Status maintenance strategy based on overall optimization and its practice

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Abstract: *This paper presents the exploration carried out in regard of the strategy of equipment maintenance and the experience obtained in recent years by Dalian Power Supply Co., China (DPSC). The critical factor of transfer from the strategy of periodic maintenance to that of maintenance based on the condition of equipment is to have the condition information of each unit of equipment in the power network, including the test data at delivery, data of all previous preventive tests (or on-line monitoring), as well as related information indicating operating conditions, etc. DPSC has realized storage of the above data and carried out consistently depiction and evaluation of the dynamic process of changes in the condition of individual units of equipment by means of synthetic management information system (MIS) in networked computers. Practice has demonstrated that follow-up management and trend analysis of equipment condition may obtain early information of deterioration of equipment, provide basis for executing appropriate maintenance in due time, and avoid the occurrence of a number of faults,*

However, some major faults, such as burning out of power transformer windings under the impact of system short-circuit current, seem to be unrelated to the maintenance strategy of equipment themselves, yet are closely related to the operating environment of the power network in which the equipment are located. Therefore, only by regarding the power network as a unity, carrying out rational adjustment to the configuration of its various relevant components to bring about their coordinated operation, and concentrating efforts to eliminate radically various sources of the network faults, i.e. working out a maintenance strategy based on overall optimization, can the occurrence of hard to predict yet highly significant abrupt faults, such as burning out of transformer windings and so on, be effectively minimized.

The maintenance management of relay protection and transmission and distribution lines is an inseparable important part of the whole maintenance management work of a power network. This paper recommends the operating practice of the external insulation of part of overhead lines under natural dirt deposition condition (i.e. without any manual cleaning) in the recent 7 years and the statistics of operation of relay protection in recent 17 years, as well as the condition maintenance strategy established on the basis of the above operating practice of DPSC.

Finally, an example of the real-time information integration of a multi-level power network is given. This is an endeavor to ensure the consistency and interrelation of power network information and further to obtain a comprehensive solution for all problems including maintenance decisions.

Key words*: power network, substation, equipment, monitoring, diagnosis, maintenance, strategy*

1. CARRYING OUT REMOTE MONITORING AND NETWORKED MANAGEMENT OF THE CONDITION OF EQUIPMENT

Power network is an exceedingly large and complicated system, its various components being closely related to each other with strong mutual influence. The damage of any equipment in the power network can result in a fault of the system. Consequently, consistent monitoring of the condition of each component, implementing storage, transmission and processing of the information of status of equipment by means of the large relative database of MIS and the powerful function of computer network, and providing further basis for the strategic decision of maintenance, are the fundament of condition maintenance. Now the MIS of DPSC has been connected up with the supervisory control and data acquisition system (SCADA), so that the communication link between the equipment maintenance control center in MIS network and all substations which can be reached by SCADA has been established, thus laying the foundation for remote monitoring and networked follow-up management of the condition of equipment.

The main contents of remote monitoring and networked follow-up management of the condition of equipment are as follows:

- Equipment static data management. The related equipment managing departments assign an equipment code to each unit of equipment in accordance with the unified equipment encoding principle as specified by DPSC. Then the various static data of the equipment (including nameplate data) are input into the large relative database of MIS through a remote network from the spot. The equipment mentioned here are mainly the primary and secondary equipment of substations and transmission and distribution lines (including power cables).
- Test data management. The test data comprise test data at delivery, all previous periodic test data, test data of the equipment before and after overhaul, and various provisional test data (for example, data obtained in measuring, the physical deformation of transformer windings after subjected to the impact of large short-circuit current).

After implementing networked management of test data, not only means of inquiring the condition of equipment is provided for the managing personnel of maintenance, but the required whole historical data are also provided for testing personnel on site. All they have to do is to input the test data obtained into the database of MIS, with software support the screen of the field computer will show a curve which is composed of all previous test data and the current test data and reflects the trend of change of equipment condition. In normal case, complicated equipment, such as power transformer, has a lot of test items. So a family of curves reflecting the trend of changes will be shown. Consequently the testing personnel can make synthetic judgement on the condition of equipment according to the "trend of change" with reference to the current test data, such synthetic judgement, as compared with the previous simple judgment method depending on "whether the current test value is beyond its limited value", can more accurately disclose the nature of problem. For the judgement of the condition of equipment, the "trend" is more decisive significance than the "limited value".

- Management of the on-line monitoring data of the condition of equipment. At present the application of on-line monitoring in DPSC is limited to individual critical item of major equipment. For example, the early-stage trouble monitoring device for power transformers, being more welcome, has been put into service on part of power transformers of 220 kV and above. More transformers will be equipped with such monitoring device in future. The on-line monitoring data are input into the large relative database via a SCADA-MIS interface to realize remote monitoring of equipment condition and provide the basis for maintenance decision.
- Management of fault information. When a fault occurs on the power line, the fault oscillograph mounted on busbar will record the interrupted current and the values of joule integral and $I^2 t$, meanwhile the distance of fault spot is determined by means of other supplementary measuring device. The fault oscillographs mounted in the upperstream portion of the power network and the adjacent substations will also come into action.

The above fault information, with the support of MIS software, will be input completely into the database. These fault information help us to understand more clearly the fault process and its influences on the system, directing appropriate maintenance management work. When short circuit current I exceeds a predetermined value, an program-controlled exchanger in accordance with a preset program will automatically give out an alarm signal to relevant testing personnel for measuring the physical deformation of transformer windings. And when the $I^2 t$ approaches a predetermined value, the above exchanger will automatically give the relevant maintenance personnel the instruction to overhaul circuit breakers. At present this project is being put into practice.

- Management of overhaul information. The overhaul plan, equipment defects and their locations discovered in overhaul as well as the seriousness of defects are input into the database with corresponding codes, so that the necessity of each overhaul may be assessed. The future maintenance strategy will be continuously adjusted and improved on the basis of numerous statistical analyses.

2. OPTIMIZING THE SAFE OPERATION CIRCUMSTANCES OF POWER TRANSFORMERS

The main objects of maintenance work in power supply companies are concentrated in substations, while power transformers are the "heart" of a substation. Therefore, keeping well condition monitoring of transformers and drawing out a rational maintenance strategy are the most important content of the work of maintenance management. Up to now, carrying out electrical and chemical tests on power transformers in service are the condition-monitoring method commonly adopted in all nations. Recently, the gas chromatographic analysis of insulating oil is universally recognized as the most effective means to discover early-stage potential fault of transformer. However, in the course of further analysis of the acquired data, the difficulties may sometimes be encountered for the diagnoses. An example is presented as follows:

DPSC has purchased from a European company three units of single-phase, 500kV power transformer, the capacity of each unit being 250 MVA. They are put into service in October 1996. At that time the content of total dissolved hydrocarbon (TDH) in all three units did not exceed 13 ppm. After an operating period of one year and more, measurement was carried out on January 7th, 1998, discovering that the TDH content in the oil of B-phase transformer arose abruptly to 48 ppm. Then the TDH content in the oil of that transformer was increasing rapidly and reached to 291 ppm on March 12th in that year, yet since then the TDH content tended to become steady up to now, indicating that the factor causing abrupt increase of TDH content has probably disappeared of itself. Table 1 lists the part of the data obtained from the chromatographic analyses of the oil in B-phase transformer. Fig. 1 shows the comparison of the TDH content variations of oil in transformers of A, B and C phase.

Table 1 Result of chromatographic analyses of the oil in B-phase transformer
Unit: ppm

Data of measurement mm/dd/yy	H_2	CO	CO_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CH
10/07/96	0	133	349	2 4	3 7	6 4	0	13
12/10/97	0	25	247	4	8	3 1	0	15
01/07/98	3 9	14 7	194	13 3	10 3	24 3	0	47
02/06/98	9 2	28 5	238	51 5	29 5	79 4	0	160
02/16/98	35	64	444	69 9	43	100	0	213
02/26/98	38	34 9	294	83	47 8	112	0	243
03/12/98	42 9	40 3	303	97	60	134	0	291
10/07/98	16 6	23	616	86 9	57	158	0	303

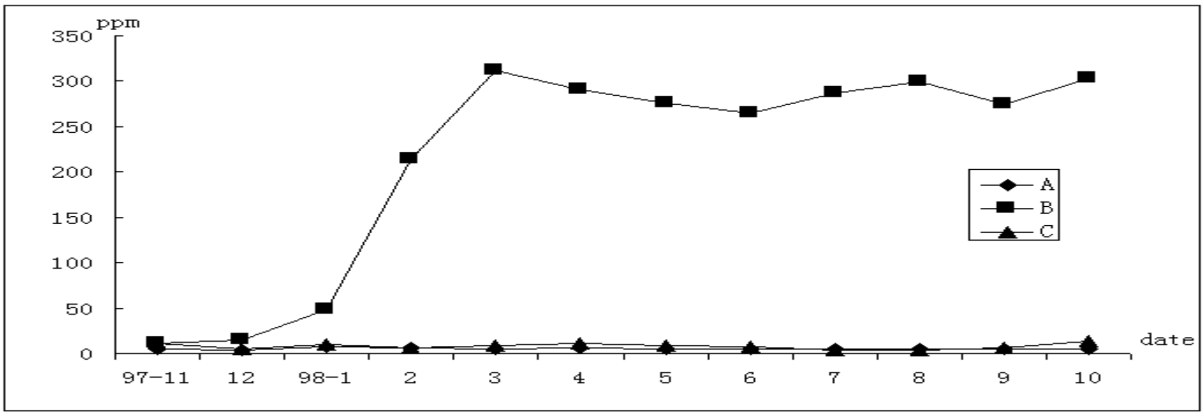


Fig.1 variation of TDH content of oil in the 3-phase 500kV transformer tank

After arising of the above-mentioned abnormal phenomenon, the manufacturer had sent engineers to the site several times to carry out special analysis, yet they could not determine the real cause of the phenomenon at all. This fact shows that although we have the diagnostic means of chromatographic analsis in hand, we are still short of the criteria for deciding the real condition of equipment from the data obtained in measurements, so that frequently no realiable statement about condition deterioration can be drawn. In fact, the condition of many electric equiment is more or less indistinct, this is just the difficulty in condition diagnosis and maintenance decision.

In March, 1998, we installed model HYDRON201R on-line early-stage trouble diagnostic device produced by a Candian company on the above-mentioned three units of transformer respectively to enhance the follow-up monitoring of the condition of the B-phase transformer.

It should pointed out that the burning out of power transformers is often aroused by the impact of an abrupt short-circuit in the power network, moreover, most of the burning out take place after many times of short-circuit current impact. This is to say breaking of dynamic stability of windings proceeds accumulatively. It can thus be seen that diminishing the occurrence of short-circuit faults in power network, especially, diminishing the occurrence of short circuit faults at outlet, is an effective way to decrease the burning-out faults of transformers. In a more profound sense this is an active maintenance strategy.

(1) Diminishing short –circuit faults on feeder busbar

- Increasing the reliability of all electric equipment connected to the busbar;
- Eliminating accidental mis-operation which can result in busbar short circuit;
- Preventing destructive action of external force (including animals) on the busbar.

(2) **Diminishing short-circuit faults in the vicinity of feeder outlet**

Increasing the reliability of the outlet section (several hundred meters) of all feeders. Here the reliability comprises insulating strength, lightning protective facilities, ability of preventing flashover caused by dirt deposition, ability of defending destruction due to various external forces, etc. The reliability of outlet sections shall be distinctly higher than that of remaining portion of the feeder. For example, it is recommended to change the bare conductors within the outlet section of several hundred meters into insulated conductors. The effectiveness of such measure has been proven in the practice of many years.

(3) **Avoiding repeated short-circuit current impacts due to faults occurred in the section of feeder close to substation**

When the detected power-line short-circuit exceeds a preset value, the power line reclosing device is locked automatically, so as to prevent the power transformer from being subjected to possible repeated impacts of short-circuit current (permanent fault).

(4) Carrying out monitoring work on transformers having subjected to serious short-circuit impact

After a transformer have been subjected to the impact of a short-circuit current exceeding a certain preset value, its windings shall be tested for their deformation by means of frequency-response analysis. The test result shall be compared with historical data for deciding whether the transformer should undergo overhaul.

(5) Adjusting part of transformers in the power network according to the principle of overall optimization

When the power transformer of a key substation presents the tendency of aging or deterioration (yet has not lost its efficacy entirely), it is suitable to install it to a substation demanding not very high reliability. Such change can make full use of the surplus value of the deteriorated transformer (yet having not lost efficacy entirely), as well as improve the safe operation condition of the key substation to achieve effective overall optimization. In the operational management of a power network such rational adjustment according to the idea of overall optimization is indispensable.

3. EXPLORING THE PATTERN OF NATURAL DIRT DEPOSITION AND READJUST THE

STRATEGY OF OVERHEAD LINE CLEANING

Periodic cleaning the outer surfaces of line insulators is one of the important items of power maintenance work. The customary practice of cleaning power lines once or twice (once in spring and autumn respectively) a year has been carried on for decades of years. The problem is, however, whether such cleaning is necessary? To draw a conclusion we have selected seven 66kV lines with a total length of 100 km to execute an experiment of natural dirt deposition (i.e. without manual cleaning) for seven years. In the course of experiment, periodic measurements on the density of salt adhered to line insulators were carried out once a season. The result of the seven-year experiment is rather contrary to our expectation.

- Only one of the seven lines has been interrupted electricity once in 1994 owing to flashover caused by dirt deposition, while no trip of circuit breaker has occurred on other power lines.
- Result of salt density tests indicates that the dirt-depositing speed is comparatively high is dry season, yet almost drops to zero at the end of rainy season. This fact shows that the cleaning effect of rainfall on salt deposit is quite high. We had carried out a measurement of salt density on insulators before and after a rainfall and found that the salt density after rainfall was only 20% of that before rainfall.
- After ending of rainy season, the salt density drops almost to zero, this indicates that the density of salt adhered to the outer surface of insulators has no accumulative effect year by year. This is exactly the reason why no flashover in large area caused by dirt deposition occurs under the prerequisite of no cleaning of insulators carried out consistently in 7 years.

The result of the experiment mentioned above gives a challenge to the necessity and frequency of insulator cleaning. At present, the experiment is being carried on. Hence, on the basis if this experiment, we have adjusted the strategy of power line cleaning work by regarding it as a whole.

- Depending upon the automatic cleaning effect of rainfall, most power lines satisfying the requirement for specific leakage distance may operate without manual cleaning for a long time interval.
- For power lines which cannot meet the requirement for specific leakage distance their creepage length on insulators is to be increased.
- For power lines located in extraordinary dirt area, necessary manual-cleaning measure such as water rinsing should be taken.

The result of the above-mentioned experiment depicts the dirt deposition peculiarity of a region, it is not certain to be applied to other regions.

4. OPTIMIZING THE MAINTENANCE STRATEGY OF PROTECTION DEVICES THROUGH STATISTICAL ANALYSIS

There are a number of assessing methods to judge the condition of protection devices, among them the statistical analysis of the condition of operation is certainly one of the fundamental assessing methods. Table 2 is the statistics for the operating conditions of protection and automatic devices in our region in recent 17 years (1982-1998). It may be seen from table 2 that the ratio of incorrect operations of 220kV, 66kV, and 10kV systems is 6.20:0.58:0.02=310:29:1. This is to say that the higher the voltage, the larger the ratio of incorrect operation is, i.e. the worse the condition of operation is. This fact conforms with the principle of reliability, because when the voltage becomes higher, the configuration of protection devices is frequently more complicate, so that the reliability gets lower. Hence we are confronted with the following problem: how can the reliability of a protection device be enhanced by simplifying its internal connections.

Table 2 Statistical list of the conditions of operations of relay protection and automatic devices in Dalian region (1982-1998)

Sort of sys. / Times of paper Assessment	Entire system			10KV system			66KV system			220KV & higher system		
Assessment	1982~1991	1992~1998	1982~1998	1982~19991	1992~1998	1982~1998	1982~1991	1992~1998	1982~1991	1982~1998	1992~1998	1982~1998
Total times of operation	11983	14166	26149	13754	10714	24468	1096	626	1722	173	166	339
Times of correct oper.	11963	14150	26113	13752	10711	24463	1088	624	1712	164	154	318
Times of incorrect oper.	20	16	36	2	3	5	8	2	10	9	12	21
Rate of correct operation(%)	99 83	99 88	99 86	99 96	99 97	99 98	99 27	99 68	99 42	94 80	92 77	93 80
Rate of incorrect operation(%)	0 17	0 13	0 14	0 04	0 03	0 02	0 73	0 32	0 58	5 20	7 23	6 20

In the course of further analyzing the cause of incorrect operation of protection devices, we also discovered that although there are many such causes, yet not an incorrect operation is due to unfavorable change of setting value. This fact gives a challenge to the traditional practice of checking frequently the setting of protection devices.

On the basis of statistical data listed above, we have carried out optimization of the maintenance strategy of relay protection.

- Transferring the major work of maintenance on the protection devices of 220kV and above;
- Decreasing the frequency of setting checks and put the key point of periodic checks on the examination of protective function.

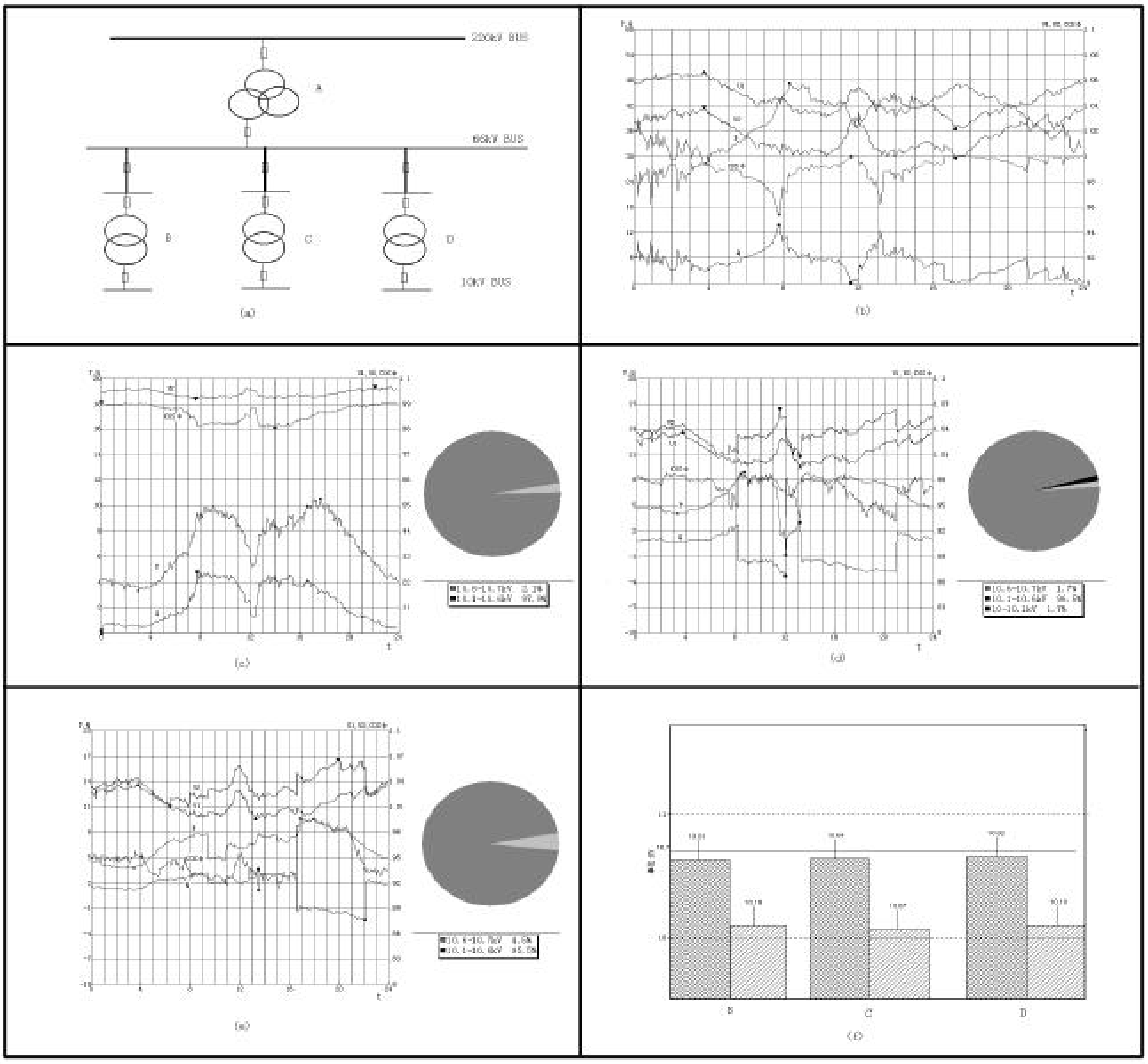
The matter worthy to note is that at present the relay protection technique is confronted with confusion, yet full of hope. The confusion lies in that both numerous traditional analog type protection devices and new digital type protection devices are adopted in the same substation, bringing about a lot of new problems to operation and maintenance. The hope lies in that the employment of digital type protection devices with self-checking feature is increasing rapidly. The latter is really a sort of device requiring no periodic check and only a little maintenance. Employment of this sort of protection device can greatly diminish redundancy yet raise the reliability to a higher level. Moreover, the protection device is integrating protection, control, monitoring and signaling functions into a single unit, so that the secondary system will be miniaturized and cheaper.

5. TOTAL INTEGRATION OF THE INFORMATION OF A MULTI-LEVEL POWER NETWORK

The condition maintenance management is based upon single unit of equipment, while the effect of maintenance affects directly the power network. Similarly, the operating condition of a power network will frequently affect the maintenance decision. Hence understanding the operating condition of the power network and carrying out optimization are the important components of the condition maintenance strategy. Fig.2 is an example of the real-time information integration of a two-level network. This is a network consisting of a 220/66kV substation and three 66/10kV substations.

The information integration of the above network consists of two parts:

- Integration of real-time information within a substation. This is the integration of the real-time information, which includes the active power P, the reactive power Q, the primary voltage 1, the secondary voltage 2 (these four kinds of information are acquired from the database of SCADA) and the real-time cos∅ generated automatically from and , thereby establishing the interrelation among various real-time information within the substation.
- Integration of the information of the two-level power network. The real-time information of all substations in the two-level power network is integrated so as to establish the interrelation of all real-time information between the upper-level and lower-level power network and adjacent substations. The interrelation between various kinds of information is itself an important source of information. Establishment of such interrelation will provide us with comprehensive necessary information for thoroughly understanding the dynamic process of complicated power network. It will contribute to the complete solution of various technical and management problems in operation and maintenance aspects involved in power networks.



(a) Connection diagram of a certain 220kV substation system, where A---220kV/66kV substation, B,C,D---66kV/10kV substations

(b) Real-time information integration diagram of the 220/66kV substation, where U_1 --- 220kV busbar voltage, U_2 --- 66kV busbar voltage, P--- active power MW Q --- reactive power (MVA cosö--- power factor

(c) ,(d),(e) are the real-time information integration diagrams of 66kV/10kV substations B,C,D respectively and the analytical circular diagrams of their 10kV busbar, where U_1 --- 66kV busbar voltage, U_2 --- 10kV busbar voltage, P--- active power, Q--- reactive power, cosö--- power factor

(f) is the column diagram of the max. and min. Values of 10kV busbar voltage of substations B, C and D respectively

CONCLUSION

1. The intrinsic characteristic of condition maintenance is that it is directed against each unit of equipment, including relatively independent modules in complicated equipment. The crux of implementing condition maintenance lies in having the condition of every unit of equipment under control, as well as carrying out consistent follow-up management for the trend of changing of its condition.
2. The networked computer-controlled information system is one of the indispensable prerequisites for carrying out remote compositive management of the conditions of various sorts of equipment spreading over the entire region. Here the remote management includes the multi-item management function of acquiring, transmitting, and processing (including trend analyzing) of the condition information.
3. The field-working testing personnel make use of all previous test data of equipment as provided by the MIS network, combine them with the current test result, and accomplish with support of software the trend analysis and combined assessment of the condition of equipment. Such practice embodies fully the common tendency of judging equipment condition; i.e. the "trend" is more significant than the "limit value".
4. A power network is an organic whole compose of a lot of equipment. Equipment usually has a definite independence, yet the development of power network seems to trend towards strong interdependency. The maintenance management will not confined to every individual unit of equipment any more (attention is paid to the consistency of the condition of individual unit of equipment, i.e. the trend of changing of its condition), yet the optimization of multi-level power network is also to be considered (attention is paid to the interrelation between units of various equipment, i.e. the treatment of unification and overall optimization of the system). The real-time information integration of multi-level power networks will bring the optimization of power networks under operation into reality.

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