Estimation of DC Time Constants in Fault Currents and Their Relation to Thévenin's Impedance

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***Abstract*—The knowledge of DC time constants in fault currents at system nodes is important to design the protection system and validate the calculation models for power system simulations. In this paper, we present methods to estimate Thévenin's impedance and DC time constants in fault currents with application to disturbance records. Additionally, a comparison between both parameters is shown.**

We demonstrate that measurements of the DC time constant of fault currents in disturbance records can be heavily distorted by the protective current transformer and additional instrument transformers (e. g. in the relay itself). This distortion depends on the transformer type (P, TPX, TPY, TPZ) and burden. However, by using current signal models and curve fitting methods it is still possible to estimate the required DC time constant and Thévenin's impedance.

The proposed methods are tested with simulated signals and real measurements from different protective relays.

***Index Terms*—Power system parameter estimation, protective relaying, fault currents, impedance, signal analysis.**

I. Introduction

Digital relays and disturbance recorders collect a lot of data when a fault occurs in the electrical power transmission (high voltage) and/or distribution (medium voltage) network. Analysis of the recorded data is usually done by skilled persons but only when a serious disturbance occurs. In the future, an automatic and deeper analysis of every disturbance record will take place to extract additional information (e. g. DC time constants, current transformer saturation [1]). Recently, such a software system has been installed at an German transmission system operator.

For protection engineers the knowledge of the short-circuit power as well as the DC time constant in fault currents is important to design the protection system (e. g. type and size of current transformers, circuit breakers, minimum delays for tripping, bus bars, relay settings). Both, DC time constant and Thévenin's impedance, are influenced by grid expansions, the state of circuit breakers (network topology), the fault type or the distance. In most cases these parameters are not known or imprecisely determined. For electrical power system modeling and calculations these parameters differ at system nodes or even with fault locations. Therefore, measured time constants are also necessary for model validation.

II. Relevance of DC time constants

The power system time constant T_N represents the ratio of resistance and reactance in the positive sequence system of a pre-located network N at a node A (fig. 1).

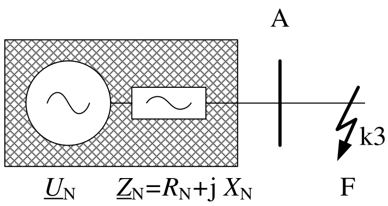

Fig. 1. Network infeed model with 3-phase fault [2]

Thévenin's impedance $\underline{Z}_\mathrm{N}$ depends on the actual switching state of the power system but is also frequency dependant [3]. Therefore, not only *one* system time constant exists.

In this paper we only consider the fundamental frequency components because they are relevant for short-circuit currents with decaying DC components. The system time constant is then defined by

$$T_\mathrm{N} = \frac{L_\mathrm{N}}{R_\mathrm{N}} = \frac{X_\mathrm{N}}{2\pi f_\mathrm{N} \cdot R_\mathrm{N}}. \tag{1}$$

Typical system time constants for high voltage networks are about $T_\mathrm{N} = 20 \dots 40\,\mathrm{ms}$ [4] while medium voltage networks can have the whole range presented in table I.

TABLE I
Relation between system time constant T_N and impedance ratio $X_\mathrm{N}/R_\mathrm{N}$ at $f_\mathrm{N} = 50\,\mathrm{Hz}$

T_N in ms	10	30	50	100	300
$X_\mathrm{N}/R_\mathrm{N}$	3.1	9.4	15.7	31.4	94.2

The system time constant influences the decaying characteristics of the DC component of short-circuit currents. The choice of type and size of current transformers, circuit breakers, minimum delays for tripping[1], bus bars and relay

[1]The decay of the AC fault current amplitude can be faster than the DC component at disturbances close to generators. In these cases, zero crossings of the fault current in the first periods might be missing . To switch of such currents might be impossible and dangerous for the circuit breaker. [5], [2]

settings depend on the short-circuit power and the DC time constants. Therefore, the actual value of the system time constant at the relay measuring point is important for the design of current transformers for protection issues.

III. Calculation of Thévenin's impedance in frequency domain

A. Proposed method

The considered positive sequence of a symmetrical power system consisting of two sub-systems $\underline{U}_{11}, \underline{Z}_{11}$ and $\underline{U}_{21}, \underline{Z}_{21}$ connected by a line $\underline{Z}_{\mathrm{L1}}$ is shown in fig. 2. The synchronous

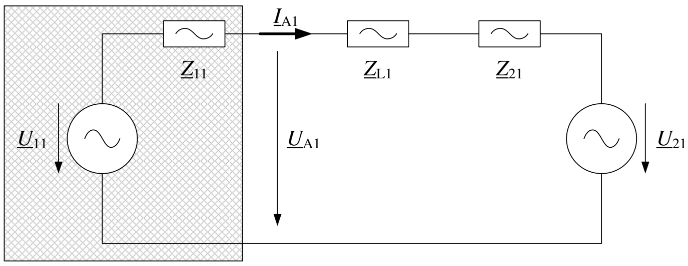

Fig. 2. Positive sequence system of two symmetrical active sub-systems connected by a line

sampled voltages $\boldsymbol{u}_{\mathrm{A}}$ and currents $\boldsymbol{i}_{\mathrm{A}}$ are measured at the relay installation node A. The fundamental frequency positive sequence phasors (symmetrical components) $\underline{U}_{\mathrm{A1}}$ and $\underline{I}_{\mathrm{A1}}$ (fig. 2) are calculated form the measurements (e. g. disturbance record).

Applying Kirchhoff's voltage law to fig. 2 leads to

$$\underline{U}_{11} = \underline{Z}_{11}\,\underline{I}_{\mathrm{A1}} + \underline{U}_{\mathrm{A1}} \tag{2}$$

with the voltage source

$$\underline{U}_{11} = \hat{U}_{11}\,\mathrm{e}^{\mathrm{j}\varphi_{11}}. \tag{3}$$

Under the assumptions

$$\omega = \mathrm{const} \qquad \varphi_{11} = \mathrm{const} \tag{4}$$

$$\hat{U}_{11} = \mathrm{const} \qquad \underline{Z}_{11} = \mathrm{const} \tag{5}$$

Thévenin's impedance $\underline{Z}_{11}$ can be calculated from two different (quasi-)stationary system states (pre-fault, fault and/or post-fault state) with a lag $\Delta t = t_2 - t_1$ as

$$\underline{U}_{11}(t_1) = \underline{U}_{11}(t_2)\,\mathrm{e}^{-\mathrm{j}\omega\Delta t} \tag{6}$$

$$\underline{Z}_{11} = \frac{\underline{U}_{\mathrm{A1}}(t_2)\,\mathrm{e}^{-\mathrm{j}\omega\Delta t} - \underline{U}_{\mathrm{A1}}(t_1)}{\underline{I}_{\mathrm{A1}}(t_1) - \underline{I}_{\mathrm{A1}}(t_2)\,\mathrm{e}^{-\mathrm{j}\omega\Delta t}}. \tag{7}$$

From the imaginary and the real part of $\underline{Z}_{11}$, the system time constant can be calculated by

$$T_{\mathrm{N}} = \frac{\Im\{\underline{Z}_{11}\}}{\omega \cdot \Re\{\underline{Z}_{11}\}}. \tag{8}$$

Because differences in voltage and current are evaluated, we call the proposed method *Delta method* [6]. We propose to estimate the system frequency f_{N} and the fundamental frequency phasors $\underline{U}_{\mathrm{A}}$ and $\underline{I}_{\mathrm{A}}$ with an iterative Prony's method [7], [8] because its results are more precise than by using a FFT algorithm.

B. Limitations of the Delta method

Beside the fulfilled assumptions (4) and (5) the network frequency f_{N} must be calculated very precisly. For this, the proposed Prony's method for estimating phasors is suitable. Another requirement is, that the triggering transient system event between the analysed stationary states must not effect the system voltage $\underline{U}_{11}$. Here, disturbance records with high load changes are more applicable than those with short-circuits [6]. However, load changes normally won't trigger protection relays and therefore aren't feasible for analysing disturbance records. By analysing fault current records the (in generally) changed network topology by switching circuit breakers in the case of clearing fault currents as well as the non-stationary currents are challenging.

Another limitation of the Delta method is the need for measurements of the total current infeed from the sub-system to be analysed. In the case of recorded signals of a double circuit line only parts of the (fault) current are measured by the relay depending on the line impedances and fault location. The user of this method has to make sure, that total currents are applied otherwise the results will not be reliable.

C. Verification of the Delta method

Tests on simulated and real disturbance records with typical sampling frequencies $f_{\mathrm{s}} = 1\,\mathrm{kHz}$ were performed to evaluate the accuracy and the applicability of the proposed method.

1) Test on simulated signals: The accuracy of the Delta method was tested on simulated voltage and current waveforms. The used network model in DIGSILENT PowerFactory is shown in fig. 3.

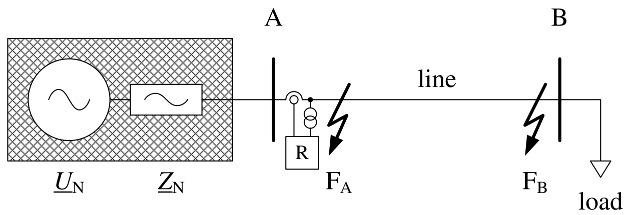

Fig. 3. Simulated single feeded network model with measuring relay R and two fault locations $\mathrm{F_A}$ and $\mathrm{F_B}$

Simulated network parameters:

- nominal voltage of system $U_{\mathrm{N}} = 220\,\mathrm{kV}$
- short circuit power $S_{\mathrm{N}} = 1000\,\mathrm{MVA}$
- length of line $l = 50\,\mathrm{km}$
- variation of system time constant $T_{\mathrm{N}} \in \{50, 100\}\,\mathrm{ms}$
- simulated load changes (LC)
  - inductive load $\underline{S}_{\mathrm{load}} = 250\,\mathrm{MVA}$; $PF = 0.95$
  - load change $\Delta\underline{S}_{\mathrm{load}} \in \{+10\,\%, +100\,\%\} \cdot \underline{S}_{\mathrm{load}}$
- simulated short-circuits (SC)
  - fault type: k1E, k2, k2E bzw. k3
  - fault location at node A $(0.1\,\% \cdot l)$ resp. B $(99.9\,\% \cdot l)$
  - fault impedance $R_{\mathrm{f}} \in \{0, 100\}\,\Omega$

Results of calculated system time constants for different system events and references are presented in table II. The relative error is less than $5\,\%$ in the case of analysing disturbance records with short-circuits. The simulated small load change[2] does not induce big differences in voltages and currents. Thus, the relative error is higher in this case.

TABLE II
CALCULATED SYSTEM TIME CONSTANTS AND ERRORS AT DIFFERENT SIMULATED SYSTEM EVENTS

Event	Reference	$T_\mathrm{N} = 50\,\mathrm{ms}$ T_N/ms	error in %	$T_\mathrm{N} = 100\,\mathrm{ms}$ T_N/ms	error in %
+10 %	LC	47.08	-5.84	87.84	-12.16
+100 %	LC	48.60	-2.80	94.55	-5.45
SC k1E	node A	48.89	-2.22	95.18	-4.82
	node B	49.17	-1.67	94.93	-5.07
SC k2	node A	48.84	-2.32	95.48	-4.53
	node B	48.92	-2.16	95.40	-4.60
SC k2E	node A	48.91	-2.17	96.43	-3.57
	node B	48.90	-2.21	95.95	-4.05
SC k3	node A	48.79	-2.42	95.38	-4.62
	node B	48.79	-2.43	95.07	-4.93

Simulations with different short-circuit power and fault impedance R_f were also performed obtaining relative errors less than $5\,\%$.

2) Test on real disturbance records: The applicability of the proposed Delta method was tested on real data from a German transmission system operator. The obtained system time constants by analysing short-circuit disturbance records were in the range of $20\,\mathrm{ms}$ to $40\,\mathrm{ms}$. Even if the correct data was not available, these values are typical for the high voltage system.

IV. Calculation of DC time constant in time domain

A. Relation between Thévenin's impedance and system time constant

The DC time constant of a decaying short-circuit current is only identical to the system time constant in the case of a 3-phase impedanceless fault close to the measuring node. It also depends on the fault type, fault location and fault impedance. Thus, every recorded fault current may lead to a different DC time constant. Thévenin's impedance as well as the system time constant are not effected by these factors. However, analysing the decaying DC component is useful to validate used simulation models.

B. Proposed signal model and method

The measured short-circuit current at node A (fig. 3) in time domain can be expressed by

$$i_\mathrm{k}(t) = \hat{u}_\mathrm{N} \cdot \frac{\cos(\omega t + \varphi_\mathrm{f}) \sum R + \sin(\omega t + \varphi_\mathrm{f}) \sum \omega L}{(\sum R)^2 + (\sum \omega L)^2} - \hat{i}_\mathrm{DC} \cdot \exp\left(-\frac{\sum R}{\sum L} \cdot t\right) \quad (9)$$

[2]Load changes usually won't start relays or trigger disturbance recorders.

with the DC current amplitude

$$\hat{i}_\mathrm{DC} = \frac{\hat{u}_\mathrm{N} \left(\cos\varphi_\mathrm{f} \sum R + \sin\varphi_\mathrm{f} \sum \omega L\right)}{(\sum R)^2 + (\sum \omega L)^2} - i_\mathrm{k}(t_0) \quad (10)$$

where $\sum R$ resp. $\sum L$ represent all resistive resp. inductive parts of the fault loop (network/system, line, fault impedance). The ratio $T_\mathrm{DC} = \sum L / \sum R$ is the *DC time constant* for that particular fault. The DC signal components in (9) and (10) depend, amongst other things, on the fault inception angle φ_f and therefore do not appear significantly in all disturbance records.

When faults occur *close to power stations* the network voltage u_N as well as Thévenin's impedance (esp. X_N) can't be assumed to be constant. In these cases, Equation (9) and (10) are not exact and the following method might fail. However, most faults in the ENTSO-E power system occur *far from generators* in the sense of [2] and the model is valid.

Several methods have been tested to estimate the DC time constant:

- Prony's method (original, least-squares, iteratively reweighted least squares)
- directly analysing the DC decay
- least squares curve fitting by applying signal models solving with
  - Levenberg–Marquardt algorithm
  - Particle swarm optimisation

The best results (accuracy, robustness and calculation speed) were obtained using a least squares curve fitting and the Levenberg–Marquardt algorithm.

The parameter vector $\boldsymbol{x} = (C_\mathrm{offset}, C_1, T_1)$ of the signal model of the decaying DC component (sampling period T_s)

$$i_\mathrm{model}(t) = i_\mathrm{model}(k\,T_\mathrm{s}) = C_\mathrm{offset} + C_1\,\exp\left(-t/T_1\right) \quad (11)$$

can be estimated by solving the least square problem

$$\min_{\boldsymbol{x}} \sum_k \left[i_\mathrm{model}(k, \boldsymbol{x}) - i_\mathrm{DC}(k)\right]^2. \quad (12)$$

The supporting points $i_\mathrm{DC}(k)$ are extracted from the relays recorded fault current i by applying a FIR notch filter w (filtering the fundamental frequency $f_0 = f_\mathrm{N}$) [9].

$$w(k) = \begin{cases} 1 & \text{for } k \in \{1, 3\} \\ -2\,\cos\left(2\pi f_0\,T_\mathrm{s}\right) & \text{for } k = 2 \\ 0 & \text{otherwise} \end{cases} \quad (13)$$

$$i_\mathrm{DC}(k) = \sum_{j=1}^{3} w(j)\,i(k+1-j) \quad (14)$$

The automated signal analysis estimates the DC time constant T_1 and consists of the following steps:

1) automated segmentation of analogue current signal [10] and selection of short circuit segment with significant DC amplitude
2) extraction of DC signal component by applying (14)
3) guessing starting values for $\boldsymbol{x}$ with simple signal analysis
4) estimation of signal parameter $\boldsymbol{x}$ by curve fitting algorithm (12)

V. Separation of more than one DC time constant

The previous assumptions of undistorted measurements of the short-circuit current $i_{\mathrm{k}}(t)$ aren't fulfilled in a typical circuitry as shown in fig. 4.

The recording device (relay or disturbance recorder) is attached to the secondary winding of the main protection current transformer ct, which transduces the primary current $i_{\mathrm{k}}(t)$. The internal current transformer R inside the relay also influences the sampled current signal. R_1 in fig. 4 includes the resistances of the main current transformer ct as well as the wiring to the relay. The internal resistances (burden and secondary winding of current transformer) are modelled with R_2. The proposed method should be able to estimate the DC time constant T_{DC} of i_{k} from measurements i_{meas}.

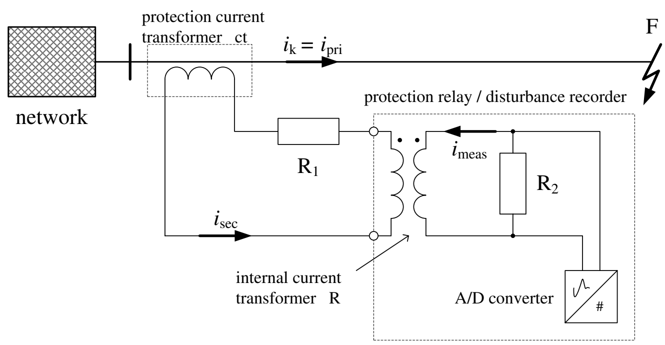

Fig. 4. Typical series connection of several current transformers for digital relays or disturbance recorders

Depending on the type of current transformers (closed iron core *or* linearised with air gaps in magnetic core) the DC components are transduced differently. For best results of the estimated time constant T_{DC} the DC component should be transduced ideally. However, decaying DC components effect the protection algorithms (e.g. based on FFT) applied and therefore linearised current transformers are widely used in relays but also for the main protection transformers (TPY and TPZ types) [11], [4].

A. Enhanced signal model

A simplified model of a current transformer is shown in fig. 5. Neglecting[3] the leakage inductance L_σ and considering only ohmic burden $L_{\mathrm{B}} \approx 0$ the following equations are valid.

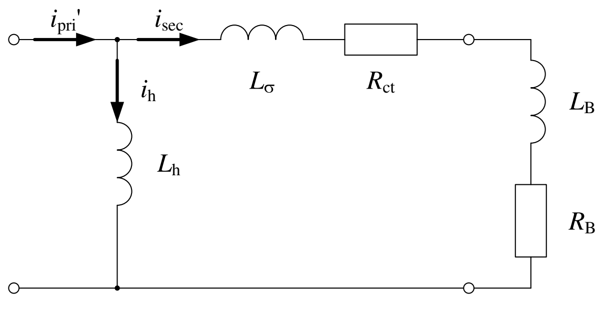

Fig. 5. Simplified model of current transformer

[3]In general fulfilled, because $L_\sigma < L_{\mathrm{B}} \ll L_{\mathrm{h}}$.

$$i'_{\mathrm{pri}} = i_{\mathrm{h}} + i_{\mathrm{sec}} \tag{15}$$

$$0 = \frac{\mathrm{d}i_{\mathrm{h}}}{\mathrm{d}t} L_{\mathrm{h}} - i_{\mathrm{sec}} \left(R_{\mathrm{ct}} + R_{\mathrm{B}}\right) \tag{16}$$

Applying (15) to (16) gives

$$0 = \frac{\mathrm{d}i'_{\mathrm{pri}}}{\mathrm{d}t} - \frac{\mathrm{d}i_{\mathrm{sec}}}{\mathrm{d}t} - i_{\mathrm{sec}} \frac{R_{\mathrm{ct}} + R_{\mathrm{B}}}{L_{\mathrm{h}}} \tag{17}$$

The signal model for an exponential decaying DC component in the primary current with a time constant T_{DC} can be expressed as

$$i'_{\mathrm{pri}}(t) = C_1 \cdot \exp\left(-\frac{t}{T_{\mathrm{DC}}}\right). \tag{18}$$

Applying (18) to (17) gives the inhomogeneous differential equation

$$0 = \frac{C_1}{T_{\mathrm{DC}}} \exp\left(-\frac{t}{T_{\mathrm{DC}}}\right) + \frac{\mathrm{d}i_{\mathrm{sec}}}{\mathrm{d}t} + \frac{i_{\mathrm{sec}}}{T_{\mathrm{ct}}} \tag{19}$$

with the time constant of the secondary current loop[4]

$$T_{\mathrm{ct}} = \frac{L_{\mathrm{h}}}{R_{\mathrm{ct}} + R_{\mathrm{B}}}. \tag{20}$$

Considering the initial conditions $i_{\mathrm{h}}(t_0) = 0$ and $i_{\mathrm{sec}}(t_0) = i'_{\mathrm{pri}}(t_0) = C_1$ the solution of (19) is

$$i_{\mathrm{sec}}(t) = \frac{C_1}{T_{\mathrm{ct}} - T_{\mathrm{DC}}} \left[T_{\mathrm{DC}}\, \mathrm{e}^{-\frac{t}{T_{\mathrm{ct}}}} - T_{\mathrm{ct}}\, \mathrm{e}^{-\frac{t}{T_{\mathrm{DC}}}}\right]. \tag{21}$$

The secondary current of the main current transformer ct i_{sec} is transduced by the internal current transformer R in the relay (fig. 4) and therefore the signal model needs further extensions[5]. In (17) i_{pri} becomes i_{sec} from (21) giving

$$0 = \frac{\mathrm{d}i'_{\mathrm{sec}}}{\mathrm{d}t} - \frac{\mathrm{d}i_{\mathrm{meas}}}{\mathrm{d}t} - \frac{i_{\mathrm{meas}}}{T_{\mathrm{R}}} \tag{22}$$

with the *relay time constant* T_{R}.

As the solution of (22) the measured current is obtained which is finally sampled and recorded by the device

$$\begin{aligned} i_{\mathrm{meas}}(t) = \frac{C_2}{T_{\mathrm{R}} - T_{\mathrm{ct}}} \Bigg\{ & T_{\mathrm{R}}\, \mathrm{e}^{-\frac{t}{T_{\mathrm{ct}}}} - T_{\mathrm{ct}}\, \mathrm{e}^{-\frac{t}{T_{\mathrm{R}}}} \\ & + T_{\mathrm{R}}\, T_{\mathrm{ct}} \left[\frac{\mathrm{e}^{-\frac{t}{T_{\mathrm{DC}}}} - \mathrm{e}^{-\frac{t}{T_{\mathrm{R}}}}}{T_{\mathrm{DC}} - T_{\mathrm{R}}} - \frac{\mathrm{e}^{-\frac{t}{T_{\mathrm{DC}}}} - \mathrm{e}^{-\frac{t}{T_{\mathrm{ct}}}}}{T_{\mathrm{DC}} - T_{\mathrm{ct}}}\right] \Bigg\} \end{aligned} \tag{23}$$

Depending on the time constants T_{ct} and T_{R} a distortion of the DC signal component takes place.

The curve fitting signal model depends on the assumed number of DC time constants in the signal. Equation (11) fits this problem best, if T_{ct} and T_{R} can be neglected (i. e. $T_{\mathrm{ct}}, T_{\mathrm{R}} \to \infty$). If only one time constant can be neglected, (21) is valid. In all other cases, (23) should be adapted for the fitting model.

[4]In this paper we call it *current transformer time constant*. If $T_{\mathrm{ct}} \to \infty$, T_{ct} can be substituted by T_{R} in the following equations.

[5]Only necessary if more than one secondary time constant is relevant (see footnote 4).

B. Measurement of DC time constant from digital relays

The time constant of some relays were measured to get an idea how much the short circuit current is distorted by the recording devices themselves. For this task an artificial rectangular current waveform was feed into the DUTs (distance and differential protection relays). The obtained recorded waveforms were analysed and the time constants T_{R} were estimated. Table III summarizes some results of selected relays. Manufacturer C uses linearised current transformers with air gaps. The DC signal components are extremely distorted.

TABLE III
ESTIMATED TIME CONSTANTS OF SELECTED PROTECTION RELAYS

Manufacturer	Device	Time constant
A	1	$T_{\mathrm{R}} \approx 85\,\mathrm{ms}$
B	2	$T_{\mathrm{R}} \approx 65\,\mathrm{ms}$
C	3	$T_{\mathrm{R}} \approx 11\,\mathrm{ms}$
C	4	$T_{\mathrm{R}} \approx 16\,\mathrm{ms}$

C. Verification of method

The proposed methods for estimating the DC time constants in decaying current signals were tested on simulated and recorded current signals. For simulations the network model in fig. 3 with an additional current transformer model (fig. 5) was used assuming a 3-phase fault at fault location $\mathrm{F_A}$. In this particular case the DC time constant T_{DC} in i_{k} equals the system time constant T_{N}. Two cases were considered:

1) only the system time constant is relevant $T_{\mathrm{N}} \in \{10, 30, 50, 100, 300\}\,\mathrm{ms}$
2) the system time constant and the current transformer time constant are present $T_{\mathrm{N}} \in \{50, 100\}\,\mathrm{ms}$, $T_{\mathrm{ct}} \in \{10, 50, 100, 200, 300\}\,\mathrm{ms}$

Applying these simulated current signals to protection relays (table III) with an OMICRON CMC 256, real measurements are obtained after readout of the 'disturbance' data.

1) Test on simulated signals: The methods were tested on the simulated data with no noise first – a maximum of two DC time constants is present. Table IV presents the results for all three signal models. Highlighted in grey are the results were the model fits the problem best[6]. If estimated time constants are higher than a second '∞' is shown in table IV.

In the first five rows of table IV results from case 1 are presented. Signal model 1 gives the best fitting results and also estimates the DC time constant with negligible error. Signal model 2 and 3 take more DC time constants into account. The additional estimated times are significantly higher than one second and therefore can be neglected.

In rows 6-15 of table IV results from case 2 are shown. Signal model 2 and 3 give good estimates of the two DC time constants. Signal model 1 estimates only one time constant

$$\frac{1}{T} \approx \frac{1}{T_{\mathrm{ct}}} + \frac{1}{T_{\mathrm{N}}} \tag{24}$$

[6]Not always the best results.

TABLE IV
ANALYSIS OF SIMULATED CURRENT SIGNALS WITH WINDOW LENGTH 160 ms — ESTIMATED TIME CONSTANTS IN MILLISECONDS

Reference		Model 1	Model 2		Model 3		
T_{ct}	T_{N}	T	T_1	T_2	T_1	T_2	T_3
∞	10	10.0	∞	10.0	-∞	∞	10.0
∞	30	30.0	∞	30.0	-∞	∞	30.0
∞	50	50.0	∞	50.0	-∞	∞	50.0
∞	100	100.0	∞	100.0	-∞	∞	100.0
∞	300	299.6	∞	300.4	-∞	∞	300.4
10	50	6.7	38.7	10.5	229.1	51.6	10.0
10	100	8.4	85.3	10.1	485.8	101.5	10.0
50	50	23.5	49.2	49.2	∞	50.9	49.1
50	100	34.8	95.4	50.6	∞	99.6	50.1
100	50	34.8	95.3	50.6	∞	100.5	50.0
100	100	56.7	99.4	99.4	∞	106.1	95.0
200	50	43.4	194.3	50.1	∞	195.3	50.1
200	100	78.1	196.7	100.3	∞	202.8	99.7
300	50	46.4	292.4	50.0	-∞	283.4	50.0
300	100	87.2	294.1	100.2	∞	297.4	100.1

which is always smaller than the smallest real time constant present.

The analysed window length (for curve fitting) is $160\,\mathrm{ms}$. In general, most faults in the German high voltage network are cleared after $80 \ldots 160\,\mathrm{ms}$. The chosen window length directly influences the highest possible time constant to be estimated. In the presence of noise the window length must be longer than the highest time constant to be estimated.

As seen from table IV, it is possible to estimate more than one DC time constant obtaining less than $5\,\%$ error with the proposed curve fitting method. Higher time constants require longer lasting short circuit currents (longer window length). However, the latter aren't typical for disturbance records in electrical power systems.

2) Test on real disturbance records: The methods were tested with recorded current signals – a minimum of two and a maximum of three DC time constants are present. In Table V the estimated parameters are shown for device 1. In case 1 the system time constant T_{N} as well as the specific relay time constant T_{R} are estimated with model 2 and 3 in most cases but can't be assigned without additional knowledge about the

TABLE V
ANALYSIS OF RECORDED CURRENT SIGNALS (DEVICE 1) WITH WINDOW LENGTH 160 ms — ESTIMATED TIME CONSTANTS IN MILLISECONDS

Reference		Model 1	Model 2		Model 3		
T_{ct}	T_{N}	T	T_1	T_2	T_1	T_2	T_3
∞	10	8.7	110.6	9.9	-523.2	98.5	10.0
∞	30	22.2	90.2	30.2	-522.6	79.7	30.7
∞	50	32.7	63.4	63.6	-314.4	61.5	61.1
∞	100	50.6	90.3	90.3	-229.9	93.0	92.9
∞	300	81.4	268.3	94.7	-∞	239.5	96.0
10	50	6.3	32.1	10.7	-126.5	30.6	10.3
10	100	7.5	54.4	10.3	61.3	557.7	10.2
50	50	17.8	39.5	39.5	42.8	280.7	42.8
50	100	25.1	51.5	51.5	-192.9	50.9	50.6
100	50	25.5	52.0	52.0	-191.0	51.4	51.3
100	100	35.6	67.7	67.7	-197.8	68.5	69.1
200	50	30.1	59.3	59.3	-224.4	58.1	58.0
200	100	42.8	78.9	78.6	-256.2	77.6	77.6
300	50	30.4	72.6	50.7	-498.4	58.0	58.0
300	100	46.1	83.5	83.5	-236.1	83.3	84.9

recording relay. If the two DC time constants are similar (i. e. $T_{\mathrm{N}} \in \{50, 100\}\,\mathrm{ms}$) the estimates are of poor quality.

To improve the results, the curve fitting signal models (21) and (23) were modified with the known relay time constant T_{R} from table III. The curve fitting results are presented in table VI for device 1. In case 1 the system time constant can be estimated with small errors by signal model 2 and 3 if $T_{\mathrm{N}} \leq 100\,\mathrm{ms}$. In case 2 (three time constants are present) model 3 estimates the smaller time constant in most cases with errors less than $5\,\%$. Similar time constants are incorrectly estimated. Overall, the estimates for the DC time constants are significantly better than without considering the relay time constant as presented in table V. However, in a practical application more than two DC time constants can't be correctly estimated and assigned.

TABLE VI
ANALYSIS OF RECORDED CURRENT SIGNALS (DEVICE 1) WITH WINDOW LENGTH $160\,\mathrm{ms}$ AND KNOWN RELAY TIME CONSTANT — ESTIMATED TIME CONSTANTS IN MILLISECONDS

Reference		**Model 1**	**Model 2**		**Model 3**		
T_{ct}	T_{N}	T	T_1	T_2	T_1	T_2	T_3
∞	10	8.7	10.6	85.0	-332.4	10.2	85.0
∞	30	22.2	31.1	85.0	$-\infty$	30.3	85.0
∞	50	32.7	50.2	85.0	841.0	52.7	85.0
∞	100	50.6	96.2	85.0	-228.1	103.5	85.0
∞	300	81.4	-698.0	85.0	$-\infty$	$-\infty$	85.0
10	50	6.3	7.3	85.0	72.4	9.5	85.0
10	100	7.5	8.9	85.0	178.4	9.9	85.0
50	50	17.8	23.6	85.0	120.7	32.3	85.0
50	100	25.1	35.7	85.0	207.8	43.9	85.0
100	50	25.5	36.3	85.0	200.7	45.0	85.0
100	100	35.6	56.0	85.0	167.8	80.9	85.0
200	50	30.1	44.8	85.0	321.2	51.6	85.0
200	100	42.8	73.3	85.0	514.8	82.0	85.0
300	50	30.4	45.6	85.0	∞	47.2	85.0
300	100	46.1	82.1	85.0	-232.7	83.7	85.0

In case 1 (e. g. using closed iron core protection current transformers, P-type with $T_{\mathrm{ct}} \rightarrow \infty$ [12]) the estimated DC time constants can be assigned non-ambiguously to T_{N} and T_{R} (dark grey results in table VI). A non-ambiguous assignment is not practical if TPY or TPZ-type protection current transformer are used (case 2).

VI. CONCLUSION

In this paper we presented the relation between DC time constants in fault currents, Thévenin's impedance and the system time constant. The knowledge of these parameters at a specific node in the electrical power system is important for the protection system design as well as network calculations. Measurements from relays or disturbance recorders are available for many system nodes and faults and they are very useful for estimating these time constants.

The estimation of the system time constant needs voltages and current waveforms (e. g. from distance protection relays). Calculation with the proposed *Delta method* is only possible if the whole (fault) current is recorded. The results are independent from fault type or fault resistance and they are of high accuracy.

By applying signal models and curve fitting techniques, we presented methods to estimate the DC time constants in decaying fault current waveforms from disturbance records. The DC time constant of the measured fault current loop depends on fault type, impedance and location.

A distortion of the decaying DC signal component can be introduced by additional current transformers in the measuring circuitry. It is possible to separate these additional time constants if they differ significantly. A non-ambiguously assignment to the DC time constant of the fault current loop is only possible in the case of further known conditions (e. g. type of used current transformers, protection relay time constant).

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