inversion of the values at the origin point; all angles increased by 180°.

Table 1 – Four significant cases of short circuit current inception angles

Case no.	Meaning	θ condition	equivalent γ condition	example for φ = 70° (Figure 12)
1	maximum DC component	θ = 0°	$\gamma = \varphi$	γ = 70°
2	maximum peak of short circuit current: $\hat{i}_p = \sqrt{2}\cdot\kappa\cdot I_{psc}$ fault inception at voltage zero crossing	$\theta = 90° - \varphi$	γ = 90°	γ = 90°
3	no DC component	θ = 90°	$\gamma = 90° + \varphi$	γ = 160°
4	fault inception at voltage maximum	$\theta = 180° - \varphi$	γ = 180°	γ = 180°

Case 4 is the one with the highest initial flux increase, and therefore the worst-case for very small values of t'_{al}.

Figure 12 shows the current curves for these 4 cases. The phase angle φ of the system short circuit impedance has been chosen extremely low, in order to point out the differences between the different cases.



Key

i_p primary current

I_{psc} rated primary short circuit current

t time

γ fault inception angle

Figure 12 – Primary current curves for the 4 cases for 50 Hz and φ = 70°

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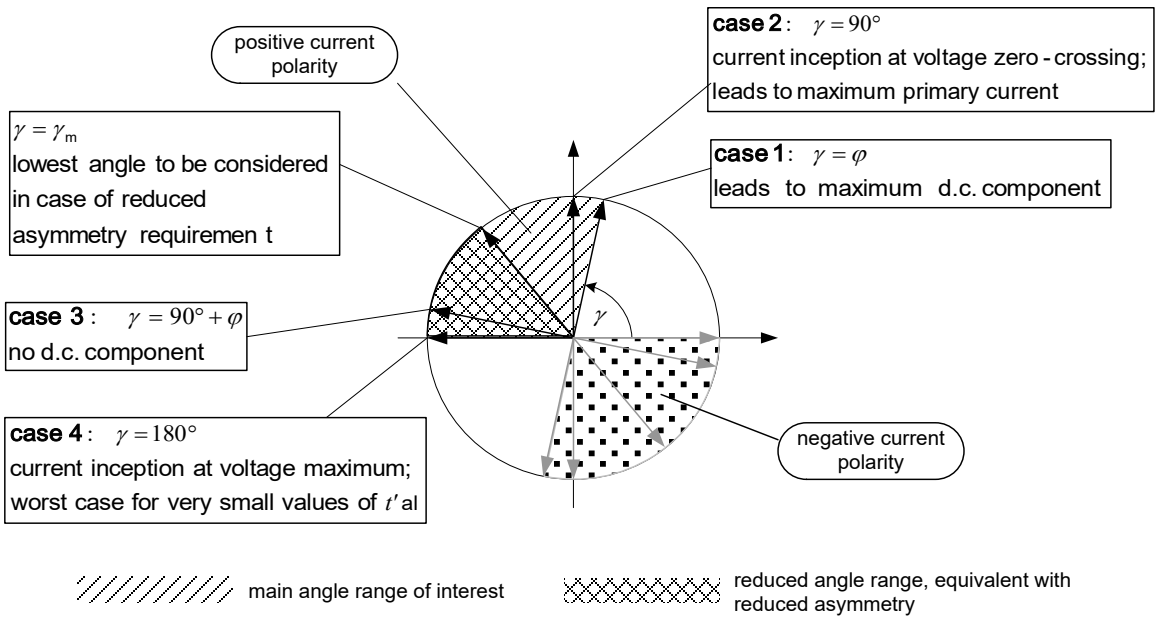
Figure 13 shows these four cases in a polar diagram.

γ_m is the lowest value of γ to be considered in the designing of the current transformer. The possible limiting of the range of the current inception angle is discussed in 6.1.4.



Key

γ_m lowest fault inception angle to be considered in case of a reduced asymmetry requirement

t'_{al} specified time to accuracy limit in the first fault

γ fault inception angle

φ phase angle of the system short circuit impedance

Figure 13 – Four significant cases of short circuit currents with impact on magnetic saturation of current transformers

6.1.3 Transient factor K_{tf} and transient dimensioning factor K_{td}

6.1.3.1 General

The transient dimensioning factor K_{td} is the final parameter for the core designing and is given on the rating plate. It can be calculated as different functions of the transient factor K_{tf} as given in the equations below and later shown in Figure 14.

In 6.1.3, the determination of the transient dimensioning factor K_{td} is discussed under the condition that every fault inception angle γ may occur. In some special cases, a reduced range of fault inception angle (expressed by γ_m) may lead to a reduced factor K_{td} (see 6.1.4).

6.1.3.2 Equations for K_{tf}

The transient factor K_{tf} given in this section is derived from the differential equation for the equivalent circuit (Figure 3) with the constant inductance L_{ct} of the current transformer core, with an ohmic burden and without consideration of hysteresis, losses and remanence. With the exact solution $i_\varepsilon(t)$ of the differential equation, the transient factor $K_{tf}(t)$ is gained from the magnetic flux ratio

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$$K_{\mathrm{tf}}(t) = \frac{\psi(t)}{\hat{\psi}_{\mathrm{sc}}} = \frac{L_{\mathrm{ct}}\, i_{\varepsilon}(t)}{\hat{\psi}_{\mathrm{sc}}} \tag{8}$$

where

$\hat{\psi}_{\mathrm{sc}}$ is the peak value of the AC component of the flux during short circuit;

L_{ct} is the linearized inductance (see Figure 6).

Similarly to the magnetic flux, K_{tf} also depends on time and, finally, on the time to accuracy limit t'_{al} as required by the protection system. When calculating using the linear inductivity, the solution is only valid up to the first saturation of the current transformer.

Strictly speaking, the time to accuracy limit t'_{al} is the only physical parameter which acts as an interface between the protection relay and the current transformer and is decisive for the proper and stable operation of the relay. In many cases, t'_{al} is assumed to be constant, independent of other physical parameters. But, in some cases, due to complex algorithms and functions, the protection system may require a t'_{al} which is not constant and which depends on different parameters of the short circuit current. Therefore, the transient dimensioning factor K_{td} can also be tested and defined directly by the manufacturer of the protection system according to the physical basics described in this technical report. For logical reasons, the perfect function of the protection is then the protection manufacturer's responsibility.

The actual transient K_{tf} containing the AC component is

$$K_{\mathrm{tf}}(t) = \omega\, T_{\mathrm{s}} \left[\frac{\mathrm{e}^{-t/T_{\mathrm{s}}}}{T_{\mathrm{p}} - T_{\mathrm{s}}} \left(\cos(\theta)\, T_{\mathrm{p}}\, \mathrm{e}^{(t/T_{\mathrm{s}} - t/T_{\mathrm{p}})} + \frac{\omega\, T_{\mathrm{s}} \sin(\theta)\left(T_{\mathrm{p}} - T_{\mathrm{s}}\right) - T_{\mathrm{s}} \cos(\theta)\left(1 + \omega^2\, T_{\mathrm{s}}\, T_{\mathrm{p}}\right)}{1 + \omega^2\, T_{\mathrm{s}}^2} \right) - \frac{\omega\, T_{\mathrm{s}} \sin(\omega\, t + \theta) + \cos(\omega\, t + \theta)}{1 + \omega^2\, T_{\mathrm{s}}^2} \right] \tag{9}$$

A simplified formula for K_{tf} exists as follows:

$$K_{\mathrm{tf}}(t) = \frac{\omega T_{\mathrm{s}} T_{\mathrm{p}}}{T_{\mathrm{p}} - T_{\mathrm{s}}} \cos(\theta)\left(\mathrm{e}^{-t/T_{\mathrm{p}}} - \mathrm{e}^{-t/T_{\mathrm{s}}}\right) + \sin(\theta)\mathrm{e}^{-t/T_{\mathrm{s}}} - \sin(\omega t + \theta) \tag{10}$$

For extremely low parameters of T_{p}, T_{s}, and t'_{al}, the K_{tf}. value of Equation (10) is lower than the one of Equation (9), and therefore not on the safe side.

With θ = 0 (equivalent to $\gamma = \varphi$), Equation (10) leads to the well-known formula in the former IEC 60044-6, which is given here for backward compatibility (with index "dc"):

$$K_{\mathrm{tf,dc}}(t) = K_{\mathrm{tf}}(\theta = 0°) = \frac{\omega T_{\mathrm{p}} T_{\mathrm{s}}}{T_{\mathrm{p}} - T_{\mathrm{s}}}\left(\mathrm{e}^{-t/T_{\mathrm{p}}} - \mathrm{e}^{-t/T_{\mathrm{s}}}\right) - \sin(\omega\, t) \tag{11}$$

When calculating the transient factor necessary for designing purposes, Equation (9) is modified by assuming the worst case condition $\sin(\omega t) = -1$. The result is the envelope curve K_{tfp} for peak values of the transient factor.

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$$K_{\text{tfp}}(t) = \omega\, T_{\text{s}} \left[\frac{\mathrm{e}^{-t/T_{\text{s}}}}{T_{\text{p}} - T_{S}} \left(\cos(\theta)\, T_{\text{p}}\, \mathrm{e}^{(t/T_{\text{s}} - t/T_{\text{p}})} + \frac{\omega\, T_{\text{s}} \sin(\theta) \left(T_{\text{p}} - T_{\text{s}}\right) - T_{\text{s}} \cos(\theta) \left(1 + \omega^2\, T_{\text{s}}\, T_{\text{p}}\right)}{1 + \omega^2\, T_{\text{s}}^2} \right) + \frac{1 + \omega\, T_{\text{s}}}{1 + \omega^2\, T_{\text{s}}^2} \right] \tag{12}$$

A simplified formula is given in Equation (13):

$$K_{\text{tfp}}(t) = \frac{\omega T_{\text{s}} T_{\text{p}}}{T_{\text{p}} - T_{\text{s}}} \cos(\theta) \left(\mathrm{e}^{-t/T_{\text{p}}} - \mathrm{e}^{-t/T_{\text{s}}} \right) + \sin(\theta) \mathrm{e}^{-t/T_{\text{s}}} + 1 \tag{13}$$

With θ = 0, we get the formula for K_{td} in IEC 60044-6, now indicated as $K_{\text{tfp,dc}}$ (14):

$$K_{\text{tfp,dc}}(t) = \frac{\omega T_{\text{p}} T_{\text{s}}}{T_{\text{p}} - T_{\text{s}}} \left(\mathrm{e}^{-t/T_{\text{p}}} - \mathrm{e}^{-t/T_{\text{s}}} \right) + 1 \tag{14}$$

The maximum values occur at the time $t = t_{\text{tfp,max}}$ (15) and $t = t_{\text{tfp,dc,max}}$ (16):

$$t_{\text{tfp,max}} = \frac{T_{\text{p}} T_{\text{s}}}{T_{\text{p}} - T_{\text{s}}} \ln \frac{\frac{T_{\text{p}}}{T_{\text{s}}} \cos(\theta) + \frac{T_{\text{s}} - T_{\text{p}}}{\omega T_{\text{s}}^2} \sin(\theta)}{\cos(\theta)} \tag{15}$$

$$t_{\text{tfp,dc,max}} = \frac{T_{\text{p}}\, T_{\text{s}}}{T_{\text{p}} - T_{\text{s}}} \ln \frac{T_{\text{p}}}{T_{\text{s}}} \tag{16}$$

The corresponding values $K_{\text{tfp,max}}$ and $K_{\text{tfp,dc,max}}$ are given in Equations (17) and (18) as

$$K_{\text{tfp,max}} = \left(\omega T_{\text{p}} \cos(\theta) + \frac{T_{\text{p}} + T_{\text{s}}}{T_{\text{s}}} \sin(\theta) \right) \cdot \left[\frac{\frac{T_{\text{p}}}{T_{\text{s}}} \cos(\theta) + \frac{T_{\text{s}} - T_{\text{p}}}{\omega T_{\text{s}}^2} \sin(\theta)}{\cos(\theta)} \right]^{\frac{T_{\text{p}}}{T_{\text{s}} - T_{\text{p}}}} + 1 \tag{17}$$

$$K_{\text{tfp, dc, max}} = \omega\, T_{\text{p}} \left(\frac{T_{\text{p}}}{T_{\text{s}}} \right)^{\frac{T_{\text{p}}}{T_{\text{s}} - T_{\text{p}}}} + 1 \tag{18}$$

In Figure 14, curve $K_{\text{tf,}\psi\text{max}}$ is plotted as “overall transient factor”, that means as transient factor regarding all specified current inception angles. It is defined as the $\psi_{\text{max}}(t)$ curve (Figure 11) divided by the peak value of the steady-state flux $\hat{\psi}_{\text{sc}}$ (Figure 9). The behaviour of the upper envelope K_{tfp} of the curve $K_{\text{tf,}\psi\text{max}}$ leads to the definition of three time ranges described in 6.1.3.3 to 6.1.3.5.

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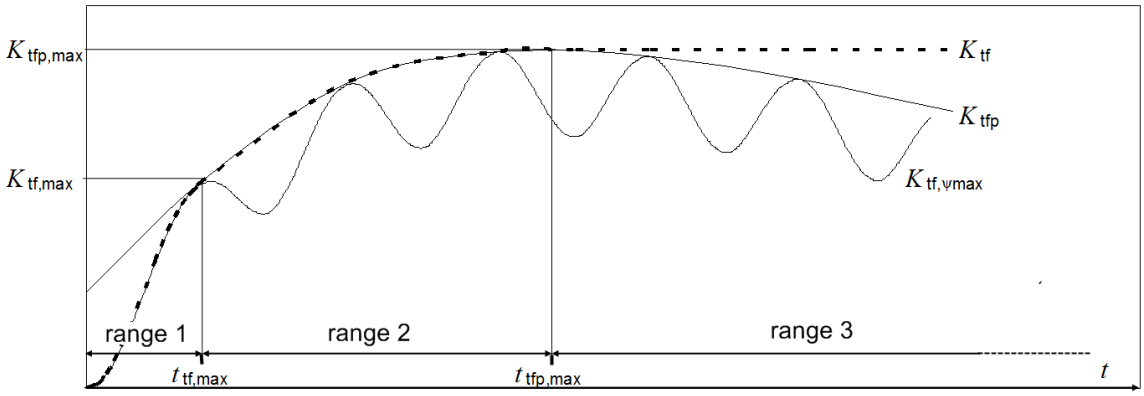

Key

$K_{tf,\psi max}$	overall transient factor
K_{tfp}	envelope of the curve $K_{tf,\psi max}(t)$
$K_{tfp,max}$	highest value of the curve $K_{tfp}(t)$
$K_{tf,max}$	K_{tf} value where the curve $K_{tf,\psi max}$ (t) touches its envelope $K_{tfp}(t)$ for the first time
K_{tf}	resulting transient factor, depending on the required saturation free time
t	time
$t_{tf,max}$	time point, where the curve $K_{tf,\psi max}$ (t) touches its envelope $K_{tfp}(t)$ for the first time
$t_{tfp,max}$	time point of the highest occurring K_{tfp} value

Figure 14 – Relevant time ranges for calculation of transient factor

6.1.3.3 Range 1: $0 \leq t'_{al} \leq t_{tf,max}$

$t_{tf,max}$ is the time, where the $K_{tf}(t)$ curve touches the envelope curve $K_{tfp}(t)$ for the first time (see Figure 14).

At this point in time, the following condition is fulfilled:

$$\sin(\omega t_{tf,max} + \gamma - \quad) = -1$$

This equation is equivalent to

$$t_{tf,max} = \frac{3\pi/2 - \gamma +}{\omega} \tag{19}$$

where

$$= \arctan(\omega T_p).$$

In Figure 15, $t_{tf,max}$ is plotted versus the primary time constant T_p for several fault inception angles γ. $t_{tf,max}$ is practically constant for higher values of T_p, what occurs in common practice.

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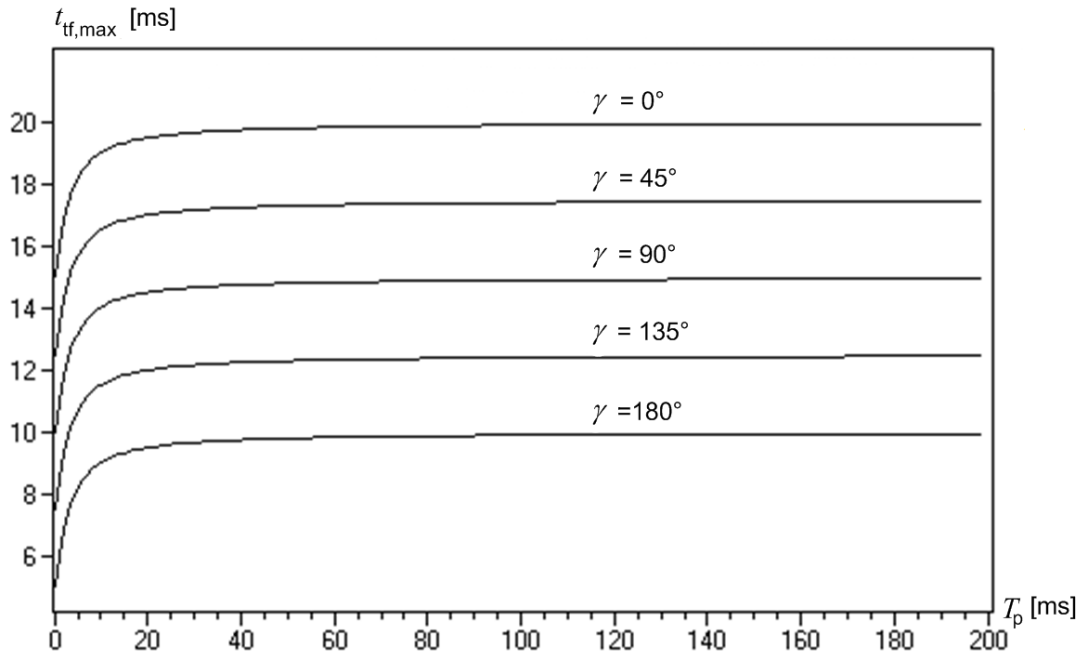

Key

$t_{tf,max}$ time point, where the curve $K_{tf,\psi max}(t)$ touches its envelope $K_{tfp}(t)$ for the first time

T_p specified primary time constant

γ fault inception angle

Figure 15 – Occurrence of the first flux peak depending on T_p, at 50 Hz

For every t'_{al}, there exists a certain worst-case angle $\theta(t'_{al})$, which leads to the highest flux $\psi_{max}(t'_{al})$ at time t'_{al}.

This angle can be found by calculating the extreme value of K_{tf} in Equations (9) or (10) for $t = t'_{al}$, with θ as the dependent variable. This defines the angle $\theta_{tf,\psi max}$ and the corresponding fault inception angle $\gamma_{tf,\psi max}$:

$$\theta_{tf,\psi max} = \arctan \frac{Y}{X} \tag{20}$$

where

$$Y = \omega T_s - e^{t/T_s}\left[\omega T_s \cos(\omega t) - \sin(\omega t)\right]$$

$$X = \frac{1}{T_p - T_s}\left[T_p\left(1+\omega^2 T_s^2\right)e^{(t/T_s - t/T_p)} - T_s\left(1+\omega^2 T_s T_p\right)\right] - e^{t/T_s}\left[\cos(\omega t) + \omega T_s \sin(\omega t)\right]$$

and

$$\gamma_{tf,\psi max} = \theta_{tf,\psi max} + \varphi \tag{21}$$

The normal arctan function only provides results for $-\pi/2 < \theta < \pi/2$. Results for angles $|\theta| > \pi/2$ (see Figure 16, Figure 17, Figure 18) can be found with an arctan function which considers all four quadrants. In many mathematical software packages, such a function is known as θ = arctan2(x,y), where x and y are coordinates.

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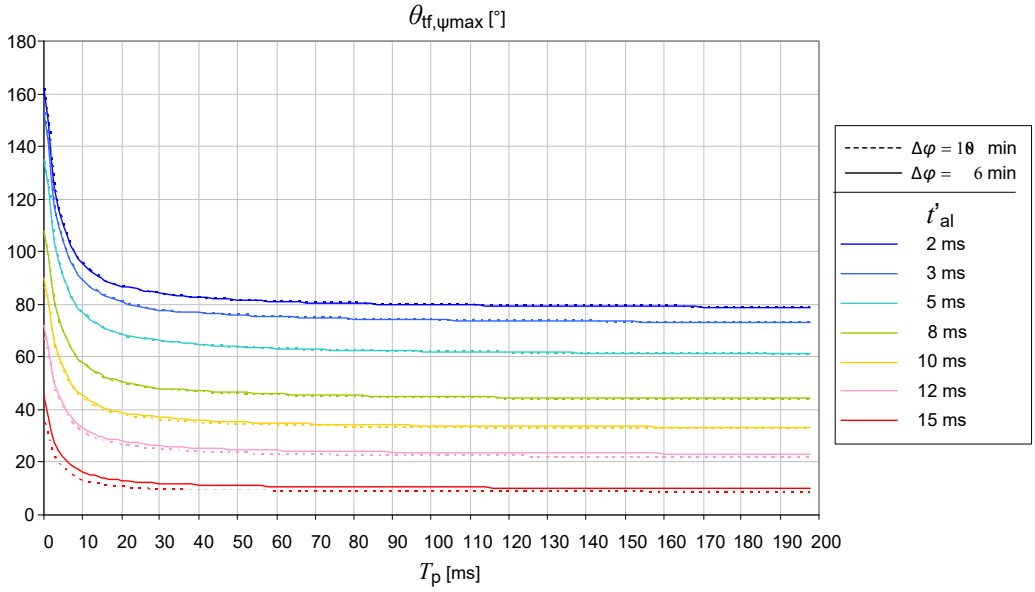
Introducing this angle in Equation (9) or Equation (10), we obtain the highest dimensioning factor for the current transformer for the specified time to accuracy limit t'_{al}.

$$K_{tf,\psi max} = K_{tf}(t'_{al}, \theta_{tf,\psi max}) \tag{22}$$

In Figure 16, the angle $\theta_{tf,\psi max}$ is plotted against the primary time constant T_p, for several values of t'_{al} and for two extreme cases of T_s, whereby the relation between T_s and the phase displacement $\Delta\varphi$ is given by

$$T_S[s] = \frac{3438}{2\pi \cdot 50[Hz] \cdot \Delta\varphi[min]}$$



Key

T_p	specified primary time constant
t'_{al}	specified time to accuracy limit in the first fault
$\Delta\varphi$	phase displacement
$\theta_{tf,\psi max}$	worst-case fault inception angle (alternative definition), which leads to the highest flux at time t'_{al}

Figure 16 – Worst-case angle $\theta_{tf,\psi max}$ as function of T_p and t'_{al}

In Figure 17, $\theta_{tf,\psi max}$ is replaced by $\gamma_{tf,\psi max}$, see Equation (21).

The appropriate values of $K_{tf,\psi max}$ are given in Figure 18.

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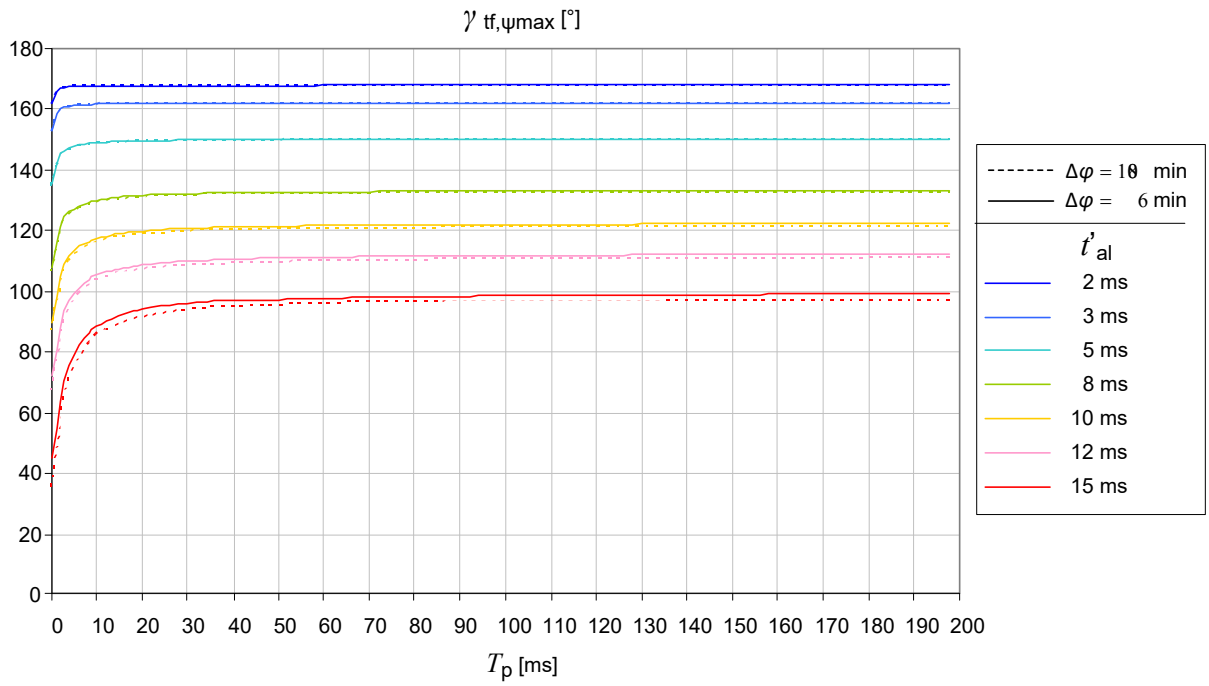
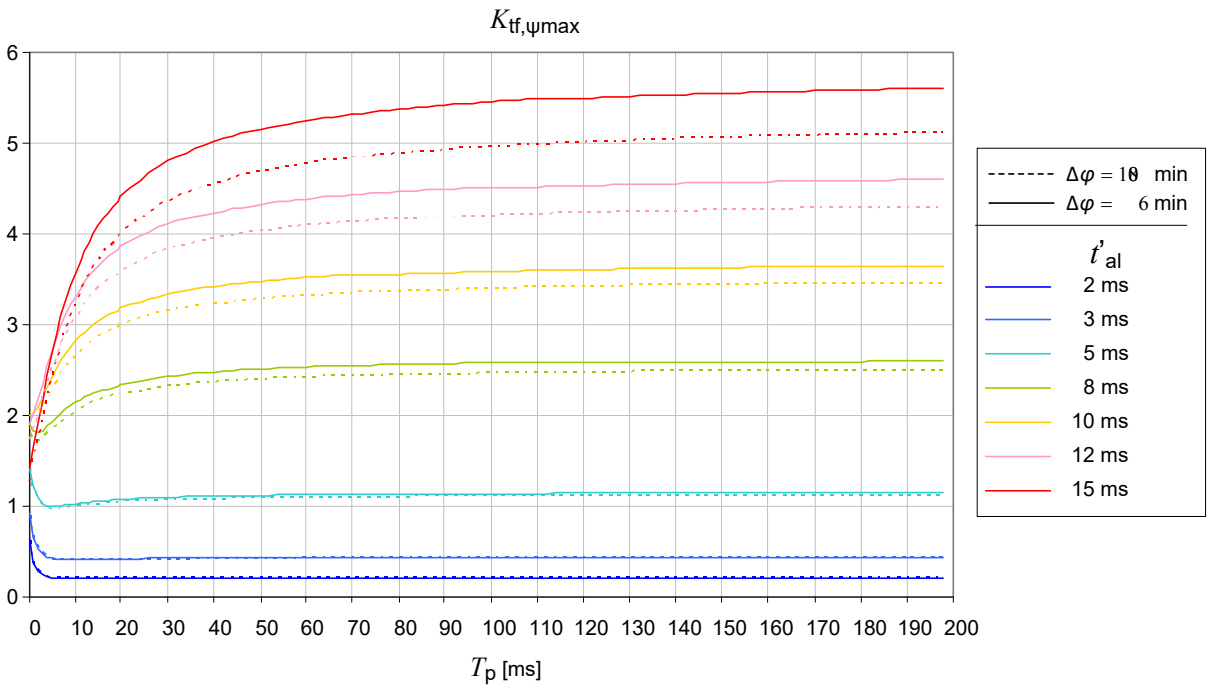


Key

T_p specified primary time constant
t'_{al} specified time to accuracy limit in the first fault
$\gamma_{tf,\psi max}$ worst-case fault inception angle which leads to the highest flux at time t'_{al}
$\Delta\varphi$ phase displacement

Figure 17 – Worst-case fault inception angle $\gamma_{tf,\psi max}$ as function of T_p and t'_{al}



Key

$K_{tf,\psi max}$ overall transient factor, see Figure 14
T_p specified primary time constant
t'_{al} specified time to accuracy limit in the first fault
$\Delta\varphi$ phase displacement

Figure 18 – $K_{tf,\psi max}$ calculated with worst-case fault inception angle $\theta_{\psi max}$

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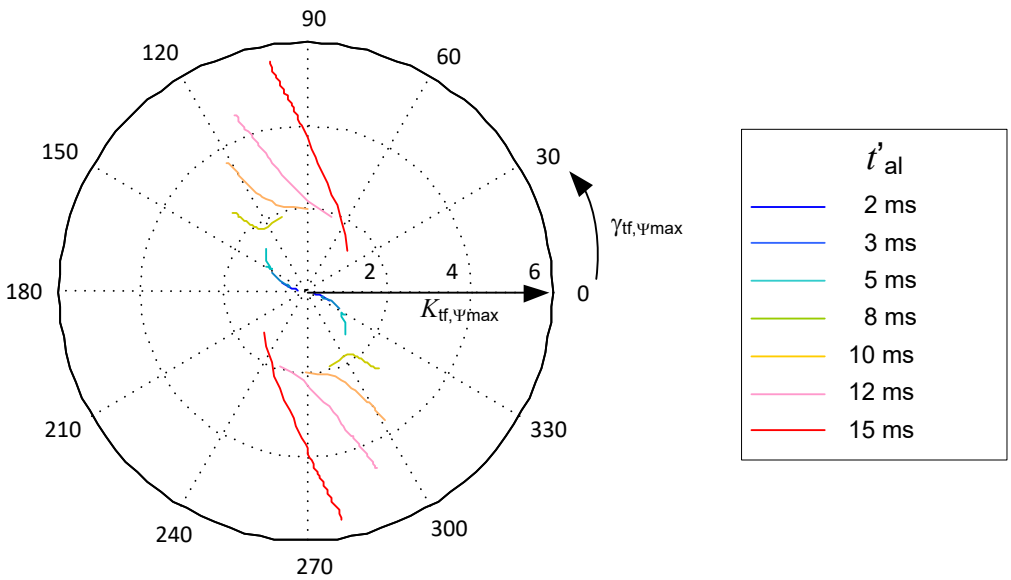
In Figure 18, some curves intersect at a very low primary time constant T_p, but some of those curve values are actually not part of time range 1, they belong to time range 2. This effect is corrected and eliminated in Figure 20.

For a better understanding, $K_{tf,\psi max}$ and $\gamma_{tf,\psi max}$ are plotted in a polar diagram (Figure 19), similar to the one in Figure 13, with T_p as parameter.



Key

$K_{tf,\psi max}$ overall transient factor, see Figure 14

$\gamma_{tf,\psi max}$ worst-case fault inception angle which leads to the highest flux at time t'_{al}

t'_{al} specified time to accuracy limit in the first fault

Figure 19 – Polar diagram with $K_{tf,\psi max}$ and $\gamma_{tf,\psi max}$

Due to the complexity and the potential mistakes that can be made in daily application, the function $K_{tf,\psi max} = K_{tf}(\gamma_{tf,\psi max}(t'_{al}))$ is shown in Figure 20 as curves for different t'_{al} and secondary time constants T_s plotted against the primary time constant T_p for given configurations of secondary time constant and frequency.

Due to the complexity of the relationships, potential mistakes can be made in the daily application. Therefore, Figure 20, shows the function $K_{tf,\psi max}$ versus the primary time constant T_p, as an array of curves with the array parameter t'_{al}.

The sub-figures a) to i) cover 3 frequency values and, for each frequency value, 3 values of the secondary time constant T_s.

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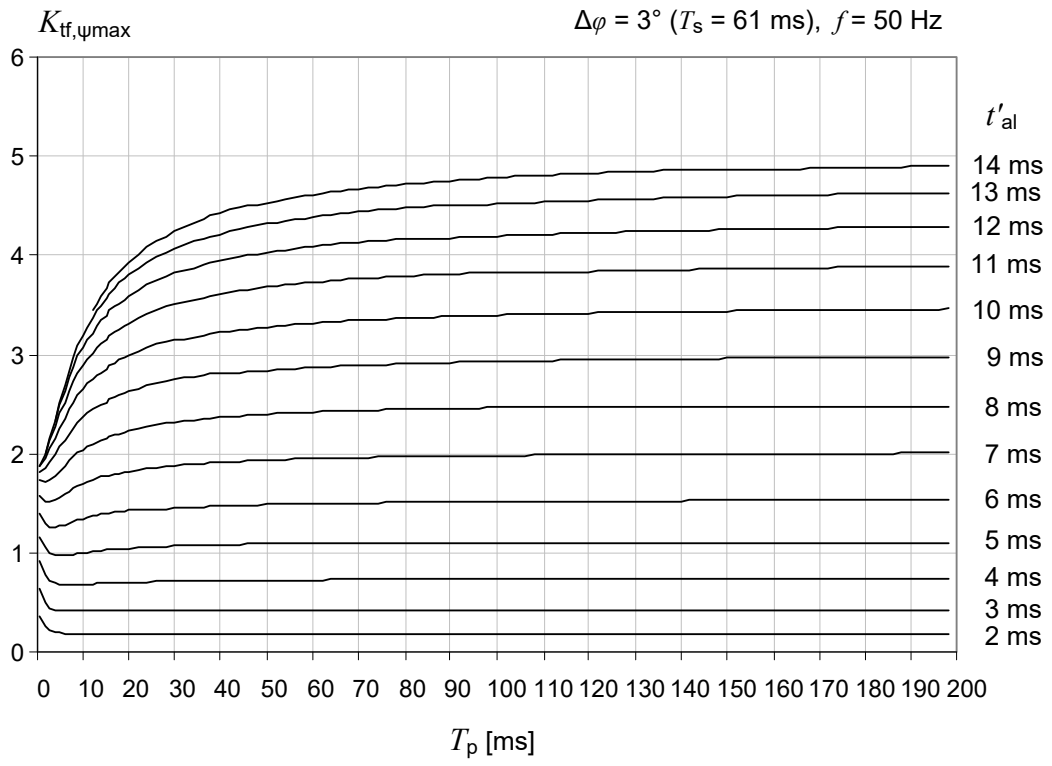
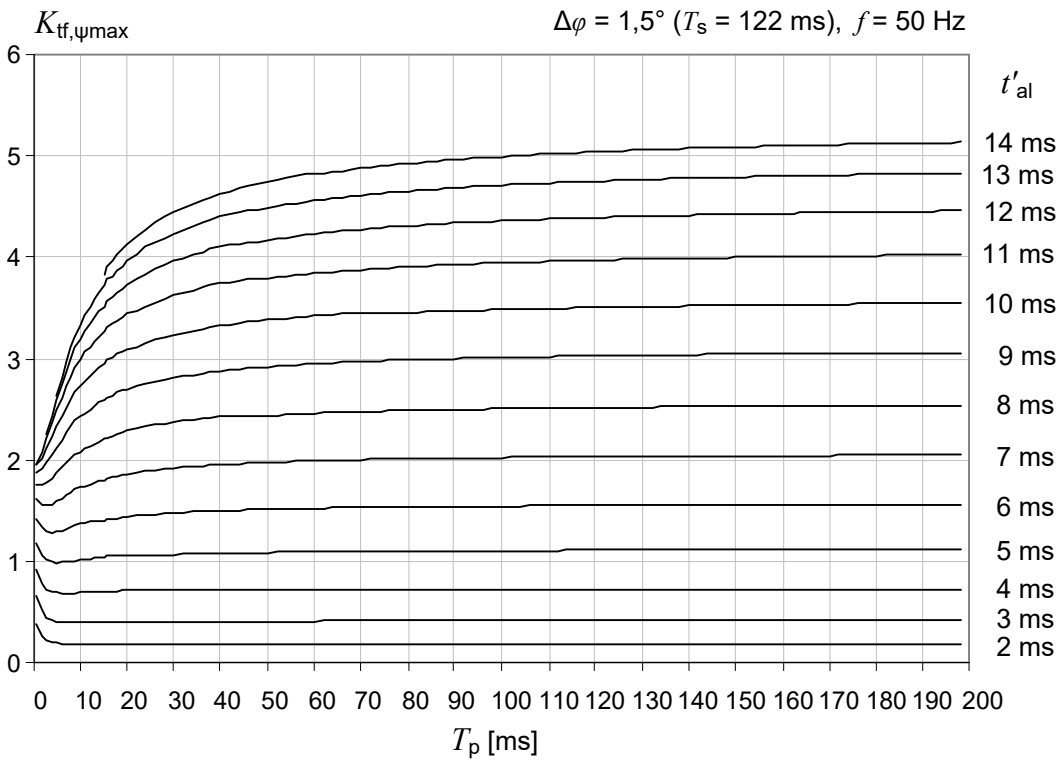


a) T_s = 61 ms at 50 Hz



b) T_s = 122 ms at 50 Hz

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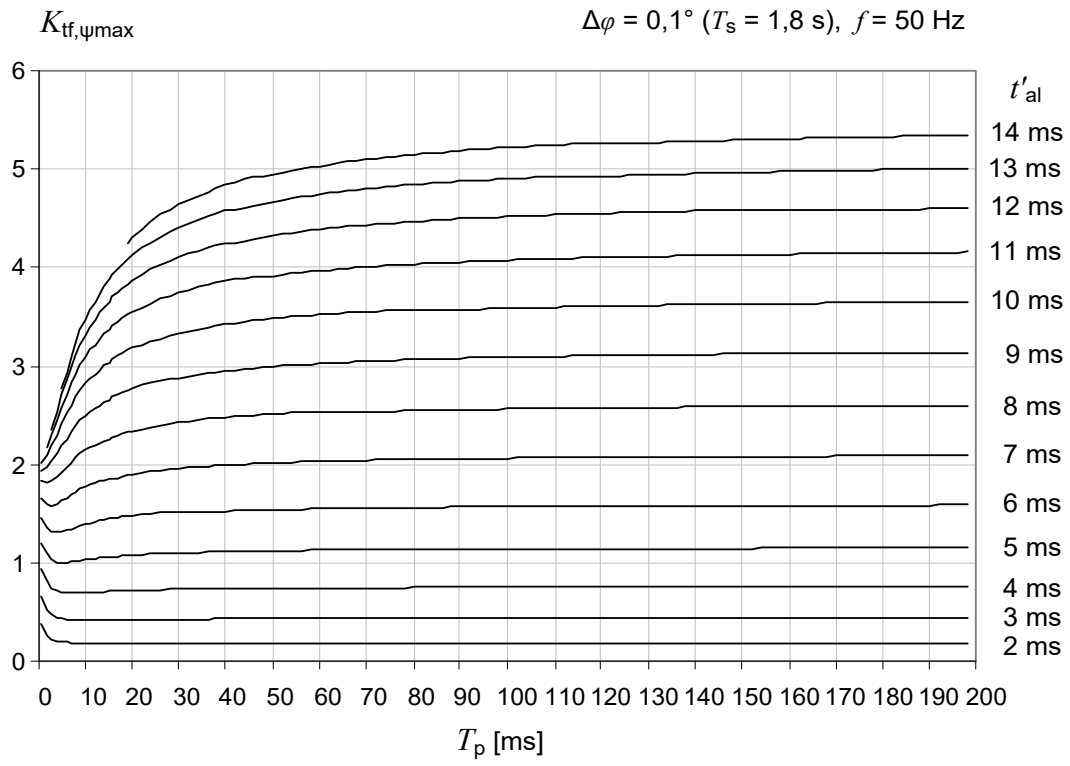
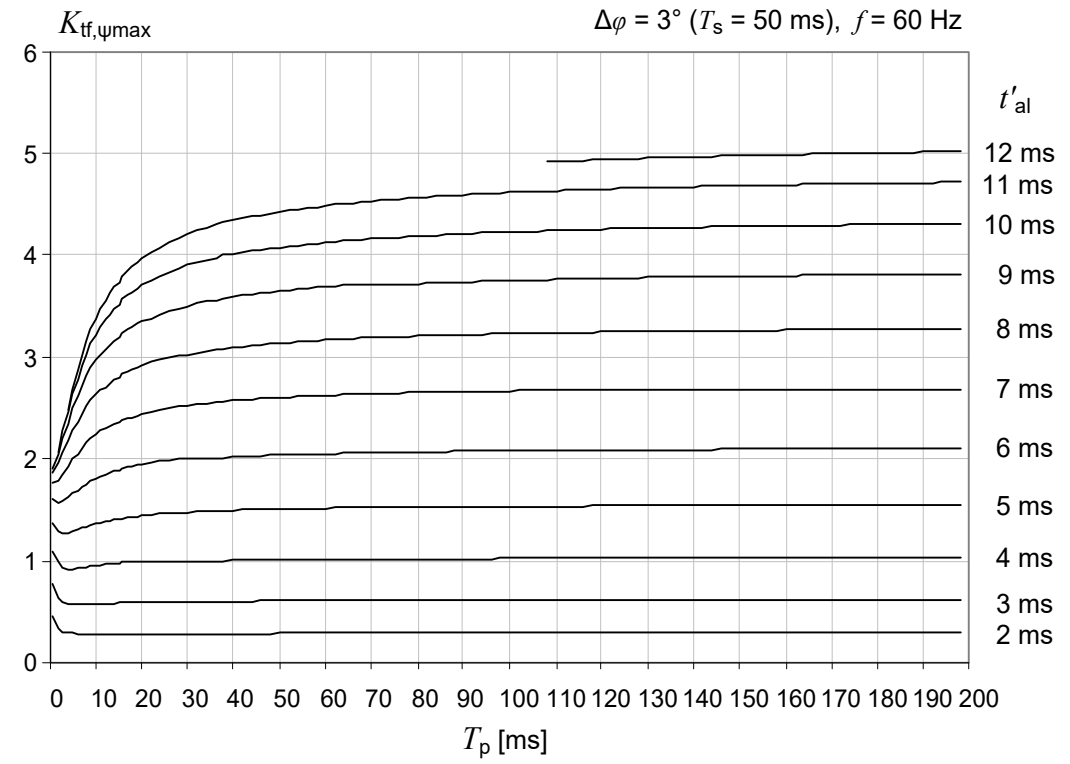


c) T_s = 1,8 s at 50 Hz



d) T_s = 50 ms at 60 Hz

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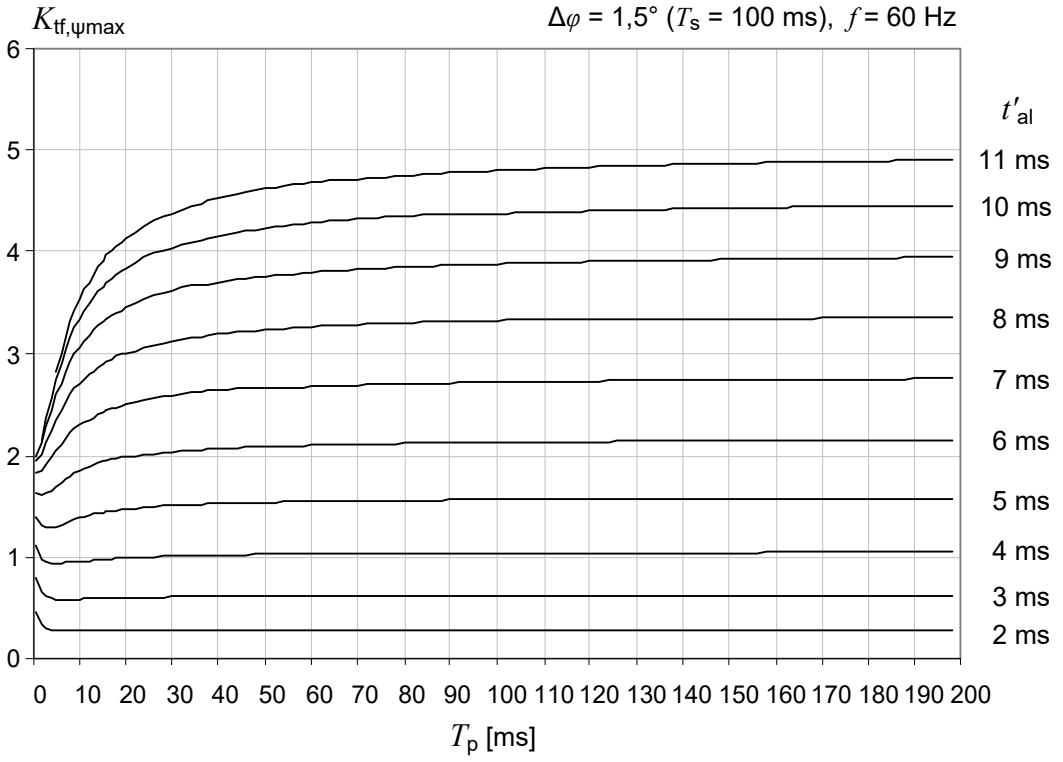
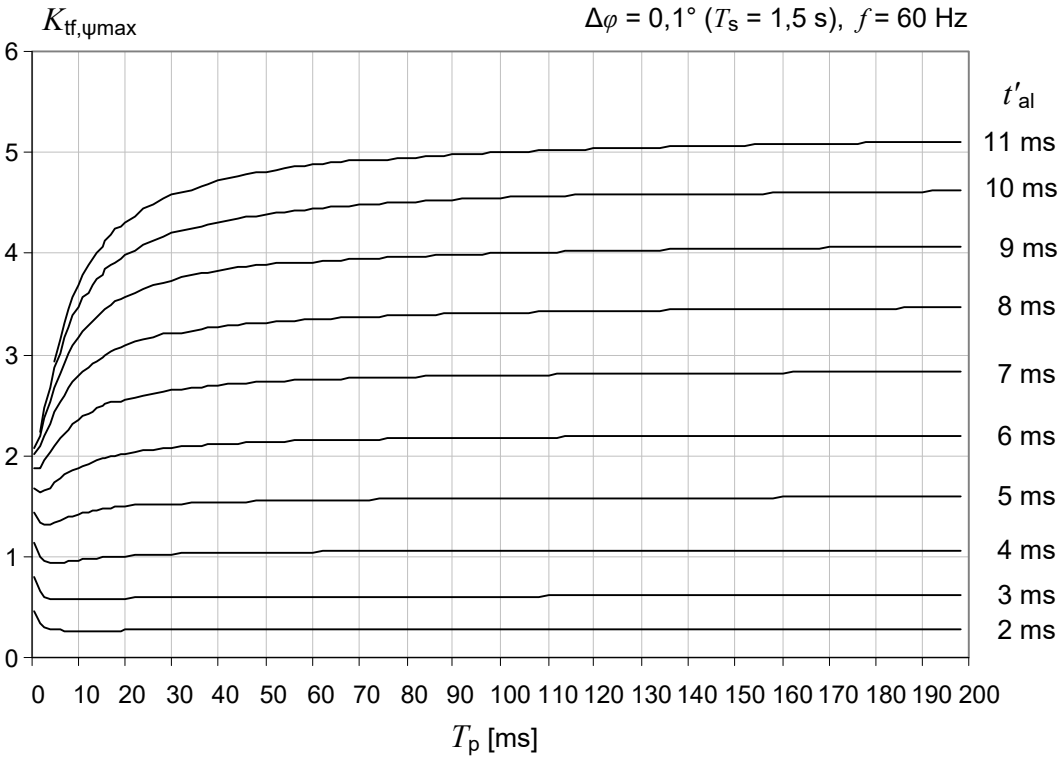


e) T_s = 100 ms at 60 Hz



f) T_s = 1,5 s at 60 Hz

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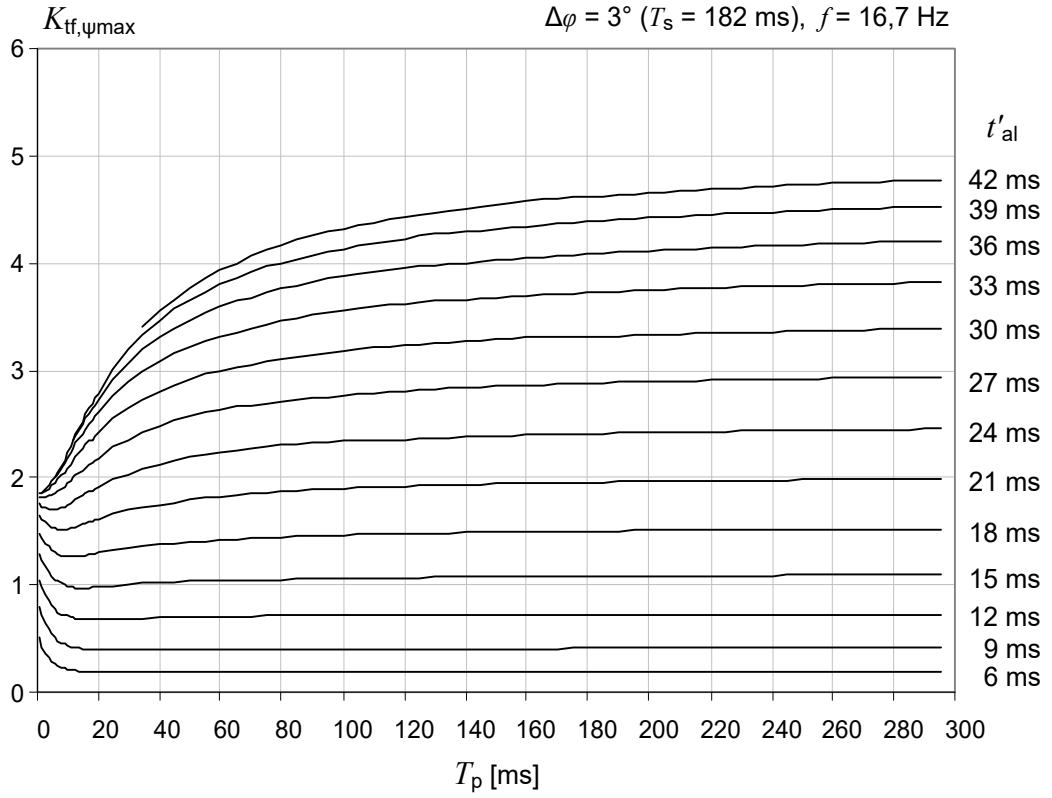
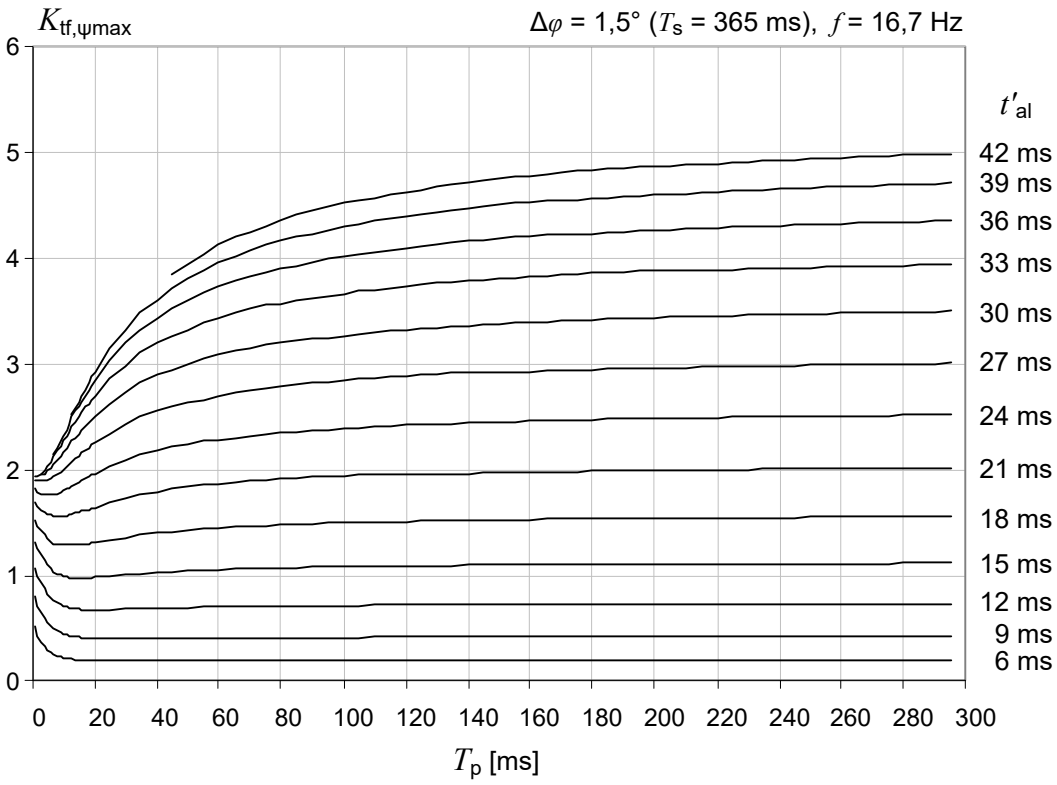


g) T_s = 182 ms at 16,7 Hz



h) T_s = 365 ms at 16,7 Hz

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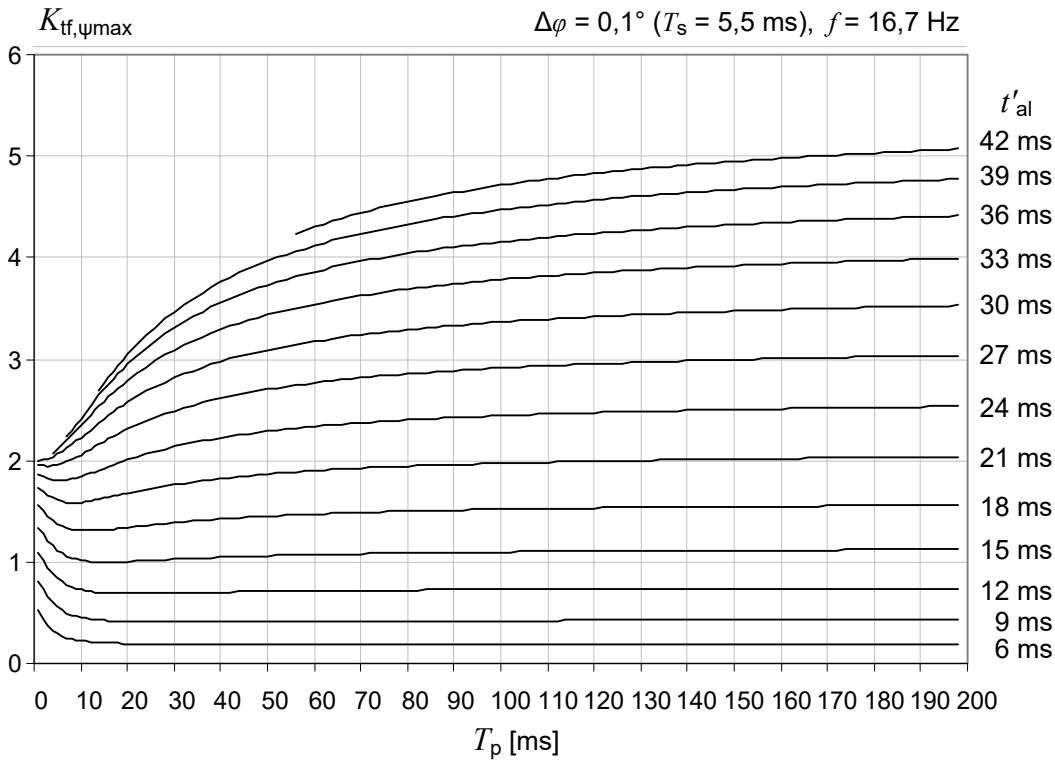

i) T_s = 5,5 s at 16,7 Hz

Key

f	frequency
$K_{tf,\psi max}$	overall transient factor, see Figure 14, in range 1 identical with K_{tf}
T_p	specified primary time constant
T_s	secondary loop time constant
t'_{al}	specified time to accuracy limit in the first fault
$\Delta\varphi$	phase displacement

Figure 20 – Determination of K_{tf} in time range 1

Usually, the normalized slope of the total primary current curve at time t=0 is between 0 (maximum DC component) and 1 (no DC component). A very small T_p, together with a negative DC component, leads to a slope higher than 1 (see Figure 21), and therefore to much earlier CT saturation. Therefore, the K_{tf} curves for short t'_{al} are higher for very short T_p. T_p is directly correlated to the X/R ratio as a finite value given by the conductor geometry of the primary circuit. For medium and high voltage networks, such low X/R ratios may be more theoretical cases, whereas, in low voltage networks, values of T_p down to 1 ms are possible and realistic. The curve i_{sin} is given as a reference, in order to compare the gradients in the first few milliseconds.

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