Dynamic line rating current calculation without ambient parameters inputs

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Abstract— **Dynamic line rating current is widely used in the smart grid for improving the efficiency and economy of the power transmission and distribution. The rating current is determined by the ambient parameters such as convection heat loss rate, solar radiation, wind power, wind direction, etc. This paper proposes a method for calculating dynamic rating current only by means of the measurement of voltage and current of the two ends of the line free from any ambient parameter inputs. The instantaneous temperature can be estimated by calculating the variation of the line parameters, and subsequently the steady state conductor temperature can be obtained. The rating current is calculated by curve fitting of the dissipating power curve based on the steady state conductor temperature obtained and the conductor current. The scientific model of this technique, which is implementable into products, is constructed using Matlab/Simulink. Simulation tests show that the calculated dynamic line rating current is reliable and accurate.**

***Index Terms*— Dynamic line rating; ambient parameter; heat generating power; heat dissipating power.**

I. INTRODUCTION

WITH development of more renewables generating power that needs distribution by the existing transmission lines, transmission line operators employ techniques such as dynamic line rating (DLR) in modern grid for improving the efficiency of power transmission.

It is a well-known fact that the rating current of the transmission line is actually dependent on the ambient parameters such as the weather, the ambient temperature, the ambient moisture, wind power, wind direction etc., because the rating current is determined by maximum allowable conductor temperature. The dynamic line rating is much more efficient than the static line rating current because the static line rating current is determined under the worst ambient conditions, resulting in conservative line rating.

As we also know that the steady state temperature of a conductor is the intersecting point of the heat-generating curve and the heat dissipating curve. The heat generating curve can be represented by equation $P_G = I^2R(Tc)$, where P_G is generated heat power and Tc is temperature of conductor. Similarly, for representing the heat-dissipating curve $P_D(Tc)$, there is a standard formula in IEEE standard, which relates to ambient parameters, such as ambient temperature, wind speed, wind direction and sun radiations. Nevertheless, extra cost will be incurred for measuring the ambient parameters for calculating the dynamic line rating current.

In order to avoid the extra costs for these additional measuring devices, several new techniques based only on the measuring voltage and current without ambient inputs have been proposed. Some of the proposed techniques are proposed to calculate the temperature based on the conductivity characteristics respective to temperature. However, the coefficient of the temperature characteristic is too small to accurately calculate the temperature. Some others proposed to calculate the temperature based on the line sags, which significantly improved the accuracy of temperature calculating. Even though, the temperature calculated by the above methods is instantaneous temperature, it could be dynamically changing. Recent techniques take the transient behavior of the temperature into account to predict the corresponding steady state temperature successfully. However, no rating current can be given out.

This paper proposes a new method for calculating the dynamic rating current only based on the measuring of voltages and currents at both terminals of a transmission line without any ambient parameters input. The line length will be significantly varying with the conductor temperature changes, which can be reflected by the calculated line parameters such as the total line impedance. The instantaneous conductor temperature can be calculated by solving the transmission equations which corresponds to instantaneous conductor temperature by giving the known variables of currents and voltages. The steady state conductor temperature can be subsequently calculated by the obtained instantaneous temperature. Based on the heat-balance principle, the dissipating heat curve then can be obtained by curve fitting method with at least two steady state conductor temperatures, which can give the value of dynamic rating current. The scientific model of DLR has already been completed and has been validated, which is now being implemented into the commercial products. The validations show that this method can accurately calculate the DLR current in real-time without any ambient inputs. Compared to the conventional method, result of the new method is closer to the real value, with error of less than 4%.

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II. THE BASIC PRINCIPLE OF PROPOSED TECHNIQUE

It is well-known that the increment of instantaneous conductor temperature is contributed by the unbalance of heat generating power and the heat dissipating power. The steady state conductor temperature is the balance point of heat generating power and dissipating power. The rating current is actually determined by the upper-limit temperature that the conductor can tolerate on the dissipating power curve, which is dependent on the ambient parameters, such as polar radiation, wind power, wind direction etc. If the steady state conductor temperature can be measured, the dissipating power curve can be estimated accurately and therefore, the rating current can be determined without ambient parameters. Of course, the variation of temperature can change the line length, and then the line parameters. The temperature can be detected and measured by the variation of line parameters.

A. The Transient Model of Conductor Temperature

The transient heat power balance equation is similar to Newton's first law,

$$M_C \frac{dT_C}{dt} = P_G(T_C) - P_D(T_C) \qquad (1)$$

where, *Mc* is the total heat capacity of conductor; T_C is the conductor instantaneous temperature; $P_G(T_C)$ is the heat generating power, $P_D(T_C)$ is the heat dissipating power.

The heat-generating power is generated by the current flowing through the conductor due to the resistance of the conductor, i.e.,

$$P_G(T_C) = I^2 R(T_C) \qquad (2)$$

In terms of the heat dissipating power, it is defined in IEEE 738 standard, which gives the standard mathematic model of dissipating power, including forced convection heat loss, natural convection heat loss, radiated heat loss, solar heat gain, etc.

B. The steady state conductor temperature and rating current determination

We already know that the steady state conductor temperature is the balance point between the heat generating power and heat dissipating power, see figure 1.

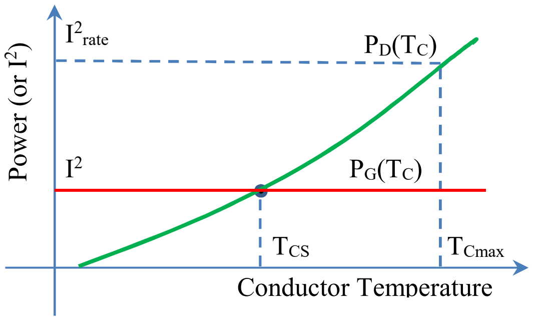

Figure 1, The relationship between heat generating power and dissipating power

From figure 1, one can see that the rating current is actually determined by dissipating power curve, which is dependent on the ambient parameters and inputs, see equation 3.

$$I_{rate} = \sqrt{\frac{P_D(T_{Cmax})}{R(T_{Cmax})}} \qquad (3)$$

If the ambient parameters are dynamically changing, the dissipating power curve dynamically changes accordingly, and so does the rating current, see figure 2.

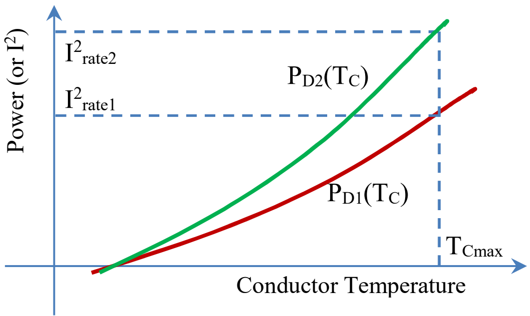

Figure 2, The changing of rating current due to the changing of ambient parameters

A conventional way of calculating the rating current is to estimate the dissipating power curve. IEEE standard 738 offers the standard mathematic model for estimating the dissipating power curve.

C. IEEE Standard Model for Dissipating Heat Power

In the IEEE standard, the dissipating heat power comprises of three parts. One is convection heat loss which depends on the ambient factors that contribute to the heat loss, such as wind speed, wind direction, ambient air temperature, density of air, thermal conductivity of air, the geometry size of conductor etc. The second one is the radiation heat loss and the third one is solar heat gain.

$$P_D(T_C) = p_c + p_r - p_s \qquad (4)$$

The details of the above equation can be seen in the IEEE standard 738. It is visible that a lot of ambient parameters and inputs are required for determining the dissipating power loss curve.

D. Estimation of Dissipating Power by means of Curve fitting

We can assume that the power dissipating curve can be expressed in polynomial terms. The 1st order or 2nd order polynomial terms have sufficient accuracy for the curve fitting, e.g.,

$$P_D(T_C) = a_0 + a_1 T_C + a_2 T_C^2 \qquad (5)$$

The coefficients a_0, a_1 and a_2 are the coefficients to be determined.

Since, at the balance point, the dissipating power equals to the generating power, one can obtain the dissipating power by calculating the generating power. At least three pairs of generating heat power with steady state temperature are required for determining the coefficients a_0, a_1 and a_2.

Assuming that N pairs of such heat generating power and temperature values are obtained, the equation for determining these coefficients can be written as shown below.

$$\begin{bmatrix} P_{G1} \\ P_{G2} \\ \cdots \\ P_{GN} \end{bmatrix} = \begin{bmatrix} 1 & T_{C1} & T_{C1}^2 \\ 1 & T_{C2} & T_{C2}^2 \\ \cdots & \cdots & \cdots \\ 1 & T_{CN} & T_{CN}^2 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} \tag{6}$$

The solution for equation 6 can be obtained by least square method. Once these coefficients are obtained the rating current can be calculated by the following equation.

$$I_{rate} = \sqrt{\frac{a_0 + a_1 T_{Cmax} + a_2 T_{Cmax}^2)}{R(T_{Cmax})}} \tag{7}$$

Nevertheless, what we need to notice is that only at the steady state the generating heat power equals the dissipating heat power. Therefore, the conductor temperature which is used for estimating the coefficients of heat dissipating power curve should be the steady state temperature. However, practically only the transient (instantaneous) conductor temperature can be obtained.

E. The Relationship of Conductor temperature between Transient and steady state

Changing current in the conductor or the ambient conditions can result in the change of steady state conductor temperature. For example, if the current in the conductor is changing from I_1 to I_2 at time t_0, then the steady state temperature can be correspondingly changing from T_{CS1} to T_{CS2}, however the instantaneous temperature gradually approaches T_{CS2} from T_{CS1}, which can be expressed as the following equation.

$$T_C(t) = T_{CS2} + (T_{CS1} - T_{CS2}) e^{-(t-t_0)/\tau_p} \tag{8}$$

where, T_C is instantaneous conductor temperature, τ_p is the time constant of the transient stage.
The signature of the instantaneous temperature can be seen in figure 3.

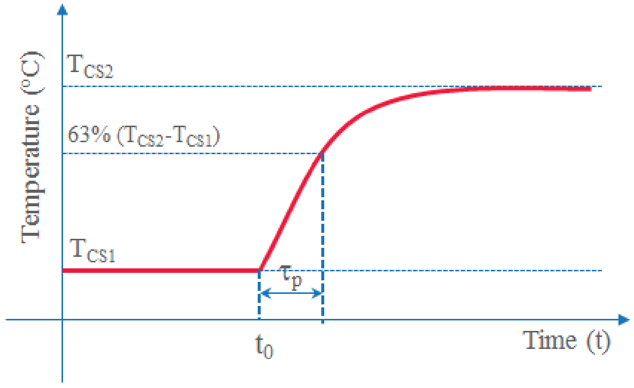

Figure 3, The relationship between the steady state and transient temperature of a conductor

The temperature measured or calculated is the instantaneous temperature of conductor. The corresponding steady state conductor temperature could change (due to the change of ambient conditions or conductor current) before the instantaneous temperature goes into the steady state, as the time constant of transient stage could be very long, for example several minutes. The steady state temperature of conductor can be estimated by solving the following equation.

$$T_C(t) = T_{CS2} + \tau_p \frac{dT_C(t)}{dt} \tag{9}$$

At least two different instantaneous temperatures of conductor are required for solving the steady state temperature T_{CS2}, because there are two unknowns in equation 9.

F. The Calculation of Instantaneous Temperature of Conductor Only using Voltage and Currents of Two Ends

The change of conductor temperature results in the change of line length due to the weight of the line, which leads to the change of line parameters. This indicates that the line equations should comprise the variable of conductor temperature as shown in the following equation.

$$\begin{bmatrix} \dot{V}_S \\ \dot{I}_S \end{bmatrix} = \begin{bmatrix} A(T_c) & B(T_c) \\ C(T_c) & D(T_c) \end{bmatrix} \begin{bmatrix} \dot{V}_R \\ \dot{I}_R \end{bmatrix} \tag{10}$$

where
$\dot{V}_S$ and $\dot{I}_S$ are respectively the voltage phasor and current of sending end;
$\dot{V}_R$ and $\dot{I}_R$ are respectively the voltage phasor and current of receiving end;
$A(T_c) = D(T_c) = \cosh(\gamma l)$;
$B(T_c) = Z_c \sinh(\gamma l)$;
$C(T_c) = \sinh(\gamma l)/Z_c$;
$l(T_c) = l_0[1 + \alpha(T_C - T_{REF}) + \beta(T_C - T_{REF})^2]$
$\gamma = \sqrt{(r + j\omega L)(j\omega C)}$
$Z_c = \sqrt{(r + j\omega L)/(j\omega C)}$
ω is angle frequency of the fundamental component;
l is the length of the power line section;
T_{REF} is the reference conductor temperature. For example, normally, T_{REF} may be selected at 20°C;
r is the resistance per unit length of line conductor;
L is the inductance per unit length of the line conductor;
C is the capacitance per unit length of the line conductor;
α is the 1st order thermal expansion coefficient;
β is the 2nd order thermal expansion coefficient;

Least square method and Newton-Raphson method can be used for solving above non-linear equation set (equation 10).

III. THE SCHEME AND ALGORITHMS FOR REALIZATION

Based on the foregoing analysis, three steps are taken for calculating the dynamic line rating current without ambient inputs. The overall scheme is shown in figure 4.

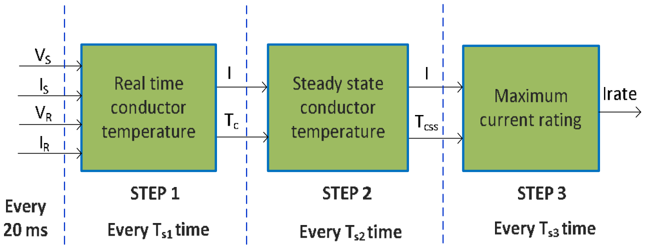

Figure 4. The overall scheme for real-time DLR calculation

Step 1, calculate the instantaneous conductor temperature by the measured voltage and current phasors by means of solving equation 10.

Step 2, calculate the steady state conductor temperature based on the obtained instantaneous temperature using equation 9.

Step 3, calculate the dynamic line rating current based on the steady state temperature and heat generating power of conductor by solving equation 6.

A. *The Calculation of Instantaneous Line Temperature*

Initially, equation 10, which contains complex numbers, should be converted to real numbers based equations as shown in the following equation.

$$Y = \begin{bmatrix} Re(\dot{V}_S) \\ Im(\dot{V}_S) \\ Re(\dot{I}_S) \\ Im(\dot{I}_S) \end{bmatrix} = F(T_c) = \begin{bmatrix} Re\left(f_1(\dot{V}_R, \dot{I}_R, T_c)\right) \\ Im\left(f_1(\dot{V}_R, \dot{I}_R, T_c)\right) \\ Re\left(f_2(\dot{V}_R, \dot{I}_R, T_c)\right) \\ Im\left(f_2(\dot{V}_R, \dot{I}_R, T_c)\right) \end{bmatrix} \qquad (11)$$

Least square principle is used for solving the equations when the number of unknowns is less than the number of equations. Newton's algorithm is employed for solving the non-linear equation and it is described by the following flow chart.

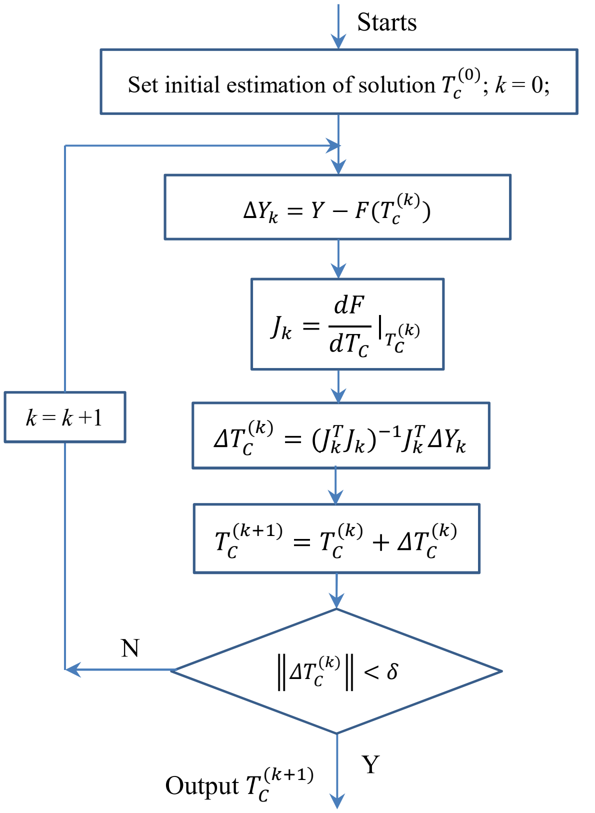

Figure 5. Flow chart for calculating conductor temperature

(1) Set an initial solution, substitute it into F(T_C), set k=0;

(2) Calculate the difference between Y and $F(T_c^{(k)})$;

(3) Substitute $T_c^{(k)}$ into Jacobian matrix;

(4) Calculate the difference between kth solution and real root value by means of least square method.

(5) Correct the kth solution.

(6) If the difference is less than an acceptable threshold, then output the solution, else go back to step 2 by increasing k to k+1 until the difference is less than the threshold.

B. *The Algorithm for Calculating the Steady State Conductor Temperature*

The algorithm for calculating the steady state conductor temperature is based on equation 9. One can digitalize equation 9 as shown below.

$$\frac{T_C(n)+T_C(n-1)}{2} = T_{CS} + \tau_p \frac{T_C(n)-T_C(n-1)}{T_s} \qquad (12)$$

where T_{CS} is steady state conductor temperature.

At least two equations are required for solving T_{CS}, for example, one equation is at time n, another equation is at time m, and then we have two equations.

$$\begin{cases} \frac{T_C(n)+T_C(n-1)}{2} = T_{CS2} + \tau_p \frac{T_C(n)-T_C(n-1)}{T_s} \\ \frac{T_C(m)+T_C(m-1)}{2} = T_{CS2} + \tau_p \frac{T_C(m)-T_C(m-1)}{T_s} \end{cases} \qquad (13)$$

Of course, if possible we can use further more equations for a better estimation of T_{CS}.

C. *Calculation of Rating Current*

To simplify the calculation, the 1st order of polynomial is used for curve fitting the heat dissipating power curve. Even though we need to do further work for determining whether or not the ambient condition has changed, because the algorithm for estimating the heat dissipating power curve is based on the assumption that during that time the dissipating curve is not changing, if the dissipating curve is changed, the inception temperature should be used for determining the curve as shown in figures 6, 7, 8 and 9.

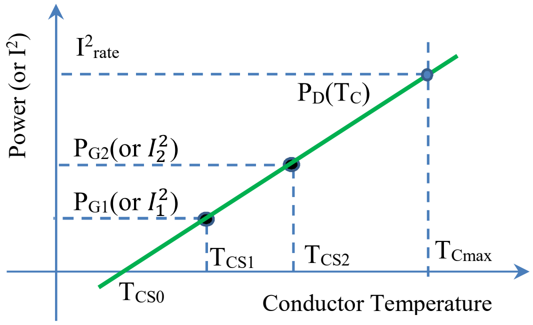

Figure 6. The ideal scenario that we expected

Figure 6 is the ideal scenario that we expected where both measured current and calculated temperature are changing aligning with the same dissipating curve. However, sometimes the heat-generating power and temperature that we obtained are on different dissipating curve, see figure 7, 8 and 9.

Figure 7 illustrates a scenario where the measured conductor temperature points and conductor current points (or heat generating power) are on different dissipating power curve. One point is on P_{D1} and another one is on P_{D2}, because the ambient conditions changes at that moment.

Figure 8 presents a scenario where the conductor temperature changes when the conductor current (or heat generating power) does not change.

Figure 9 shows the scenario where the conductor temperature maintains the same value but the conductor current changes.

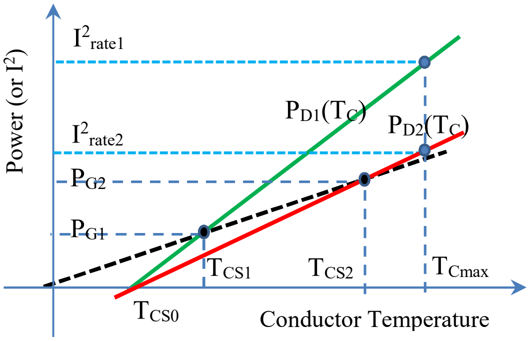

Figure 7. Both the current and ambient condition change

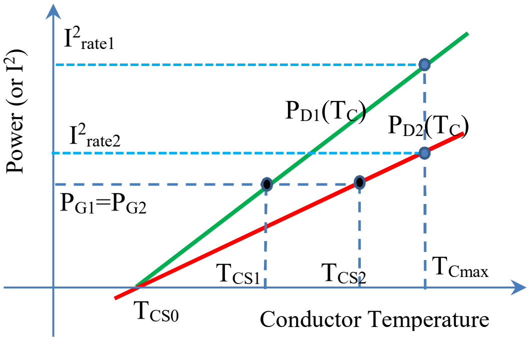

Figure 8. Current does not change but conductor temperature changes due to the change in ambient conditions

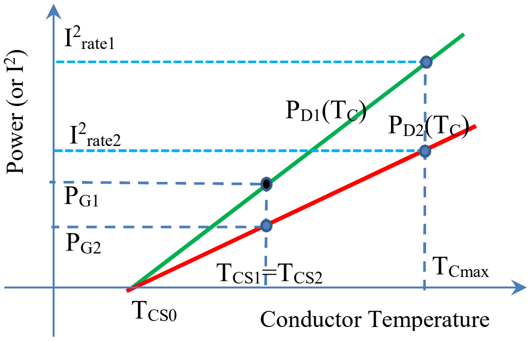

Figure 9. Current changes however conductor temperature does not change due to ambient condition changes

The solution for overcoming a scenario where the two points are not in the same dissipating curve is that these scenarios should be identified by checking the initial conductor temperature. The algorithm for calculating the dynamic rating current is presented as shown in the flow chart in figure 10.

Before the algorithm is running, in the initialization stage, the inception conductor temperature T_{CS0} is set as the possible minimum value of the ambient temperature.

First of all, make a discrimination to see whether the current and the temperature are changed or not. In figure 10, ε1 is set as 0.1kA, and ε2 is set as 5°C. If they are over the setting threshold, then calculate the inception temperature Tc0 as shown in figure 10. If the temperature is within the reasonable region and the difference to the previous inception temperature is not larger than 5°C, then update the inception temperature by this calculated value. That indicates that the two points are on the same dissipating curve. Hence calculate the rating current by these two points. Otherwise, the rating current is calculated by the inception temperature.

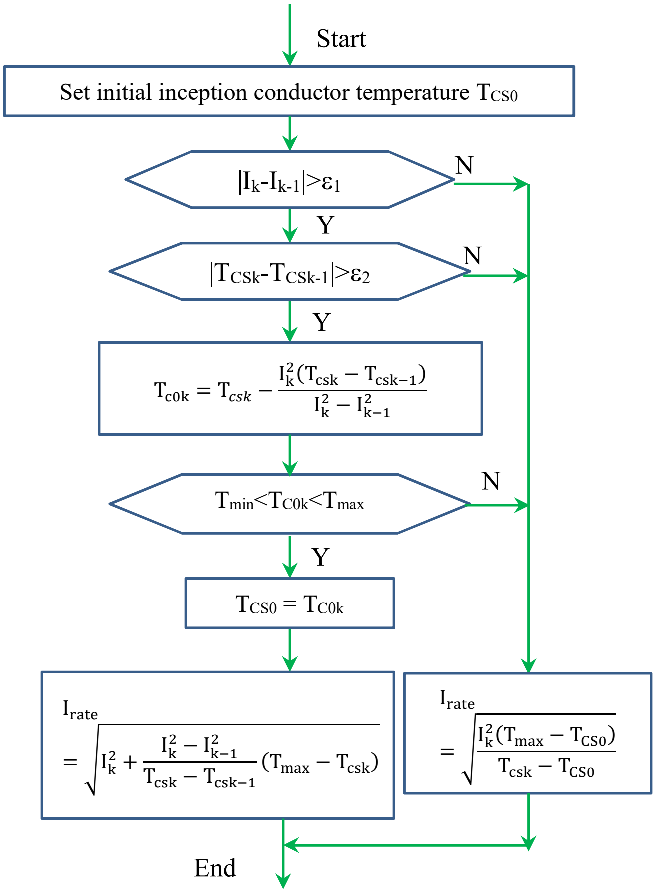

Figure 10. Flow chart of calculating rating current

IV. VALIDATIONS AND TESTING RESULTS

The data for validating the new algorithm are generated by simulations in Matlab/Simulink and the structure of the simulation system is shown in figure 11.

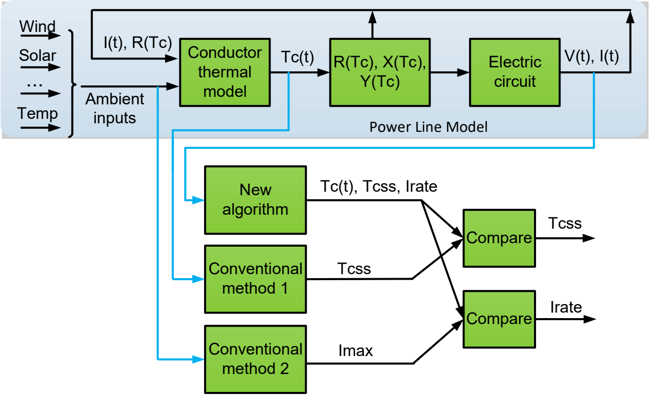

Figure 11 The simulation system for validation

A. *The Simulation Model for Thermal-electric System*

In the simulation model, the conductor thermal model is based on equation 1, in which the inputs are heat-generating power and heat-dissipating power, and the output is the instantaneous conductor temperature. The heat-generating power is calculated by the feedback current from electric circuit, and the dissipating power is calculated based on the IEEE standard model. Correspondingly, the real time line parameters are calculated based on the calculated instantaneous temperature. Consequently, in the electric circuit, the voltage and current of the line are changed accordingly. The electric circuit simulated for the tests are as shown in the following figure 12.

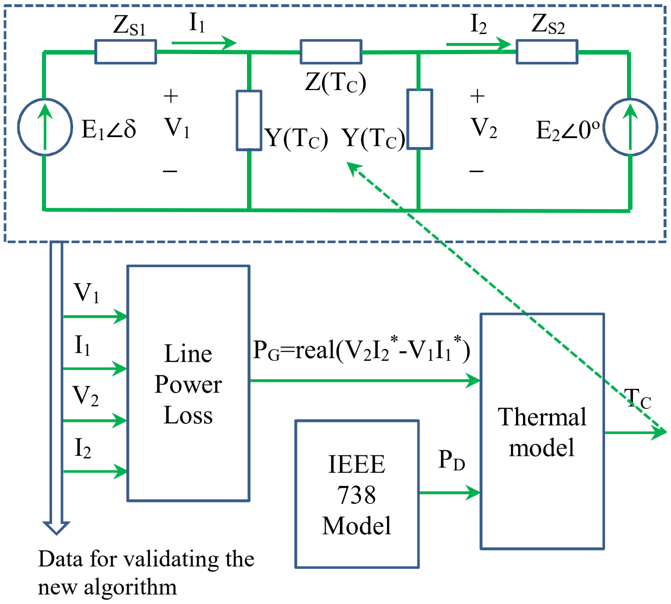

Figure 12. The simulation model in details

B. *Validation Results*

The validation results are presented in figure 13. The line current is adjusted by changing the angle of the source E1. The ambient conditions are varied by changing the wind speed and direction which are the main factors that impact the conductor temperature.

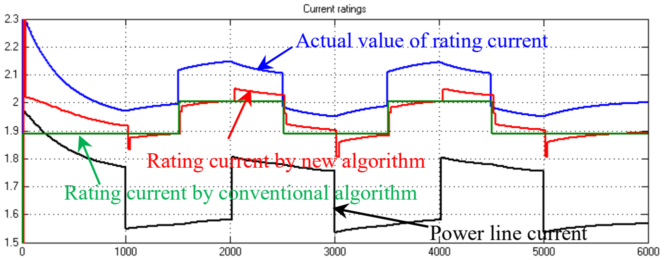

Figure 13 The validation result

In comparison, the difference between the results of new algorithm and the results of the conventional algorithm is less than 4%.

V. CONCLUSIONS

This paper proposes a method for calculating the dynamic line rating current without ambient inputs. The rating current is calculated by calculated steady state conductor temperature and the heat generating power made of power loss of the line. The conductor temperature is calculated by the variation of the line parameters. The results of the validation show that this method is reliable and the difference between the new method and the conventional method which requires large amount of ambient inputs is less than 4%.

REFERENCES

[1] Tony Yip, Chang An, Graeme Lloyd, Martin Aten, Bob Ferris, Dynamic Line Rating Protection for Wind Farms Connections. Integration of Wide-Scale Renewable Resources into the Power Delivery System, 2009 CIGRE/IEEE PES Joint Symposium, 2009.

[2] Yip, H.T., An, C., Aten, M., Ferris, R., Dynamic Line Rating Protection for Wind Farms Connections. IET 9th International Conference on Development in Power System Protection, 2008. DPSP 2008.

[3] N.D. Sadanandan, A.H. Eltom, Power Donut Systems Laboratory Test and Data Analysis, IEEE Southeastcon Proceedings 1990. p. 675-979.

[4] IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors, IEEE Power Engineering Society. IEEE Std 738-2006 (Revision of IEEE Std 738-1993)

[5] Thermal Behaviour of Overhead Conductors. Cigre Working Group 22.12, Brochure ref. 207. August 2002.

[6] C. Borda , A. Olarte and H. Diaz., PMU-based line and transformer parameter estimation, Proc. IEEE Power Syst. Conf. Expo., pp.1 -8 2009

[7] Y. Liao, Some algorithms for transmission line parameter estimation, in Proc. 2009 41st Southeastern Symposium on System Theory, pp. 127-320, Tullahoma, TN, March 15-17 2009.

[8] L. Yuan and M. Kezunovic, Online optimal transmission line parameter estimation for relaying applications, IEEETrans. Power Del., vol. 24, no. 1, pp.96 -102 2009

[9] Il-Dong Kim and R. K. Agarwal, A study on the on-line measurement of transmission line impedances for improved relaying protection, Electric Power and Energy Systems, 28 (2006), pp. 359-366.

[10] D. Shi, D. J. Tylawsky, N. Logic, K. M. Koellner, Identification of short transmission-line parameters from synchrophasor measurements, 40th North American Power Symposium, 28-30 Sepember 2008.

[11] Shi D, Tylavsky DJ, Koellner KM, Logic N, Wheeler DE, Transmission line parameter identification using PMU measurements. European Transactions on Electrical Power 2011*;* 21*(4):* 1574–1588. *DOI:* 10.1002/etep.522

[12] Z. Hu and Y. Chen, New Method of Live Line Measuring the Inductance Parameters of Transmission Lines Based on GPS Technology, IEEE Transactions on Power Delivery, Vol. 23, Issue 3, July 2008, pp. 1288–1295.

[13] Kalyan Dasgupta, S. A. Soman, Line Parameter Estimation using Phasor Measurements by the Total Least Squares Approach, IEEE Power and Energy Society General Meeting ,July 2013,pp 1- 5

[14] Indulkar CS, Ramalingam K, Estimation of transmission line parameters from measurements, Electr Power Energy System, Vol 30, Issue 5,pp.337–342, June 2008

[15] Y. Liao, Some algorithms for transmission line parameter estimation, Proc. 41st Southeastern Symp. Syst. Theory, pp.127 -132, 2009

[16] Ding Lan, B. Tian Shu, Z. Dao Nong, Transmission Line Parameters Identification Based on Moving-Window TLS and PMU Data, The International Conference on Advanced Power System Automation and Protection, 978-1-4244-9621, 2011, pp. 2187-2191.

[17] Chen. F, Xueshan. H, Mengxia. W, Ming.Y, Tracking Estimation of Transmission Line Temperature Based on PMU Measurement, Automation of Electric Power Systems, Vol 33, NO 19, pp.25-29, Oct 2009

[18] Ding.L, Zhile.O, Zhikai.T, Research on Factors Influencing Idendification of Transmission Line Paramters, Power System Technology, Vol 37, NO 7, pp. 1948-1953, July 2013

[19] Mai RuiKun, Fu ling, Xu HaiBo, Dynamic Line Rating Estimator with Synchronized Phasor, Advanced Power System Automation and Protection, 2011 International Conference, Vol 2, pp 940-945, Oct 2011