PMU-based Cable Temperature Monitoring and Thermal Assessment for Dynamic Line Rating

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Abstract—The aim of this paper is to present a novel phasor measurement unit (PMU) data-based cable temperature monitoring method with an intended application towards facilitating dynamic line rating. First part of the paper presents the method to estimate and track the temperature of a 3-phase cable segment. The benefit of this temperature monitoring method is that no additional temperature measurement sensors are required to be placed along the cable. The method is based on a novel algorithm which gives accurate resistance estimates for 3-phase cable segments even in the presence of random and bias errors in the grid measurements. The performance of the method is demonstrated by utilizing data from PMUs in a distribution grid. The results from the grid data show that the method is capable of monitoring the cable temperature up to an accuracy of ±5°C. The later part of the paper presents a system to utilize the temperature estimates given by the monitoring method to predict the dynamic thermal state of the cable for forecasted power-flow scenarios. This is demonstrated by using the available temperature estimates to initialize and solve the system of equations given by the thermoelectric equivalent (TEE) model of the cable.

Index Terms—Cable Temperature Monitoring, Cable TEE Model, Dynamic Line Rating, PMU Application.

I. INTRODUCTION

COST-OPTIMIZED generation and distribution of electrical energy from eco-friendly sources has become the objective of modern power network operation. Distribution networks are being reinforced with more decentralized and renewable power generation sources. Electrical power demand of urban areas is also increasing continuously. This increasing generation and demand of electrical energy puts growing stress on the network assets including the distribution cables. One of the constraints for routing the extra power away from the source centers or towards the load centers is the capacity or loadability of the cables. The loadability is dependent on the thermal rating of the cables and the ambient conditions. For cables, the insulation especially is very sensitive to the temperature higher than the recommended maximum temperature. For example, thermal limit of XLPE cable is 90 °C.

IEC standard 60287 presents a method to calculate the steady-state rating of a cable system [1]. Steady-state cable ratings are suitable for cables under high load factor. This means that the ratio of daily average of hourly load to the daily maximum load is close to unity. The standard uses the thermoelectric equivalent (TEE) model for cables which has lumped thermal resistance and capacitance parameters in a thermal ladder network.

However, many cable sections such as cables connecting off-shore wind park to land substation or cables connecting solar and wind parks to the grid transport intermittent renewable power. Many urban load centers have time-dependent peaks. In such cases, if steady-state current rating is applied then due to the thermal inertia of the cable system, the cable may never approach its thermal limits. This results in under-utilization of the loading capacity of the cables. To utilize the cables more optimally, dynamic loading models are required.

Increasing the loadability of the cables to maximize the accommodation of the intermittent peaks of power flows would help acquire more clean energy and deliver more power to load centers using the existing cable infrastructure. Time based flexibility in loading limits of power lines, also known as dynamic line rating (DLR) has been a topic of interest in the recent past. Authors in [2] presented a case where DLR applied to a 132 kV overhead line section enabled connection of up to 50% extra wind power. Results from a large number of simulations presented in [3] investigating the application of DLR on overhead conductors connecting wind farms showed DLR to have a significant economic potential.

For underground power cables, two ways to decide the flexible loading limits are the cyclic and the emergency rating for cables which are presented in the standard IEC 60853:2 [1]. Cyclic rating of the cables can be used when cables are exposed to a daily cyclic pattern. However, no such pattern is required to calculate the emergency rating which gives the amount of current a cable can carry for a specified time period before the temperature limit is breached. The emergency rating is calculated by studying the dynamic thermal response of the cable system in presence of a load step. The state variables of the TEE cable thermal model are the conductor, screen, jacket and soil temperature. Initial temperature of these state variables are necessary to calculate the dynamic thermal response and hence the emergency rating.

A method to estimate the time-dependent thermal state of the power cables utilizing the TEE model was presented in [4]. A finite element model (FEM) based method was used to compute dynamic rating in [5]. However both methods require temperature measurements to initialize the TEE model. This requires one or more temperature sensing measurements installed along the cable path. Information about the temperature could be achieved using the distributed temperature sensing (DTS) equipment [6]. However, installation of sensors for DTS in existing cables requires retrofitting the cable system with fiber-optic cables and could be a major challenge in multiple ways. This paper presents a solution to this challenge using the presented temperature estimation method.
In absence of temperature measuring devices, data from phasor measurement units (PMUs) at both ends of a cable could be used to estimate the cable resistance and eventually the cable temperature in real-time. However, for medium and short length cable sections, achieving temperature estimates with the desired accuracy and precision could be challenging. It is also important to get accurate temperature estimates continuously using the real-time data. In the past, work has been presented to showcase the feasibility of this idea albeit mostly in a simulation environment and only for high-voltage long-distance overhead lines.

Authors in [7] proposed a method to estimate parameters and temperature of overhead line conductors. However the algorithm is presented only for single phase line and no measurements errors were considered. A review of different methods to estimate the parameters of a 3-phase overhead line is presented in [8] and [9]. Single and double measurement methods and multiple measurement method using linear and non-linear regression were compared. It was shown that the multiple measurement method using linear regression performed the best for short lines. However, quantitative effect of random errors and systematic bias errors present in the measurement chain was not studied. The results from a field experiment using a robust estimator showed that further investigation of the uncertainty caused by bias errors is required [10]. According to the authors, the uncorrected systematic bias present in the measurement chain could cause the algorithm to give incorrect results.

A calibration method to accurately estimate the line parameters of a 1-phase line segment along with the bias errors was presented in [11]. This method uses simplification based an assumptions that the phase errors in the current and voltage transformers (CTs and VTs) are smaller that 0.530°. This however, could be untrue for real cases. An optimization-based method was presented in [12] which estimated the bias errors along with other unknown parameters of a 1-phase line segment which would minimize the difference function between the measured and estimated phasors at one end of the line.

A review of methods to enable PMU based thermal monitoring of overhead transmission lines is presented in [13]. Real PMU data from a 400 kV overhead line was utilized and the results based on methods presented in [8], [11] and [12] are compared. It was concluded that only the optimization based method could give reasonably accurate results. However, the data-window to calculate the parameters was 6 hours long, while the duration of power-flow transients and the thermal time constant for the cables could be as low as 30 minutes. Such a long window may give smoother average results but might miss the vital transients in the temperature.

Both calibration and optimization methods presented in [11] and [12] calculate the line parameters and bias error correction coefficients considering a 1-phase line model. The impedance model used did not include any mutual impedance parameters which might be present in a 3-phase line segment. Estimating the parameters for a 3-phase system could be more challenging if it includes additional mutual impedance and admittance parameters depending on the nature of the system.

Previous methods also did not provide any confidence interval (CI) for the calculated resistance and temperature parameters. CIs around the results would make the application more trustworthy when tracking the temperature of a critical cable-section in real-time. To overcome these drawbacks, this paper presents a new method which is capable of giving accurate and reliable temperature estimates for 3-phase cable systems in presence of bias and random errors.

A. Paper Contribution

This paper presents a solution to perform thermal assessment of cable sections to implement DLR without using specific temperature measurement infrastructure. The focus is on a relatively new domain of MV-distribution networks where the feeder lengths are relatively short.

At first, a new method to provide temperature estimates in real time is presented. Unlike the other methods, this method uses a 3-phase cable model to give accurate temperature estimates of all the conductors, even in the presence of random and systematic bias errors. This paper presents the modelling of a 3-core cable to make the impedance matrix and discusses how an error in the model is a contributing factor to the errors in resistance and temperature estimates. To facilitate the small thermal time-constant of the cables and small duration power-flow transients a much shorter and continuously sliding 1 hour data window was used. To complete the temperature estimation process, CI around the estimates are computed. The performance of the algorithm is demonstrated using two days long field PMU data. This long period is useful in observing any trends in the change of cable temperature along with the trends in the power flow.

Subsequently, application of the proposed temperature monitoring method in thermal assessment of a cable in presence of load forecasts is presented. A flowchart describing the whole process of temperature estimation and its utilization for advanced thermal assessment of cables is presented in Fig. 1. The capability to track cable conductor temperature in real-time also becomes an important tool for monitoring and a safe implementation of a DLR scheme.

B. Paper Structure

The remainder of the paper is arranged as follows: Section II discusses the requirements in terms of accuracy of the resistance estimates which in turn help to estimate the temperature of the cable conductors within a desired range. Section III presents the resistance estimation algorithm in detail. The process of cable modelling to identify significant parameters and the process of uncertainty calculation is also presented. Section IV presents the process of estimation of the temperature and associated uncertainty. Demonstration of the method utilizing the field PMU data is presented in Section V. The intended application of thermal assessment using TEE models of underground cable is discussed in Section VI. The conclusions are drawn in Section VII.
II. REQUIRED ACCURACY OF RESISTANCE ESTIMATES

This section discusses about the required accuracy in resistance estimates for the cable temperature estimation method. The fundamental factor is the desired accuracy range of the temperature of the cable being monitored. This temperature range could then be translated into the accuracy range for resistance estimates. According to IEC-60287-1-1, the AC resistance of a conductor at temperature \( T \) is given by [14]:

\[
R_i = R_0(1 + \alpha(T_i - T_0))(1 + y_s + y_p)
\]  

(1)

where \( \alpha \) is the temperature coefficient \((^\circ C^{-1})\) of the resistivity for a given material, \( R_0 \) is the DC resistance of the conductor at temperature \( T_0 \), and \( y_s \) and \( y_p \) are the skin and proximity coefficients. The above constants depend upon the particular conductor material which is typically copper or aluminum.

A test in the laboratory was performed to investigate the effect of heat on the resistance of a copper coil. The DC resistance was measured at temperature ranging 10-50 \(^\circ C\). At each temperature point, 200 readings were taken. The mean and uncertainty up to three standard deviations of the measured values are presented in Table I.

### TABLE I

<table>
<thead>
<tr>
<th>Temperature (^{\circ} C)</th>
<th>DC Resistance ((\Omega))</th>
</tr>
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<tbody>
<tr>
<td>10.425 ±0.1</td>
<td>2.3561 ±0.0420</td>
</tr>
<tr>
<td>19.972 ±0.1</td>
<td>2.4458 ±0.0432</td>
</tr>
<tr>
<td>29.753 ±0.1</td>
<td>2.5365 ±0.0417</td>
</tr>
<tr>
<td>39.587 ±0.1</td>
<td>2.6288 ±0.0426</td>
</tr>
<tr>
<td>49.00 ±0.1</td>
<td>2.7245 ±0.0426</td>
</tr>
</tbody>
</table>

The change in the DC resistance of the copper coil in the temperature range 10 - 50 \(^\circ C\) was used to calculate \( \alpha \) using a linear regression model. The hypothesis for the linear model was found correct in the measured temperature range and the value of \( \alpha \) with uncertainty up to 3 standard deviations was found to be 0.003742 ±2.7914 × 10\(^{-4}\) \(^{\circ}C^{-1}\). The uncertainty calculated for \( \alpha \) was used as a contributing factor for uncertainty in the final temperature estimates. The value of \( \alpha \) for aluminum conductor was taken to be 0.00403 \(^{\circ}C^{-1}\) [1]. Table II shows the accuracy requirement of resistance estimates corresponding to different range of accuracy of estimation of the Cu and Al conductor temperature. It serves the purpose of a reference maximum level of uncertainty budget we have for the resistance estimates to achieve a certain desired range of accuracy in the temperature estimates. It is presented as maximum allowed uncertainty because there are several other sources of uncertainties as well. It is calculated using the value of \( \alpha \) in (1). So, for monitoring method to determine the temperature of a cable conductor made of aluminum with an accuracy of ± 5 \(^\circ C\), the errors in resistance estimates must be less than 2.01\% of the true resistance.

### TABLE II

<table>
<thead>
<tr>
<th>Temperature Uncertainty</th>
<th>Resistance Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>± 3 (^\circ C)</td>
<td>&lt; 1.12 %(%)</td>
</tr>
<tr>
<td>± 5 (^\circ C)</td>
<td>&lt; 1.85 %(%)</td>
</tr>
<tr>
<td>± 10 (^\circ C)</td>
<td>&lt; 3.74 %(%)</td>
</tr>
</tbody>
</table>

III. RESISTANCE ESTIMATION

This section presents the cable resistance parameter estimation which is the core of the temperature estimation process. The resistance estimation process was divided into three parts. First a correct model of the cable system was made to identify the other unknown parameters needed to be estimated along with the resistance. After estimating the parameters, uncertainty of the estimates are evaluated. The three parts are presented in the following subsections.

A. Cable System Modelling

Accurate modelling of the cable system impedance and admittance matrix is of prime importance as it facilitates the selection of significant parameters to estimate. Impedance and admittance models of overhead line and a cable for 3-phase parameter estimation is shown in [10] and [15] respectively. The cable section in the grid was a 3-core cable whose cores are arranged in a trefoil arrangement. A cross-section with representational construction details of the cable is presented in Fig. 2. As the PMUs are measuring current and voltage at the conductors, only core-core sub-matrices of the complete cable impedance and admittance model are used to select the significant parameters [16].

Unless a very low current, the percentage current unbalance in the grid cable was found out to be between 1-2\%. Thus
Using 2, (3) and (4), it can be shown that:

$$V_{ab} = \frac{1}{2\pi \varepsilon_i} \left( q_a \ln \frac{D_a}{r} + q_b \ln \frac{r}{D_b} + q_c \ln \frac{D_c}{D_b} \right)$$  \hspace{1cm} (8)$$

Similarly,

$$V_{ac} = \frac{1}{2\pi \varepsilon_i} \left( q_a \ln \frac{D_a}{r} + q_c \ln \frac{r}{D_c} \right)$$  \hspace{1cm} (9)$$

Using the balanced power-flow condition, $$q_a + q_b + q_c = 0$$,

$$V_{ab} + V_{ac} = \frac{1}{2\pi \varepsilon_i} \left( 2q_a \ln \frac{D_a}{r} - q_a \ln \frac{r}{D_a} \right)$$ \hspace{1cm} (10)$$

For a three phase network it can be shown that, $$V_{ab} + V_{ac} = 3V_{an}$$, where $$V_{an}$$ is the voltage of phase $$a$$ with respect to the neutral. Further simplification of (10) leads to the result for phase $$a$$:

$$3V_{an} = \frac{1}{2\pi \varepsilon_i} 3q_a \ln \frac{D_a}{r}$$ \hspace{1cm} (11)$$

and the charge and voltage relation using the capacitance matrix can be written as:

$$\begin{bmatrix} q_a \\ q_b \\ q_c \end{bmatrix} = \begin{bmatrix} C_{aa} & 0 & 0 \\ 0 & C_{bb} & 0 \\ 0 & 0 & C_{cc} \end{bmatrix} \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix}$$  \hspace{1cm} (12)$$

where,

$$C_{aa} = C_{bb} = C_{cc} = \frac{2\pi \varepsilon_i}{\ln \left( \frac{D_a}{r} \right)}$$  \hspace{1cm} (13)$$

are the self capacitances of the conductors. This shows that there is no off-diagonal element in the admittance matrix for 3-core trefoil cable with balanced power-flow.

Thus the parameters identified to be estimated for the 3-phase cable system are the self resistance, reactance and susceptance of each phase ($$r_{aa}, r_{bb}, r_{cc}, x_{aa}, x_{bb}, x_{cc}, b_{aa}, b_{bb}$$ and $$b_{cc}$$) where, $$x$$ and $$b$$ are the reactance and susceptance given by $$j\omega L$$ and $$\frac{1}{j\omega C}$$ and $$\omega$$ is the angular frequency. However, this model is valid only for balanced power-flow in the cable. With the increase of unbalance, the significance of off-diagonal impedance and admittance components also increases. Identification of correct set of parameters to estimate is important and its effect on the performance of the algorithm is discussed in the next subsection.

**B. Estimation Algorithm**

The resistance estimation algorithm is aimed to give accurate and reliable estimates. The algorithm takes into account the presence of bias errors in the measurement of current and voltage phasors. The bias errors are caused due to error in or unavailability of correction coefficients for ratio and phase errors in the CTs and VTs. Extra parameters in the linear regression model were added which would model these bias errors. These bias errors are assumed to be constant for duration of one window length of sampled data. It can be shown that for a sinusoidal signal of the form $$V = |M|e^{j\theta}$$,
Coefficients adjusted correction + three phase impedance (Z Cartesian coordinates. Diagonal matrices where, km was simulated. A power flow profile recorded from the measurements of the receiving end are corrected using the cable (the sending end in this case) as error free. The it allows the treatment of the measurements at one end of it. The nominal Pi model for a medium length medium voltage cable.

Fig. 3. Nominal Pi model for a medium length medium voltage cable.

de the measured signal Vm with a magnitude error of γ% and phase error of δθ can be written as:

\[ V_m = V(1 + \gamma)e^{j\delta\theta} \]  

(14)
The correction coefficients for the bias errors can be represented as \( \frac{1}{1 + \gamma} \). In Cartesian coordinates, this could be represented in the form \( a \pm jb \), where a is the real part given by \( \cos(\delta\theta) \) and b being the imaginary part given by \( \sin(\delta\theta) \).

Using the correction coefficients at both ends, voltage and current phasors at both ends of a 3-phase system represented by a pi-model shown in Fig. 3 can be written in the following form:

\[ C_1S^2I^S - C_1R^I^R = \frac{B}{2} (CvS^1V^S + Cv^R^1V^R) \]  

(15)

\[ C_1V^S - C_1V^R I^R = Z \left( \frac{B}{2} Cv^R^1V^S + C_i R^I^R \right) \]  

(16)

where, \( C_1S, C_iR, CvS, Cv^R \) are the complex three phase correction coefficients for the ratio and phase errors of CTs and VTs at both ends of the line. Superscripts S and R distinguish the sending and receiving ends of the cable. Voltage and current phasors are represented as complex numbers in Cartesian coordinates. Diagonal matrices Z and B contain the three phase impedance \((r+jx)\) and shunt susceptance \((jb)\) elements of the cable. Using a new set of Adjusted Correction Coefficients, (15) and (16) can be rewritten as:

\[ I^S - K_1 I^R = \frac{B}{2} (K_2 V^S + K_3 V^R) \]  

(17)

\[ V^S - K_4 V^R = Z (K_5 I^R + K_6 V^R) \]  

(18)

where,

\[ K_1 = \frac{C_1R}{C_1S}, \quad K_2 = \frac{C_1S}{C_1S}, \quad K_3 = \frac{C_1V^R}{C_1S^2}, \quad K_4 = \frac{C_1V^R}{C_1S^2}, \quad K_5 = \frac{C_1R}{C_1S}, \quad K_6 = \frac{B}{2} K_4 \]

are the adjusted complex coefficients.

In this way, (17) and (18) represent (15) and (16) such that it allows the treatment of the measurements at one end of the cable (the sending end in this case) as error free. The measurements of the receiving end are corrected using the adjusted correction coefficients.

To reduce the number of unknowns, a sensitivity analysis was performed to identify the most prominent correction coefficients. For this, an MV cable of 20 kV and length 10 km was simulated. A power flow profile recorded from the 50 kV network was used. Now all the CT and VT ratio errors were varied as per a random uniform distribution in the range between 0 to 1 %. Similarly the phase angle errors of the CTs and VTs were varied between 0 to 1 degrees. The coefficients \( K_1 - K_6 \) were calculated based on these ratio and phase errors and are substituted in (17) and (18). Deviations in estimates of the elements of B and Z matrices were calculated. For the simulated system, it was observed in [15] that the error in B is most sensitive to \( K_1 \). It was found that ignoring coefficients \( K_1 \) alone could lead to a maximum error of 15% in B estimates. However, ignoring \( K_2 \) and \( K_3 \) only caused about 0.5% error each. Similar analysis showed that the resistance R is sensitive to \( K_4 \) resulting in maximum error of more than 50% on ignoring it, while ignoring \( K_5 \) and \( K_6 \) resulted in maximum errors of around 3% and 0.25% respectively. Hence only the adjusted correction coefficients \( K_1 \) and \( K_4 \) were included into the system of linear equations.

\[ I^S - K_1 I^R = \frac{B}{2} (V^S + V^R) \]  

(19)

\[ V^S - K_4 V^R = Z (\frac{B}{2} V^R + I^R) \]  

(20)

To solve for the parameters of B and Z matrices, (19) and (20) were written as two separate equations for real and imaginary parts. This was done for all the three phases resulting in twelve equations. Now, the parameter estimation process was divided in two parts. All the measured data was arranged according to the six equations from (19) forming a set of over-determined system of linear equations. The set of linear equations can be written as:

\[ Y = A\beta + \epsilon \]  

(21)

where, \( Y \) is a vector made up of multiple measurements of \( reI^b, reI^c, imI^b, imI^c \) and \( imI^a \), the parameter vector \( \beta \) is \( [reK_{1a} reK_{1b} reK_{1c} imK_{1a} imK_{1b} imK_{1c} B_{aa} B_{bb} B_{cc}]^T \). The most optimal estimate \( \hat{\beta} \) is given as:

\[ \hat{\beta} = (A^T A)^{-1} A^T Y \]  

(22)

Now, estimated susceptance parameters \( B_{1a} \) were substituted in (20) where the new parameter vector \( \beta \) is \( [reK_{4a} reK_{4b} reK_{4c} imK_{4a} imK_{4b} imK_{4c} re_{aa} re_{bb} re_{cc} x_{aa} x_{bb} x_{cc}]^T \). A new relationship matrix A and vector Y was formed and the parameter vector \( \beta \) was estimated using (22).

If the cable system was modelled to include the off-diagonal components of the capacitance and inductance matrices then the resulting matrix A would be near rank-deficient and hence ill-conditioned. The near rank deficiency would be caused by the extra almost linearly dependent columns of voltage and current phasors used to find out the non-existent off-diagonal components. The condition of the matrix A is quantified by the condition number. The higher the condition number the more ill-conditioned the matrix is. Solutions given by (22) using ill-conditioned A matrix would vary significantly even in case of
small errors in the elements of $A$ and hence would have high variance.

This is an important realization because all the variables used to form the LS problem shown in (21) are measurements with some amount of error. Hence for a given power-flow condition, the accuracy of the resistance parameters estimate would depend on the validity of the cable model along with the accuracy of the measurement devices.

After estimation of the cable parameters, uncertainty in the estimates was quantified in terms of CI associated with each parameter. Since cable resistance has a direct relationship with the cable temperature, accuracy of the resistance estimates was of prime concern.

C. Uncertainty in Estimates

The deviation in the resistance estimates was calculated in two parts. One part of the deviation was due to random errors in PMU estimates and the other part of the deviations was caused by the bias errors in the CTs, VTs and the phasor estimates given by the PMUs. The uncertainty due to random errors in PMU estimates were taken as per the specification provided by the manufacturer. The random errors were the absolute maximum errors distributed uniformly with zero probability of errors outside the range. The standard deviation caused by the random errors ($u_{r_{\text{nd}}}$) of the impedance estimates were derived based on the co-variance of solution of the LS problem. It can be shown that expected variance in the impedance estimates is given by:

$$u^{2}_{r_{\text{nd}}} := \text{Var}[b|A] = \frac{\epsilon \epsilon^T}{n - K(A^TA)^{-1}} \label{eq:23}$$

where, $\epsilon$ is the residual vector, $n$ is length of the vector $Y$ and $K$ is the number of parameters.

The CT and VT correction coefficients are used by the PMUs while estimating the voltage and current phasors. However, to cater any change in correction coefficients and minimize the effect of bias errors in the measurements, prominent adjusted coefficients $K_1$ and $K_4$ were added. However, neglecting the coefficients of $K_2$, $K_3$, $K_5$ (assumed 1) and assuming $K_6$ as $\frac{\epsilon}{2}$ causes deviation in the cable impedance parameters from their true values. This deviation is quantified as a bias error ($u_b$). The deviation in the impedance parameters caused by the bias errors in measurements is estimated by calculating the combined uncertainty calculation as specified in the Guide to the Expression of Uncertainty in Measurement (GUM) [20]. In this work the magnitude and phase errors were assumed to vary normally with a standard deviation of ±10% from their last calibrated values. The uncertainty (variance $u^2_b$) in resistance estimate due to believed bias in the measurements was quantified by:

$$u^2_b = \sum_{i=1}^{N} \left( \frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) \label{eq:24}$$

where, $f$ is the analytical function to calculate the resistance and is given by the real part of (18). Each $u(x_i)$ is the believed standard deviation in real and imaginary parts of coefficients $K_5$ and $K_6$. The total standard deviation in the resistance estimates is given by:

$$u(R_i) = \sqrt{u^2_{r_{\text{nd}}} + u^2_b} \label{eq:25}$$

The following section presents the process of calculating the temperature estimates and associated uncertainty of the estimates.

IV. Temperature Estimation

The resistance estimates from the solution given by (22) are used in (1) to achieve the temperature estimates. The uncertainty in the temperature estimates comes from the individual uncertainty associated with the resistance estimates ($R_i$), the measured DC resistance at 20 °C ($R_0$) and the used coefficient of resistivity ($\alpha$). Treating these individual uncertainties as independent from each other, the combined uncertainty in the temperature estimates is then given by:

$$u^2(T_i) = \sum_{i=1}^{N} \left( \frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) \label{eq:26}$$

where, $u(T_i)$ is the standard deviation of each temperature estimate $T_i$, $f$ is the function given in (1) and each $u(x_i)$ is the standard deviation associated with all the parameters $x_i$. The skin and proximity effects however, were ignored in this paper because the values of harmonic currents are limited in the analyzed system 50 kV network. The total harmonic distortion (THD) of the current ranges between 5-10% with about 95% of the contribution by the lower order fifth harmonic (250 Hz). This makes the impact of the skin effect very limited, if not negligible.

The following section V demonstrates the results using PMU data from the mentioned 50 kV ring network in the Netherlands.

V. Results from Field Data

This paper takes data from a 50 kV ring distribution network in the Netherlands provided via the Dutch National Metrology Institute (VSL) [21]. The ring network has five substations and six PMUs. One of the intended research goal for installing PMUs in the network was application of PMU data to estimate the cable impedance and explore possibilities of implementing DLR. Hence the cable between substations Oosterland and Tholen has two PMUs (one at each end). The monitored cable between substations Oosterland and Tholen is 15.313 km long and has an AC resistance of 1.98 Ω at 20 °C [22]. The current rating of the cable per phase is 350 A.

Voltage and current phasors at both sides of the monitored cable were collected for 40 hours at a rate of 5 phasor estimates

| Table III
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Entity</td>
<td>Uncertainty</td>
</tr>
<tr>
<td>voltage magnitude</td>
<td>±0.02%</td>
</tr>
<tr>
<td>current magnitude</td>
<td>±0.03%</td>
</tr>
<tr>
<td>voltage and current phase</td>
<td>±0.01°</td>
</tr>
</tbody>
</table>
The cable and its surroundings are represented using lumped representations in [1] and [4]. In the TEE model, various layers of the cable are divided into three layers with different thermal resistance and capacitance. The thermal capacitance of a long-duration transient where the soil layer has been subdivided into smaller layers [1]. The thermal capacitance of the insulator has been divided into two parts using the van Wormer coefficient \( p \). For a specific cable system in [4], the soil layer of the TEE model was sub-divided into 100 layers to get accurate results comparable to FEM based method. In this paper also, the soil layer is divided into 100 equally small layers.

The following section discusses the process of utilizing real-time temperature estimates of a cable to calculate its dynamic thermal response to power-flow forecasts.

**VI. THERMAL ASSESSMENT USING TEE MODEL**

A TEE model of the cable is created as per recommendations in [1] and [4]. In the TEE model, various layers of the cable and its surroundings are represented using lumped parameters of thermal resistance and capacitance. The temperature estimates from the monitoring method are proposed to set the initial temperature of layers of the cable and the soil.

Fig. 5 presents a TEE model of a single core cable for a long-duration transient where the soil layer has been divided into three layers with different thermal resistance and capacitance. **W**<sub>c</sub> is the ohmic joule loss in the conductor caused by current flowing and the real time resistance given by (1). **W**<sub>d</sub> is the dielectric loss in the insulator which has been divided into two equal parts. **W**<sub>s</sub> is the joule loss in the screen of the cables. **Q**<sub>c</sub>, **Q**<sub>d</sub>, **Q**<sub>s</sub>, **Q**<sub>j</sub> and **Q**<sub>s</sub> are the thermal capacitances of the conductor, insulator, screen, jacket and \( i^{th} \) layers of the surrounding soil.

To keep the temperature gradient within the layer small, components like insulation and surrounding soil must be subdivided into smaller layers [1]. The thermal capacitance of the insulator has been divided into two parts using the van Wormer coefficient \( p \). For a specific cable system in [4], the soil layer of the TEE model was sub-divided into 100 layers to get accurate results comparable to FEM based method. In this paper also, the soil layer is divided into 100 equally small layers.
thick layers. Thermal resistance of the insulator, jacket and the surrounding soil is represented by $T_1$, $T_3$ and $T_{si}$. The modelled cable in Fig. 5 has no armor hence the thermal resistance of armor ($T_{2a}$) is ignored.

A. Parameters of the TEE model

Thermal resistances ($T_i$) and capacitances ($Q_i$) for various layers of the cable and its surrounding need to be accurately computed. For known internal and external diameters $Di$ and $De$ of a layer, its thermal resistance is [1]:

$$T_i = \frac{\rho_i}{2\pi} \ln \left( \frac{De_i}{Di} \right)$$ (27)

where, $\rho_i$ is the thermal resistivity of the material of layer $i$. For each sub-layer of the soil, thermal resistivity $T_{si}$ was calculated as [4]:

$$T_{si} = \frac{\rho_i}{2\pi} \ln \left( \frac{De_i}{Di} + \frac{\ln(2)}{N} \right)$$ (28)

where, $N$ is the number of soil sub-layers. Thermal capacitance of any layer can be calculated as [1]:

$$Q_i = \frac{\pi}{4} (De_i^2 - Di^2) C_i$$ (29)

where, $C_i$ is the volumetric specific heat of the respective cable layer or soil sub-layer.

A transient is considered long when it lasts longer than $1/3\Sigma T\Sigma Q$, where $\Sigma T$ and $\Sigma Q$ are the internal thermal resistance and capacitance of the cable. Short duration transients for different cable types last anywhere between 10 minutes to 1 hour. This paper focuses on transients lasting longer than 1 hour that is the long transients. For long duration transients, van Wormer coefficient $p$ to divide the insulation is given by [1]:

$$p = \frac{1}{2\pi} \ln \left( \frac{De_{ins}}{Di_{ins}} \right) - \frac{1}{\left( \frac{De_{ins}}{Di_{ins}} \right)^2 - 1}$$ (30)

where, $De_{ins}$ and $Di_{ins}$ are the external and internal diameter of the insulator.

B. Transient Thermal Analysis

The state variables of interest are the temperature of the conductor, screen, jacket and the multiple soil layers. The rate of change of the state variables can be described by the set of equations:

$$\begin{align*}
\dot{\theta}_c &= \frac{1}{Q_1} \left( W_c + W_{d1} - \theta_c - \theta_{scr} \right) \\
\dot{\theta}_s &= \frac{1}{Q_3} \left( W_s + W_{d2} + \frac{\theta_c - \theta_{scr}}{T_1} - \theta_s - \theta_j \right) \\
\dot{\theta}_j &= \frac{1}{Q_2} \left( \theta_{scr} - \theta_j - \frac{\theta_s - \theta_{s1}}{T_3} \right) \\
\dot{\theta}_{s1} &= \frac{1}{Q_{s2}} \left( \frac{\theta_j - \theta_{s1}}{T_3} - \frac{\theta_{s1} - \theta_{s2}}{T_{s1}} \right) \\
\vdots & \quad \vdots \\
\dot{\theta}_{sN} &= \frac{1}{Q_{sN}} \left( \frac{\theta_{sN-1} - \theta_{s2}}{T_{sN-1}} - \frac{\theta_{sN} - \theta_a}{T_{sN}} \right)
\end{align*}$$ (31)

where parallel thermal capacitances are added together such that $Q_1 = Q_c + pQ_i$ and $Q_2 = Q_j + Q_{scr} + (1 - p)Q_i$.

However, this system of equation implies that the resistance of the cable remains constant. The heat generated by joule heating is dependent on varying current values but a constant resistance. This is contradictory to realistic case where the resistance of the cable also varies according to the temperature of the cable. This relationship between the cable temperature and resistance is defined by the (1). To rectify this, $W_c$ at time $t_i$ is modified and written as:

$$W_c(t_i) = I(t_i)^2 \left( R_0(1 + \alpha(\theta_c(t_i) - \theta_c(t_0))) \right)$$ (32)

where $R_0$ and $\theta_{co}$ are the cable conductor resistance and temperature estimated by the temperature monitoring method and used as the initial conditions for (31) at time $t_0$.

The modified system (31) can be written using the state-space notation:

$$x' = Ax + Bu$$ (33)

where the state vector $x$ is $[\theta_c \theta_{scr} \theta_j \theta_{s1} \ldots \theta_{sN}]^T$ and conductor and ambient temperatures ($\theta_c$ and $\theta_a$) are known.

The driving function (B) for a given time period can be determined using the forecasts of the generation and load units. The thermal response of the cable over the given period of time can be obtained by solving the system of differential equations.

The time domain solution of (33) is the superposition of natural and forced response of the system and for a given period ($t_0-t_1$) can be given as:

$$x(t) = Pe^{At} P^{-1} x(t_0) + Pe^{At} B \int_{t_0}^{t_1} e^{-At} dt$$ (34)

where $\Lambda$ is the diagonal matrix made of the eigenvalues of the matrix $A$ and $P$ is the left eigenvector.

As discussed, the initial value of the state vector ($x(t_0)$) can be calculated during the steady-state conditions using the available real-time estimates of the conductor temperature. Using the steady-state condition $x' = 0$, and substituting the value of conductor temperature ($\theta_c$) and the known ambient temperature ($\theta_a$), (31) can be rewritten as a system of linear equations of form (21). Initial Values of unknown state variables are estimated using the solution given by (22) and utilized in (34).

The solution of the complete TEE model of a cable and the surrounding soil was verified by comparing it to the solution given by a FEM based model created in the commercial software Consol Multiphysics 5.4. For demonstration purpose a single-phase 10 kV cable was modelled with four layers. A copper conductor, an XLPE insulation, a Lead alloy sheath as a single-phase 10 kV cable was modelled with four layers. A software Consol Multiphysics 5.4. For demonstration purpose a single-phase 10 kV cable was modelled with four layers. A copper conductor, an XLPE insulation, a Lead alloy sheath as a single-phase 10 kV cable was modelled with four layers. A software Consol Multiphysics 5.4. For demonstration purpose a single-phase 10 kV cable was modelled with four layers. A copper conductor, an XLPE insulation, a Lead alloy sheath as a single-phase 10 kV cable was modelled with four layers. A software Consol Multiphysics 5.4. For demonstration purpose a single-phase 10 kV cable was modelled with four layers. A copper conductor, an XLPE insulation, a Lead alloy sheath as a single-phase 10 kV cable was modelled with four layers. A software Consol Multiphysics 5.4. For demonstration purpose a single-phase 10 kV cable was modelled with four layers. A copper conductor, an XLPE insulation, a Lead alloy sheath as a single-phase 10 kV cable was modelled with four layers. A software Consol Multiphysics 5.4. For demonstration purpose a single-phase 10 kV cable was modelled with four layers.
The static rating of the single cable according to IEC 60287 was calculated to be 947 A. A step of rated current was given for 24 hours and the conductor temperatures from each method were recorded. A 24 hours step was for day-ahead planning and assessment of thermal limits. The results are presented in the Fig. 6. It was observed that the TEE method gives a reasonably accurate solution with a maximum deviation of around 1 °C.

Next, thermal response to a multi-step driving function was calculated. After a steady state condition, a 24 hour forecasted power flow as shown in the top half of the Fig. 7 was simulated. The initial temperatures of the screen, jacket and other soil layers were calculated based on the steady-state temperature of the conductor and the ambient soil temperature. The thermal response was calculated using (34) and Fig. 7 presents two solutions: original state-space model with constant resistance and modified model with varying conductor resistance. The rated current and maximum conductor temperature are marked as constants in the plots. It is observed that using real-time resistance based temperature updates, thermal profile of cables can be predicted to allow the assessment of the dynamic thermal state of the conductor for predicted loading scenarios.

VII. CONCLUSION

This paper presented a new method for monitoring of cable temperature using PMU data. The method is based on an algorithm which can estimate accurate resistance of a 3-phase cable system in real-time to calculate the temperature of the cable conductor. Application of this temperature monitoring method was demonstrated utilizing PMU data from a cable section present in the Dutch MV network. The results showed that the method in the current setup was capable of monitoring the cable temperature up to an accuracy of ±5°C. In this work, the skin and proximity effect were not included in estimation problem. Their inclusion in either the temperature estimation or uncertainty calculation could be a task for the future.

Application of the real-time cable temperature monitoring method in assessment of thermal state of the cable for forested loading scenario was shown. Utilization of the TEE model was shown to match the FEM results. For the modelled cable the uncertainty in the predicted thermal response of the cable lied within 2 °C. However to simplify the demonstration process, TEE model of a single cable was used. More complex TEE models of multiple cables laid in different formations is a task for the future. The thermal resistivity of the whole soil layer was assumed to be the same. However different soil types and humidity levels at different layers could require multiple thermal resistivity values. More work is also required to study additional cases where the cables cross multiple soil types.

Application of the presented thermal assessment method to facilitate DLR is most suitable for cable sections connected to varying wind or solar power parks where the goal is to maximize the absorption and delivery of renewable power using the available cable infrastructure. The grid operators could in advance analyze the thermal response of the critical cable infrastructure and request production curtailment/storage actions if necessary. This would help them to optimize the capacity planning of cables.

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"JCGM 100:2008, Evaluation of measurement data guide to the expression of uncertainty in measurement."


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