

Postprint: Evaluation Method for Power Supply Reliability of Multi-Component Parallel-Operated Power Systems

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Abstract

In view of the structural characteristics and operational features of power supply systems composed of multiple lines and multiple transformers in parallel, a reliability assessment method for multi-line, multi-transformer parallel systems is proposed. Based on statistical data confirming that both line and transformer failures follow an exponential distribution, probabilistic analysis methods are employed to model multiple-line parallel systems and multiple-transformer parallel systems separately, thereby determining the reliability, failure rate, and unavailability of such systems. Taking the 500kV Hengli Substation and Dongguan Substation in the Dongguan power grid as examples, calculation results demonstrate that the power supply reliability of multi-line, multi-transformer parallel systems is very high, but gradually decreases with increasing operating years.

Full Text

A Probability Assessment Method for Power Supply Reliability of Power Systems with Multiple Devices in Parallel

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Abstract

This paper proposes a probability assessment method for power supply reliability of systems with multiple transmission lines and transformers operating

in parallel, addressing the structural and operational characteristics of such configurations. Based on statistical data confirming that both line and transformer failures follow exponential distributions, probability analysis is employed to model multi-line parallel systems and multi-transformer parallel systems separately, determining the reliability, failure rate, and loss-of-efficacy rate of these combined systems. Using the 500kV Hengli and Dongguan substations in the Dongguan power grid as case studies, the calculations demonstrate that parallel multi-line, multi-transformer supply systems achieve very high reliability, though this reliability gradually decreases with increasing operational years.

Keywords: 500kV substation, multi-line and multi-transformer parallel system, power supply reliability assessment, failure rate, loss-of-efficacy rate

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1 Introduction

The series and parallel connections of equipment in power grids have a significant impact on power supply reliability [1-2]. In substations, multiple incoming lines connected to high-voltage buses form parallel line configurations, while multiple transformers connected between high- and low-voltage buses create parallel transformer structures. Such supply systems composed of multiple lines and transformers in parallel exhibit substantially enhanced reliability.

Equipment characteristics, including those of transformers and transmission lines, affect system reliability, and their connection topology also plays a crucial role. As the most critical component in power supply systems, substation reliability has long been a key focus in the industry [3]. Various methods have proven effective and found practical application, including simulation methods [4], analytical methods [5-10], and multi-state model evaluation algorithms [11-13], with simulation and analytical approaches already applied to maintenance decision-making [14-15]. Other power system reliability assessment methods, such as importance sampling algorithms [16], convolution calculation methods [17], operational reliability assessment methods [16-21], failure mode and effect analysis [20], minimal path and minimal cut set methods [21], network equivalent methods, and fault propagation methods [22-25], also offer insights for evaluating the reliability of multi-line, multi-transformer parallel systems. However, given the unique structural features and operational characteristics of these systems, a targeted approach to reliability assessment is necessary.

This paper addresses the structural and operational characteristics of multi-line, multi-transformer parallel supply systems by employing probability analysis to

model these systems separately and determine their failure rates and reliability metrics.

2 Reliability of Multi-Component Parallel Systems

Multi-line, multi-transformer parallel supply systems possess distinct structural and operational characteristics. Structurally, these systems feature two or more incoming lines connected to different power sources or infinite systems, and two or more transformers between high- and low-voltage buses that can operate in parallel or independently through switching configurations. Operationally, multiple transformers can be adjusted between parallel and independent operation based on their bus connection patterns, load demand levels, and reliability requirements, while multiple lines can be reconfigured based on their connections to different power sources and high-voltage buses.

In large-scale power grids (110kV, 220kV, and 500kV substations), typical configurations consist of eight incoming lines and four main transformers, forming parallel-operated supply systems with diverse structural and operational features. Different structural states and operational modes affect the reliability level of the power supply. Therefore, applying existing reliability analysis and assessment methods to these specific configurations is clearly necessary.

2.1 Reliability of Parallel Line Systems

Consider a supply system with NL parallel lines $L_1, L_2, L_3, \dots, L_{NL}$ and NT parallel transformers $T_1, T_2, T_3, \dots, T_{NT}$, as shown in [Figure 1: see original paper].

Assuming the failure probability density function $f_{L_i}(t)$ for the i -th transmission line is given, the distribution function for each line is:

$$F_{L_i}(t) = \int f_{L_i}(t) dt$$

The reliability function for each transmission line is:

$$R_{L_i}(t) = 1 - F_{L_i}(t) = 1 - \int f_{L_i}(t) dt$$

The reliability function $R_{SL}(t)$ for the incoming line system composed of NL parallel transmission lines is:

$$R_{SL}(t) = 1 - \prod_{i=1}^{NL} [1 - R_{L_i}(t)]$$

Assuming the transmission line failure probability density function follows an exponential distribution:

$$f_{L_i}(t) = \lambda_{L_i} e^{-\lambda_{L_i} t} \quad (t \geq 0, \lambda_{L_i} \geq 0)$$

The reliability and failure rate of parallel transmission lines are:

$$R_{SL}(t) = 1 - \prod_{i=1}^{NL} [1 - e^{-\lambda_{L_i} t}] = \sum_{i=1}^{NL} (-1)^{i-1} \sum_{1 \leq j_1 < \dots < j_i \leq NL} e^{-(\lambda_{L_{j_1}} + \lambda_{L_{j_2}} + \dots + \lambda_{L_{j_i}}) t}$$

$$\lambda_{SL}(t) = -\frac{R'_{SL}(t)}{R_{SL}(t)}$$

If each transmission line has the same failure rate, the reliability and failure rate of parallel transmission lines simplify to:

$$R_{SL}(t) = 1 - (1 - e^{-\lambda_L t})^{NL}$$

$$\lambda_{SL}(t) = \frac{NL \lambda_L e^{-\lambda_L t} (1 - e^{-\lambda_L t})^{NL-1}}{1 - (1 - e^{-\lambda_L t})^{NL}}$$

2.2 Reliability of Parallel Transformer Systems

If the failure probability density function $f_{T_n}(t)$ for the n -th transformer is given, the distribution function for each transformer is:

$$F_{T_n}(t) = \int f_{T_n}(t) dt$$

The reliability function for each transformer is:

$$R_{T_n}(t) = 1 - F_{T_n}(t) = 1 - \int f_{T_n}(t) dt$$

For NT parallel-operated transformers, the reliability function $R_{ST}(t)$ is:

$$R_{ST}(t) = 1 - \prod_{n=1}^{NT} [1 - R_{T_n}(t)]$$

Assuming the transformer failure probability density function follows an exponential distribution:

$$f_{T_i}(t) = \lambda_{T_i} e^{-\lambda_{T_i} t} \quad (t \geq 0, \lambda_{T_i} \geq 0)$$

The reliability and failure rate of parallel transformers are:

$$R_{ST}(t) = 1 - \prod_{i=1}^{NT} [1 - e^{-\lambda_{Ti}t}] = \sum_{i=1}^{NT} (-1)^{i-1} \sum_{1 \leq j_1 < \dots < j_i \leq NT} e^{-(\lambda_{Tj_1} + \lambda_{Tj_2} + \dots + \lambda_{Tj_i})t}$$

$$\lambda_{ST}(t) = -\frac{R'_{ST}(t)}{R_{ST}(t)}$$

If each transformer has the same failure rate, the reliability and failure rate simplify to:

$$R_{ST}(t) = 1 - (1 - e^{-\lambda_T t})^{NT}$$

$$\lambda_{ST}(t) = \frac{NT\lambda_T e^{-\lambda_T t} (1 - e^{-\lambda_T t})^{NT-1}}{1 - (1 - e^{-\lambda_T t})^{NT}}$$

2.3 Reliability of Multi-Line, Multi-Transformer Parallel Systems

Since the system consists of parallel lines, parallel transformers, and series connections between lines and transformers, with independence among lines, transformers, and between lines and transformers, the system failure probability density function $f(t)$ is:

$$f(t) = \prod_{i=1}^{NL} f_{Li}(t) \prod_{n=1}^{NT} f_{Tn}(t)$$

The system failure probability distribution function $F(t)$ is:

$$F(t) = \prod_{i=1}^{NL} F_{Li}(t) \prod_{n=1}^{NT} F_{Tn}(t)$$

The system reliability function $R_S(t)$ is:

$$R_S(t) = R_{SL}(t)R_{ST}(t)$$

The system failure rate $\lambda_S(t)$ is:

$$\lambda_S(t) = \lambda_{SL}(t) + \lambda_{ST}(t)$$

3 Case Study and Analysis

3.1 Reliability Assessment of 500kV Hengli Substation

For reliability analysis of multi-line and multi-transformer parallel systems, the 500kV Hengli substation in Dongguan power grid is examined. The 500kV Hengli substation has six 500kV transmission lines (Hengdong A/B, Suiheng A/B, Boheng A/B) and four 1000MVA transformers, as shown in [Figure 2: see original paper].

Assuming a transmission line failure rate of 0.153 failures/(year · 100km) and a transformer failure rate of 0.0318 failures/year, the reliability indices—including reliability, failure rate, and average failure rate—are evaluated over a 10-year operational period. The data are presented in and [Figure 3: see original paper] through [Figure 5: see original paper].

As shown in and [Figure 3: see original paper]-[Figure 5: see original paper], since transformer failure rates are lower than line failure rates, the reliability of parallel transformers at the 500kV Hengli substation is higher and the failure rates are lower than those of parallel lines. Because the substation consists of multiple parallel lines in series with multiple parallel transformers, its overall reliability indices are slightly lower than those of the parallel lines and parallel transformers individually.

With increasing operational years, the reliability of multi-line, multi-transformer parallel systems decreases while failure rates increase, with more pronounced degradation over longer periods. For example, at one year of operation, the 500kV Hengli substation achieves a supply reliability of 0.999991 with a failure rate of 0.000049 failures/year, but at five years, reliability drops to 0.976183 and the failure rate rises to 0.019456 failures/year. This indicates that regular inspection and maintenance of lines and transformers are essential to maintain high reliability.

3.2 Reliability Assessment of 500kV Dongguan Substation

The 500kV Dongguan substation has eight transmission lines (Fudong A/B, Kundong A/B, Donghui A/B, Hengdong A/B) and four parallel 750MW transformers, as shown in [Figure 6: see original paper].

The reliability indices for the 500kV Dongguan substation are presented in and [Figure 7: see original paper] through [Figure 9: see original paper].

Analysis of the 500kV Dongguan substation reliability indices shows high reliability. At one year of operation, the multi-line, multi-transformer parallel system achieves a reliability of 0.999999 (approximately 1) with a failure rate of 0.000005 failures/year (approximately 0), demonstrating that with reliable upstream power sources, the 500kV Dongguan substation provides high reliability conducive to continuous power supply.

Comparing the reliability indices of the 500kV Dongguan and Hengli substations reveals that Dongguan substation exhibits higher reliability. At two years of operation, Dongguan substation has a reliability of 0.999962, a failure rate of 0.000108 failures/year, and an average failure rate of 0.000121 failures/year, whereas Hengli substation shows a reliability of 0.999650, a failure rate of 0.000889 failures/year, and an average failure rate of 0.000549 failures/year. This suggests that increasing the number of transmission lines or transformers can enhance system reliability.

4 Conclusion

Based on annual failure rates of lines and transformers and assuming exponential failure probability density functions, this paper conducts probability analysis of multi-line, multi-transformer parallel supply systems, establishing assessment methods for operational reliability, failure rate, and average failure rate. Through theoretical analysis, simulation calculations, and comparison with historical data, the following conclusions are drawn:

1. Multi-line, multi-transformer parallel supply systems achieve very high reliability, reaching 0.999999, whereas single-line, single-transformer systems rarely exceed 0.9 reliability.
2. The reliability of multi-line, multi-transformer parallel supply systems gradually decreases with increasing operational years. To maintain high reliability, necessary maintenance and even replacement of lines and transformers are required.
3. Increasing the number of parallel transmission lines or transformers can improve system reliability. Therefore, in the design of large substations, the number of incoming lines and transformers should be comprehensively determined based on reliability requirements and economic considerations.

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