The Optimization of Redundancy Design for Solid State Transformer

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Abstract. As the essential device in future integrated energy system, the reliability of solid state transformer is highly related to the security and reliability of the distribution power grid. With the redundant sub-modules, the system reliability as well as the system cost of solid state transformer will both increase. The reliability of various redundancy designs for solid state transformer are analyzed and an objective function is studied for optimized solution. The redundancy design of relatively high reliability and low additional cost for various configurations are discussed, and the optimized solution which are appropriate in both reliability and economy is obtained.

1. Introduction

In recent years, with the increase of connection in renewable energy sources (RESs), new loads such as electric vehicles as well as the promotion of electric power reform and market-oriented electricity, the concept of integrated energy system and active distribution network is becoming the future direction of power grid development. As a result, the future renewable electric energy delivery and management (FREEDM) system is proposed in [1].

Solid state transformer based on power electronics technology and information technology is the core equipment for integrated energy system and active distribution network. It can provide flexible and diverse interface forms of electricity to meet the various requirements of distributed generation, energy storage device and loads, and integrate AC and DC bus in different voltage levels, hence achieve unified and efficient integrated energy management. As an important node for the future power system, the reliability of solid state transformer is related to the reliability of the power grid. Once a fault occurs, it will bring huge losses. However, compared with traditional power devices, power electronic devices are more vulnerable, and power electronic devices used in solid state transformer will reduce the reliability of devices. As a common solution to improve the reliability of equipment, the redundancy configuration is very important for the solid state transformer to improve its reliability.

In fact, one of the important problems to all large power and high voltage power electronic equipment is how to improve the reliability of the equipment.
The redundancy protection for sub-module faults in modular multilevel converter is studied in [2] for HVDC transmission, and the calculation on sub-module redundancy configuration in modular multilevel converters is studied in [3-5].

For cascade H-bridge structure, researchers have studied the redundancy and control technology in STATCOM [6, 7] and electronic power transformer [8-10].

However, due to the 10kV grid voltage of solid state transformer in distribution power grid, the number of sub-modules, and different solutions of sub-module in numbers and voltage levels, the optimization of voltage level and number of sub-modules will benefit the reliability and economy of the solid state transform as well as the related integrated energy system and active distribution network. In this paper, the topology structures of solid state transform are introduced in Section 1. The redundancy design including analysis on reliability and configuration optimization is given in Section 2. The case study about a 10kV/400V/500kVA solid state transformer is shown in Section 3, and conclusion is presented in Section 4.

2. Structures of Solid State Transformer

To achieve the integrated energy management, the solid state transformer can not only operate as a traditional power transformer in power transmission, electro-magnetic isolation, energy conversion, but also connect with multiple AC and DC links with different voltage level.

Applied with telecommunication and automation devices, the solid state transformer substation can connect both AC and DC terminals; hence the transmission system can connect distributed generation which includes wind farm, solar energy and hydro-power, which is shown in Figure 1.

![Figure 1. Solid state transformer based substation](image)

A traditional topology of 10kV/400V/500kVA solid state transformer developed by Huazhong University of Science and Technology[11-14] is shown in Figure 2. The AC-DC module of SST converter the 10kV grid AC voltage to DC voltage for DC-DC module by modular H-bridge converters. The DC-DC part then change the voltage level for DC-AC module also by modular H-bridge converters. The DC-AC module will invert the DC voltage into AC voltage by paralleled modular H-bridge converters.
3. Redundant Configuration

3.1. The reliability analysis

The reliability of the device is related to many factors, such as production process, operating conditions, working hours. It is difficult to obtain the reliability function of the device accurately. However, a large number of different types of device failure data show that the failure rate function is in the shape of a bathtub curve [15]. The specific performance is that the early failure rate of the device is higher, mainly caused by design and manufacturing defects, and then the device enters a random failure period. At this time, the device performance is stable, the failure rate is low and close to a constant. Finally, with the increase of time, the failure rate shows an upward trend. The description of device reliability is in the random failure period of stable operation, when the failure rate function is constant and the reliability function is exponential distribution.

As shown in Figure 2, the failure rate of a sub-module that includes one AC-DC module, one DC-DC module and one DC-AC module can be given by:

$$\lambda_{cell} = 16\lambda_I + 3\lambda_C + \lambda_L + \lambda_T$$  \hspace{1cm} (1)

and the reliability of the sub-module can then be given by:

$$R(t) = e^{-\lambda t}$$  \hspace{1cm} (2)

hence the total reliability of SST that includes n sub-modules can be given by:

$$R(t) = e^{-n\lambda t}$$  \hspace{1cm} (3)

where, $16\lambda_I$ represents 16 IGBT modules, $3\lambda_C$ represents 3 capacitors, $\lambda_L$ represents input inductor and $\lambda_T$ represents high frequency transformer in one sub-module, respectively.

In order to ensure the reliability of equipment, on the basis of meeting the voltage and capacity, redundant sub-modules are usually added. Once the fault is detected, the fault module will be removed quickly and put into redundant backup to maintain the normal and stable operation of the equipment. According to whether the redundant module participates in the work or not, the equipment can be divided into two control modes: cold standby operation and hot standby operation [16].

Cold standby operation refers to: 1) When the equipment is running normally, the redundant sub-module does not participate in the work. 2) When there is a sub-module failure, the bypass fault sub-module is put into the redundant sub-module; when there is no redundant sub-module, the device will quit operation. Before and after sub-module switching, the device circuit topology has not changed, so the control is relatively simple under this mode of operation, but the charging process of the redundant sub-module will make the transient process longer.
Hot standby operation refers to: 1) When the equipment is running normally, the redundant sub-module participates in the work. 2) When the sub-module fails, the bypass fault sub-module adjusts the control parameters, and the remaining sub-module continues to work; when the remaining sub-module fails to meet the system voltage withstand requirements, the equipment will withdraw from operation. Redundant sub-module participates in the work, making the level series more, so the power quality is better and harmonics are less under this operation mode, but the control is relatively complex, and the use of redundant sub-module reduces its reliability.

![Redundant Sub-Module](image)

Figure 3. Redundant sub-module including AC-DC module, DC-DC module and DC-AC module

The single-phase redundancy structure is shown in Figure 3. On the basis of the original structure of the SST, a redundant sub-module is added for backup, and the connection mode is the same as other sub-modules. In addition, when the device considers adding redundancy configuration, each sub-module needs to add a switch at the input and output stages for isolation and backup of failure sub-modules, as shown in Figures 3. When switch S1 is closed and the switch S2 is open, the sub-module will be bypassed, and vice versa, the sub-module will be put into operation. The control system can control the switching state according to the configuration. The redundant sub-module can work in the cold standby state or the hot standby state according to the different switching state. A simple and reliable mechanical switch or a reverse-parallel thyristor switch can be selected for the switch.

If SST needs at least k-level sub-modules to work properly, there are n (n≥k) level sub-modules, in which (n-k) level sub-modules are redundant sub-modules. When SST is running in cold standby, the expression of the mean time between failures T can be given by:

$$T = T_1 + T_2 + T_3 + ... + T_{n-k+1}$$  \hspace{1cm} (4)

where, $T_i$ represents the working time of SST before the number i failure, and then the reliability and mean time between failures can be given by:

$$R(k,n,t) = e^{-k\lambda t} \sum_{i=0}^{n-k} \frac{(k\lambda t)^i}{i!}$$  \hspace{1cm} (5)

$$T_k = \frac{n-k+1}{k \times \lambda}$$  \hspace{1cm} (6)

If SST works in hot standby operation mode, the reliability and mean time between failures can then be given by:

$$R(k,n,t) = \sum_{i=k}^{n} C_{n}^{i}e^{-i\lambda t}(1-e^{-\lambda t})^{n-i}$$  \hspace{1cm} (7)

$$T_{hot} = \frac{1}{\lambda} \sum_{i=k}^{n} \frac{1}{i}$$  \hspace{1cm} (8)

Comparing hot and cold standby operation modes, due to the fact that:
Therefore, the reliability of hot standby operation is worse than that of cold standby operation. From another point of view, when cold standby runs, the redundant sub-module does not participate in the work, and its failure rate is zero; while when hot standby runs, the redundant sub-module participates in the work, and its failure rate is the same as other sub-modules. In addition, when cold standby is used, the average fault-free working time increases linearly with the increase of redundant sub-modules, while when hot standby is used, the increment of average fault-free working time decreases with the increase of redundant sub-modules.

Therefore, when designing the circuit topology, if the selected sub-modules have higher voltage level and fewer numbers, and have higher reliability, the hot standby operation can be used to increase the series of sub-modules to improve their power quality; while the selected sub-modules have lower voltage level and lower reliability when the number is large, cold standby operation should be adopted to improve their reliability.

3.2. The configuration optimization analysis
From the previous analysis, although the reliability of cold standby operation is different from that of hot standby operation, the reliability of equipment can be improved by adding redundant sub-modules, so it is necessary to configure redundant sub-modules. On the other hand, adding redundant sub-modules will increase the cost of equipment and reduce the economy of equipment, so it is necessary to allocate redundant sub-modules reasonably to balance reliability and economy.

If the number of sub-modules are known, the redundant sub-module can give the value of k and n, hence the Cost-Loss function can be given by:

$$ E(k, n, t) = cn + d(1 - R(k, n, t)) $$  \hspace{1cm} \text{(10)}

where c represents the cost of a sub-module, d represents the loss caused by device failure. The minimum of the function represents the optimized balance between reliability and economy.

The function of cost E is highly related to the number of sub-modules n, while k is known as sub-modules and t is known as overhaul interval.

To analyze the relation between cost E and the number of sub-modules n, the incremental cost can be given by:

$$ \Delta E(n) = E(n + 1) - E(n) $$

$$ = c + d(R(n) - R(n + 1)) $$

$$ = c - d\Delta R(n) $$  \hspace{1cm} \text{(11)}

By applying cold standby operation, the incremental reliability can be given by:

$$ \Delta R(n) = e^{-k\lambda t} \frac{(k\lambda t)^{n+1-k}}{(n+1-k)!} > 0 $$  \hspace{1cm} \text{(12)}

hence

$$ \Delta(R(n)) = e^{-k\lambda t} \frac{(k\lambda t)^{n+1-k}(k\lambda t + k - n - 2)}{(n+2-k)!} $$  \hspace{1cm} \text{(13)}

When $k\lambda t \geq 2$, $\Delta R$ will first increase then decrease with n, which makes $\Delta R(n_0)$ the maximum. When $k\lambda t < 2$, $\Delta R$ will decrease with the increase of n, which makes $\Delta R(k)$ the maximum.

As a result, the conclusion can be given as:
(1) If $\Delta R_{\text{max}} \leq \frac{c}{d}$, then $E_{\text{min}} = E(k)$.

(2) If $\Delta R_{\text{max}} > \frac{c}{d}$, and $k \lambda t \geq 2$, $\Delta R(k) < \frac{c}{d}$, then $E_{\text{min}} = \min(E(k), E(n_1))$, and $n_1$ is the maximum integral number for $\Delta R(n_1) > \frac{c}{d}$.

(3) If $\Delta R_{\text{max}} > \frac{c}{d}$, and $k \lambda t \geq 2$, $\Delta R(k) > \frac{c}{d}$, then $E_{\text{min}} = E(n_1)$, and $n_1$ is the maximum integral number for $\Delta R(n_1) > \frac{c}{d}$.

(4) If $\Delta R_{\text{max}} > \frac{c}{d}$, and $k \lambda t < 2$, then $E_{\text{min}} = E(n_1)$, and $n_1$ is the maximum integral number for $\Delta R(n_1) > \frac{c}{d}$.

By applying hot standby operation, the incremental reliability can be given by:

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

hence

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

When $k \leq n \leq n_0$, $\Delta R$ will increase with the increase of $n$. When $n_0 < n$, $\Delta R$ will decrease with the increase of $n$, where $n_0 = \left\lfloor \frac{k - 1}{e^{-\lambda t} - 1} \right\rfloor$.

As a result, the conclusion can be given as:

(1) If $\Delta R(n_0) < \frac{c}{d}$, then $E_{\text{min}} = E(k)$.

(2) If $\Delta R(n_0) \geq \frac{c}{d}$, and $\Delta R(k) \geq \frac{c}{d}$, then $E_{\text{min}} = E(n_1)$, and $n_1$ is the maximum integral number for $\Delta R(n_1) > \frac{c}{d}$.

(3) If $\Delta R(n_0) \geq \frac{c}{d}$, and $\Delta R(k) < \frac{c}{d}$, then $E_{\text{min}} = \min(E(k), E(n_1))$, and $n_1$ is the maximum integral number for $\Delta R(n_1) > \frac{c}{d}$.

The voltage to the SST applied in distribution power grid is usually 10kV, which offers massive options on sub-module, hence it can be designed according to the actual needs. When the SST is in the early stage of design and considering the balance between reliability and economy, the voltage level and type of sub-module should be reasonably selected. As a result, the minimum number of sub-modules $k$ is uncertain, and the configuration $k$ and $n$ should be considered at the same time, hence the cost-loss function can be given by:

$$E(k,n,t) = c(k)n + d(1 - R(k,n,t))$$

(16)
where \( c(k) \) represents the cost of a sub-module which is highly related to the voltage level of sub-module. The optimized combination of \( k \) and \( n \) can be given by calculating the minimum value of \( E(k,n,t) \). To simplify the analysis, the overhaul interval \( t \) can be introduced to compare different \( E_{\min} \) in different \( k \) and \( n \) for optimized solution.

4. Conclusions
Based on the topology of the Solid State Transformer (SST), its reliability model is proposed in different redundant operation modes including hot standby operation mode and cold standby operation mode. The reliability and economy factors are highly related to the number of redundant sub-modules, the minimum number of sub-modules for the SST to work properly, and the mean time between failures for sub-module in SST. By introducing Cost-Loss function, the balance between the reliability of SST system and cost of SST components is studied, and the optimized redundancy configuration design on SST can be obtained. The redundancy configuration design proposed in this paper has good adaptability to all devices applying modular power electronic components including SST.

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