The Redundancy Scheme Optimization of DC Distribution Transformer for Electric Vehicle Charging Facility

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Abstract. The DC distribution transformer for electric vehicle charging facility is the key equipment in future active distribution power system, whose reliability relates to robust and reliable operation of distribution power system. With redundancy modules, reliability of the DC distribution transformer is increased as well as the cost. The reliability with different control methods for general DC distribution transformer is analyzed and compared, and an objective function is presented for optimized design. Solutions for minimum value of the function under different circumstances are discussed, and the best scheme for balance between reliability and economy is obtained. Finally, an engineering application is analyzed. Suggested model and number of sub-modules is given, and validity and feasibility of the proposed method is verified.

1. Introduction
As electric vehicles has nearly no environmental pollution, the related research about the connection between electric vehicle and power system is widely discussed by many studies. The influence of varies penetration stages of plug-in electric vehicles in a distribution power grid is discussed in [1], with a demonstration of voltage sag caused by electric vehicles charging action. Actually, the electric vehicles charging action will lead the load increase and power losses to the distribution power system in [2], and in some circumstance leads to higher maximum value of the load. Due to the research in [3-5], the additional DC distribution transformer for electric vehicle charging facility will lead to additional investment costs and the power losses, and furthermore introduce DC bias and harmonics problems [6-8], and as a result reduce the life duration of traditional distribution transformers due to the high penetration of electric vehicles [9].

The voltage sag, additional power losses, harmonics, DC voltage bias and life duration problems caused by introducing electric vehicles to the power system attract the attention of lots of researchers. The studies includes electric vehicles charging with intelligent algorithm to realize the economic benefits and fulfill the unique demand of electric vehicles [10]. Intelligent charging for electric vehicles will make the electric vehicles not only the DC power load, but also DC power supply to the power system [11].

In this paper, the redundancy scheme optimization of DC Distribution transformer for electric vehicle charging facility is proposed with the consideration of reliability and economy to the...
Distribution transformer for electric vehicle charging facility, and the validity and feasibility of the proposed method is verified with engineering examples.

2. Redundancy scheme optimization analysis of DC transformer

2.1. Basic structure of distribution DC transformer
The DC transformer for electric vehicle charging facility is an important component in the modern DC distribution power system. Figure 1 illustrates different components in the DC distribution power system, including distributed generation, AC load, DC load EV charging station and HVDC [4,11].

The normal structure of distribution DC transformer can be illustrated in Figure 1, which connects the 10kV high voltage distribution AC power system, 9kV high voltage distribution DC power system, 375V or 400V low voltage distribution DC power system and 380V distribution AC power system with power electronic converters.

![Figure 1. Single phase structure in distribution DC transformer](image)

2.2. The reliability analysis
The failure rate of the power cell in Figure 1 can be described as the sum of all converters:

\[ \lambda_{cell} = 16\lambda_I + 3\lambda_C + \lambda_L + \lambda_T \]  

(1)

Hence the total reliability is:

\[ R(t) = e^{-\lambda t} \]  

(2)

As a result, the DC transformer consisted of n power cell is with the reliability:

\[ R(t) = e^{-n\lambda t} \]  

(3)

![Figure 2. Redundant power cell for phase A](image)

Figure 2 illustrates the most common redundancy scheme for DC distribution transformer. Assume that the DC distribution transformer can operate normally with k power cells in a DC distribution transformer with n power cells, the mean time between failures (MTBF) T in cold standby scheme can be described as:
\[ T = T_1 + T_2 + T_3 + \ldots + T_{n-k+1} \]  

the reliability as well as MTBF will be:

\[ R(k, n, t) = e^{-k \lambda t} \sum_{i=0}^{n-k} \frac{(k\lambda t)^i}{i!} \]  

\[ T_\lambda = \frac{n-k+1}{k \times \lambda} \]  

The reliability as well as MTBF with hot standby scheme will be:

\[ R(k, n, t) = \sum_{i=k}^{n} C_n^i e^{-i \lambda t} (1 - e^{-\lambda t})^{n-i} \]  

\[ T_{hot} = \frac{1}{\lambda} \sum_{i=k}^{n} \frac{1}{l} \]  

2.3. The optimization analysis

The equation for transformer cost and damage or loss for the power failures will be:

\[ E(k, n, t) = cn + d(1 - R(k, n, t)) \]  

and the total cost varies as the total number of sub-modules:

\[ \Delta E(n) = E(n+1) - E(n) = c + d(R(n) - R(n+1)) = c - d \Delta R(n) \]  

By applying cold standby operation:

\[ \Delta R(n) = e^{-k \lambda t} \frac{(k\lambda t)^{n+1-k}}{(n+1-k)!} > 0 \]  

hence

\[ \Delta(R(n)) = e^{-k \lambda t} \frac{(k\lambda t)^{n+1-k} (k\lambda t + k - n - 2)}{(n+2-k)!} \]  

By applying hot standby operation:

\[ \Delta R(n) = C_n^{k-1} e^{-k \lambda t} (1 - e^{-\lambda t})^{n+1-k} > 0 \]  

hence

\[ \Delta(\Delta R(n)) = C_n^{k-1} e^{-k \lambda t} (1 - e^{-\lambda t})^{n+1-k} \left[ \frac{(n+1)(1 - e^{-\lambda t})}{n+2-k} - 1 \right] \]  

By considering both least number of sub-modules and total number of sub-modules, the equation of cost and loss will be:

\[ E(k, n, t) = c(k)n + d(1 - R(k, n, t)) \]

3. Case Study

Table 1 shows the cost and required number of sub-modules, and Table 2 shows the failure rate of converters.
By assuming that the time variable is 1 year, the reliability and number of sub-modules can then be analyzed with the calculation methods above. When 6500V sub-module is selected, its initial reliability is high due to the small number of sub-modules; with the increase of the number of sub-modules, its reliability will soon reach a high level; when the same number of redundant sub-modules is selected, the reliability of cold standby operation with red line $Ke1$ is higher than hot standby operation with blue line $Ke2$, as shown in Figure 3.

Figure 3. The number of redundancy module and reliability(6500V)

Figure 4 shows the relationship between the number of redundant sub-modules and the reliability increment, and intuitively obtains the reasonable number of redundant sub-modules. Due to the high cost of 6500V level sub-module and its high initial reliability, after adding one redundant sub-module, its reliability increment will drop to the economic condition.

Figure 4. The number of redundancy module and incremental reliability(6500V)
Figure 5 and Figure 6 show the process of optimizing the configuration of the sub-modules with a voltage class of 3300V. It can be seen that its initial reliability is relatively low, and more redundant sub modules are needed to achieve a high level of reliability. In different redundant control modes, the reliability increment is different, which leads to different results of the final optimal configuration. Under the cold standby operation mode, the third redundant sub module is added.

![Figure 5. The number of redundancy module and reliability(3300V)](image1)

![Figure 6. The number of redundancy module and incremental reliability(3300V)](image2)

By comparing the optimal configuration results of sub modules with different voltage levels, it can be seen that when the sub module with 3300V voltage level is selected and the cold standby control mode is adopted, the economy and reliability of the equipment are optimized. Due to the high price of 6500V IGBT, its economy has no advantage. However, by increasing the voltage level of sub modules, the number of sub modules and the volume of equipment can be reduced to the greatest extent. The total cost of the system can be minimized by cold standby operation, but the reliability and economy of hot standby operation are almost the same. If considering the improvement of power quality and the dynamic performance of switching, hot standby operation is also an available option.

4. Conclusions
The reliability and incremental reliability of DC distribution transformer for electric vehicle charging facility for active distribution power system are analyzed theoretically. According to the objective function of the theoretical research, the different configurations with redundancy modules of the DC distribution transformer are compared with reliability and incremental reliability.

The relationship between the reliability and the system cost of DC distribution transformer converters is discussed. The redundant sub-module scheme proposed in the paper is with better performance in economy evaluation and reliability.
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