Multi-load model for reliability assessment of HVDC converter

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Abstract: Because of ignoring common cause failures and load diversity,the conventional reliability assessment models for HVDC transmission systems are over-optimistic. Load-property interference analysis method is introduced to provide a valuable understanding of failure modes and mechanism of HVDC converter. Operating loads of HVDC converters are classified according to endurance performances of thyristor element and a multi-load model taking different loading conditions into account is established. Comparative calculations are performed on a 12-impulse HVDC converter to illustrate the effectiveness of the proposed model. Importance and sensitivity of different loads in influencing converter failure probability are also evaluated by critical importance index. Results show that the proposed model is more precise and reliable.

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Key words: reliability; load-property interference analysis; multi-load model; common cause failure; load diversity

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0 Introduction

Reliability evaluation of HVDC system is usually implemented by analytic methods based on two-state models or capability models[1-4]. However,the evaluation results are always found to be over-optimistic during engineering experiences,and some even has rather a big error to practical statistical data. So these results can not provide meaningful instructions for engineering planning or operation. The root reason of this situation comes from two inherent weaknesses of the traditional models.

One is the statistical independency assumption of the models,which loses sight of the potential common cause events that would be likely to cause serious results. The other is ignoring diversity of operating conditions,which assumes that failure probability distributions of one component under different conditions are always the same. In reality,dependent degree inside complex system is rather high due to common or correlative loads on multiple components, especially for systems containing numbers of similar components,such as HVDC converters. Otherwise, electronic components usually have strict demands on operation conditions,and they differ a lot in properties under different environments. So,these two fatal weaknesses may cause obvious errors,or even bring on a mistake.

CCF(Common Cause Failure) is a multi-component failure phenomena induced by a common reason. It is an unavoidable failure mode for complex systems, and universally exists in ecumenic systems. Researchers have placed extensive recognition and researches on it for years. Many effective models have been developed[5-10],such as BFM(Beta Factor Model),MGLM(Multiple Greek Letter Method),AFM (Alpha Factor Model),BPM(Basic Parameter Model), BFRM(Binomial Failure Rate Model),CLM(Common Load Model),etc. Although the existing CCF models can forecast system failures from component properties or from history failure experiences,there're still many tough issues in applications to be solved, due to the plant specific characteristics of CCF and the scarcities of primal data,especially for high rank redundant systems. Consequently,it's necessary to develop a failure model based on happening mechanisms of CCF for a given practical engineering system. Recently,relaying on load-property interference analysis,Professor Xie[11-12] revealed that load randomness

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was the root cause for system dependency, and hereby proposed a load-property model for CCF. This provided an effective means to deal with CCF issues in complex system.

There're always multiple loads working on component performances simultaneously in practical operation. Each load has its own distribution form. So does the property. Therefore, a multi-load model will be established in the following sections based on load-property analysis method.

1 Load-property interference analysis

According to stress-strength interference theory[13], component destruction is the result of stress overriding strength. Extending stress and strength to a more generalized concept — load and property, we'll get that component failure is the result of environment load overriding component property. Here, the load is a generalized stress, including casual accidents, such as earthquakes, fires and supporting system failures, etc, as well as working environments and physical stresses.

Commonly, load and property are all stochastic. And consequently, the failure probability is also stochastic. When the probability distribution of a load has interferential area with that of the corresponding property, shown as shadow portion in figure 1, the component's reliability is $0<R<1$.

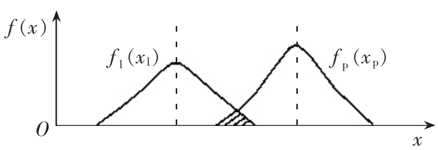

Fig.1 Load-property interference relationship

Under such a common circumstance, components are neither completely dependent, nor completely independent. Once the shadow area increases, the failure probability of component increases too. If the probability density functions of load x_1 and property x_p are denoted by $f_1(x_1)$ and $f_p(x_p)$ respectively, the component failure probability can be expressed as

$$P_c=P(x_1>x_p)=\int_0^{\infty} f_p(x_p)\left[\int_{x_p}^{\infty} f_1(x_1)\mathrm{d}x_1\right]\mathrm{d}x_p \qquad (1)$$

For an r/n redundant system, the probability of k out of n components is

$$P_{S,k}=\binom{k}{n}\int_0^{\infty} f_1(x_1)\left[\int_0^{x_1} f_p(x_p)\mathrm{d}x_p\right]^k\left[\int_{x_1}^{\infty} f_p(x_p)\mathrm{d}x_p\right]^{n-k}\mathrm{d}x_1 \qquad (2)$$

where $0\leqslant k\leqslant r$.

Now consider a special case, where load is constant, as shown in figure 2(a). Denote the load as X_1, and then equation (1) is transformed into

$$P_c=P(x_p<X_1)=\int_0^{X_1} f_p(x_p)\mathrm{d}x_p \qquad (3)$$

As we can see, failure of one component relies entirely on the component's individual performance. And failures of different components are independent of each other. This kind of failures is called FIF (Full Independent Failure). For r/n redundant system, the probability of k out of n components is

$$P_{S,k}=\binom{k}{n}\left[\int_0^{X_1} f_p(x_p)\mathrm{d}x_p\right]^k\left[\int_{X_1}^{\infty} f_p(x_p)\mathrm{d}x_p\right]^{n-k} \qquad (4)$$

Consider another special case, where component property is constant, denoted by X_p, as shown in figure 2(b). The failure probability of one component is

$$P_c=P(x_1>X_p)=\int_{X_p}^{\infty} f_1(x_1)\mathrm{d}x_1 \qquad (5)$$

For components bearing a common load, when load varies randomly, those components either keep intact simultaneously or fail simultaneously. This kind of system failure modes is called FDF(Full Dependent Failure), and the failure probability for arbitrary redundant system is the same as that of one component.

$$P_S=\int_{X_p}^{\infty} f_1(x_1)\mathrm{d}x_1 \qquad (6)$$

Another form of FDF is shown in figure 2(c). As seen, there's no interference area, which means that the load always overruns the property. Hereby, the component fails inevitably once the load occurs, and so does the system composed of n components. This kind of environment is called lethal environment and the corresponding system failure is called FDLF(Full Dependent Lethal Failure). The system failure probability is $P_S=1$.

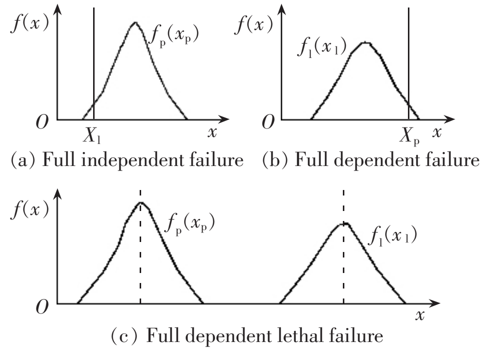

Fig.2 Special cases for load-property relationship

2 Multi-load model for HVDC converter

HVDC converter is composed of hundreds to several thousand thyristors and its accessories, which is a typical complex redundant system. Loads on a converter can be divided into two major classes, normal working load and abnormal casual load. Since temperature and electrical stresses are the key factors influencing thyristor's performance, we define the working load for converter according to its basic working demands as that all the electrical stresses put on the valve should not override the valve's rated endurances within the specified working temperature extremes. The abnormal casual loads include overvoltage, fault current and supporting system failure.

2.1 Notations

The following symbol definitions will be used throughout current and the next sections.

x_{w1} : rated load.

x_{w2} : overload.

x_{ov} : overvoltage.

x_{v1} : protection threshold of valve arrester.

x_{v2} : interruption voltage of valve.

x_{vv} : interruption voltage of thyristor.

x_{oc} : fault current.

x_{pc} : overcurrent endurance of thyristor.

$f_v(\cdot)$: density distribution functions of overvoltage.

$f_{v1}(\cdot)$: density distribution functions of arrester protection threshold.

$f_{v2}(\cdot)$: density distribution functions of valve interruption voltage.

P_{w1} : happening probability of rated load.

P_{w2} : happening probability of overload.

P_{ov} : happening probability of overvoltage.

P_{oc} : happening probability of fault current.

P_{a1} : happening probability of auxiliary power supply failures.

P_{a2} : happening probability of firing system failures.

P_{a3} : happening probability of cooling system failures.

P_{a4} : happening probability of control and protection system failures.

K_{SI} : asymmetry distribution coefficient of manipulation shock voltage.

P_V : failure probability of one valve.

p_{thi} : failure probability of thyristor element under load x_{wi} $(i=1,2)$.

I_{cr} : critical importance index.

2.2 Normal working load

Since each converter is equipped with one individual cooling system, it can be considered to work at constant temperature if only the cooling system works well. Operating voltage of valve bridges of the converter can also be supposed to be constant, since the operating voltage of DC system normally swings near the rated value. Furthermore, HVDC systems usually operate on constant power control mode, at rated load power or short-time overload power. Thereby, normal working loads of converter includes two constant cases, rated load and overload, with the following relation:

$$P_{w1}+P_{w2}=1 \tag{7}$$

According to the above discussions, the failure process of thyristors under normal working load is full independent.

2.3 Overvoltage

In order to prevent thyristors from misconducting, the protection level of valve arresters should cooperate with overvoltage capability of thyristors. However, there's still likelihood of valve's misconduction in practice, because of voltage asymmetry, nonlinear factors inside the valve and performance decentralization of arresters. All these factors may reduce the valve's interruption voltage to a level below the protection threshold of valve arresters. The influence of valve's misconduction is similar to a short circuit inside the valve. So it will cause the maloperation of the valve control and protection system, and accordingly leads to an outage of the valve. So this type of failure is the so-called FDF.

The major form of overvoltage threatening converters is manipulation overvoltage, and the value failure probability owning to overvoltage is defined as

$$P_V=P[(x_{ov}>x_{v2})\cap(x_{v1}>x_{v2})] \tag{8}$$

It should be noticed here that manipulation overvoltage is deeply concerned with operation parameters, working conditions and manipulation details of the AC and DC hybrid system, and its distribution parameters are hard to directly measure or count from the system. So, mathematical simulation methods are always needed to make a forecast.

Taking into account the distribution dependency of threshold and property, equation (8) can be transformed into:

$$P_V=P(x_{ov}>x_{v2})P(x_{v1}>x_{v2})= \int_0^\infty f_{v2}(x_{v2})\left[\int_{x_{v2}}^\infty f_{ov}(x_{ov})\mathrm{d}x_{ov}\right]\mathrm{d}x_{v2}\times \int_0^\infty f_{v2}(x_{v2})\left[\int_{x_{v2}}^\infty f_{v1}(x_{v1})\mathrm{d}x_{v1}\right]\mathrm{d}x_{v2} \tag{9}$$

2.4 Fault current load

The process of fault current flowing through converter valves is rather short and is almost an adiabatic process. The cooling system and radiators nearly don't work, so the junction temperature of thyristor will go up sharply. When the actual junction temperature becomes higher than the limit junction temperature, the thyristor will be destroyed permanently. Not only fault current generated by faults inside the converter but those generated from the AC system or DC lines will flow through the valves. Assessment of fault current distribution is similar to that of overvoltage, which needs the help of mathematical simulation methods. Using equation (2), valve failure probability under fault current load can be worked out.

2.5 Failure of supporting systems

Supporting systems, including auxiliary power supply, firing system, cooling system and control and protection system, provide basic working conditions for converter. If any of them fails, then the converter fails. So the supporting system failure events can be considered as a class of generalized lethal environment, and the corresponding system failure belongs to FDLF.

2.6 Procedure for failure probability calculation of converter

Based on the model discussed above, procedure for calculating the failure probability of an m-impulse converter with r/n redundant valves can be described as follows.

a. Calculate the probabilities of $k\,(0\leqslant k\leqslant r)$ thyristors destroyed under x_{w1} and x_{w2} respectively:

$$P_{wi,k}=\binom{k}{n}p_{thi}^{k}\times(1-p_{thi})^{n-k}\quad i=1,2$$

Consider the mutual exclusion of x_{w1} and x_{w2} and combine the probabilities of the two environments:

$$P_{w,k}=P_{w1}\times P_{w1,k}+P_{w2}\times P_{w2,k}\quad 0\leqslant k\leqslant r$$

b. Calculate the overvoltage endurance for one valve when $k\,(0\leqslant k\leqslant r)$ thyristors of it have failed:

$$x_{v2}=(n-k)x_{vv}/K_{SI}$$

Apply equation (8) to calculate the corresponding failure probability $P_{ov,k}$ of one valve.

c. Calculate failure probability $P_{oc,k}$ of $k\,(0\leqslant k\leqslant r)$ thyristors out of one valve under fault current load using equation (2).

d. Calculate failure probability $P_{V,k}$ of $k\,(0\leqslant k\leqslant r)$ thyristors out of one valve combining all the loads, taking into account the independency of working load and any other abnormal loads and using enumeration methods.

$$P_{V,k}=\left(\sum_{i=0}^{k}P_{w,i}\times P_{oct,k-i}\right)\times(1-P_{ovt,k})$$

where $P_{oct,i}=\begin{cases}1-P_{oc}+P_{oc,0}\times P_{oc} & i=0\\ P_{oc,i}\times P_{oc} & i\neq 0\end{cases}$

$$P_{ovt,k}=P_{ov,k}\times P_{ov}$$

e. Sum up the valve's working probability:

$$P_{Vw}=\sum_{k=0}^{r}P_{V,k}$$

f. Calculate the failure probability of converter taking into account supporting system failures:

$$Q_S=P_{Vw}^{m}\prod_{i=1}^{4}(1-P_{ai})$$

3 Case study

An example calculation based on the proposed method is performed on a 12-impulse converter in a 500 kV HVDC system. The converter consists of 12 valves and each valve consists of 78 thyristor elements, 3 of which are redundant. Happening probability of each load is listed in table 1. Distribution parameters for x_{ov}, x_{v1}, x_{vv}, x_{oc} and x_{cp} are listed in table 2. The failure probability of thyristor element under load x_{w1} and x_{w2} are $p_{th1}=0.002$ and $p_{th2}=0.006$ respectively. And the asymmetry distribution coefficient of manipulation shock voltage K_{SI} adopts 0.8.

Tab.1 Happening probabilities of each load

Load	Happening Probability	Load	Happening Probability
x_{w1}	0.980	x_{a1}	0.000 1
x_{w2}	0.020	x_{a2}	0.000 4
x_{ov}	0.004	x_{a3}	0.001 0
x_{oc}	0.002	x_{a4}	0.002 0

Tab.2 Norm distribution parameters

Variable	Mean value/kV	Error	Variable	Mean value/kA	Error
x_{ov}	560	15	x_{oc}	3.3	0.1
x_{v1}	506	7	x_{cp}	3.6	0.05
x_{vv}	8	0.8			

Applying the procedure discussed above, the converter's failure probability is calculated out to be 0.004 5. In order to illustrate the superiority of the proposed model more clearly, the failure probability based on a traditional model is also worked out as a contradistinctive case, which just taking into account the failures under rated load and the influence of supporting system failures. After some probability manipulation, we get 0.004 0. The latter result is 12.5 % lower than the former one. That is to say, the traditional model is optimistic in contrast to the proposed model, which is usually undesirable in practical engineering. The number 12.5 % also shows the importance of CCF events in converter's failure processes.

A valuable index named critical importance[14] is used here to evaluate the importance of each load's occurrence on system failure probability and indicate the difficulty degree of decreasing the happening probability of a disadvantageous load. It's defined as the ratio of the changing rate of system failure probability to that of the corresponding load happening probability, which is expressed as

$$I_{cr}(x_j)=\lim_{\Delta P_j\to 0}\frac{\Delta Q_S}{Q_S}\Big/\frac{\Delta P_j}{P_j}$$

Calculation results are listed in table 3.

Tab.3 Critical importance index I_{cr} for each load

Load	I_{cr}	Load	I_{cr}
x_{a3}	0.446 0	x_{w2}	0.067 7
x_{a4}	0.222 6	x_{a1}	0.022 2
x_{oc}	0.096 4	x_{ov}	2.045×10^{-8}
x_{a2}	0.089 0	x_{w1}	−3.350 1

The negative value of I_{cr} means that the occurrence of x_{w1} is in favor of reducing system failures, while the other positive values are the adverse. As seen in the table, among those bad loads with positive I_{cr}, $I_{cr}(x_{a3})$ is the biggest. That means x_{a3} has the most important influence on system failures. On the other hand, decreasing the happening probability of x_{a3} is comparatively the most effective and the easiest measure to improving system reliability.

4 Conclusions

Through load-property interference analysis, this paper presents a valuable understanding of failure modes for HVDC converter. A novel multi-environment model considering CCF events and load diversity is established and proved to be an effective model for assessing failure probability of HVDC converter.

a. Influencing factors in failure modes of HVDC converter are randomness of electrical variables, occurrence of assistant systems failures and performance decentralization of components.

b. According to endurance performances of thyristor elements, operating loads of HVDC converter can be classified into 4 major types, working load, overvoltage, fault current and supporting system failures.

c. The proposed model is proved to be more reliability and more precise than conventional ones.

d. Critical importance indices show that control and protection system failure is the most important and sensitive disadvantageous load in influencing converter failure.

CCF considerations occupy an increasingly important place in reliability engineering practice, since engineering systems are growing larger and more complex. There're still many tough issues under settlement. Models and methods for CCF are always subtle tasks. Seriously lacking of history data, immature of data managing methods and imprecision of models are all bottlenecks of reliability technological development. In a word, further work is waiting on the way.

References:

[1] BILLINTON R, AHLUWALIA D S. Incorporation of a DC link in a composite system adequacy assessment — DC system modeling[J]. **IEE Proceedings-C**, 1992, 139(3): 211-220.

[2] DIALYNAS E N, KOSKOLOS N C. Reliability modeling and evaluation of HVDC power transmission systems[J]. **IEEE Transactions on Power Delivery**, 1994, 9(2): 872-878.

[3] 任震,伍娟,陈丽芳. 高压直流输电可靠性评估的等效模型[J]. 电力系统自动化,1999,23(9):38-41.
REN Zhen, WU Juan, CHEN Li-fang. Equivalent model for HVDC reliability evaluation[J]. **Automation of Electric Power Systems**, 1999, 23(9): 38-41.

[4] 陈永进,任震. 模型组合及其在直流输电系统可靠性评估中的应用[J]. 电网技术,2004,28(13):18-22.
CHEN Yong-jin, REN Zhen. Models combination and its application in reliability evaluation for HVDC systems[J]. **Power System Technology**, 2004, 28(13): 18-22.

[5] MALHOTRA M, TRIVEDI K S. Power-hierarchy of dependability-model types[J]. **IEEE Transactions on Reliability**, 1994, 43(3): 493-502.

[6] VAURIO J K. Common cause failure models, data, duantification[J]. **IEEE Transactions on Reliability**, 1999, 48(3): 213-214.

[7] HAUPTMANNS U. The multi-class binomial failure rate model[J]. **Reliability Engineering and System Safety**, 1996, 53(1): 85-90.

[8] MANKAMO T, KOSONEN M. Dependent failure modeling in highly redundant structurals-application to BWR safety valves[J]. **Reliability Engineering and System Safety**, 1992, 35(3): 235-244.

[9] KVAM P H. A parametric mixture-model for common cause failure data[J]. **IEEE Transactions on Reliability**, 1998, 47(1): 30-34.

[10] LI W, BILLINTON R. Common cause outage models in power system reliability evaluation[J]. **IEEE Transactions on Power Systems**, 2003, 18(2): 966-968.

[11] 谢里阳,林文强. 共因失效概率预测的离散化模型[J]. 核科学与工程,2002,22(6):186-192.
XIE Li-yang, LIN Wen-qiang. A discrete model for the prediction of common cause failure[J]. **Chinese Journal of Nuclear Science and Engineering**, 2002, 22(6): 186-192.

[12] 谢里阳,林文强. 冗余系统共因失效的载荷–性能分析与概率估算[J]. 核科学与工程,2003,23(4):289-295.
XIE Li-yang, LIN Wen-qiang. Load-property interference based common cause failure mechanism analysis and probability estimation[J]. **Chinese Journal of Nuclear Science and Engineering**, 2003, 23(4): 289-295.

[13] 郭永基. 可靠性工程原理[M]. 北京:清华大学出版社,2002.

[14] 郭波. 系统可靠性分析[M]. 长沙:国防科技大学出版社,2002.

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高压直流换流器的多载荷可靠性评估模型

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摘要：传统的高压直流输电系统可靠性评估模型忽略了共因失效和负荷多样性的问题而过于乐观。应用载荷－性能干涉分析方法对高压直流换流器的失效模式和机理进行了分析说明，并根据晶闸管元件的耐受性能对换流阀的运行载荷进行分类，进而建立了一种能计及不同载荷条件的新颖的多载荷模型。为了验证所提模型的有效性，在一 12 脉波高压换流器上进行了对比算例，同时引入了关键重要度指标对不同载荷在换流器失效模式中的重要性和灵敏度进行了评价。结果表明，所提模型较之传统模型更为精确和可靠。

关键词：可靠性；载荷－性能干涉分析；多载荷模型；共因失效；负荷多样性

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