Failure causes and solutions of relay protection switching power supply

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Abstract—Relay protection device plays a key role in the stable operation of power grid, and the failure of switching power supply is the main reason for the unstable operation of relay protection device. This paper studies the failure causes of relay protection switching power supply, and concludes that electrolytic capacitor is the key component leading to the failure of power plug-in. At the same time, the failure mechanism and life influencing factors of aluminum electrolytic capacitor are deeply studied, and the improvement measures are put forward. According to the research results of this paper, the switching power supply has the characteristics of high reliability and long life.

1. Introduction

Relay protection is the first line of defense to ensure the safe operation of power grid [1]. With the construction of HVDC and flexible AC transmission projects and the development and utilization of large-scale new energy, power electronic devices are widely used in power generation, transmission, distribution and use, and the power system presents the trend of power electronization. On the one hand, the problems caused by transient processes such as transformer airdrop are more complex, and the high-order harmonic components in the transient current have a destructive effect on power electronic devices [2-3]. On the other hand, the power electronic devices in the power system make the operation environment of relay protection more complex, and the protection faces many new problems. Many scholars have carried out targeted research. As a complete protection device, the premise of normal operation of relay protection is that the secondary DC power supply of substation can supply power reliably [4-5]. The relay protection device generally has a special switching power supply module, which can change the 110 kV public DC power supply into 3.3 ~ 24 V low-voltage DC for each component of the Board [6]. Compared with the traditional linear regulated power supply, the switching power supply module has the advantages of small volume, high efficiency, low cost and high degree of automation. It is widely used in the field of industrial control. Once the switching power supply of the relay protection device disappears and the system fails again, the protection device cannot work normally and can only rely on another relay protection device to remove the fault, which greatly reduces the reliability and safety requirements of the protection device configuration [7-10]. There is little research on the failure causes of relay protection devices in power electronic power system, especially the failure causes of switching power supply and the corresponding solutions. In this paper, the failure causes of relay...
protection switching power supply are analyzed in detail, and the corresponding solutions are put forward.

2. Operation characteristics of switching power supply

2.1. Relay protection reliability principle
For relay protection, its reliability refers to the requirements of protecting the components of the system and enabling the components to complete the power operation without fault in a certain environment and time. The fault protection of relay protection is mainly divided into two kinds of faults, one is repairable and the other is non repairable. The following three types of indicators are usually used to measure the reliability of components [11]:

(1) reliability. This index is also considered as the probability that the system and its components complete the specified power within the specified time, and this reliability index is usually considered as one of the main indexes to measure its reliability.

(2) availability. This index only measures whether the system can complete the specified functions within the specified time. In other words, it is the ability of the system to repair itself quickly, so that the system has high reliability.

(3) the average failure time. This indicator usually indicates the average time for the system to maintain stable operation within the specified time until the next fault occurs. Through this index, it can usually reflect the average time for a system to maintain reliability, and then provide reference for system maintenance.

The service life of relay protection devices directly affects the operation stability and security of power system. As the most common bad manufacturing phenomenon of relay protection devices, switching power supply damage can not only prolong the service life of switching power supply, but also improve the operation stability and safety of power system if the switching power supply is improved in the three indexes of reliability, availability and average failure time.

2.2. On site use of switching power supply
On site use of switching power supply since 2017, 267 switching power supply failures have occurred in a power grid, and 267 plug-ins have been replaced, with an average of about 80 power plug-ins replaced every year, showing an increasing trend year by year.

In order to further study the relationship between power plug-in failure and operation life, the operation life of the replaced failed power plug-in is counted, as shown in Table 1.

| Table 1 list of service life of failed power plug-Ins (years) |
|-------------------------------------------------------------|
| failures | 1 ~ 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| failures | 15 | 6 | 5 | 6 | 7 | 15 | 17 | 23 | 28 | 31 |

According to the statistical data of the service life of the failed power supply plug-in in Table 1, the failure rate of the switching power supply roughly conforms to the bathtub curve in the time dimension. The ordinate is the failure rate and the abscissa is the time. In the "early failure period" stage, the failure rate of switching power supply is high, but the failure rate decreases rapidly with the increase of service time; The failure rate at this stage is mainly caused by design errors, imperfect process and unqualified quality. "Accidental failure period" is the best working state of switching power supply, and the failure efficiency is relatively stable. The failure at this stage is often caused by accidental causes. "Loss failure period" refers to the late stage of product use. At this stage, the components degenerate, the life area fails, and the failure rate rises rapidly and increases gradually; The failure at this stage is mainly caused by product performance degradation or strength degradation.

According to incomplete statistics and relevant research, the causes of switching power supply failure include electrolytic capacitor failure, triode failure, diode failure, switching power supply aging and poor manufacturing process, among which electrolytic capacitor is the main cause of component failure.
In order to find the solutions to the failure of key components, it is necessary to analyze and study the working principle of switching power supply.

2.3. Working principle of switching power supply
Switching power supply is the basis for the stable operation of relay protection device. It mainly includes filter, transformer, control unit and semiconductor switch, output rectifier circuit, output voltage stabilizing circuit, feedback loop and voltage monitoring loop, as shown in Figure 1. The switching power supply converts DC220 V (DC110 V) voltage into 5V, ±15V (±12V) and 24V DC voltage to provide working power for other plug-ins of the protection device. Among them, 5V is used to supply power to CPU, memory chip, FPGA, ADC, communication and other chips, 15V is used to supply power to the device A/D sampling circuit, and 24V is the relay working voltage and 24V input voltage.

According to the statistical data and the research of domestic scholars, the failure of switching power supply is mainly caused by the failure of components such as electrolytic capacitor, three-stage transistor and diode, in which the failure rate of electrolytic capacitor accounts for 60% of the total number of failed devices. In addition, under the working environment of 25 ℃ at room temperature, compared with key devices such as triode, diode, inductive element and chip, electrolytic capacitor has the fastest aging speed and the shortest service life. Therefore, electrolytic capacitor is the key element restricting the service life of switching power supply. The research on the causes of electrolytic capacitor failure is helpful to understand the key causes of switching power supply failure and find reasonable countermeasures to deal with switching power supply failure.

3. Aging mechanism of electrolytic capacitor
Electrolytic capacitors are mainly used for smoothing, energy storage or filtering after AC voltage rectification, as well as non precision timing delay. The parameters of aluminum electrolytic capacitor are greatly affected by working environment factors, which are mainly restricted by working temperature.

3.1. Temperature characteristics of capacitance
(1) Temperature characteristic of capacitance
The capacitance here refers to the value of ideal capacitance C, which is an important part of aluminum electrolytic capacitor filtering and energy storage. The capacitance is greatly affected by temperature. With the increase of temperature, the capacitance gradually increases, and its temperature characteristics are shown in Fig. 2. The figure shows the variation curve of the ratio of the actual capacitance C (measured when the ambient temperature is T) to the rated capacitance C0 (measured when the ambient temperature is 20 ℃) of electrolytic capacitors with different rated voltages with the increase of temperature.
(2) Temperature characteristics of equivalent series resistance ESR

The ESR of aluminum electrolytic capacitor is composed of electrolyte resistance, alumina resistance of negative electrode plate, aluminum plate and anode foil resistance. Electrolyte resistance is the main component of ESR. The electrolyte resistance decreases with the increase of ambient temperature, while the resistance of alumina, aluminum plate and anode foil increases with the increase of ambient temperature. After superposition, the ESR of aluminum electrolytic capacitor will decrease with the increase of ambient temperature. When the temperature rises to a certain extent, the ESR will basically remain unchanged.

From the above analysis, it can be seen that the main parameters of aluminum electrolytic capacitor, namely electric capacity C and ESR, are greatly affected by ambient temperature. With the increasingly harsh working environment of electronic system, the performance of aluminum electrolytic capacitor has become a key restrictive factor for the reliability of electronic system. Therefore, improving the performance of aluminum electrolytic capacitor and real-time monitoring the change of aluminum electrolytic capacitor performance are the main means to improve the reliability of power plug-in in harsh environment.

3.2. General improvement measures of relay protection switching power supply

The working environment of relay protection devices is generally poor, especially under the influence of adverse factors such as overcurrent, strong electromagnetic interference and high temperature, the probability of failure of relay protection switching power supply is high. In order to ensure the safe operation level of relay protection device, the protection device manufacturer shall study improvement measures for key components affecting the service life of switching power supply, improve the production and manufacturing process and quality control process, improve the product quality of switching power supply and control the quality from the source; For power grid users, the operating environment of protection devices should be improved as much as possible and the ambient temperature of switching power supply should be reduced to achieve the goal of prolonging the service life of switching power supply; Meanwhile, power grid users should regularly replace the switching power supply according to the service life of the switching power supply recommended by the manufacturer and in combination with relevant specifications to improve the operation reliability of the protection device.

4. Solution of switching power supply

Relay protection devices are usually installed in substations or converter stations, which belong to high-frequency environment. Generally, the temperature rise of electrolytic capacitors working in high-frequency environment is difficult to be reduced to the extent that it does not affect the service life. This is because the existing switching power supplies pursue compactness. Generally, for the switching power supply of relay protection devices, the temperature rise of electrolytic capacitors above 30 °C is very common. For the electrolytic capacitors with temperature resistance of 105 °C, the service life is only 20000 ~ 40000 h, compared with the relay protection devices running for 24 hours. Obviously, there are great hidden dangers.
For the on-site operating switching power supply and the future developed switching power supply, we propose the following solutions.

4.1. Solution basis
According to the external environment of the power plug-in, several typical substations are selected for statistical analysis to predict the service life of the switching power supply of the relay protection device. We adopt the life prediction model formula of electrolytic capacitor based on ambient temperature:

\[
L_N = L_R \times 2^{\frac{T_R - T_1}{10}} \times 2^{C - \frac{T_R}{10 - 0.25T_r}}
\]  

(1)

Where:
- \(T_R\) is the maximum allowable working temperature of the capacitor given in the product manual;
- \(T_1\) is the actual working ambient temperature of the capacitor;
- \(L_R\) is the capacitance at temperature \(t\) given in the product manual;
- \(C\) is the characteristic life of the capacitor under temperature \(T_R\) given in the product manual;
- \(L_N\) is the predicted life of the capacitor at temperature \(T_1\). When the ripple current is constant, it can be seen that the service life of electrolytic capacitor will be doubled for every 10 °C drop in the working ambient temperature. Therefore, the service life of electrolytic capacitor can be prolonged by reducing the working ambient temperature as much as possible.

4.2. Heat dissipation design of relay protection device
The device adopts a novel Invisible breathing heat dissipation hole design structure and adds heat sink to change the natural convection heat dissipation mode of the traditional chassis, export the large heat of the heating power device from the root and reduce the temperature in the sealing device, so as to ensure the safe and stable operation of the device and avoid the failure rate and accidents of the device. On the premise of ensuring the IP protection level, EMC and stable and reliable operation of the device, the upper cover plate of the chassis is designed into upper and lower layers, the lower layer is designed with concave guide tank and hidden breathing heat dissipation hole, the metal dust screen is set under the hidden breathing heat dissipation hole, and heat conduction plates and heat sinks are installed at the bottom and upper parts of devices with high power and easy to heat, so as to reduce the temperature in the sealing device. As shown in Figure 3.

![Fig3. case cooling design](image)

Using the above method, the chassis temperature of the relay protection device decreases by an average of 4-10 °C.

4.3. Replacing liquid aluminum electrolytic capacitor with solid aluminum electrolytic capacitor
The biggest difference between solid aluminum electrolytic capacitor and liquid aluminum electrolytic capacitor is that different dielectric materials are used. The dielectric material of liquid aluminum electrolytic capacitor is electrolyte, while the dielectric material of solid aluminum electrolytic capacitor is conductive polymer material. In terms of capacitance value, solid aluminum electrolytic capacitor is more stable than liquid aluminum electrolytic capacitor. The switching power supply before and after replacement is shown in Figure 4.
As can be seen from Figure 4, the solid-state capacitance of the input end of the switching power supply cannot be reached due to the high voltage withstand requirements. 10kh electrolytic capacitance is used to replace 2KH electrolytic capacitance, and all other electrolytic capacitors are replaced with solid-state capacitance. From the actual effect of the application of solid aluminum electrolytic capacitor in the DC output circuit of switching power supply, its failure time is significantly later than that of liquid aluminum electrolytic capacitor, which significantly prolongs the service life of switching power supply and obtains better economic benefits.

4.4 Improvement of monitoring measures

(1) Improvement on output fluctuation of switching power supply
An electronic switching device is added to the delay capacitor of switching power supply to improve the output fluctuation of power supply. Once the input voltage rises, the electronic switchgear will restart with delay, which effectively avoids the misjudgment of the false signal of power restart by the power plug-in, so as to effectively avoid the occurrence of fault.

(2) Improvement of switching power supply overload
Because the power is rated during the operation of the power grid, in order to reduce the overload current, it is necessary to appropriately increase the output voltage, so that the instantaneous input current can be reduced on the basis of ensuring the constant power, so as to effectively avoid the overload phenomenon, so as to solve the problem of power plug-in failure caused by overload. Generally speaking, during the actual power grid operation, the output voltage of the switching power supply can be increased to 130-140v. At this time, the starting instantaneous current will be maintained at about 300mA, while the rated allowable passing current of the switching power supply for relay protection is 500mA, and its instantaneous current is within the current range of the normal operation of the switching power supply. There will be no switching power supply failure caused by overload.

(3) Improvement on software design of relay protection device
Switching power supply itself is also the source of electromagnetic interference, so there will be some high-order harmonics in the power output. The protection device takes a series of measures against the peak pulse phenomenon to prevent the misoperation of the relay protection device. The main measures are as follows: first, the main protection startup link adopts steady-state quantity startup and transient quantity startup or logic; second, the positive power supply at the outlet of the open relay protection device adopts steady-state quantity startup and transient quantity startup and logic; third, the tripping at the outlet of the relay protection device increases the discrimination conditions of high-frequency interference. As shown in Figure 5. The part marked in red in the figure is innovation.
5. Conclusion
This paper studies the failure causes of relay protection switching power supply, and concludes that electrolytic capacitor is the key component leading to the failure of switching power supply. At the same time, the failure mechanism and life influencing factors of aluminum electrolytic capacitor are deeply studied, and the improvement measures are put forward. The switching power supply developed in this paper has the characteristics of high reliability and long service life.

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References
[1] WANG Zengping, JIANG Xianguo, ZHANG Zhichao, et al. Relay protection for smart grid[J]. Power System Protection and Control, 2013, 26(2): 13-18.
[2] Hao Zhiguo, Zhang Baohui, Chu Yunlong, et al. Research on inrush current suppression technology for transformer no-load closing [J]. High voltage apparatus, 2005, 02:3-6.
[3] Liu W, Li G, Liang J, et al. Protection of single-phase fault at the transformer value side of FB-MMC-based bipolar HVDC systems [J]. IEEE Transactions on Industrial Electronics, 2020, 67(10): 8416-8427.
[4] Qiu Qunhui, Fu Jin, Fei Yunzhong, et al Research and practice of uninterruptible power supply strategy for dual transformation of DC power supply [J] Zhejiang electric power, 2015, 34 (12): 31-33.
[5] Yan Haojun, fan Ruifeng Problems and improvement suggestions of DC power supply system in substation [J] Zhejiang electric power, 2006, 25 (1): 27-30.
[6] LIU Yingjun,LIU Chang,WANG Wei,et al. Analysis of development status and trend of energy storage technology[J].SINO-GLOBAL ENERGY,2017,22(4):80-88.
[7] Wang Xingzhu, Qi Xuanwei, Wang song, et al Reliability analysis of substation secondary DC loss protection system [J] Zhejiang electric power, 2019, 38 (11): 40-45.
[8] Li Yiquan, Wang Zengchao, Liu Wei, et al Method of interactive wide area backup protection for adjacent substations to deal with DC voltage loss for stations [J] Zhejiang electric power, 2019, 38 (6): 17-20.
[9] Chen Ying Analysis of transformation scheme of DC power supply system in substation [J] Zhejiang electric power, 2008, 27 (2): 73-75.
[10] Zhang Baohui, Zhou Liangcai Centralized backup protection of substation [J] Power automation equipment, 2009, 29 (6): 1-5.
[11] Wang Lugang Reliability analysis of relay protection system in intelligent substation [J] Electronic production, 2017 (18): 44-45.