Reliability Optimization Design for Mechanical Transmission Based on Hybrid Genetic Algorithm

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Abstract
This paper applies the reliability optimization design theory to the design of automotive mechanical transmission gear train, in accordance with the requirements of vehicle dynamics, under the condition to ensure the reliable use of the parts in the structural strength and rigidity, with the minimization of the transmission volume and maximization of the power usage as the objective function, to establish a mathematical model of the multi-objective reliability optimization design for automotive mechanical transmission, so as to achieve the solution and application of the hybrid genetic algorithm in the model, and ultimately obtains the reliability optimization design results. By the comparison of the reliability optimization design results with the raw data, draw the conclusion that the reliability optimization design method is feasible in the field of transmission design, with a relatively high value in engineering application.
Key words: MECHANICAL TRANSMISSION, RELIABILITY OPTIMIZATION DESIGN, HYBRID GENETIC ALGORITHM

1. Introduction

In modern automobile structure, in order to achieve the reasonable lightweight, the application of modern optimization design method in automotive design can be an important approach. However, the simple application of optimization design method for the specific automotive structural design may not be entirely feasible. According to statistics, every year in our country there are about 80,000 person-times killed or injured in the car accidents, among which there are some accidents caused by vehicle failure [1]. Therefore, as the transport vehicle, automobile must have sufficient reliability and security. And it is also necessary to make reliability design for the specific structure of the automobile; however, this sometimes has certain contradiction with the specific structural lightweight design [2]. Therefore, in order to ensure sufficient reliability and absolute security for the lightweight structure at the same time, it is necessary to combine the reliability design with modern optimization design to achieve reliability optimization design for automobile structure [3].

In the 60s and 70s, the United States already introduced the reliability technology into the automotive, power generation equipment, tractors, engines and so on. American famous engine manufactu- rers such as Caterpillar Co. have done a lot of work in respect of the engine reliability, and the level of engine reliability is relatively high [4]. Japan vigorously promotes the application research on the mechanical reliability, and the most notable achievement is the successful introduction of Failure Mode Effects Analysis (FMEA) technology to the engineering industrial enterprises, and through the accumulation of experiences in the application of mechanical products for the long term, to obtain the reliability by fault finding and continuous design improvement [5]. Reliability optimization design methods are roughly divided into two categories [6]: one category is to establish the mathematical model with the condition of constraints (or objective function) for the failure probability of structural element, or the single failure mode, which is an approach to apply the first-order second-moment method, and convert the probability constraints into the determination of constraint problems to solve the optimization issue [7-8]. The other category is to establish the mathematical model with the condition of constraint (or objective function) for the failure probability of structural systems. Now the auto parts reliability optimization design method commonly applies the mean first-order second-moment method [9]. The genetic algorithm is an effective method to solve the multi-objective optimization problem, and the feature of such algorithm is that there is no need to define the weight of each objective manually, but to find all the Pareto optimal solutions by the running of the algorithm one-time, and then the decision-makers make the judgment and selection [10].

This paper takes a two-axis gearbox as the object of study to establish the mathematical model for multi-objective reliability optimization design, and applies hybrid genetic algorithm to solve the mathematical model.

2. Mathematical model for automotive transmission reliability optimization design

Transmission is a relatively important component in the automotive drive line system, whether the design is good or not will have a direct impact on the actual performance of the automobile, in order to ensure the dynamic and economic indicators of the automobile, it is necessary to select the appropriate gear of transmission, the variable speed ratio and all paring gears.

2.1. The Establishment of Transmission Optimization Design Objective Function

(1) The Establishment of Objective Function Based on the Volume Minimization

As the overall size of the automobile transmission depends primarily on its gear system, this paper takes the minimization of the sum of the transmission gear volume as the objective function. And the objective function is:

$$V = \frac{\pi}{4}\sum_{1}^{10} b_i d_i^2 \tag{1}$$

Since the gear train adopts the involutes cylindrical gear as the driving motion, the modulus of the two mutually meshing gear indexing circles is equal to each other, and the indexing circles have the equal pressure angles, as far as the pair of helical gears are concerned, the helix angles of the indexing cylinder of the gear are equal, in the opposite direction. As can be seen from the design scheme of the reverse gear of the object of study in this paper, the reverse gear modulus and helix angle should have the same value as the first gear; hence the volume of the reverse gear depends on the reverse gear ratio. After the forward gear design is completed, according to the reverse ratio, the other parameters of the reverse gear can be calculated. Therefore, the design of the reverse gear set is not taken into account in the optimization design in this paper. Therefore, the volume of the gear train is:

$$V = \frac{\pi}{4}\left[\frac{m_{n1}^2}{\cos\beta_1^2}\left(z_1^2+z_2^2\right)b_1 + \frac{m_{n2}^2}{\cos\beta_2^2}\left(z_3^2+z_4^2\right)b_2 + \frac{m_{n3}^2}{\cos\beta_3^2}\left(z_5^2+z_6^2\right)b_3 + \frac{m_{n4}^2}{\cos\beta_4^2}\left(z_7^2+z_8^2\right)b_4 + \frac{m_{n5}^2}{\cos\beta_5^2}\left(z_9^2+z_{10}^2\right)b_5\right] \tag{2}$$

Where:

$m_{ni}\left(i=1,2,3,4,5\right)$ - the i-th gear normal module:

$\beta_i\left(i=1,2,3,4,5\right)$ - the i-th gear indexing cylinder helix angle:

$z_i=\left(i=1,2\cdots10\right)$ - Gear tooth number;

$b_i=\left(i=1,2\cdots5\right)$ - The tooth width of each gear.

Each transmission gear ratio is:

$$i_1=\frac{z_2}{z_1}, i_2=\frac{z_4}{z_3}, i_3=\frac{z_6}{z_5}, i_4=\frac{z_8}{z_7}, i_5=\frac{z_{10}}{z_9} \tag{3}$$

Automotive transmission is the multi-gear meshing in the shift between two parallel axes, which is characterized by the equal center distance A of each gear, which is:

$$A=\frac{m_{n1}\left(z_1+z_2\right)}{2\cos\beta_1}=\frac{m_{n2}\left(z_3+z_4\right)}{2\cos\beta_2}=\frac{m_{n3}\left(z_5+z_6\right)}{2\cos\beta_3}=\frac{m_{n4}\left(z_7+z_8\right)}{2\cos\beta_4}=\frac{m_{n5}\left(z_9+z_{10}\right)}{2\cos\beta_5} \tag{4}$$

From the above equations, the following can be obtained:

$$z_3=\frac{m_{n1}\cos\beta_2}{m_{n2}\cos\beta_1}\times\frac{z_1+z_2}{1+i_2} \tag{5}$$

$$z_4=z_3\times i_2 \tag{6}$$

$$z_5=\frac{m_{n1}\cos\beta_3}{m_{n3}\cos\beta_1}\times\frac{z_1+z_2}{1+i_3} \tag{7}$$

$$z_6=z_5\times i_3 \tag{8}$$

$$z_7=\frac{m_{n1}\cos\beta_4}{m_{n4}\cos\beta_1}\times\frac{z_1+z_2}{1+i_4} \tag{9}$$

$$z_8=z_7\times i_3 \tag{10}$$

$$z_9=\frac{m_{n1}\cos\beta_5}{m_{n5}\cos\beta_1}\times\frac{z_1+z_2}{1+i_5} \tag{11}$$

$$z_{10}=z_9\times i_5 \tag{12}$$

Substitute the above equations into the equation to obtain one of the sub-objective functions:

$$F(X)=V \tag{13}$$

(2) The Establishment of the Overall Objective Function for the Optimization Transmission Design

Multi-objective function optimization issues are often contradictory, they cannot reach the optimal solution at the same time, and sometimes may even produce completely opposite situations; that is, it may be a superior point to one objective function, but an inferior point to another objective function. This requires the coordination of the optimal solutions among the various objectives, and to make appropriate "concessions" in order to achieve the optimal overall solution, therefore, we should use the unified objective method. And the overall objective function for the transmission optimization design is

$$F(X)=\sum_{j=1}^{2}\omega_j F_j(X) \tag{14}$$

Wherein $\omega_j(J=1,2)$ is the weighting factor for the *J*-th item sub- objective function $F_j(x)$, and it is a number greater than zero.

2.2. The Establishment of the Condition of Constraints

(1)The Constraints of the Maximum Gear Ratio of the Transmission

The maximum transmission gear ratio of the automobile is the product of the first gear ratio of the transmission i_1 and the transmission ratio of the main reducing gear. It is subject to the pavement adhesion and the constraint of the auto maximum climbing degree.

According to the drive wheels and the condition of the pavement adhesion, it can be obtained that [21]:

$$i_1 \le \frac{G_2\varphi r_r}{T_{e\max} i_0 \eta_r} \tag{15}$$

Hence the condition of constraints is obtained:

$$g_1(X)=i_1-\frac{G_2\varphi r_r}{T_{e\max} i_o \eta_r}\le 0 \tag{16}$$

From the maximum climbing degree requirements it can be obtained that [1]:

$$i_1 \ge \frac{mg\left(f\cos\alpha_{\max}+\sin\alpha_{\max}\right)r_r}{T_{r\max} i_o \eta_r} \tag{17}$$

So the condition of constraints is obtained:

$$g_2(X)=\frac{mg\left(f\cos\alpha_{\max}+\sin\alpha_{\max}\right)r_r}{T_{e\max} i_o \eta_r}-i_1\le 0 \tag{18}$$

Where:

$\alpha_{\max}$: The automotive maximum climbing degree, generally taking the value of 16.7 °:

f : Road rolling resistance coefficient, generally taking the value $f=0.0165+0.0001(V_{\max}-50)$

φ : The pavement adhesion coefficient, ranging from 0.5 to 0.6

η_r : Power train mechanical efficiency, generally taking the value of 0.835

: The load N on the drive wheels when the automobile is in full load

m : Total vehicle mass of the automobile, Kg

$T_{r\max}$: The maximum engine torque: $N\cdot m$

(2)The Constraints of the Axial Force of the Output Shaft

The application of helical gear in the transmission can reduce the volume of the transmission, improve the stability of the driving motion and reduce noise; however, in the meantime it may also bring some problems. For example, when the helical gear has a large helix angle, it will generate great axial force. As shown in Figure 1[1]. As the drive gear of the main reducer is integrated with the output shaft of the two-axis mechanical transmission, the output shaft is impacted by the axial force, in order to make the axial force as small as possible, the drive gear of the main reducer shall have reverse assembly from each follower gear, such design allows the axial forces of the two helical gear to cancel each other in a portion, and the remainder is withstood by the transmission case via a bearing cap. In order to minimize the stress on the transmission case, in the selection of the helix angle of the helical gear, the substantial offset of the axial force on the output shaft of the transmission is preferred. As can be obtained from Figure 1:

$$\|Q_1-Q_2\|\le\delta \tag{19}$$

δ is a given value in the design, and the unit of measurement is Newton, when the value of δ is too large, it will give the bearing of the transmission too much load, and will reduce the transmission efficiency. For the details of the calculation formula of Q_1,Q_2 , please refer to document [11].

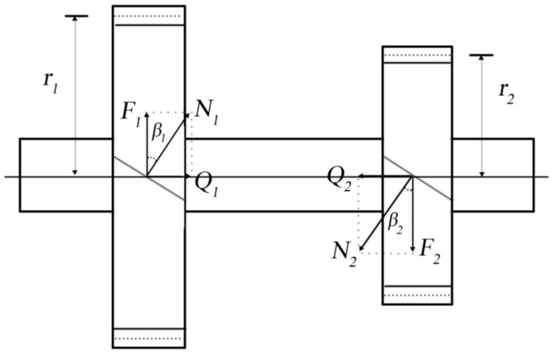

Figure 1. Balance Diagram of the Output Shaft Axial Force

Simplify equation 18 to get:

$$\left\| m_{n2} z_2 1g\beta_1 - m_{n1} z_1 1g\beta_2 \right\| \le \delta' \quad (20)$$

δ' should be selected based on the empirical data of the design, which in this paper is selected according to reference document as $\delta' = 30$ 。

Whereby for the first gear transmission, the axial force balance constraints condition for the gear 2 and gear 11 is as follows:

$$g_{13}(X) = \sin\beta_1 m_{n0} z_{11} - \sin\beta_0 m_{n1} z_2 - 30 \le 0 \quad (21)$$

$$g_{14}(X) - \sin\beta_0 m_{n1} z_2 - \sin\beta_1 m_{n0} z_{11} - 30 \le 0 \quad (22)$$

3. The application of hybrid genetic algorithm in the reliability optimization design of transmission

With the development of optimization design theory, there have been a variety of optimization design methods so far to solve the constrained optimization problems. In particular, the recent emerging genetic algorithm and artificial neural network is widely applied. Therefore, this paper adopts the hybrid genetic algorithm, which includes the advantages of both the genetic algorithm and the traditional optimization design method, so as to achieve faster convergence, thus with wider range of applications.

Genetic algorithm is widely used in many fields due to its simplicity in operation and its effectiveness to solve problems. And it has been proven in theory that the genetic algorithm can seek and obtain the optimal solution for the problems from the meaning of probability in a random manner. But on the other hand, the application practice shows that there may still be some undesirable issues in the application of the genetic algorithm, among which the main problem is that it is easy to produce premature phenomenon, poor capabilities of local optimization search and so on. And generally speaking, for many issues, the basic genetic algorithm is often not the most effective way to solve the problem, and it has less efficiency in solving the problem than the knowledge-based heuristic algorithm specifically for the problem, although this knowledge-based algorithm do not necessarily guarantee that the optimal solution will be found. Furthermore, the genetic algorithms cannot avoid the multiple searches for the same feasible solution, which is also a factor that affects the operating efficiency of the genetic algorithm. On the other hand, the gradient method, hill climbing method, simulated annealing method, list optimization method and some other optimization algorithms have strong local search ability, and other heuristic algorithms that contain the issues and the related knowledge also have relatively high operating efficiency. It can be expected that the integration of the concept of these optimization methods in the genetic algorithm search process, and the constitution of a hybrid genetic algorithm is an effective means to improve the operational efficiency of genetic algorithm and the solution quality.

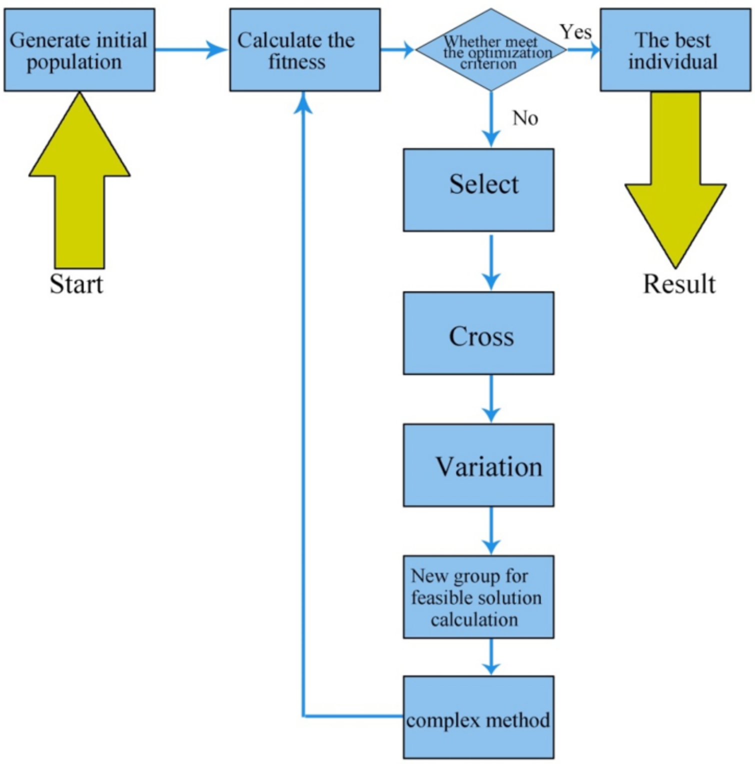

Figure 2. Flowchart of Hybrid Genetic Algorithm

The application research shows that, at present some conventional genetic algorithms are not the best methods to solve a particular problem. While the hybrid genetic algorithm constituted by the problem-specific knowledge integrated through the genetic algorithms may possibly have the method with perfect solving performance, which also continues to provide a new way of thinking to improve the search performance of genetic algorithm. Figure 2 shows the constitution framework for the basic hybrid genetic algorithm [10].

Figure 2, this hybrid genetic algorithm is an ideology with the fusion of local search algorithm in the standard genetic algorithm, which is mainly characterized by: The introduction of the local search process. Based on the corresponding phenotype of each individual in the population, local search is performed, so as to find the corresponding local optima for each individual in the current environment, so as to achieve the purpose of improving the overall performance of the group. The basic principles for the constitution of hybrid genetic algorithm: In formation of the hybrid genetic algorithm, there are three basic principles: (1) Maximize the application of the original algorithm coding. This will facilitate the application of the relevant knowledge of the original algorithm, and also easy to implement the genetic algorithm. (2) Make use of the advantages of the original algorithm. This can ensure the quality of the solution obtained by the hybrid genetic algorithm will not the lower than the quality of the solution obtained by the original algorithm. (3) Improve the genetic operator. Design genetic operators that can adapt to the new genetic coding scheme.

4. Calculation case study

In this paper, for the example of certain car transmission, the original entire vehicle parameters are: $m=1845Kg$, tire radius $r=0.361m$, and the main reducer ratio $i_0=3.89$, gear material $20C, M, T_i$, engine adopts 492Q engine external characteristic curve, $T_{i\max 2200}=180N.m(2200r/\min)$,five-speed transmission, with the highest gear ratio of 0.68, $P_{\min}=68\lambda u\left(3800\,r/\min\right)$ .The original parameters of the transmission are shown in Table 1:

Table 1. Transmission Gear Chain Original Parameters

Optimization Variable	z_1	i_1	i_2	i_3	i_4
Raw Data	24	3.47	1.95	1.22	0.83
Optimization Variable	i_5	m_{r1}	m_{r2}	m_{r3}	m_{r4}
Raw Data	0.67	2.25	2.5	2.5	2.25
Optimization Variable	m_{r5}	β_1	β_2	β_3	β_4
Raw Data	2.25	21.37	24.43	22.30	23.55
Optimization Variable	β_5	b_1	b_2	b_3	b_4
Raw Data	21.47	24.22	19.15	21.32	19.28
Optimization Variable	b_5				
Raw Data	21.24				

For the ease of calculation, polynomial is adopted to describe the external characteristics of the torque curve of the engine. 492Q engine, the torque characteristics as measured by the test is shown in Table 2:

Table 2. Torque - Speed Relation Table

Engine Speed $(n/\min)$	1000	1500	2000	2500	3000	3500	4000
Engine Torque $T_\eta\left(N\cdot m\right)$	135.33	147.10	152.98	156.91	147.10	138.27	125.53

As can be represented in the fifth polynomial as the following:

$$T\left(N\cdot m\right)=160.39-0.110913n+1.36485\times10^{4}n^{2}$$
$$-6.191286\times10^{-8}n^{3}+1.20898\times10^{-11}n^{4}-8.85607\times10^{-16}n^{5}$$

As the usage of each of the five-speed transmission gears is generally 0.5%, 3.5%, 7%, 59%, 30%, therefore, in the combined optimization, the utilization rate of each gear takes the above values respectively. And the optimization results are shown in Table 3.

Table 3. Combined Optimization Results

Optimization Variable	z_1	i_1	i_2	i_3	i_4	i_5
Raw Data	24	3.47	1.95	1.22	0.83	0.68
Combined Optimization Data	21.9727	3.0706	1.6993	1.0210	0.8331	0.6817
Optimization Variable	m_{n1}	m_{n2}	m_{n3}	m_{n4}	m_{n5}	β_1
Raw Data	2.25	2.5	2.5	2.25	2.25	21.37
Combined Optimization Data	2.3045	2.2571	2.2712	2.2537	2.2567	20.0185
Optimization Variable	β_2	β_3	β_4	β_5	b_1	b_2
Raw Data	24.43	22.30	23.55	21.47	24.22	19.15
Combined Optimization Data	24.0980	23.1287	23.7266	22.3132	27.6419	17.3954
Optimization Variable	b_3	b_4	b_5			
Raw Data	21.32	19.28	21.24			
Combined Optimization Data	18.1872	17.6169	18.7022			

After rounding off, the comparison of raw data and the combined optimization data is shown as table 4.

Table 4. Combined Optimization Data after Rounding Off

Optimization Variable	z_1	i_1	i_2	i_3	i_4	i_5
Raw Data	24	3.47	1.95	1.22	0.83	0.68
Combined Optimization Data	22	3.07	1.70	1.02	0.83	0.68
Optimization Variable	m_{n1}	m_{n2}	m_{n3}	m_{n4}	m_{n5}	β_1
Raw Data	2.25	2.5	2.5	2.25	2.25	21.37
Combined Optimization Data	2.25	2.25	2.25	2.25	2.25	20.02
Optimization Variable	β_2	β_3	β_4	β_5	b_1	b_2
Raw Data	24.43	22.30	23.55	21.47	24.22	19.15
Combined Optimization Data	24.10	23.13	23.73	22.31	27.64	17.40
Optimization Variable	b_3	b_4	b_5			
Raw Data	21.32	19.28	21.24			
Combined Optimization Data	18.19	17.62	18.70			

The Optimization Design Result Analysis:

After combined optimization, the volume of the transmission is changed into $1.9247\times10^{6}mm^{3}$, and the original volume of the transmission is $2.9962\times10^{6}mm^{3}$, the volume becomes smaller. The drive power limiting rate is 0.67889, before the optimization the drive power limiting rate was 0.6498, and the drive power limiting rate increased by 2.09%. As can be drawn from the above analysis, the established mathematical model is correct, and the hybrid genetic algorithm is also very effective for the optimization calculation on the established mathematical model for transmission.

The comparison of the drive power ratio before and after the optimization of the speed ratio - the speed curve is shown in Figure 3, as can be seen from the figure that, when the high gear utilization gets more and more, the speed ratio of gear interval between high gears gets smaller and smaller, which reflects the impact of the actual condition of automobile gear usage to the speed ratio distribution.

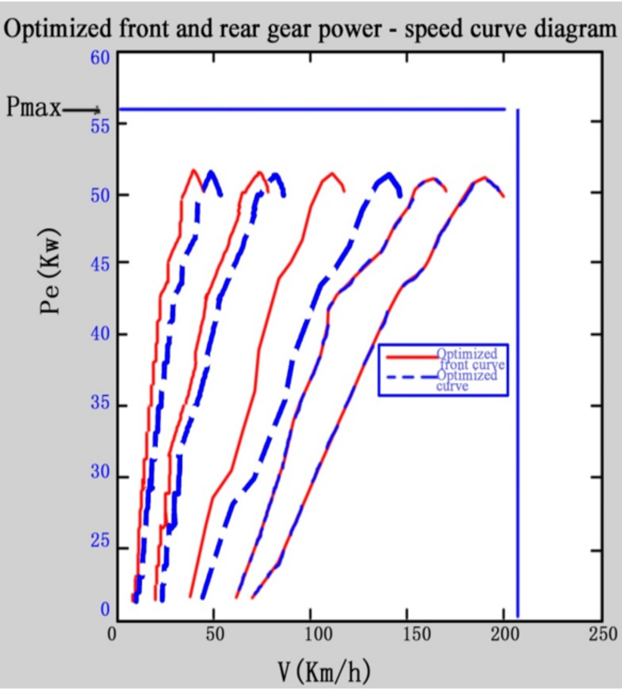

Figure 3. Five-speed Transmission Drive Power before and after Optimization – Speed Curve

5. Conclusion

Automobile transmission is one of the critical components in the automobile driving motion system, whether its design is good or not has a direct impact on the actual performance of the automobile. According to automobile power requirements, economic requirements and gear reliability requirements, by analyzing the advantages and disadvantages of traditional distribution of speed ratio in geometric progression, this paper proposes to take the minimization of the transmission volume and the maximization of the actual utilization of the engine as the objective function to perform multi-objective reliability optimization design, and builds the reliability optimization design model.

The hybrid genetic algorithm is applied to the optimization calculation of the mathematical model, to achieve the relatively ideal optimization result. The establishment of the mathematical model herein refers to some of the previous research results, but its complexity is much greater than what the predecessors have done, and there are also more complicated design variables and constraints conditions; the application of hybrid genetic algorithm mathematical model to achieve the reliability optimization design for the transmission is more creative, and closer to practical application. Therefore, it can be said that it has made a step forward in the design of automotive mechanical transmission gear system.

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Fault Diagnosis of Rural Power Network Based on GIS Platform and Rough Set

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Abstract
By analyzing the rural power network topology of GIS platform, to obtain a simplify structure of relay protection and circuit-breaker as key equipment, and then use rough set fault diagnosis algorithm designed rural power network fault diagnosis module based on GIS platform, for quickly determine the fault point position of rural power network, given troubleshooting solutions. The problem of spatial search speed bottleneck in GIS platform is solved by using the rough set fault diagnosis algorithm. The practical engineering application shows that the search speed and accuracy are improved. Combined with the existing 4G communication mode, the circuit-breaker states are quickly detected. Finally, the system automatically generates the operation order of the power network, which can guide the staff to quickly eliminate the fault, shorten the power outage time and improve the reliability of power supply.
Key words: ROUGH SET, RURAL POWER NETWORK, FAULT DIAGNOSIS

1. Introduction

At present, the main power network fault location is based on the scheduling model which is lack of the necessary simulation, and does not provide the line load transfer scheme, and the control of the line is based on the natural on/off power. As the circuit-breaker control state and line relationship is not quantified, the problem of solving problems is lack of relevant mathematical model, so that the efficiency of fault diagnosis algorithm is not high, and there is no information about the structure of the overhead line, and the structure of the power network is lack of vi-