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Technical Study on Improvement of Endurance Capability of Limit Short-circuit Current of Charge Control SMART Meter

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Abstract. Smart meter represents the development direction of energy-saving smart grid in the future. The load switch, one of the core parts of smart meter, should be of high reliability, safety and endurance capability of limit short-circuit current. For this reason, this paper discusses the quick simulation of relationship between attraction and counterforce of load switch without iteration, establishes dual response surface model of attraction and counterforce and optimizes the design scheme of load switch for charge control smart meter, thus increasing electromagnetic attraction and spring counterforce. In this way, this paper puts forward a method to improve the withstand capacity of limit short-circuit current.

1.Introduction

As the terminal equipment of smart power grid, smart meter is no longer a traditional product with only basic function of electric energy measurement, but the one with multiple functions, such as storage of electricity consumption information, two-way data communication. Therefore, smart meter represents the development of energy-saving smart grid in the future. The load switch, one of the core parts of smart meter, can automatically cut off users' power when their electric charge is not enough and switch on the power after recharging. So the quality of load switch will directly influence the safety and reliability of power supply and consumption. In addition, the quality is also related to interests of thousands of households and the corporate image of the State Grid.

At present, magnetic latching relay is mainly adopted for built-in load switch for smart meter. For its low energy consumption and small size, the magnetic-latching load switch has been widely used. However, during real operation of the load switch for smart meter, fault rate of built-in load switch is high. The failure causes include burn-out of smart meter due to disconnection at short circuit, temperature rise of contact due to increasing of contact resistance and accelerated aging of plastic parts because of overheating. In addition, the design of load switch in some domestic manufacturers mainly depends on imitation and experience. Aside from that, great fluctuation of materials' distributed parameters and different technical levels lead to relatively large dispersion of key characteristic parameters of load switch, poor consistency of quality and short service life. Therefore, it's necessary to research the optimization design method to improve endurance capability of limit short-circuit current of load switch for charge control smart meter. The research can urge manufacturers to ensure product quality, improve technical



level in design phase, enhance power system's safety and reliability, reduce failure rate and prevent potential safety hazards.

2. Analysis on Endurance Capacity of Short-circuit Current of Load Switch

When there is current in a load circuit, electro-dynamic force on dynamic contactor mainly includes Lorentz force and Holm force. Out-of-phase current takes place due to Lorentz force at circuit. According to electro-magnetic induction, the conclusion that out-of-phase can produce repulsive force can be drawn. While, Holm force takes place because real contact area is far less than apparent contact area, which will lead to reduction of current before and after flowing through real contact points. In this way, out-of-phase current will appear, resulting in repulsive force (see Fig.1 and Fig.2).

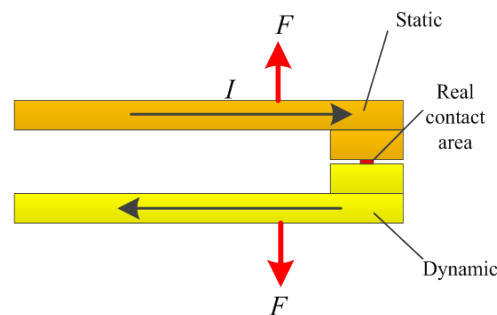


Fig.1 Schematic Diagram of Lorentz Force

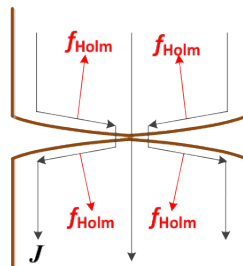


Fig.2 Schematic Diagram of Holm Force

As for the load switch for electric meter in Fig.3, the foldable and moveable spring makes the Lorentz force, resulting from short-circuit current, compress contactors easily, which in turn increases their pre-compression and keeps contact status. However, Holm force, as the force to separate contactors, is the main reason leading to abnormal disconnection of contacts at short circuit.

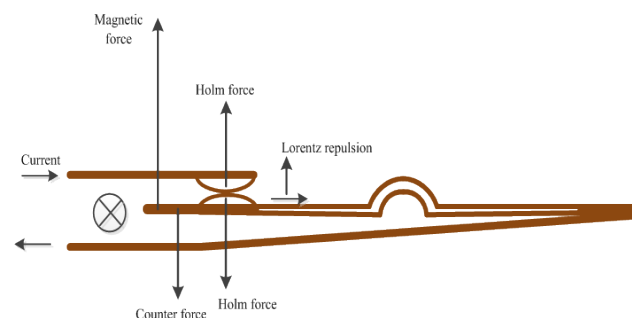


Fig.3 Force Analysis on Load Switch for Charge Control Smart Meter

Due to dispersed processing, some products have relatively small retention after closing of contacts; herein, the retention is the difference between permanent magnetic attraction and spring counterforce. When the load circuit incurs short circuit, several thousand amperes will flow through contacts. If Holm force, resulting from contraction of current line, is larger than contact retention, off-contact and electric arc of short-circuit current will take place, and lead to electric meter burnout. As a result, contact closure retention needs to be increased to improve resistance of contacts to short-circuit current. Increase of counterforce can lead to rise of contact pressure at contacts and their contact area, thus reducing Holm force.

3.Design Technology on Resistance Improvement to Short-circuit Current of Load Switch

3.1 Fitting design of dual response surface model. Response surface methodology (RSM) is a statistical treatment technology used for multivariable modeling and analysis. In most designs, the relationship between response surface and independent variable is unknown. Accordingly, the first step of response surface method is to determine an appropriate approximation of $f(x)$ by adapting the least square method. By using the least square method, error sum of squares between the calculated data and real data can be the smallest. Generally, lower-degree polynomial can be used for approximation within independent variables in limited range. For example, use the independent variables in linear function (e.g. function of first degree) in formula (1); or use higher-degree polynomial (e.g. quadratic polynomial) in formula (2).

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n + \varepsilon \quad (1)$$

$$y = \beta_0 + \sum_{i=1}^n \beta_i x_i + \sum_{i=1}^n \beta_{ii} x_{ii}^2 + \sum_{i < j} \beta_{ij} x_i x_j + \varepsilon \quad (2)$$

Combination of Taguchi method and response surface method will get dual response surface method, as is shown in formula (3) and (4), where ε_u and ε_σ are error terms of mean value model and variance model respectively. Similarly, response surface models of mean value and variance with third and fourth orders or even higher can be constructed. Performance and fluctuation characteristic of products can be reflected more intuitively through building response surface models of mean value and variance.

$$Y_u = b_0 + \sum_{i=1}^k b_i x_i + \sum_{i=1}^k b_{ii} x_{ii}^2 + \sum_{i < j} b_{ij} x_i x_j + \varepsilon_u \quad (3)$$

$$Y_\sigma = c_0 + \sum_{i=1}^k c_i x_i + \sum_{i=1}^k c_{ii} x_{ii}^2 + \sum_{i < j} c_{ij} x_i x_j + \varepsilon_\sigma \quad (4)$$

Unknown coefficients are determined through the least square method. Specifically, unknown coefficient $B = [b_0, b_1, b_2, \dots, b_L]^T$ can be determined by formula (5) and calculation of $C = [c_0, c_1, c_2, \dots, c_L]^T$ is similar.

$$\begin{cases} E(\varepsilon) = \sum_{j=1}^p \{ [Y(\mathbf{X}_j^0) - \sum_{i=0}^L b_i \phi_i(\mathbf{X}_j^0)]^2 \} \\ \left. \frac{\partial E(\varepsilon)}{\partial b_i} \right|_{b_i^*} = -2 \mathbf{X}^T \mathbf{Y} + 2 \mathbf{X}^T \mathbf{X} \mathbf{B} = 0 \end{cases} \rightarrow \mathbf{B} = (\mathbf{X}^T \mathbf{X})^{-1} \mathbf{X}^T \mathbf{Y} \quad (5)$$

Where, $\mathbf{Y} = [Y(\mathbf{X}_1^0), Y(\mathbf{X}_2^0), \dots, Y(\mathbf{X}_P^0)]^T$ is the response vector at P ($P > L$) test points; $\mathbf{X}$ refers to primary function matrix, as is shown in formula (6).

$$X = \begin{bmatrix} \phi_1(X_1^0) & L & \phi_L(X_1^0) \\ M & & M \\ \phi_1(X_P^0) & L & \phi_L(X_P^0) \end{bmatrix} \quad (6)$$

Carry out error estimation to models from dual response surface method; namely, verify fitting of response surfaces and sample points by using determination coefficient R^2 and adjusting determination coefficient R^2_{adj} . See formula (7) and (8) for definition.

$$R^2 = \frac{\sum_{i=1}^P (\hat{y}_i - \bar{y}_i)^2}{\sum_{i=1}^P (y_i - \bar{y}_i)^2} \quad (7) \quad R^2_{adj} = 1 - \frac{\sum_{i=1}^P (y_i - \hat{y}_i)^2 (P-1)}{\sum_{i=1}^P (y_i - \bar{y}_i)^2 (P-k-1)} \quad (8)$$

Where, P refers to the number of selected test points; adjustment factor minus 1 is k , degree of freedom; y_i and $\bar{y}_i$ mean measured value and average value of response variable; $\hat{y}_i$ is predicted value of response variable; when R^2 and R^2_{adj} are closer to 1, fitting degree of response surface model is better.

Based on U-type design, uniform design is a design method to pursue high quality and disperses test points evenly into input parameter space. And the method can be applied to various models and has robustness on model change. Uniform design is to arrange tests through the uniform design table, without randomness. The design is aimed at finding the minimum deviation between grand average of output variable and real total average among test points.

According to the analysis, the key structural design parameters of electromagnetic system with a significant influence on attraction and counterforce are respectively right half-length of long-pole face, left half-length of long-pole face, left half-length of short-pole face, and right half-length of short-pole face. Key design parameters of contact springs system are respectively offset at Ω initial position, thickness of spring of two lower layers, thickness of spring of upper layers and width of spring. There are two determined key output characteristic parameters, namely F_1 , electromagnetic attraction at pick-up position under 0V and F_2 , corresponding counterforce at the pick-up position.

Uniform design sampling table will be used in uniform design of the sample. In parameter fitting of dual response surface model, expressions of F_1 (electromagnetic attraction at pick-up position under 0V) and F_2 (the maximum counterforce at corresponding pick-up position) are defined as follows:

$$\begin{aligned} F_1 &= 1537.75 + 102.84 \cdot x_1 - 235.76 \cdot x_2 - 292.57 \cdot x_3 + 77.79 \cdot x_4 + 8.79 \cdot x_1 x_2 \\ &\quad + 8.75 \cdot x_1 x_3 - 34.55 \cdot x_1 x_4 + 14.06 \cdot x_2 x_3 + 7.072 \cdot x_2 x_4 + 15.17 \cdot x_3 x_4 \\ F_2 &= 4744.77 + 5956.13 \cdot x_5 + 28829.53 \cdot x_6 - 11631.49 \cdot x_7 - 554.97 \cdot x_8 - 7748.27 \cdot x_5 x_6 \\ &\quad + 5472.32 \cdot x_5 x_7 - 525.36 \cdot x_5 x_8 + 11906.20 \cdot x_6 x_7 - 3258.89 \cdot x_6 x_8 + 2180.72 \cdot x_7 x_8 \end{aligned} \quad (9)$$

Where, x_1 refers to long right armature length, x_2 long left armature length, x_3 short right armature length, x_4 short left armature length, x_5 Ω offset, x_6 thickness of spring of two lower layers, x_7 thickness of spring of upper layers and x_8 width of spring.

3.2. Optimization design of multi-objective particle swarm. Constraint conditions:

(1) Feasible domain constraints: particles are confined within feasible region, with optimization parameters being subject to the upper and lower bounds. Given real assembly links and the feasibility in real production, dimensions of relevant parts cannot be infinitely increased and reduced, but limited within a certain range. Assuming dimension X , then $X \in [X_{\min}, X_{\max}]$.

(2) Other index constraints: retention (difference between F_1 and F_2 at pick-up position under 0V) at pick-up position under 0V should be greater than F_{Holm} .

According to standard particle swarm optimization (PSO), the key step is to find out local optimal position of individuals and global optimal position of swarms. An ordering strategy of niche fitness has been introduced based on general multi-objective particle swarm optimization (MOPSO), so a niche sorting multi-objective particle swarm optimization (NSMOPSO) can be provided to solve multi-objective optimization of load switch's electromagnetic system. Key strategies to improve MOPSO calculation are as follows:

(1) Selection of historical local optimal parameters of individuals and global optimal parameters of swarms

Particles' individual historical local optimal parameters can be selected according to Pareto dominance relation. If parameters of particle under current iteration dominate the historical local optimal parameters of particle (P), then P will be adopted as current parameters; if P dominates the parameters of particle under current iteration, then P will not be adopted; If the two cannot be compared, one of them will be selected randomly with probability of 50%. Particle swarm's global optimal parameter (Pg) is sorted according to all particles' fitness values of historical global optimal parameters under current iteration. The particle with the best fitness value will be selected as the swarm's global optimal parameters.

(2) External space of particle of particle

To improve computational efficiency of the calculation, external space of particle with capacity of N will be established to store Pareto optimal solutions. After iteration, all the new historical local optimal parameters of particles shall be put into the external space. Meanwhile, sort fitness according to descending order in the external space and delete dominated and repeated solutions. At this moment, if the number of particles in external space exceeds the standard capacity N, the tail end should be deleted to ensure validity of optimal parameters in the external space.

(3) Niche strategy

Niche sharing strategy is adopted as the calculation to sort fitness, with calculation formula defining fitness of particle X_i in the external space being as follows:

$$F_i = \frac{1}{S_i}, \quad i = 1, 2, \dots, N_s \quad (10)$$

Where, N_s refers to the number of particles in the external space;

S_i sharing degree of particle X_i .

$$S_i = \sum_{j=1}^{N_s} f_{sh}(d_{ij}), \quad j = 1, 2, \dots, N_s \quad (11)$$

Where, $f_{sh}(d_{ij})$ is a sharing function between X_i and X_j , representing osculation of particles in the external space.

$$f_{sh}(d_{ij}) = \begin{cases} 1 - \left(\frac{d_{ij}}{\sigma_{share}}\right)^\alpha, & 0 \leq d_{ij} \leq \sigma_{share} \\ 0, & d_{ij} \geq \sigma_{share} \end{cases} \quad (12)$$

Where, α (usually 1 or 2) refers to power of sharing distance;

σ_{share} value of predetermined sharing distance (usually constant);

d_{ij} distance between X_i and X_j .

$$d_{ij} = \|X_i - X_j\| = \sqrt{\sum_{k=1}^n (x_{ik} - x_{jk})^2} \quad (13)$$

In the external space, the denser the particles at someplace are, their sharing function will be larger and the fitness will be smaller; on the contrary, the more sparsely particle distribution is, the fitness of particle will be larger. Through fitness sorting in external space, the niche strategy has avoided densely-distributed particles and enhanced the exploitation ability of calculation.

(4) Gaussian mutation

Gaussian mutation mechanism has been added into MOPSO to initialize again those particles inferior to P with some probability. Meanwhile, random initialization will be conducted to particles (out-of-range particles) going beyond the feasible region so as to improve availability of particles. See Fig.4 for NSMOPSO solution flow of optimization model of structure parameters.

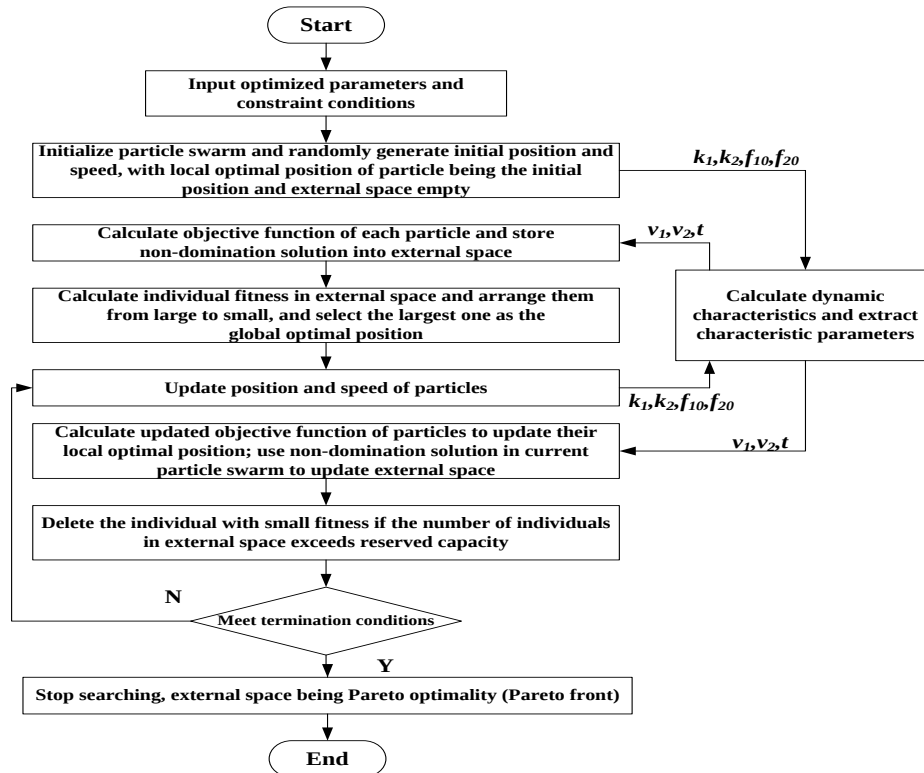


Fig.4 NSMOPSO Flow of Multi-objective Optimization of Structure Parameters

4.Design Results on Improvement of Load Switch's Endurance Capability of Limit Short-circuit Current

According to the aforesaid analysis, the mathematical model of multi-objective optimization of load switch is determined below:

$$\begin{aligned} \min y &= f(x) = (f_1(x), f_2(x)) \\ \text{s.t.} &\begin{cases} \frac{1}{f_1(x)} - \frac{1}{f_2(x)} > F_{\text{Holm}} \\ x \in R^8 \end{cases} \end{aligned} \quad (14)$$

Where, $x = x_1, x_2, \dots, x_8 \in R^8$ are 8 optimized parameters; $f(x)$ refers to objective function, including $f_1(x)$ and $f_2(x)$, of which $f_1(x)$ is reciprocal of attraction F_1 at pick-up position under 0V and $f_2(x)$ reciprocal of the maximum counterforce F_2 at corresponding pick-up position; g_i is the constraint of inequality and h_i the constraint of equality.

In this paper, we take a common load switch as an example, with its optimized parameter boundary and constraints shown in Table 1. Parameter setting of NSMOPSO calculation:

inertia weight $w_{\text{start}} = 0.9, w_{\text{end}} = 0.4$, accelerated factor $c_1 = c_2 = 2$, niche radius $\sigma_{\text{share}} = 1$, controls parameter $\alpha = 1$, capacity of external space N is 200, the number of particles in a swam 30 and the maximum

number of iterations 40. See Fig.5 for Pareto front.

Table 1. Optimized Parameter Boundary

	Long Right Armature Length	Long left Armature Length	Short Right Armature Length	Short Left Armature Length
min	7.6mm	8.1mm	8.1mm	7.1mm
max	7.9mm	8.4mm	8.4mm	7.4mm
	Ω offset	Thickness of spring of two upper layers	Thickness of spring of lower layers	Width of spring
min	-1.65mm	0.205mm	0.255mm	10.85mm
max	-1.35mm	0.235mm	0.283mm	11.15mm

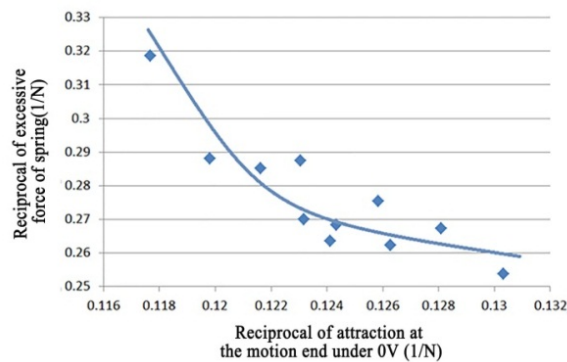


Fig.5 Optimization Results of Structure Parameters

According to PSO and processing technology, final optimal combination of parameters is shown in the following table.

Table 2. System Parameters of Electromagnetic System and Spring after Optimization (Unit: mm)

Parameters	Long Right Armature Length	Long left Armature Length	Short Right Armature Length	Short Left Armature Length
Before optimization	8.25	8.25	7.25	7.25
After optimization	7.74	8.57	8.21	7.32
Parameters	Ω offset	Thickness of spring of two upper layers	Thickness of spring of lower layers	Width of spring
Before optimization	0	0.2	0.25	11
After optimization	-1.42	0.21	0.27	11

5. Effect Verification

In Fig.3, contact pre-compression is about 5.5-6.5N, proposed short-circuit current 1k-5kA, surface material of contactors AgS_nO_2 and BH 80-100N/mm². Holm force is calculated under these conditions. See formula (15) for empirical calculating formula of Holm force.

$$F_h = \frac{\mu_0}{4\pi} I^2 \ln \frac{R_0}{R_c} \quad (15)$$

Where, F_h refers to Holm force, μ_0 magnetic conductivity in vacuum, I short-circuit current, R_0 contactor

radius and R_c real contact area. Among them, real contact area can be calculated according to formula (16).

$$R_c = \sqrt{\frac{F}{\varepsilon \pi H}} \quad (16)$$

Where, F means contact pre-compression, ε correction factor generally related to status (surface roughness) of contact surface and the value ranges between 0.3 and 0.6, the typical value is generally 0.45 and H refers to BH of contactor material.

First, calculate contact radius R_c and the ratio (R_c/R_0) of contact radius to contactor radius under different correction factors according to formula (16), where contactor pre-compression is 6N and correction factors range between 0.3 and 0.6. See Fig.12 for calculation results. The ratio of contact radius to contactor radius fluctuates between 0.05 and 1 and a median of 0.45 is generally taken as the correction factor and then the ratio reaches 0.064.

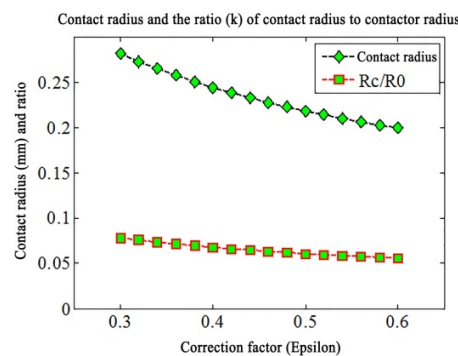


Fig.6. Calculated Value of Contact Radius (contact force: 6N)

When the correction factor is 0.45, contact pre-compression ranges between 5 and 7N. See Fig.17 for Holm forces under different short-circuit currents. Holm force will increase rapidly according to the square of current when short-circuit current increases. When the contact pre-compression varies, it has little influence on Holm force due to little change of real contact area.

When short-circuit current approaches 6kA, Holm force is closed to 5N, which means it nears contact pressure (i.e. contact retention). At this moment, contactors may be separated by short-circuit current, leading to contact failure.

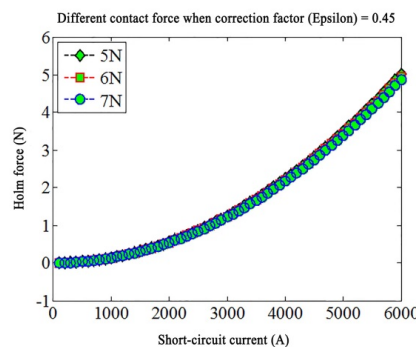


Fig.7. Holm Force under Different Pre-compressions

To understand the influence of different contact pre-compressions on Holm force more clearly, we also calculate the change rule of Holm force under different ratios of real contact area to contactor radius. See

Fig.8 for the results.

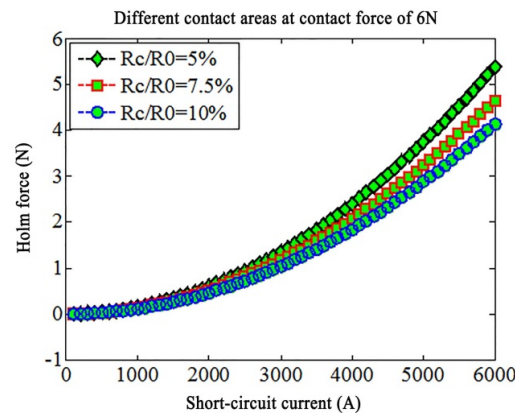


Fig.8. Influence of Contact Area on Holm Force

According to the results, the real contact area in this range has a certain influence on Holm force, but the effect is small. That means estimation formula of real contact area and results have little influence on calculation results of Holm force, which is of relatively credibility. In addition, short-circuit current is the decisive factor of Holm force.

If the load switch is to be subjected to a short-circuit current of 6 kA, then the retention must be at least over 6N.

In summary, short-circuit current is the decisive factor of Holm force and the retention must be at least over 6N to ensure the load switch can endure a short-circuit current of 6kA. Holm force can also be calculated precisely by modeling through simulation software such as ANSYS. Literature shows that the difference between the results and empirical formulas is less than 5%.

According to the aforesaid analysis, the resistance of contact to short-circuit current can be improved to 6kA after the contact pressure having been increased from 4.5N and 6.3N, ensuring no abnormal disconnection between contacts when a short-circuit current of 6kA takes place in the loading circuit.

6. Conclusion

Based on general MOPSO calculation, this paper introduces ordering strategy of niche fitness and puts forward an improved multi-objective particle swarm calculation (Niche Sorting NSMOPSO) to solve multi-objective optimization of load switches. This calculation adopts niche sorting to select global optimal parameters and Gaussian mutation mechanism to repeatedly utilize particles beyond the boundary, making Pareto solution distribute more widely and evenly. The optimization design scheme on load switch for charge control smart meter from study of this paper can ensure that the endurance capacity of limit short-circuit current can be improved to 6kA, which effectively guarantees safe operation and reliability of smart meter.

References

- [1] Clarke S M, Griebisch J H and Simpson T W 2005 Analysis of Support Vector Regression for Approximation of Complex Engineering Analyses. *Journal of Mechanical Design*. **127** 1077-87.
- [2] Turner C J 2012 Metamodeling In Product and Process Design. *ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. 639-651.
- [3] Jin R, Chen W and Simpson T W 2001 Comparative Studies of Metamodelling Techniques under Multiple Modeling Criteria. *Structural and Multidisciplinary Optimization*. **23** 1-13.
- [4] Coulomb J L, Kobetski A, Costa M C, Maréchal Y and Jönsson U 2003 Comparison of Radial Basis

- Function Approximation Techniques. *The International Journal for Computation and Mathematics in Electrical and Electronic Engineering*.22616-629.
- [5] Mehta D M and Pant R S 2013 Surrogate Based Design Optimization of Aerostat Envelope. *AIAA Lighter-than-Air Systems Technology (LTA) Conference*.43-50.
- [6] Kim J B, Hwang K Y and Kwon B I 2011 Optimization of Two-Phase In-Wheel IPMSM for Wide Speed Range by Using the Kriging Model Based on Latin Hypercube Samplin. *IEEE Transactions on Magnetics*.471078-81.
- [7] Douglas C M 2014 Stu Hunter's Contributions to Experimental Design and Quality Engineering. *Quality Engineering*.265-15.
- [8] Hunter J S 1985 Statistical Design Applied to Product Design. *Journal of Quality Technology*.17210-221.
- [9] Diplaris S C 2000 Sfantsikopoulos M M. Cost-Tolerance Function: A New Approach for Cost Optimum Machining Accuracy. *International Journal of Advanced Manufacturing Technology*.1632-38.
- [10]Chi, C.T 2006 A Study of Closing Adaptive Control in Electronically Controlled Intelligent Contactor. *2006 IEEE Region 10 Conference*.82-88.