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An Improved Dynamic Thermal Current Rating Model for PMU-Based Wide Area Measurement Framework for Reliability Analysis Utilizing Sensor Cloud System

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ABSTRACT Information technology expressively improves remote electricity measurement and monitoring. Integrating Dynamic Thermal Current Rating (DTCR) software packs with the exclusive phasor measurement-based Wide Area Measurement (WAM) framework, the remote Transmission Lines (TLs) current rating can be measured. WAM is used for data acquisition from different sensors, and also allows data transmissions and processing for which sensor cloud system (SCS) plays a vital role. DTCR with phasor-measurement based WAM framework is mainly used to analyze and determine the current ratings of overhead TLs using weather condition estimation or prediction methods. However, the recent study suggests that the accuracy of the DTCR has become an issue in the smart grid of Sarawak Energy Berhad (SEB). Hence, this article studies and discusses the relevant models and systems, and then proposes an improved thermal pi (π) model for the transmission line thermal model of DTCR software in WAM Framework. The performance of the improved π model will be distinguished from the existing thermal model. The weather factors that bring a substantial impact on the current rating is also considered, where the relevant data is monitored via different weather sensors. Besides, this study also focuses on calibrating the DTCR through phasor measurement in the WAM system, as well as the field measured data. All the data is collected from relevant sensors, and a detailed comparative analysis is provided based on the proposed model for the sake of improving the reliability of the system. The performance analysis of the thermal models is evaluated using Matlab software-based numerical analysis.

INDEX TERMS Dynamic thermal current ratings, data acquisition system, information technology, phasor measurement unit, reliability, sensors, sensor cloud system, wide area measurement.

NOMENCLATURE

ABBREVIATIONS

ACSR	Aluminum Conductor Steel Rectifier
CTE	Conductor Temperature Evaluation
CTGM	Clearance-To-Ground Measurement
DTCR	Dynamic Thermal Current Ratings
EKF	Extended Kalman Filter
FSM	Full-scale monitoring
HDFS	Hadoop Distributed File System
LSE	Least Square Error

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LSM	Line Sag Measurement
MCC	Motor Control Centre
PDC	Phasor Data Concentrator
PMU	Phasor Measurement Units
SCS	Sensor Cloud System
SER	Seasonal Rating
STR	Static Rating
TL	Transmission Line
TM	Tension Monitoring
WF	Weather Forecast
WM	Weather Model

I. INTRODUCTION

With the development of sensor cloud system (SCS), the applications can be extended for the improvement of the real-time monitoring system, which in turn enhances the reliability of the smart grid system [1], [2]. One of the problems that always arise on the transmission line (TL) is overcurrent. The large current flow through a conductor may reach up to its maximum value that leads to an increase in the conductor temperature. Therefore, the thermal effect degrades the performance of the TL. As a result, it decreases the power efficiency of the overhead TL. The Dynamic Thermal Current Ratings (DTCR) software is used to estimate the thermal effect in TLs to make sure that loading (i.e. thermal current) does not exceed the limit. It is beneficial to calculate line rating with the DTCR based on predicted or measured weather conditions. However, currently, the existing DTCR is not fully functional due to some Phasor Measurement Units (PMU) and thermal estimation issues raised since its ambiguity as well as reservation in the calibration of constant atmospheric circumstances such as wind speed, ambient temperature, and solar irradiation intensity. However, these weather conditions cannot be constant due to the random weather effects on the TL. Therefore, in calibrating the dynamic thermal model in DTCR, these weather factors are integrated with the extended thermal model in the empirical estimation to improve the DTCR performance. There are several important components in the Wide-area measurement system. These include PMU, Phasor Data concentrator (PDC), and other communication networks. For the data transmission from PMU to PDC, the types of network configuration are grouped into two: dedicated network and shared network [3], [4]–[6].

PMU is a device that is capable of providing phasor measurement to estimate phase angle and magnitude of phasor quantity (like voltage and current) in the transmission lines by using a common time source for synchronization.

The resulting outcome is also called as Synchrophasors. For a firm operation of the TL, a real-time monitoring system is necessary, and PMUs are key elements for the real-time monitoring system. [7]. Besides, PMU can report 30-60 measurements per second with high temporal resolution. Therefore, the data generated by the PMU can be helpful to the engineers for the whole power system analysis. However, it is not worth to use PMU across the whole network because of the high expense and the device demands optimization.

The DTCR quality is greatly influenced by the data type used for the system evaluation, meanwhile, a potential monitoring system is important in DTCR for data collection and different companies use different devices. One of the approaches used for power system operation, Dynamic Line Rating (DLR) ensures an effective approach for the system. Besides, in a smart grid solution, DLR denotes a key requirement tool for the increase of the utilization level. In DLR technology, a real-time monitoring system is used to calculate the changing line rating of the TL with the change of weather conditions like wind direction, wind speed, ambient temperature, and solar radiation. For real-time monitoring and data acquisition, SCS is utilized to form a wireless sensor network to incorporate all the sensors data. Wireless sensor networks have proved significant effectiveness in terms of reliability, security, and smart monitoring in the literature [8], [9]. Furthermore, SCS also provides scalability, and flexibility during real-time monitoring [10]. After receiving measures of data, DLR measures the tension of the TL. Moreover, the effective wind speed can be calculated by the conductor temperature immensity [11], [12]. To evaluate dynamic system monitoring, nine main determinations have considered evaluating the system in terms of complexity and accuracy as follows [13]:

A- No rating or static rating (STR): a specified national and international standard rating of the transformers and the transmission lines.

B- Seasonal rating (SER): also known as summer-winter or summer-autumn-winter rating in some cases. This rating is used for seasonal conditions.

C- Weather Model (WM): this rating has more precision compared to the seasonal rating. The rating is measured with the collected several years' data of average weather.

D- Weather Forecast (WF): is an online monitoring technique. The real-time weather data is collected near the conductor to forecast the rating.

E- Conductor Temperature Evaluation (CTE): is also an online monitoring technique, where temperature sensors are used to measure the conductor temperature.

F- Tension Monitoring (TM): load cells have been placed in series with the insulator strings for the process of tension monitoring. However, most of the cases require an extra installation of a weather monitoring device for the calculation of the ampacity of the TL.

G- Line Sag Measurement (LGM): this system is more advance than can measure the sag of the TL, which helps to operate within the safety margin. Therefore, applicable equipment is placed on the critical zones of the TL.

H- Clearance-To-Ground Measurement (CTGM): considered as a new generation of the overhead lines monitoring system that doesn't measure sag, while a clearance-to-ground. This measurement system provides information about the distance between conductor and ground.

I- Full-scale monitoring (FSM) or On-line monitoring of the entire TL (every overhead line segment): this method is feasible with the integration of several methods as mentioned above. By placing several sensors along with the lines can fulfill the feature of this category. However, placing several devices with TL does not cost worthy today.

The above dynamic system monitoring is possible by integrating wireless sensor network, which constitutes of different sensor technology, embedded technology, network technology, and communication technology for data acquisition [14]. DLR provides necessary calculations and analysis based on these data collected during real-time operations. As the monitoring process is carried out remotely, there is a sensor cloud system, where all the necessary data get updated continuously, and in later stage, these data are analyzed for empirical assessments and pertinent forecasting for improving the reliability of the system. In this paper, we are considering different weather factors, such as ambient temperature, wind direction and speed, and solar radiations for which simultaneous data acquisition from different weather sensors is essential for utilizing them for our proposed model.

The main contributions of this article are as follows:

1. A systematic investigation modeling to verify the validity of the existing data of the conductor temperature of the transmission line by considering weather factors, where the relevant weather data will be collected continuously from different sensors. A sensor cloud system is also proposed to incorporate all the sensor data into one platform for seamless monitoring and better security purpose.
2. Propose an improved DTCR model that integrates the dynamic parameters to facilitate the calibration of DTCR software dynamically.
3. A state of art comparison of measured data of the WAM system (using PMU measurement) with the estimated data that is achieved through the empirical assessment. This is to extricate the performance of the improved DTCR thermal model over the existing model.

The rest of the paper is arranged as follows: Section II describes the related works performed in the literature. In section III, the IEEE AND CIGRI standards are explored for the approximation, measurement, and execution of dynamic current rating. The estimation of conductor temperature is explained in Section IV. The detailed experimental setup and configuration are demonstrated in section V. Section VI illustrate the relevant results with discussions. Finally, the paper is concluded in section VII.

II. RELATED WORKS

The conductor temperature can be increased because of the overcurrent flow and the amount of current can be reached to its maximum limits that finally carries to the overhead TLs conductor sag [15]. The overhead TLs sag is considerably the conductor category, loads, temperature, and length of span in some cases [16]. Besides, the conductor sag can also appear with the conductor age as it is equally proportional to the conductor age. This is because of external reasons like thermal condition, weather condition (wind and ice), and load.

High Voltage Laboratory-Budapest University of Technology and Economics (HVL-BUTE) has developed a new factor called the Sag parameter. It has been developed concerning the DLR system as the average temperature of the conductor can be measured for a specific line-span [17]. It is observed that the conductor ampacity has been measured by the DLR system. It has been also suggested that the conductor sag and temperature can be forecasted by using the DLR model. On the other hand, some other parameters have been utilized to measure DLR and conductor temperature of the TL like geographical data, atmospheric conditions, insolation, wind speed and direction, transmission tower data, power line data, and ambient temperature. GPS is being used to monitor overhead transmission lines [16]. In [18], Power Donut^{TM} is used to monitor conductor sag, whereas in [19] EPRI's Video Sagometer is utilized for the same perspective. A distribution temperature measurement (DTM) system is proposed in [20] for monitoring temperature of transmission lines. In many literatures, forecasted weather data for short-time horizons are utilized for estimating dynamic thermal rating [21], [22].

The conductor sag (S_{SAG}) is expected considering the estimated sag as well temperatures during the sagging progression, the span value, weights/m, elasticity modulus as well as conductor creep [23]. The relation between the square length of the conductor span and its total weight can be expressed by Eqn. (1) [24].

$$S_{SAG} = {Wl^2}\big/{8T} \tag{1}$$

where W is the overall weight of conductor then T is the value of tension of TL. A general overview of PMU measurement is demonstrated in figure 1. The performance of the DTCR model greatly depends on the simultaneous data that is collected via DLR technology with the assistance of sensor cloud system. The promising applications and the characteristics of DTCR are comprehensively reviewed in [25].

III. EXISTING IEEE AND CIGRI STANDARD

For an energized conductor, it is easy to calculate the maximum operating temperature by incorporating all associated parameters (i.e. wind speed, solar radiation, wind integration, and ambient temperature) into the heat balance equation as expressed in Eqn. (2) [26]. In [27], a comparative analysis of the ampacity calculation between the IEEE and CIGRE standard has been discussed briefly. As it is observed from the authors' findings on the heat balance (figure 2), the proposed equation has expressed the concept of joule and magnetic heating. Meanwhile, to conserve the IEEE and CIGRE standards, various estimation has been analyzed based on

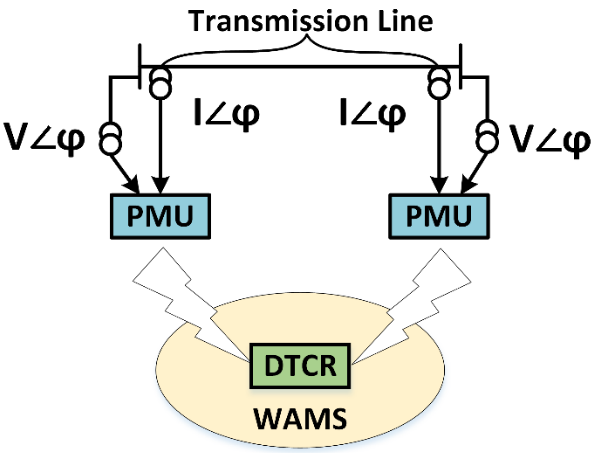

FIGURE 1. A general overview of the phase measurement unit (PMU) in the transmission line [30], [40], [46].

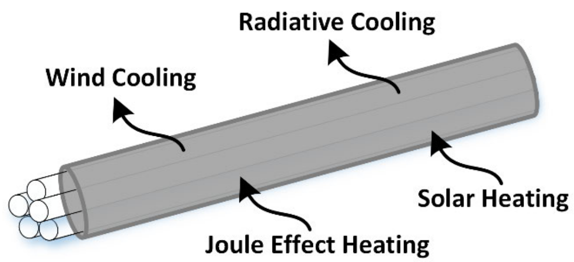

FIGURE 2. Heat balance within a conductor between Joule effect heating and environmental condition [28], [46].

the types of cooling. It is observed from the paper that the measurement data has good agreement as suggested by the analysis. Besides, the standards have decent accuracy esteem to the line rating measurement, while alongside compare to the direct measurement. Therefore, IEEE and CIGRE standards for ampacity calculations have been accepted by the power industry. In this paper, the IEEE standard has been considered for approximation, measurement, and execution of dynamic current rating as found that it has been widely accepted by the researchers and power industry. Moreover, SEB implements the IEEE standard for dynamic rating to their smart grid. It has been observed that the heat balance model is a key factor in the IEEE standard and a steady-state based on the heat balance model can be expressed in Eqn. (2) as mentioned in [28].

$$I^2R\,(T_c) + Q_s = Q_c + Q_r \tag{2}$$

where conductor temperature is defined by $\boldsymbol{T_C}$, the solar heat gain is stated by Q_s, the convective heat loss is Q_c and the radiation heat loss is stated by Q_r. The thermal heat balance (THB) model in a steady-state condition has been presented in Eqn. (2) [28], [41], [42], showing the heat gain and heat loss is equal, while the line reached the symmetric condition. Usually, the THB equation is applied for a real-time solution due to the small error in the steady-state situation, while, less suitable for calculating conductor temperature

TABLE 1. Model type in IEEE Std.738-2012.

Model type	Line current	Conductor temperature model	Environmental & Weather conditions
Steady-state	Constant (specified or calculated)	Steady-state (calculated or specified)	Constant
Transient	Step change (specified)	Dynamic (exponential response) (calculated)	Constant
Dynamic	Varying	Dynamic (calculated)	Varying
Hybrid	Varying	Dynamic (calculated)	Constant

in this case. It is necessary to note that for highly variable weather conditions, thermal dynamic rating. Three different models have been widely used for overhead line calculation namely CIGRE, IEEE, and IEC (International Electrochemical Commission) [28], [35]–[42]. In [29], an explanation of all three heating type models has been carried out that have been expressed in Eqn. (3), (4) and (5).

$$q_r = 0.0138D\varepsilon\left[\left(\frac{T_c+273}{100}\right) - \left(\frac{T_c+273}{100}\right)\right] \tag{3}$$

$$q_s = \alpha Q_{SE} sin\,(\theta)\,A \tag{4}$$

$$qc1 = \left[1.010.0119\left(\frac{DV_WP_f}{\mu_f}\right)^{0.52}\right]K_fK_{ang;e}(T_c - T_c) \tag{5}$$

where D denotes for conductor diameter and ϵ denotes for emissivity, α denotes for solar absorptivity, QSA denotes for the total sky and solar radiated heat intensity corrected for elevation, θ denotes for the effective angle of incidence of the sun's rays, and A' denotes for the projected area of the conductor. And qc1 has used for less wind speed which is less than 3 mph, qc2 denotes for higher wind speed, $\boldsymbol{\rho_f}$ denotes for air density, $\boldsymbol{\mu_f}$ denotes for dynamic viscosity, $\boldsymbol{K_f}$ is the thermal conductivity, $\boldsymbol{K_{angle}}$ is the wind direction factor, $\boldsymbol{T_C}$ is the conductor temperature and $\boldsymbol{T_a}$ is the ambient temperature.

Using the existing IEEE Std 738-2012 all the DTCR models calculations were performed for each PMU sample however, measurement errors were not calibrated. In addition, certain environmental parameters such as solar irradiation intensity $S(w/m^2)$, wind velocity Vw (m/s) and ambient temperature, $Ta\ (°C)$ were assumed as constant values instead of being dynamic variables. However, this cannot happen since such weather condition have a great impact on the transmission line. Furthermore, this is not comply with the dynamic thermal model (refer Table 1) stated in the IEEE Std 738-2012.

IV. CONDUCTOR TEMPERATURE

The corona effect or in another way electric discharge phenomenon can occur in the high voltage TL because of the

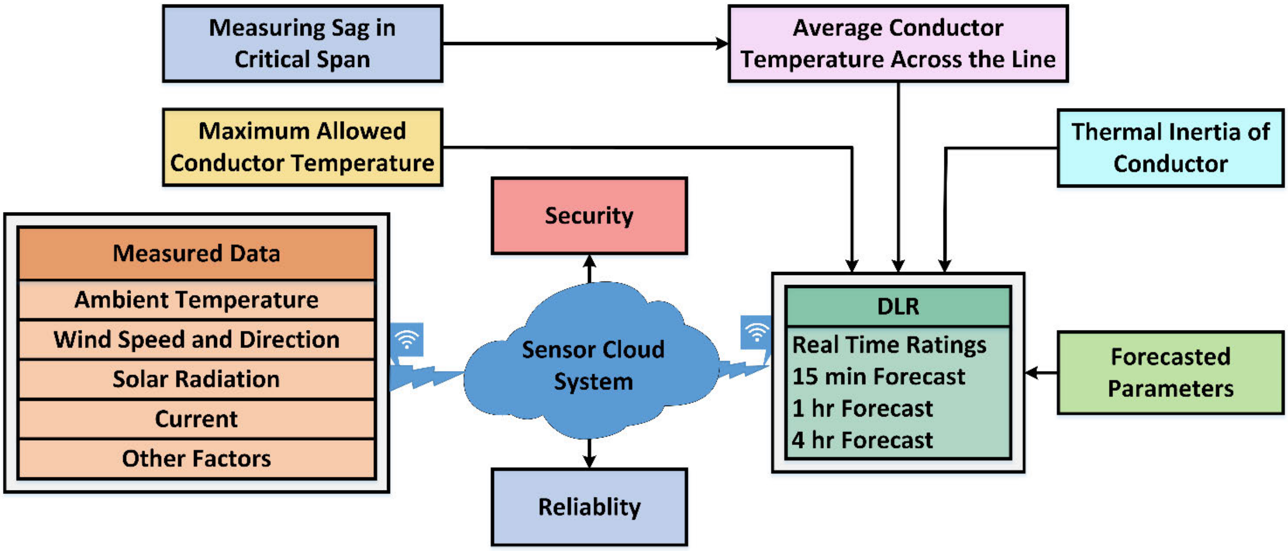

FIGURE 3. Overview of the simplified dynamic line rating (DLR) model, which collects data continuously from a sensor cloud system for forecasting in the later part [13].

ionization of the fluid-like air surrounding the conductor that is electrically charged. This corona occurrence depends on the rate of the collision of the molecules in TL [30] and the molecule collisions in a conductor line can be increased with the increase of conductor temperature [35], [41]. Meanwhile, high temperatures can increase the molecule collision in the conductor that can increase the corona loss in the TL. Therefore, conductor temperature should be estimated accurately by the electricity dispatchers as it has significant impacts on the TL [31]. For conductor temperature estimation, Hadoop MapReduce has been used to estimate large data set analysis as reported in [32], [37]–[39]. This programming model contains the Hadoop Distributed File System (HDFS) file that is designed to consistently store and stream large data sets within a large bandwidth. Besides, Map Reduce is a basic programming model for distributed computation. For electricity dispatch in the future, the Hadoop MapReduce framework can be useful for smart grid applications by providing a smart system service for the dispatchers.

The efficient line capacity is modeled by implementing of sensing probe on the TL [32]. It is mainly used for monitoring the conductor temperature and measure important parameters in real-time. A real-time temperature monitoring system based on sensor cloud database is also shown in [33]. The line rating can be defined by the calculation of the recorded data sets and the proper algorithm has been stored in the system for the calculation. The conductor temperature is measured by the current flow of the line along with the surrounding weather conditions [32]. Besides, the variation in the conductor temperature can lead to non-uniformity in the TL.

The calibration of the DTCR thermal model was largely focused on the calculation model of DTCR software. To investigate the impact of weather factors on the current rating, all the related formula that has been documented in IEEE standard-738. The result of the findings will be performed in graph form and they will be presented in the result and discussion section.

V. EXPERIMENTAL SETUP AND CONFIGURATION

In the proposed new model, the cooling effect of precipitation was also involved. The researchers finally developed the new DLR model in HVL-BUTE which able to calculate the conductor temperature precisely. DLR's new model can estimate the conductor temperature and the sag-temperature calculation is very important since it tends to avoid the violation with electrical clearance. Figure 3 shows an overview of the simplified DLR model.

From figure 3, the measured data are ambient temperature, wind speed and direction, solar radiation, current, and other factors. All of these data have been collected by using different sensors. Afterward, the integration of the sensor cloud system is proposed, which will act as a platform to integrate all of these sensors data for providing seamless dataflow, and analysis. These data will be updated continuously in real-time in the sensor cloud system. The sensor cloud system plays a key role in this workflow to ensure the security and reliability of the data. It will also ensure safe data transfer to the DLR model, which will utilize the data for real-time forecasting.

Due to the online sensors, one of the major challenges of this project was the power supply. In such case, high voltage is a condition that needed to be focused on because the international standard practices to qualify the equipment under the condition like corona and high electromagnetic field are still not sufficient. The study of the reliability of the thermodynamic model especially for high-temperature conductors was still not very common at that time. Besides, the accuracy of the heat balance model at high temperatures is always becoming an issue among the system operator. This is

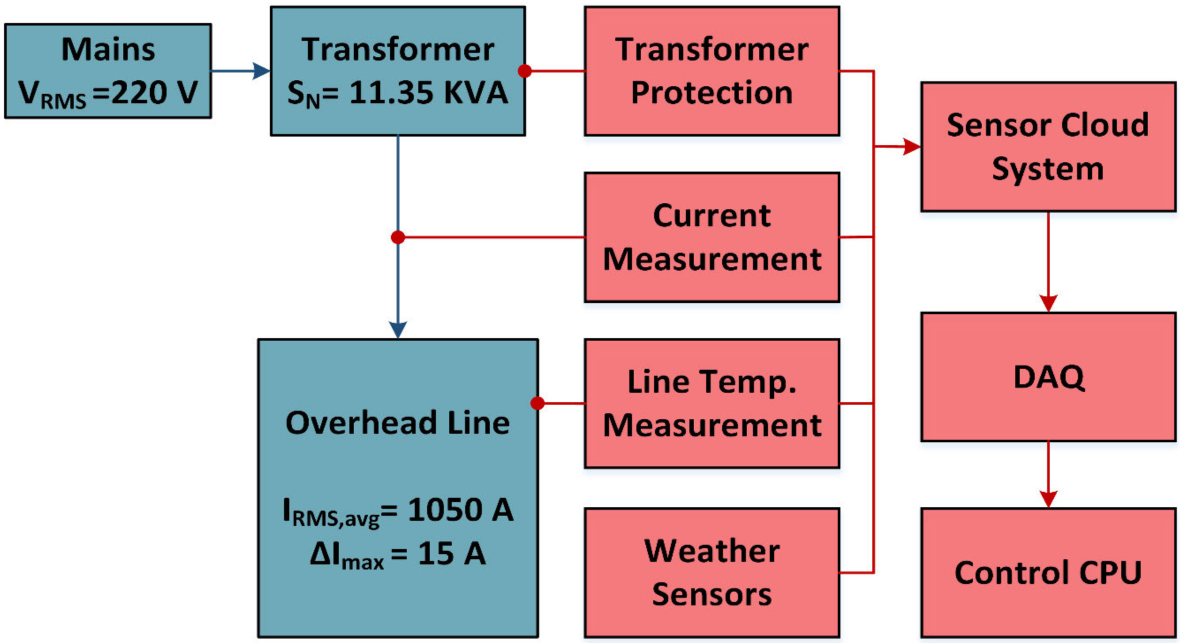

FIGURE 4. Block diagram of experimental setup [43]. The blue boxes indicate the connections among Mains, Transformers, and overhead lines. The red boxes illustrate the Sensor cloud system, and Data Acquisition System (DAQ) with relevant monitoring sensors.

because in real-time, the conductor temperature is lower than the Motor Control Centre (MCC). To carry the project, a new test facility was built outdoor of the High Voltage Laboratory in ETH Zurich. This is one of the great contributions that was successfully made (see Figure 4). In this figure, the red boxes indicate the sensor cloud system with relevant sensors and data acquisition systems. The fast responsiveness and the credibility that is provided by the sensor cloud system make it an appropriate choice to incorporate it into the workflow and make the system more reliable

Finally, yet importantly, High-Temperature Equivalent Model (HTEM) was proposed to decrease the errors made by inaccurate meteorological parameters such as temperature, wind speed, and solar irradiation [44]. After went through the trial for more than 30 months on 110kV to 500kV, HTEM is considered an online system monitoring that has great reliability and easy maintenance [44].

For the experimental measurements purpose, a testing site was built as shown in the Figure 5, where the setup was considered line temperature measurement sensor, surface temperature measurement sensor, DTR regulator, and the Wi-Fi with the cloud computations.

VI. RESULT AND DISCUSSION

The real-time data were collected from Sarawak Energy which is mainly from PMU measurement using the DTCR software of the WAM system. It utilizes a sensor cloud system for data acquisition remotely for further analysis. SCS plays an important role not only for data acquisition but also for data security [45]. The PMU measurements were only focused on the TL between Mambong and Engkilili, Sarawak. During

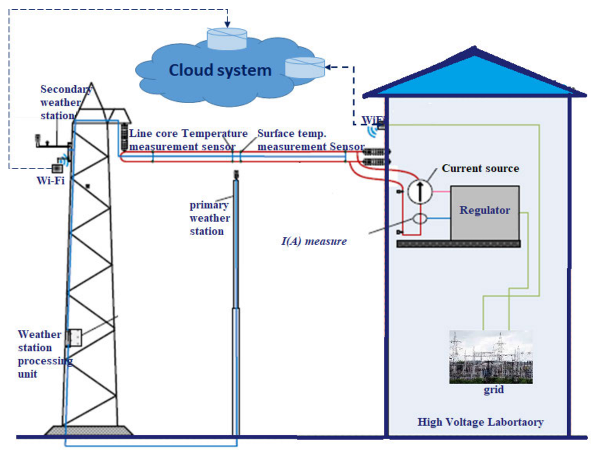

FIGURE 5. Schematic diagram of Dynamic Thermal Rating laboratory testing site [30], [40].

the data collection, it is observed that the DTCR Engine is a software that was installed in the WAM system. It is also observed that the DTCR software is used to perform calculations where the results will be written in Historian Server. The results can be stored in the Historian Server for a minimum of one year. To safeguard the data, a regular backup system is needed to save the measured data in external media. The evaluation is made using Matlab software. The selected parameters are given in Table 2.

Before the thermal model of DTCR is being analyzed and calibrated, it is very important to check the functionality of the PMU measurement of the TL. Thus, Figures 6, 7, 8, and 9 were presented to characterize the voltage and current along the line. The TL in between Mambong

TABLE 2. Selected parameters [16]–[26], [34]–[42].

Parameters	Standards		
	IEEE	CIG RE	Measured
Conductor temperature (°C)	29.4	29.2	30.7
Wind speed (m/s)	2.0	2.0	20
Direction/ angle with conductor (Degree)	58	58	58
Ambient Temperature (°C)	22.7	22.7	22.7
Solar Radiation (W/m2)	960	960	960
Load Current (A)	800	800	800
Equal current sharing (A)	200	200	200
Conductor height above sea level (m)	1500	1500	1500

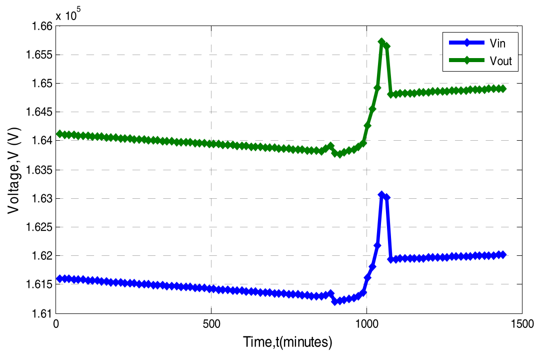

FIGURE 6. Voltage (magnitude) vs Time, where the pattern of Vin and Vout is quite similar.

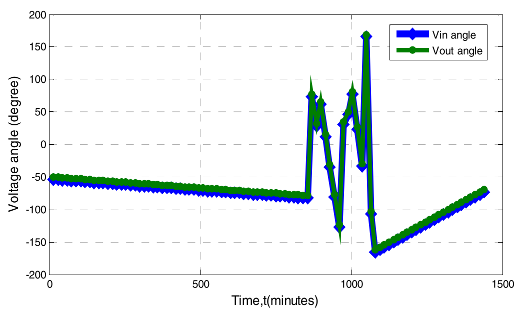

FIGURE 7. Voltage (angle) Versus Time, which shows close proximity to each other.

and Engkilili was selected to measure by the PMU system. These PMUs data includes the measurement of voltage angle, voltage magnitude, current angle, and current magnitude for every 15 minutes. For each graph, the y-axis shows the magnitude and angle of (V and me) and the x-axis shows the period in minutes. The green line represents the input values (Mambong) and the blue line represents the output values (Engkilili). The performance of the existing series model of DTCR software is analyzed in Figures 6, 7, 8, and 9. Figure 6 shows the voltage magnitude over time (minutes) of the highvoltage transmission line ratings. It is observed from Figure 6 that the pattern of Vin and Vout is quite similar. If there is a steady change in Vin, Vout will also experience the same changes. Besides, their values are close to each other. The graph of voltage angle over time (minute) is presented in Figure 7. Like Figure 6, the values of both curves are also

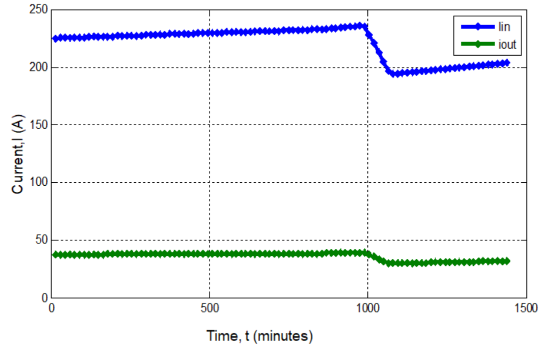

FIGURE 8. Current (magnitude) Versus Time, which shows current input and current output has an almost similar configuration.

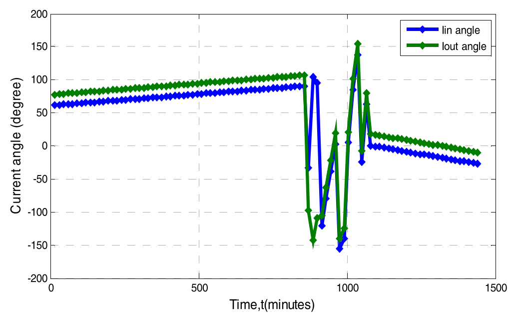

FIGURE 9. Phasor relation of input and output current of Overhead TL.

close to each other. Figure 8 also demonstrates the character of the current magnitude over some time in a minute. Most of the time, the current input and current output have a similar configuration of the curve. If there is a slight change in the current input, the current output will also experience the same condition. Figure 8 is to exposes the phasor relation of current in and current out on the selected span of overhead TL.

The data analysis of Figure 6, Figure 7, Figure 8, and Figure 9, suggests that the condition of the current rating is stable in PMU measurement with no fluctuation. Henceforth, these PMUs measured data can be used as the sample data for the improved PI model assessment in calibrating the existing DTCR thermal model.

A. EXISTING SERIES MODEL

The results from the existing series model are presented in Figure 10 and Figure 11. The graph in Figure 10 is about the presentation of conductor temperature ($T°c$) over time (minute) for one week. These conductor temperature shows that there is a variation of conductor temperature along with the TL between Mambong and Engkilili.

To estimate the conductor temperature over time (min) along with the TL between Mambong and Engkilili, one-day PMU measured sample data was used to evaluate both the improved PI model and series model. In Figure 11, the estimated conductor temperature over time (min) along the TL between Mambong and Engkilili is shown where T_c is calculated using the existing DTCR model. For the comparison purpose with the π (proposed) model, it is very important

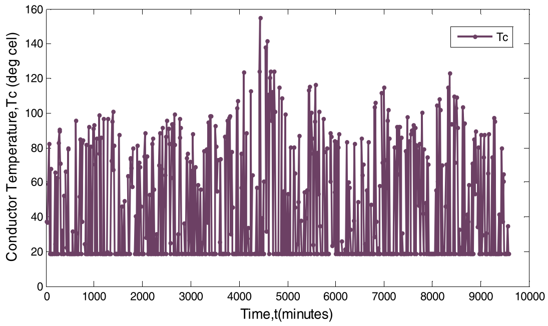

FIGURE 10. Conductor temperature (°c) Versus Time (minute) for one week.

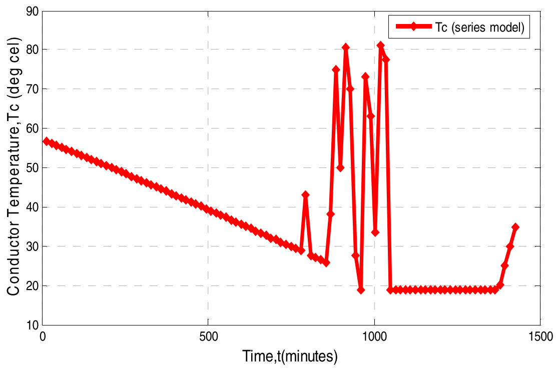

FIGURE 11. Conductor temperature Versus Time (series model) for making comparative analysis with the proposed π model.

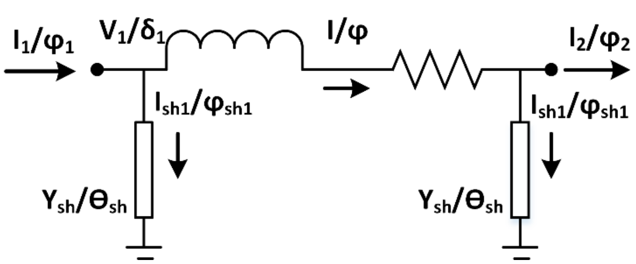

FIGURE 12. Proposed π mode for the estimation of the temperature of the TL.

to perform first the calculated conductor temperatures based series model in graph 11.

To calculate the value of conductor temperature, the value of resistance needed to be determined first by using the PMU measurement. The calculation was performed for every 15 minutes of PMU measurement. Besides the PMU measurement, the estimation of some constant values of the DTCR software application is considered.

B. IMPROVED PI MODEL

An improved π model is used to estimate the conductor temperature of the transmission line from Mambong to Engkilili. The diagram of the π model can be referred to in Figure 12.

In the improved conductor temperature estimation model, the equation from (6) to (9) are the derivations from the π model that were applied for the conductor temperature calculation.

$$\tilde{I}_1 = \tilde{I}_{sh2} + \tilde{I} \tag{6}$$
$$\tilde{I}_2 = \tilde{I} - \tilde{I}_{sh2} \tag{7}$$
$$\tilde{I} = \tilde{Y}_{se}(\tilde{V}_1 - \tilde{V}_2) \tag{8}$$

where $\tilde{I}_{sh1} = \tilde{V}_1\tilde{Y}_{sh}, \tilde{I}_{sh2} = \tilde{V}_2\tilde{Y}_{sh}$,

$$\tilde{Y}_{sh} = G_{sh} + j.B_{sh}$$
$$Let\ \tilde{I}_1 = I_{1r} + j.I_{1r}$$
$$\tilde{I}_2 = I_{2r} + j.I_{2i}$$
$$\tilde{Y}_{se} = \frac{1}{(R + j.x)} = G_{se} + j.B_{se}$$

Equation (8) was then substituted in Equation (6) and (7). After done with equating their real and imaginary components, these four equations were performed in matrix notation as in (8). This means that the PMU measurements were breakdown into equation (9).

$$\begin{bmatrix} I_{1r} \\ I_{1i} \\ I_{2r} \\ I_{2i} \end{bmatrix} = \begin{bmatrix} V_{1r} & -V_{1i} & V_{1r} - V_{2r} & -(V_{1i} - V_{2i}) \\ V_{1i} & V_{1r} & V_{1i} - V_{2i} & V_{1r} - V_{2r} \\ -V_{2r} & V_{2i} & V_{1r} - V_{2r} & -(V_{1i} - V_{2i}) \\ -V_{2i} & -V_{2r} & V_{1i} - V_{2i} & V_{1r} - V_{2r} \end{bmatrix} \begin{bmatrix} G_{sh} \\ B_{sh} \\ G_{se} \\ B_{se} \end{bmatrix} \tag{9}$$

Equation (10) is the representation of Equation (9)

$$B = A.X \tag{10}$$

where,

$$= \begin{bmatrix} V_{1r} & -V_{1i} & V_{1r} - V_{2r} & -(V_{1i} - V_{2i}) \\ V_{1i} & V_{1r} & V_{1i} - V_{2i} & V_{1r} - V_{2r} \\ -V_{2r} & V_{2i} & V_{1r} - V_{2r} & -(V_{1i} - V_{2i}) \\ -V_{2i} & -V_{2r} & V_{1i} - V_{2i} & V_{1r} - V_{2r} \end{bmatrix}$$

$$B = \begin{bmatrix} I_{1r} \\ I_{1i} \\ I_{2r} \\ I_{2i} \end{bmatrix}$$

$$X = \begin{bmatrix} G_{sh} \\ B_{sh} \\ G_{se} \\ B_{se} \end{bmatrix}$$

The X can be theoretically solved since there were four equations to solve the four equations. Thus,

$$X = A^{-1}B \tag{11}$$

The Equation (11) could be solved for every PMU sample but the obtained results will include the measurement errors. Thus, an alternative approach is needed to minimize measurement errors. By considering N PMU samples to solve Equation (9), another four equations of (10) were obtained from a new PMU sample. Similarly, there were two PMU samples applied in the same matrix calculation. For example, a total of 4N equations. Thus, (10) becomes;

$$[B]_{4N\times 1} = [A]_{4N\times 4}\,[X]_{4\times 1} \tag{12}$$

In this project, N equals 2. However, this matrix calculation cannot be solved because there were more equations than unknown that needed to be determined. This case was considered as an over-determined system equation. But this issue was solved by applying the rule of the Least Square Error (LSE) method. In this technique, both sides of the equation were multiplied with the transpose of matrix A ($[A]^T$). Equation (13) was summarized in Equation (14).

$$[A]^T_{4\times 4N}\,[A]_{4N\times 4}\,[X]_{4\times 1} = [A]^T_{4\times 4N}\,[B]_{4N\times 1} \tag{13}$$

$$[C]_{4\times 4}\,[X]_{4\times 1} = [D]_{4\times 1} \tag{14}$$

where,

$$[C]_{4\times 4} = [A]^T_{4\times 4N}\,[A]_{4N\times 4} \tag{15}$$

$$[D]_{4\times 1} = [A]^T_{4\times 4N}\,[B]_{4N\times 1} \tag{16}$$

Thus,

$$[X]_{4\times 1} = [C]^{-1}_{4\times 4}\,[D]_{4\times 1} \tag{17}$$

Hence, to calculate the R, the values of G_{se} and B_{se} that were obtained from the matrix of X could be applied in the Equation (16).

$$\tilde{Z}_{se} = R + j.x = \frac{1}{(G_{se} + j.B_{se})} \tag{18}$$

The value of R was then calculated from the Equation (18) and this is important for the T_c estimation as in Equation (19);

$$T_c = T_{ref} + \left(\frac{1}{\alpha}\right)\left(\frac{R(T_c)}{R_{ref} - 1}\right) \tag{19}$$

Figure 13 shows the estimated conductor temperature using an improved conductor temperature estimation model (π model).

The variation of conductor temperature is noticed in Figure 10 as compared to Figure 11. In this PI model, the PMU measured one-day sample data is used to estimate the conductor temperature. The improved PI model is derived to minimize system errors. The Improved PI model is considered the least square error sense method that reduces the chances of the errors.

But this will be solved for every PMU sample including the measurement errors. Unless we have a very perfect measurement for any data collection, it cannot be avoided that there is noise presented in the PMU measurement. Thus, considering N PMU or adding another sample in the matrix multiplication is considered an alternative approach to minimize the errors. By adding another PMU sample in the calculation, the size of the A and B changed to [8 × 4] and [8 × 1] respectively. Nevertheless, it is then become an over-determined system of equations where there are more equations than unknowns. In other words, the matrix form of A and B have more number of rows (m) than columns (n). This often happens that the new matrix of $Ax = B$ has no solution.

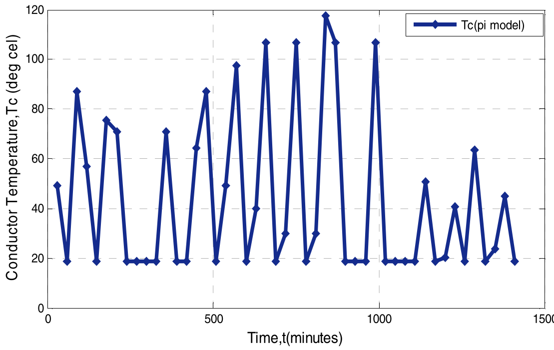

FIGURE 13. **Conductor temperature Versus Time based on an improved conductor temperature estimation model (π model).**

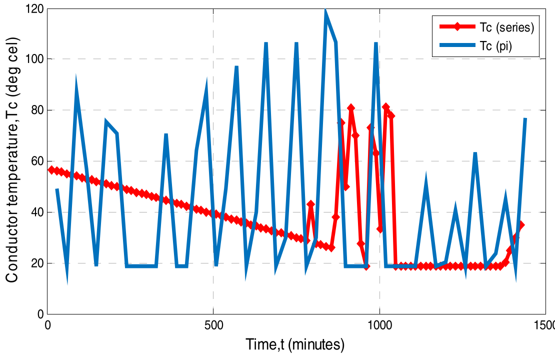

FIGURE 14. **Comparison of series and π model, where the variation of temperature is high for π model compared with the other.**

Still, the target of this study is to compute the x by decreasing the length of error as small as possible. Henceforth, the x is solved in the least square error solution. In the theory of the least square error method, when the matrix of $Ax = B$ has no solution, it needs to be multiplied with the transpose of matrix A(A^T).

Alternatively, the comparison of the improved model with the existing model is highlighted in Figure 14. There are two graphs in the figure where the blue graph is for the π model and the red graph is for the series model. It can be seen that the variation of T_c in the π model is high as compared to the series model.

It can be concluded that the performance of the proposed model is better than the existing model where it considers undeniable errors in the calculation. For example, errors during the measurement were taken. Moreover, it can be said that some weather parameters that were considered constant do have to bring an impact on the performance of the transmission line.

C. IMPROVEMENT OF DTCR MODEL

In this section, the performance of the improved calibrated DTCR model is assessed considering the weather factors. For the improvement of the DTCR model, the PMU measurement was also applied to observe the characteristic of weather conditions such as wind speed and solar irradiation intensity on the transmission line. The effect of solar

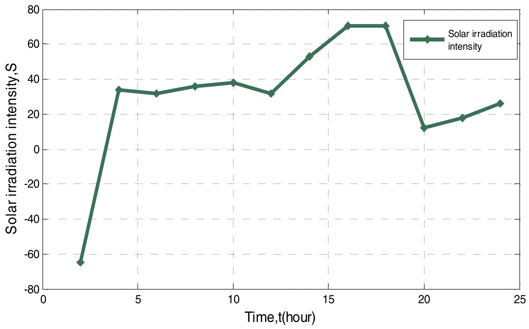

FIGURE 15. Solar radiation intensity Versus Time along the transmission line.

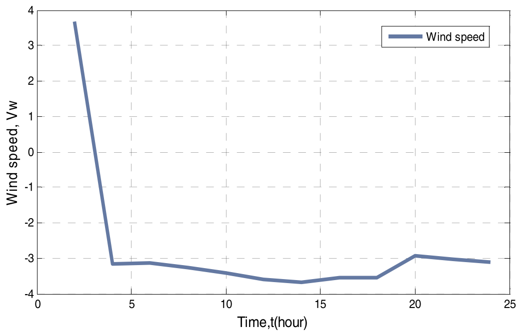

FIGURE 16. Characteristic of wind speed on the overhead transmission line.

irradiation intensity and wind speed on the transmission line was observed for one day. Figure 15 illustrates the changes in solar irradiation intensity along the transmission line. Based on Figure 15, there are always differences between values of solar irradiation intensity along the line. This suggests that this environmental factor brings a random weather effect on the transmission line.

On the other hand, Figure 16 presents the characteristic of wind speed on the overhead transmission line. It can be seen from Figure 15 and Figure 16 that both of them having a nonlinear graph. Henceforward, these two weather parameters cannot be assumed as constant. So, it is evident that using the dynamic weather condition in the improved PI model is more efficient than the consideration of static factors.

Figure 17 demonstrates the relation between wind speed and current rating. It can be observed from Figure 16 that the current rating is affected by the variation of the wind speed. The current rating is affected linearly if the wind speed increases.

Hence, it can be observed that the wind plays an important role in line cooling, and therefore, under most circumstances proposed dynamic model's limit is higher than static line ratings are more accurate even. Higher wind generation related to higher current ratings.

According to studies conducted, due to the presence of various wind speed on the overhead conductor temperature, there two equations used for convective heat loss calculation. These two are natural and forced convection. In the natural convection case, wind speed is not considered in the

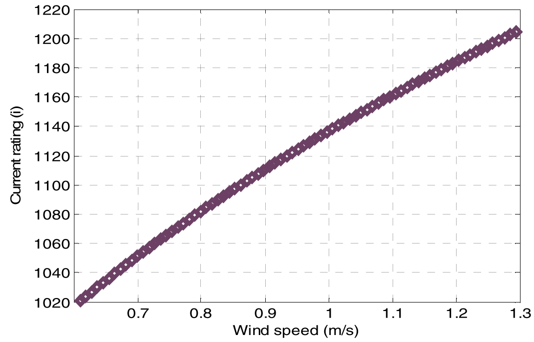

FIGURE 17. Relation between current rating and wind speed, where the current rating can be seen affected by the variation of the wind speed.

calculation. This against the forced convection formula which considered wind speed parameter in the calculation. There are normally two equations were one for low wind speed and the other for high wind speed.

Ultimately, it can be said that the presence of wind along the transmission line brings a cooling effect as heat will be transferred from the conductor into the environment. In this study, the conductor type is Aluminum Conductor Steel Reinforced (ACSR) Drake.

In summary, the performance of the proposed model is compared with the existing DTCR model. In calibrating the thermal model of DTCR, it is very important to ensure that the PMU measurement is inconsistent condition and the thermal models are working precisely. This is due to the inconsistent data measurement using PMU and improper thermal models that can lead to errors in the system. The performance of the improved PI model is significant since it adopts the Least Square Errors (LSE) method with the various weather conditions the transmission line. Thus, by the calibration of the DTCR thermal model, the conductor temperature can be monitored and controlled. Therefore, estimating the conductor temperature is needed for electricity dispatch purposes. For the further improvement of the DTCR thermal model, the effect of weathers condition (wind speed and solar irradiation intensity) on the overhead transmission is also studied. It is observed that if the wind speed is higher, wind incident on transmission lines is expected to be higher than the one considered for calculating the static limit. It is also monitored that when the solar radiations are higher than the effect on current rating expectedly higher. Therefore, it can be summarized that the transmission capacity of lines increases along with wind speed.

This is because if the wind speed increases, it also increases the cooling. So, this weather factor integration at the improved PI model is significant in terms of the dynamicity of the thermal model. This study can extend to the nonlinear Extended Kalman Filter (EKF) method which focused on the estimation over a long time duration (more than a day). In this thermal model, besides wind speed and solar intensity, the ambient temperature is also considered in the thermal rating calculation. Moreover, the design of the thermal rate system for the mechanical approach can be focused to get the accurate conductor temperature. Due to the insufficient time, these considerations were unable to carry out. Therefore, these considerations could be used for further research to develop the prototype for the thermal line rating.

VII. CONCLUSION

This study emphases the improvement of the DTCR thermal model in the WAM system through the PMU measurement. These PMUs are mainly engaged to measure the synchronized voltage and current along the transmission line. The atmospheric conditions such as wind speed and solar irradiation intensity that might have a great impact on the thermal occurrences of the DTCR model has been investigated accordingly in this study. For such analysis, a sensor cloud system was required, which collects all the relevant real-time sensor data, and acted as inputs for the DLR model. Utilizing these online sensor data our proposed model has been analyzed. Consequently, the DTCR model accuracy can be studied and analyzed using the PMU measurement. In this project, the calibration of the DTCR model was mainly concentrated on the conductor temperature calculation. For the conductor temperature calculation, two formulas based on the series (existing model) and π (improved) model was applied. This is to distinguish the performance of the improved DTCR model from the existing model. Last but not least, the calculation model of the existing DTCR model has been improved by following the IEEE standard 738-2012. One critical purpose of this paper was to investigate the phasor measurement data in calibrating the transmission line thermal model. The proposed improved PI model could be used to estimate the current rating of a transmission line in real-time with instant monitored weather conditions acquired from the sensor cloud system. Therefore, it can be summarized that the transmission capacity can be increased by integrating the improved dynamic thermal PI model in DTCR software. In conclusion, the major extent of this study had been performed on the matter of Dynamic Thermal Current Rating. The performance of the proposed model has been compared with the existing DTCR model. The performance of the improved PI model is significant since it adopts the Least Square Errors (LSE) method with the various weather conditions the transmission line. The integration of weather factors at the improved PI model is also significant in terms of the dynamicity of the thermal model. For obtaining weather-based data simultaneously with proper security, SCS plays a key factor in the overall process to ensure the reliability of the grid system. In the future, a thermal rate system can be designed for the mechanical approach for getting accurate conductor temperature data.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest to report regarding the present study.

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