USING FITTING SLOPE METHOD PREDICTING ICING PARAMETERS BASED ON ICE MASS OF ROTATING MULTI-CONDUCTORS

Shen Qiang[1], Jiang Xingliang[2], Liu Chonghan[1,2], Kuang Jun[1] and Dong Lina[1]
(1. Chongqing Electric Power Corporation, Chongqing, 400067, China; 2.State Key Laboratory of Transmission & Distribution Equipment and Power System Safety and New Technology, Chongqing University ,Chongqing, 400030, China)
*Email: s.qiang@126.com

***Abstract**:* Aim at the problem of icing monitoring and icing parameters measurement, this paper has proposed using fitting slope method predicting icing parameters, which is using the two fitting slope as the approaching target of the calculated and experimental ice mass values to predict icing parameters by iterative computations of the icing model. According to simulate the influence relationship between the multi-conductors ice mass and the five icing parameters and analyze how the five icing parameters affect the two fitting slope, the icing parameters numerical solving method has been found. A MATLAB icing parameters solving program was completed to calculate the five icing parameters simultaneously. The calculation results of the test data and simulated data show the two fitting slope can be used to be the approaching target of test and calculated ice mass, the five icing parameters can be calculated simultaneously only by testing the ice mass of the known initial diameter of multi-conductors. The calculation convergence and stability are good, and the calculation rate is fast. This icing parameters computation method of this paper overcomes the measurement difficulty of the dynamic changes of the icing parameters. The calculated icing parameters can provide foundation and reference for predicting the icing state on the transmission structures, such as conductor, based on some icing model, and for power system anti-icing and against icing work.

1. INTRODUCTION

This paper builts a icing model, obtains the function relation between ice mass and icing parameters as fellows:

$$m = f(v, \theta, p, t, D_0, r\%, L, w, a) \quad (1)$$

v is air speed, θ is temperature, p is air pressure, t is icing time, D_0 is initial diameter of cylinder, $r\%$ is air relative humidity, L is length of cylinder, w is liquid water content(LWC), a is droplet median volume diameter(MVD).After a simplified, we get:

$$m = f\left(v, \theta, t, D_0, w, a\right) \quad (2)$$

If we know ice mass on N cylinders, we will get two-dimensional array:

$$M_{2N} = \begin{bmatrix} M \\ M^* \end{bmatrix} = \begin{bmatrix} m_1, m_2, \cdots m_N \\ m_1^*, m_2^*, \cdots m_N^* \end{bmatrix} \quad (3)$$

M is calculated ice mass array, M^* is test ice mass array. Based to equation (3), get two fitting slope (through origin fitting slope (k_d) and not through origin fitting slope (k_a)). Then we analysis how the five icing parameters impact on k_a and k_d, find a calculation method of solving the five icing parameters based on k_a and k_d, and program a MATLAB solving program.

2. RESULTS AND DISCUSSION

The calculation results of experimental data as follows:

TABLE 3 COMPUTED RESULT OF TEST DATA OF TABLE 2

No.		1#	2#	3#	4#	5#	6#	7#	8#
test value	m^*(g)	33.99	41.50	48.71	56.78	62.18	70.89	79.59	87.19
	b^*(g)	8.63	8.1	7.68	7.62	7.26	6.75	6.57	6.62
	test parameters	w_t=7.33g/m³； a_t=39.14μm； v_t=4.1m/s； θ_t=-5℃； t_t=60min							
calculated results	m (g)	32.18	40.62	48.66	57.10	64.86	72.32	79.36	85.51
	b(g)	8.32	7.96	7.65	7.36	7.12	6.90	6.68	6.49
	calculated parameters	w_c=20.88g/m³； a_c=84.83μm； v_c=3.72m/s； θ_c=-2.77℃； t_c=55.00min							
results comparison	σ_m(%)	-5.32%	-2.12%	-0.10%	0.57%	4.31%	2.02%	-0.29%	-1.92%
	σ_b(%)	-3.65%	-1.69%	-0.42%	-3.45%	-1.94%	2.23%	1.72%	-1.94%
	parameters comparison	σ_w%=184.9%； σ_a%=116.7%； σ_v%=-9.3%； σ_θ%=-44.6%； σ_t%=-8.3%；							

σ(%) is relative error percentage of the calculated value and test value, corresponding to the subscript values

Table 3 results show that the deviation between the five calculated parameters and test results are a little large. The maximum deviation is LWC reached 184.9%. Reasons are that the calculated parameters are a combination of parameters calculated based on the ice mass relationship, and an optimal set of iterative approach calculation of the icing model, and relation on the initial settings. However, from the calculated ice mass on the conductors are well approximations with the experimental data. And calculated ice thickness is close to test thickness. The slope index k_a and k_d are both near to 1, which reflects the quality of ice calculated and experimental results are more good approximation.

3. CONCLUSION

This paper proposes a kind of thought that sdudy icing parameters according to ice mass, and then study icing state. The MATLAB calculation program is given, with good convergence, computational stability, fast calculation, proves two combinations of icing parameters is equivalent to predict icing state. Avoid the study problem of real icing parameters change in the icing process. It is feasible as the icing indirect measurement method.

4. REFERENCES

[1] YANG Jing-bo, LI Zheng, YANG Feng-li, etc. Analysis of the Features of Covered Ice and Collapsed Tower of Transmission Line Snow and Ice Attacked in 2008[J]. 2008, 24(4)：004-008.

[2] et. al

USING FITTING SLOPE METHOD PREDICTING ICING PARAMETERS BASED ON ICE MASS OF ROTATING MULTI-CONDUCTORS

Shen Qiang[1,2] Jiang Xingliang[1], Liu Chonghan[1,2] , Kuang Jun[1] and Dong Lina[1]
1.State Key Laboratory of Transmission & Distribution Equipment and Power System Safety and New Technology, College of Electrical Engineering, Chongqing University, Shapingba District ,Chongqing, China.
2. Chongqing Electric Power Corp. Maintenance Branch Company, Yuzhong District Street, Chongqing, China)
s.qiang@126.com

***Abstract*—Aim at the problem of icing monitoring and icing parameters measurement, this paper has proposed using fitting slope method predicting icing parameters, which is using the two fitting slope as the approaching target of the calculated and experimental ice mass values to predict icing parameters by iterative computations of the icing model. According to simulate the influence relationship between the multi-conductors ice mass and the five icing parameters and analyze how the five icing parameters affect the two fitting slope, the icing parameters numerical solving method has been found. A MATLAB icing parameters solving program was completed to calculate the five icing parameters simultaneously. The calculation results of the test data and simulated data show the two fitting slope can be used to be the approaching target of test and calculated ice mass, the five icing parameters can be calculated simultaneously only by testing the ice mass of the known initial diameter of multi-conductors. The calculation convergence and stability are good, and the calculation rate is fast. This icing parameters computation method of this paper overcomes the measurement difficulty of the dynamic changes of the icing parameters. The calculated icing parameters can provide foundation and reference for predicting the icing state on the transmission structures, such as conductor, based on some icing model, and for power system anti-icing and against icing work.**

Keywords: Rotating Multi-conductors, Icing Model, Fitting Slope, Icing Parameters, MATLAB

I. INTRODUCTION

With the global climate getting warm, ice damagement on the power system has become increasingly prominent [1, 2]. The ice disaster, which was happened in South China region , 2008, rarely seen in history, causing power blackouts and serious harm to national life, mainly due to lack of ice and the serious lack of monitoring on power systems[3~5]. The icing of Transmission Line has been a concern technical problem at home and abroad, only in full recognition of the actual situation of icing could effectively strengthen the anti-ice design. Currently the main measurement methods are icing detection method and on-line monitoring method,

The main methods to icing detection are manual inspection and detecting at ice station. Labor intensity, high investment, and differences between test results and actual situations are the shortcomings of existent methods. Meanwhile, On-line monitoring methods are: tension monitoring method, wire angle method, image monitoring method, and small automatic weather stations, etc. These are non-icing method. Tension monitoring method and wire angle method mostly depend on the precision of the sensor, which didn't accurately reflect the thickness of icing and other information. The image monitoring method, which easily freezing on the lens, also have difficulties to measure. The small automatic weather station could monitor some conventional meteorological parameters, but have no ideals to monitor the liquid water content (LWC) and droplet median volume diameter (MVD).

Therefore, the technology of icing measurement hasn't been solved in the international arena, and there is not mature icing sensor. As the improvement of icing prediction model, some have achieved good accuracy; in addition, the icing on rotating conductors is often used to characterize the icing on insulator, so it can measure the parameters of icing by rotating multi-conductor method to characterize the icing on Transmission Line and insulators.

The main parameters of impactting the icing of transmission line are temperature, air speed, air direction, the time of icing, LWC and MVD, etc. [7, 8]. Presently, the methods to measure LWC and MVD are microwave method 、 laser method and so on [9, 10]. Because parameters are changing dynamically, it's difficult to measure accurately. Different pavements may lead to great differences in the results of icing. Presently, it is no common to study parameters of icing based on the icing results. Literatures [9, 10] measure the LWC and MVD by rotating cylinder method, which are the Numerical Methods of fitting the correlation coefficient and slope through the origin. But literature [15] has done a preliminary study on the method of calculating parameters based on ice mass, ignoring the process of icing.

This article will study on the parameters of temperature, wind speed (effective speed, including wind direction), LWCt, MVD and effective ice time.

II. THE CYLINDRICAL ICE MODEL

A. The Process of modeling

From the paper [15], we know that the process of modeling is following. Assuming the wind and the conductor axis angle is 90°, and rotation speed of cylinder is *n* switch/ min. Showed in Figure 1.

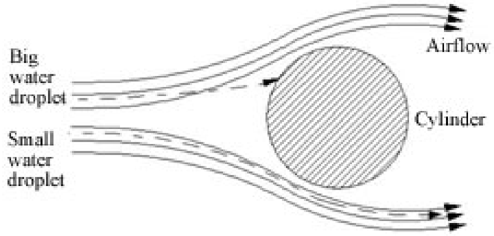

Figure 1 Icing of droplets collide cylinder

We assume the interval time of icing Δt(s) is short enough that the parameters of icing do not change in the Δt time. So we can get the quality of ice on the conductor during the time Δt determined by the wind speed v(m/s), the ambient temperature θ (℃), air pressure p (kPa), conductor diameter D (m), the conductor length L (m), LWC w (g/m^3) and MVD a (m).

$$\Delta m = \alpha_1 \alpha_2 \alpha_3 wvDL\Delta t \qquad (1)$$

Where: α_1 is the collision coefficient, α_2 is the collection coefficient, α_3 is the freeze coefficient. $E = \alpha_1 \alpha_2 \alpha_3$ E is defined as the efficiency coefficient of ice.

(1) According to paper [15], the collision coefficient α_1 can be calculated from the following formula.

$$\alpha_1 = \begin{cases} A - 0.028 - C(B - 0.0454)\ (\phi > 100) \\ 0.457(\log_{10}(8K_0))^{1.634}\ (\phi < 100 \text{ 且} K < 3) \\ K/(K + H_e) \qquad (\phi < 100 \text{ 且} K > 3) \end{cases} \qquad (2)$$

Which:

$$\begin{cases} R_e = \rho_a av/\mu;\ K = \rho_w a^2 v/(9\mu D); \phi = R_e{}^2/K \\ A = 1.066K^{-0.00616} e^{-1.103/K^{0.688}} \\ B = 3.641K^{-0.498} e^{-1.487/K^{0.694}} \\ C = 0.00637(\phi - 100)^{0.381} \\ K_0 = 0.125 + (K - 0.125)/\left(1 + 0.1206R_e{}^{0.59}\right) \\ H_e = 1 + 0.5708 \times F - 0.73 \times 10^{-4} R_e{}^{1.38} \\ F = 1 + 0.212R_e{}^{0.6} + 2.6 \times 10^{-4} R_e{}^{1.38} \end{cases} \qquad (3)$$

Where: Re is Reynolds number, μ is dynamic viscosity of air. In this paper, it is 1.71×10-5Pa·s; ρ_w is the droplet diameter, it's 1000 kg/m^3; ρ_a is air density, it can be obtained by the following formula.

$$\rho_a = \frac{3.48p}{273.15 + \theta}\left(1 - 0.23\frac{r\%}{p}e^{0.077\theta}\right) \quad (4)$$

r% is relative humidity.

(2) The collection coefficient α_2 denotes the ratio of super-cooing droplets resided over the conductor surface and the total collision droplets of the conductor surface. We usually ignore droplet rebound, so assume α_2 is 1.

(3) The freezing coefficient of ice surface is determined by the heat balance equation. From the paper [15], the heat balance equation is

$$q_f + q_v + q_k + q_a + q_n = q_c + q_e + q_l + q_s + q_r \quad (5)$$

Where: q_f for the latent heat when the freezing; q_v for the air friction heating; q_k for the kinetic energy when droplet collision; q_a for the heat released when the ice from cold to the steady-state temperature; q_n for the solar short-wave radiation heating; q_c for the ice surface and the air convection heat loss; q_e for the ice surface, produced by evaporation or sublimation heat loss; q_l for the heat loss which heat the collided droplets to freezing temperature; q_s for the ice surface radiation heat loss; q_r for the heat loss which drop away to leave the ice surface. Units of each parameter is J/(m^2·s^{-1})。

Put the parameters of the above variables into equation (5), we can find that:

$$\begin{aligned} &\alpha_1\alpha_3 wvL_f + \frac{hr_c v^2}{2c_a} + \frac{\alpha_1 wv^3}{2} - \alpha_1\alpha_3 wvc_i\theta_s \\ &= \pi h(\theta_s - \theta) + \frac{\pi hk_{air}L_e}{c_a p}(e_s - e_a) - \alpha_1 wvc_w\theta - \quad (6) \\ &4\pi\varepsilon\delta(273.15 + \theta)^3\theta + \alpha_1 wvc_w(1 - \alpha_3)(\theta_s - \theta) \end{aligned}$$

Where: L_f is ice melting heart, it's 3.34×105J/kg; r_c is the partial recovery coefficient for the conductor surface, taking 0.79; c_a is air specific heat, it is 1014 J/(kg·K); c_i is the specific heat when ice in the membrane temperature, J/(kg·K). It does not exist in the wet growth. θ_s and θ are the ice surface temperature and the ambient temperature, ℃; k_{air} is the thermal conductivity of the air medium, 0.0241W/(K·m); L_e is the latent heat of evaporation or sublimation when temperature is θs. The θs is 0 when wet growth, then L_e is 2.501×106 J/kg; e_0、e_a is the Saturation pressure when the surface temperature respectively is 0 and θ. e_0 is 0.61121kPa, the unit of e_a is kPa.

$$e_a = 0.61121\exp\left(\frac{18.678 - \dfrac{\theta}{234.5}}{257.14 + \theta} \times \theta\right) \quad (7)$$

Where: c_w is the specific heat of water, 4220 J/(kg·K); ε is ice surface relative to the total blackbody radiation coefficient, approximately equal to 0.95; δ is the Stefan-Boltzman constant, 5.67×10^{-8}W/(m^2·K^4); h is convective heat transfer coefficient, J/(m^2·K). $h = k_{air} \cdot Nu/D$, Nu is the Nusselt Number, its value is $0.032R_e{}^{0.85}$。

When icing process is wet growth, the θ_s is 0℃. Then we can obtain this equation.

$$\alpha_3 = \alpha_3(\alpha_1, w, v, \theta)$$

$$= \frac{-\pi\theta h + \dfrac{\pi h k_{air} L_e(e_0 - e_a)}{c_a p} - \dfrac{h r_c v^2}{2c_a}}{\alpha_1 w v(L_f - c_w\theta)} - \frac{4\pi\varepsilon\delta(273.15+\theta)^3\theta}{\alpha_1 w v(L_f - c_w\theta)} - \frac{2c_w\theta + v^2/2}{L_f - c_w\theta} \quad (8)$$

From the equation (2) and (8), we can calculate α_1 and α_3. If we take α_2=1, from equation (1) we can get the quality of ice in Δt time.

After Δt, the quality of ice increase Δm, and the wire diameter changes. Because the conductor is rotating, the ice uniformly distributes in the circumference of the conductor. Assume the ice thickness increment is Δb, it can be calculated based on the density of ice. In the process of ice, ice density depends on air temperature, air speed, LWC and MVD and conductor size and other factors. It can be calculated by π theory:

$$\begin{cases} \rho_i = 249 - 84.0\ln\pi_c - 6.24(\ln\pi_\phi)^2 \\ \quad +135\ln\pi_k + 18.5\ln\pi_k\ln\pi_\phi - 33.9(\ln\pi_k)^2 \\ \pi_c = 1000\times[k_{air}(\theta_s - \theta)/D_m]/(wvL_f) \\ \pi_\phi = 9\rho_a{}^2 D_m v/(\rho_w\mu) \\ \pi_k = \rho_w a^2 v/(9\mu D_m) \end{cases} \quad (9)$$

Where: ρ_i is the ice density. $D_m=(D_0+D)/2$. It is the average diameter of the conductor. D_0 is the initial diameter of conductor. D is the diameter of the conductor after the icing.

The minimum density we take 100kg.m^{-3}. There must be some air gap in the ice when the droplets collide. The density of ice is difficult to achieve the theoretical value, 917kg.m^{-3}. So in this article, the density of ice is taken as 900kg.m^{-3} in wet growth 。

Ice thickness increment Δb and conductor diameter after icing $D(t_0+\Delta t)$ during the time Δt are :

$$\begin{cases} \Delta b = \dfrac{D(t_0)}{2}\times\left(\sqrt{1+\dfrac{4\Delta m}{1000\pi L\rho_i D^2(t_0)}} - 1\right) \\ D(t_0+\Delta t) = D(t_0) + 2\Delta b \end{cases} \quad (10)$$

Comparing this model Ping Fu numerical analysis icing model in paper [16] and Jones precipitation icing model in paper [17], the results show below:

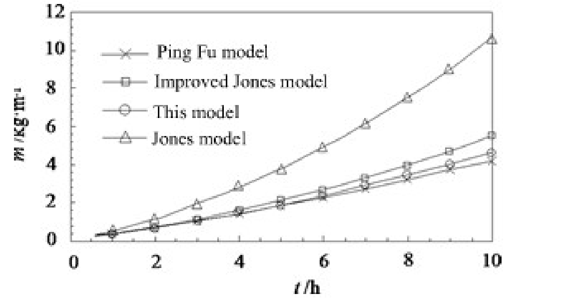

Figure 2 Comparison of models

Calculation conditions：θ=-12℃, v=5m/s, w=0.47g/m^3, D_0=34.9mm, a=200μm

Jones model is aimed at simple icing models of precipitation. It has certain precision when used to predict precipitation icing. Ping Fu model is set out from icing mechanism. It comprehensively analysis water droplet stress on the process of icing, and it is the complex numerous model of getting from the droplets of collision and frozen. From the above figure 2, we know this paper model are closer with Ping Fu numerous icing model, but Jones model is about twice of this paper model and Ping Fu numerous icing model. Jones model consider the vertical component of large water droplets collision. Through the Ping Fu remove vertical component of water droplets collision and get improved Jones model in literature [17]. Thus, it gets more similar with this paper model and Ping Fu numerous icing model. This model is accurate, and can be used to predict icing.

B. *Simplification of the number of parameters*

From the previous section, we know the ice mass of the conductor relate with 9 parameters:

$$m = f(v, \theta, p, t, D_0, r\%, L, w, a) \quad (11)$$

There are so many parameters that we should reduce the number of parameters which are effect icing slightly under some conditions.Weather station in Tibet Bangor where is altitude of 4,700 meters has the lowest annual average air pressure in China. It's 57.11kPa. According to the section, a MATLAB icing prediction program is finished and used to simulate ice mass on different initial diameter of conductor under certain conditions. The relationship between ice mass and air pressure from 55 to 105kPa is shown below.

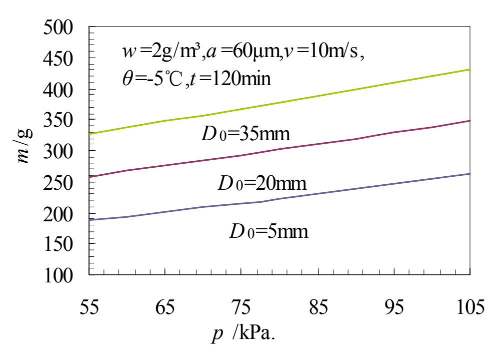

Figure 3 Simulation relationship between ice mass and air pressure

Figure 3 shows ice on different initial diameter conductors are good linear to air pressure. Ice mass

Identify applicable sponsor/s here. *(sponsors)* increases less than 38% from sea level 101.325kPa to the highest elevation of 4700m of 57.11kPa. We know the change of air pressure p in a particular location is small, so we ignore its change at some specific place.

r%, relative humidity, mainly impacts on air density, according to the literature [7] that icing happens when air relative humidity is 85% or above, and in the artificial climate chamber the air relative humidity is about 100%. The relationship between r% and ice mass as follows:

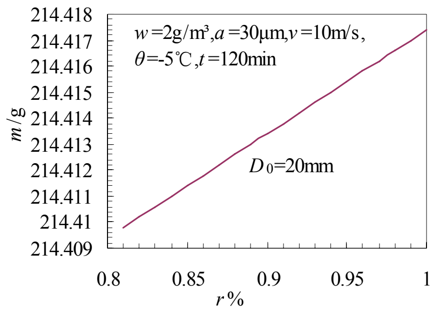

Figure 4 Simulation relationship between ice mass and relative humidity

From Figure 4 we can see the ice mass changes a little with relative humidity. The ice mass of the simulation conditions increases only 0.0036% when the relative humidity increases from 80% to 100%. So we can completely ignore the relative humidity impact on icing. Usually, it can be assumed to take 90% (artificial ice to take 100%).

When multi-conductor length L is known, then equation (11) is simplified as follows:

$$m = f(v,\theta,t,D_0,w,a) \qquad (12)$$

III. PRINCIPLE OF MEASURING ICING PARAMETERS BY THE ROTATING MULTI-CONDUCTORS

A. Metrical principle analysis

Although the numbers of parameters is simplified, but the relation between ice mass and parameters is very complicated. Meanwhile ice mass which is changing with various parameters of quality growth situation affected by the varied growth is considerable difference. It is hard to solve the parameters by using conventional mathematical methods.

When the diameters of conductors are different, the relation of ice mass of each conductor and five icing parameters are shown as follows:

$$\begin{cases} m_1 = f(v,\theta,t,D_{01},w,a) \\ m_2 = f(v,\theta,t,D_{02},w,a) \\ \vdots \\ m_N = f(v,\theta,t,D_{0N},w,a) \end{cases} \qquad (13)$$

According to using five icing parameters, ice mass of N-conductors can be calculated. Thus, the method of mathematical fitting iteration can be used to solve the parameter of optimal solutions. Two fitting slope method are used to solve icing parameter in this paper. The principle is such as:

In a group of five parameters combination, ice mass (M) of different diameter of N-conductors are calculated by the icing model, the calculated ice mass (M) and test data(M*) are composed a 2d array:

$$M_{2N} = \begin{bmatrix} M \\ M^* \end{bmatrix} = \begin{bmatrix} m_1, m_2, \cdots m_N \\ m_1^*, m_2^*, \cdots m_N^* \end{bmatrix} \qquad (14)$$

According to the array $M_{2N,}$ linear least-square method is used to calculate fitting slope k_a. If calculated value of ice mass is equal to test value, then, M=M*, fitting slope k_a=1 and fitting line get through the origin. It likes linear $L2$ shown in figure 5. The different combination of parameter will get different M. Therefore, we can take various parameters to change k_a, and then change iteration value of parameters. When calculated ice quality is bigger than test value, fitting slope k_a < 1, such as the fitting line $L3$ shows. Now need to chang parameters to decrease ice mass value. When calculated ice mass is smaller than test value, fitting slope k_a > 1, such as the fitting line $L1$ shows, now need to chang parameters to increase ice mass value. Ideally, fitting line get through the origin. But with the combination of ice parameter different, the fitting line does not pass origin. Such as the fitting line $L4$ shows. Even if fitting slope k_a=1, but calculated quality is bigger than test value. The fitting parameters are not accord with experiment conditions. So, conditions of the fitting line getting through the origin are added. Fitting slope k_d (fitting slope of fitting through the origin) is calculated. New k_d is calculated at the condition of line $L4$. And we get k_d<k_a=1, ice mass calculated value m is bigger than test value m*. Then need to change the five parameters decrease ice quantity, and k_d is changed with direction of greater. Only when k_d=1and k_a=1, line L_2 can be get. At that time, calculation of ice mass is equal to test value, and the calculated parameters can be considered a group of effective parameters which is that ice quantity achieve test value. These calculated parameters can be as the result of prediction of icing parameters.

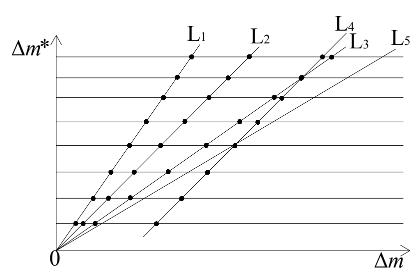

Figure 5 Relationship between calculated ice mass and test ice mass

B. Structure and parameters of the rotating multi-conductors

The figure 6 shows the rotating multi-conductors which is used in this paper:

Figure 6 Rotating multi-conductors

Each conductor diameter is different, specific size listed in table 1:

TABLE 1 MULTI-CONDUCTORS PARAMETERS

No.	1#	2#	3#	4#	5#	6#	7#	8#
D_0/mm	5.30	10.00	14.77	19.97	24.98	30.03	35.20	39.96
L/mm	100.16	100.08	99.72	99.80	99.56	99.78	99.88	100.00

No. is conductor number; L is each conductor length, D_0 is conductor diameter

IV. COMPUTATIONAL METHODS OF ICING PARAMETERS BASED ON ICE MASS ON ROTATING MULTI-CONDUCTORS

Through the above section analysis we can see when we know the ice mass on N (N=8) different diameter conductors, then calculate the approximate degree of the calculated and measured values based on a set of five parameters, which can solving a optimal set of five parameters. Some icing experiment was completed in multi-function artificial climate lab of Chongqing University. The ice test mass(m_N*) on the rotating multi-conductors and test conditions as follows:

TABLE 2 TEST ICE MASS AND TEST CONDITIONS

No.	1#	2#	3#	4#	5#	6#	7#	8#
m*(g)	33.99	41.50	48.71	56.78	62.18	70.89	79.59	87.19
test conditions	θ_t=-5℃；p_t=98.7kPa；r%=99%；v_t=4.1m/s；w_t=7.33g/m³；a_t=39.14μm；t_t=60min							

a_t and w_t are tested by laser particle size analyzer, the parameters are average value during the experiment but the ice time t_t.

Based on the available data in Table 2, how the MVD, LWC, temperature, time and wind influence the k_a and k_d will be shown in the below figures.

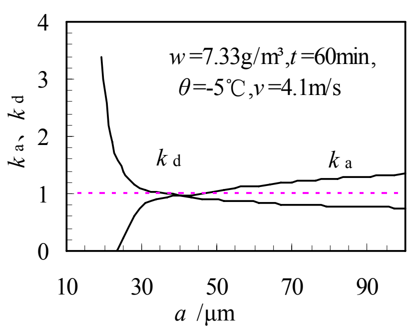

Figure 7 Relationship between k_a, k_d and MVD

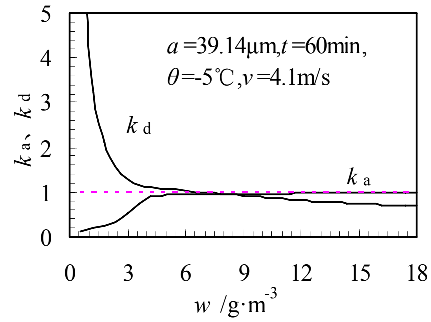

Figure 8 Relationship between k_a, k_d and LWC

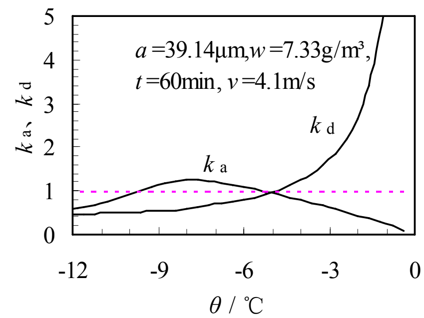

Figure 9 Relationship between k_a, k_d and temperature

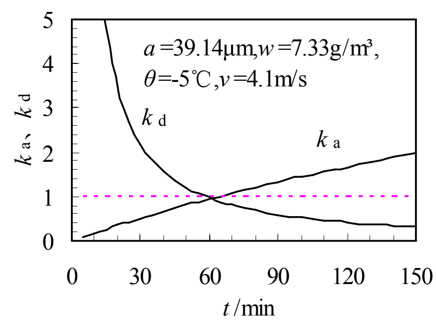

Figure 10 Relationship between k_a, k_d and icing time

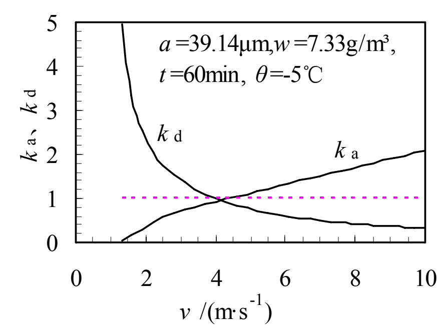

Figure 11 Relationship between k_a, k_d and air speed

Figure 7 shows that, with the MVD increases to the wet growth, the curve of k_a and k_d becomes relatively flat, but the rate of change of k_a is relatively large, so it can be used to preliminarily estimate MVD. Figure 8 obtains the variation of LWC basically same as the Figure 7. But in the wet growth phase k_a is constant of 1, if use k_a to judge LWC will not converge. Because the change rate of k_d is large than k_a, and k_d relatively stablely decreases in the wet growth process with the increase of LWC, so using k_d to judge LWC is retional. Figure 9 shows temperature changes more obvious impact on the ice growth of wet and dry.

Although there is a turning point at k_a curve, but the change is relatively stable and it conducive to the convergence of computin. We can adopt the method of judging wet or dry growth. So k_a still be used to estimate temperature. As it is shown in Figure 10, k_d relatively stable changes over icing time, so using k_d to estimate icing time. And it is very helpful to improve the computing speed. Figure 11 shows the air speed impacts k_a and k_d seriously. So we judge whether k_a and k_d are all near to 1 to estimate air speed and correct the other four parameters.

Based on the above method and in order to improve computing speed, MVD, LWC, temperature and icing time are not nested iteration, but k_a and k_d are cross-calculation. Using before and after average iterative value as the next new value to improve the stability and convergence of computing. The calculation steps are as follows:

At first, give w, a, θ, t and v initial value. (1) Calculated ice mass M_N based on the icing model which is introduced at the previous section, and fit it and the test value M_N* to calculate k_a, then judge whether the deviation between k_a and 1 or the change rate of k_a meets the requirement, if not, using $(a/k_a+a)/2$ as the new value of a, and continues. (2) Calculated ice mass M_N and k_d based on the condition of the calculated value of a and other above initial value, judge whether the deviation between k_d and 1 or the change rate of k_d meets the requirement, if not, using $(w\times k_d+w)/2$ as the new value of w, and continues. (3) Calculated ice mass M_N and k_a based on the condition of the calculated value of a and w, judge whether the deviation between k_a and 1 or the change rate of k_a meets the requirement, if not, using $(\theta/k_a+\theta)/2$ as the new value of θ when wet growth, using $(\theta\times k_a+\theta)/2$ as the new value of θ when dry growth, and continues. (4) Calculated ice mass M_N and k_d based on the condition of the calculated value of a, w and θ, judge whether the deviation between k_d and 1 meets the requirement, if not, using $(t\times k_d+t)/2$ as the new value of t, and continues. (5) Judge whether the deviation between k_d, k_d and 1 all meets the requirement, if not, using $(2v/(k_a+k_d)+v)/2$ as the new value of v, return step (1) and continues.

V. FIVE PARAMETERS SIMULTANEOUSLY SOLVING AND RESULTS ANALYSIS

Based on the the previous section calculation method and the steps, the MATLAB computer program of solving five parameters simultaneously has been programmed, and calculate the experimental data of Table 2,the results as follows:

TABLE 3 COMPUTED RESULT OF TEST DATA OF TABLE 2

No.		1#	2#	3#	4#	5#	6#	7#	8#
test value	m*(g)	33.99	41.50	48.71	56.78	62.18	70.89	79.59	87.19
	b*(g)	8.63	8.1	7.68	7.62	7.26	6.75	6.57	6.62
	test parameters	w_t=7.33g/m³; a_t=39.14μm; v_t=4.1m/s; θ_t=-5℃; t_t=60min							
calculated results	m (g)	32.18	40.62	48.66	57.10	64.86	72.32	79.36	85.51
	b(g)	8.32	7.96	7.65	7.36	7.12	6.90	6.68	6.49
	calculated parameters	w_c=20.88g/m³; a_c=84.83μm; v_c=3.72m/s; θ_c=-2.77℃; t_c=55.00min							
results comparison	σ_m(%)	-5.32%	-2.12%	-0.10%	0.57%	4.31%	2.02%	-0.29%	-1.92%
	σ_b(%)	-3.65%	-1.69%	-0.42%	-3.45%	-1.94%	2.23%	1.72%	-1.94%
	parameters comparison	σ_w%=184.9%; σ_a%=116.7%; σ_v%=-9.3%; σ_θ%=-44.6%; σ_t%=-8.3%;							

σ(%) is relative error percentage of the calculated value and test value, corresponding to the subscript values

Table 3 results show that the deviation between the five calculated parameters and test results are a little large. The maximum deviation is LWC reached 184.9%, the smallest is the icing time is -8.3%. The mainly reasons are that the calculated parameters are a combination of parameters calculated based on the ice mass relationship, and a optimal set of iterative approach calculation of the icing model, and relation on various parameters of the initial settings. However, from the calculated ice mass on the conductors we can see they are well approximation with the experimental data. The maximum deviation is only -5.32% of #1 conductor. And ice thickness which is calculated according to the parameters is close to test thickness, and error within ±4%. The slope index k_a is 1.0142, and k_d is 1.0043, both are near to 1, which reflects the quality of ice calculated and experimental results are more good approximation.

According to the results of Table 3, a set of icing parameters can be calculated solely based on the ice mass of 8 different diameter conductors, although this set of parameters and test measurements vary greatly, but the ice mass calculated based on the parameters can reflect the real icing effect. It indicates that the test icing parameters and calculated icing parameters are equivalent in predicting the ice thickness and mass. We don't need to concern about the icing parameters change in the icing process.

VI. CONCLUSIONS

(1) This icing model is correct, to forecast ice has certain accuracy.

(2) In this paper, the two fitting slopes can be used as two indicators of the approximation degree of calculated ice mass and experimental ice mass.

(3) This paper proposes a kind of thought that sdudy icing parameters according to ice mass, and then study icing state. Based on the two fitting slope, a numerical calculational method and a MATLAB calculation program are given, with good convergence, computational stability, fast calculation.

(4) Experimental measurement of ice mass is smaller deviation with the calculation ice mass based on calculated icing parameter. It proves the two combinations of icing parameters is equivalent to predict icing state. Avoid the study problem of real icing parameters change in the icing process. It is feasible as the icing indirect measurement method.

VII. REFERENCES

[1] YANG Jing-bo, LI Zheng, YANG Feng-li, etc. Analysis of the Features of Covered Ice and Collapsed Tower of Transmission Line Snow and Ice Attacked in 2008[J]. 2008, 24(4)：004-008.

[2] Chinese Society for Electrical Engineering, “Natural disasters” impact on the power system// China Association for Disaster Prevention and Reduction Forum 2008,Henan Zhengzhou：2008.

[3] XING Yi,ZENG Yi,SHENG Ge-hao,etc. On line Monitoring System of Overhead Transmission Line Icing Based on Mechanical Measurement [J]. Auto- mation of Electric Power Systems,2008, 32(23)：081-085.

[4] ZHANG Yu. Overhead Transmission Line Icing on Line Monitoring System [J]. High Voltage Engineering, 2008, 34(9)：1992-1995.

[5] XU Kun-yao, KUANG Jun, WU Bin. Chongqing Transmission Line Icing Real-time Monitoring Program [J]. China Electric Power Education, 2008 special issue of Review and Technical Forum：619-621.

[6] ZHANG Zhi-jin, JIANG Xing-liang, SUN Cai-xin, etc. Icing Flashover Performance of UHV DC Composite Insulators at Low Atmospheric Pressure[J], Proceedings of the CSEE, 2008, 28(6)：007-012.

[7] Jiang Xing-liang, Yi Hui, Transmission line’s icing and protection[M]. Beijing：China Power Press, 2002.

[8] Finstad K. J., Lozowzki E. P., Makkonen L.. On the median volume diameter approximation for droplet collision efficiency[J]. J. Atmos. Sci, 1988, 45(24)： 4008 – 4012.

[9] JIANG Fang, WEI Zhong, LEI Hengchi, etc. Measurement of Column Cloud Liquid Water Content by Airborne Upward-Looking Microwave Radiometer（Ⅱ）：Retrieval Method[J]. Plateau Meteorology, 2004, 23(1)：33-39.

[10] HUANG Zhu-qing, YANG Ji-ming, SU Chun-sheng, etc. Application of the Laser Scattering Theory for Monitoring Steam Wetness and Droplet Size in Steam Turbines[J]. Journal of Power Engineering, 2006, 26(2)：0241-0244.

[11] Knezevici D., Kind R.J., Oleskiw M.M. . Determination of Median Volume Diameter (MVD) and Liquid Water Content (LWC) by Multiple Rotating Cylinders[R] . America：43rd AIAA Aerospace Sciences Meeting and Exhibit, 2005.

[12] Robert F. Ide. Comparison of liquid water content measurement techniques in an icing wind tunnel[R]. America Washington:National Aeronautics and Space Administration, 1999.

[13] Mazin I.P., Korolev A.V., Heymfiel A., etc. Thermodynamics of icing cylinder for measurement s of liquid water content in supercooled clouds[J]. Journal of Atmospheric and Oceanic Technology, 2001, 18(4)：543-558.

[14] ZHU Chunling, LI Yuqin, ZHANG Quan, Analysis method of droplets parameters based on rotating multicylinder in an icing wind tunnel[J]. Journal of Aerospace Power, 2007, 22(2)：180-186.

[15] JIANG Xin-liang, SHEN Qiang, SHU Li-chun, etc. Wet Growth Icing Parameters Prediction Base on the Icing Quantity of Rotating Multi-cylindrical Conductors[J]. High Voltage Engineering, 2009, 35(12)：3071-3076.

[16] Ping Fu, Masoud Farzaneh, Gilles Bouchard. Two-dimensional Modeling of The Ice Accretion Process on Transmission Line Wires and Conductors[J]. Cold Regions Science and Technology, 2006, 46(2)：132–146.

[17] Kathleen F. Jones. A Simple Model for Freezing Rain Ice Loads[J]. Atmospheric Research, 1998,46(2):87–97.

[18] SUN Caixin, JIANG Xingliang, XIONG Qixin, etc. Analysis of Critical Icing Conditions of Conductor and Wet-dry Growth [J]. Proceedings of the CSEE, 2003, 23(3)：141-145