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IMPROVEMENTS ON THE HVDC RELIABILITY ASSESSMENT INDEX SYSTEM CONSIDERING PREVENTIVE MAINTENANCE

POPRAWA SYSTEMU WSKAŹNIKÓW NIEZAWODNOŚCI HVDC Z UWZGLĘDNIENIEM KONSERWACJI ZAPOBIEGAWCZEJ

This paper proposes two novel reliability indexes for HVDC and a risk evaluation system for quantifying the risk brought by HVDC outage. Based on a proactive and preventive strategy of maintenance arrangement, the paper puts forward the "Power Availability" index to correct the situation that Energy Availability leads to inconsistent problems with power system reliability and security in the process of application. Then, the paper introduces the quantitative evaluation method which provides an effective analysis tool for scheduling department to arrange maintenance during the appropriate time by judging the operation risk. Based on this method, the index of "Active Planned Energy Unavailability" is put forward in order to encourage the scheduling department to arrange maintenance initiatively according to the power grid risk. It could change and improve the maintenance mode of HVDC using the guiding role of the reliability index. Blend the proposed new index into the original reliability index system of HVDC, sphere of application and the assessment objects will not only be limited to the equipment department and the dispatching department, power grid corporations will also be involved. Finally, this paper chooses the China Southern Power Grid as the simulation and analysis case. The results demonstrate a practical application of the proposed procedure and method.

***Keywords**: power system; HVDC; reliability assessment; reliability index system; preventive maintenance.*

Niniejszy artykuł proponuje dwa oryginalne wskaźniki niezawodności dla linii wysokiego napięcia prądu stałego (HVDC) oraz system oceny ryzyka dla kwantyfikacji ryzyka na skutek przerw w dostawie HVDC. W oparciu o aktywną i prewencyjną strategię konserwacji, artykuł proponuje wskaźnik „Power Availability (Dostępności mocy)" w celu naprawy sytuacji, gdy Dostępność Energii prowadzi do niespójnych problemów z niezawodnością systemu elektroenergetycznego i bezpieczeństwem w procesie eksploatacji. Następnie artykuł wprowadza metodę oceny ilościowej, który zapewnia skuteczne narzędzie analizy dla działu planowania tak, aby można było zarządzać konserwację we właściwym momencie dzięki odpowiedniej ocenie ryzyka operacyjnego. Na bazie tej metody, zaproponowano wskaźnik „Aktywnego planowania niedostępności energii" w celu zachęcenia działu planowania do ustalania konserwacji zgodnej z poziomem ryzyka sieci energetycznej. Może to zmienić i poprawić tryb konserwacji HVDC za pomocą wskaźnika niezawodności. Proponowany nowy wskaźnik mógłby zostać wprowadzony do pierwotnego systemu wskaźników niezawodności HVDC i mógłby znaleźć zastosowanie i służyć ocenie obiektów nie tylko w działach sprzętu i dziale dyspozytorskim ale także w firmach eksploatujących sieci energetyczne. Na potrzeby symulacji i analizy, artykuł omawia przedsiębiorstwo China Southern Power Grid. Wyniki pokazują praktyczne zastosowanie proponowanej procedury i metody.

***Słowa kluczowe**: system zasilania; HVDC; ocena niezawodności; system wskaźników niezawodności; konserwacja zapobiegawcza.*

1. Introduction

HVDC means high voltage direct current. HVDC transmission has been the main technology of the power exchange cross province and power grid interconnection in the Chinese power system. The channels and size of the power transmission from west to east are still increasing during the period of the 12th Five-Year plan [17]. Optimizing the maintenance of HVDC and improving the reliability of the HVDC system play a vital role in the safe operation and risk prevention of power grid.

The purpose of maintenance is to extend the lifetime of equipment. Effective maintenance strategy can reduce the frequency and undesirable consequences of interruptions [10]. The realization of integrating power grid reliability and equipment reliability is an extremely complicated and systematic project, which need the full collaboration of the scheduling department and the equipment department. In reliability index system [7, 13], however, we regard Energy Availability as the core evaluation index of the HVDC equipment department. The reliability evaluation system is lack of index for encouraging the scheduling department to arrange maintenance actively. On the consideration of system security, the scheduling department is obliged to arrange less maintenance of the HVDC system in order to maintain a higher redundancy of it. Due to the limitation of power system dispatchers, the equipment department can't apply a greater share of maintenance frequency and duration, and have no choice but to reduce the planned maintenance. The equipment runs with defects, which will threaten the whole system reliability. According to the literature [4, 5, 18], we can see that the Energy Availability is up to 90%, but the Energy Utilization is only about 60%. The load rate of HVDC transmission isn't 100% at all times. On the contrary, HVDC channels are at a level of light load frequently.

Maintenance clearly affects component and system reliability: if done too little, this may lead to poor system performance and reliability; done too often, reliability may improve but the redundancy will sharply decrease. In a redundancy-maintenance scheme, the two expenditures must be balanced [9]. In the past, maintenance routines mostly consisted of scheduled activities carried out at regular intervals (periodic maintenance) and abrupt activities carried out after power system failure (post-fault maintenance). However, such a maintenance strategy may be ineffective: it may be too costly and may not extend component lifetime as much as possible. Along with the development of condition monitoring technology, many researchers proposed more flexible programs to replace the periodic maintenance and post-fault maintenance schedules.

The literature [1] presents an overview of two maintenance techniques: time-based maintenance (TBM) and condition-based maintenance (CBM). The paper [2] investigates human error in CBM functions and develops a systemic model for integration of human error in CBM optimization. The article [19] presents a life cycle cost (LCC) analysis with CBM strategies to improve maintenance planning for wind power industry. The paper [12] presents an overhaul scheme based on risk theory, but there is no specific research about how to evaluate the impacts of transmission equipment maintenance on the grid risk. The literature [16] proposes a quantified impact assessment of the planned outage on operation reliability of the whole transmission system. However, it only chooses the index of the expected energy not supplied (EENS) to reflect the risk degree that it is not accurate enough. Besides, reliability centered maintenance (RCM) is also applied in the maintenance strategy optimization. The document [8] presents a general straightforward RCM framework that can be easily put in practice in a power distribution network. The paper [11] proposes a modified semi-Markov chain as an equipment state model and a genetic algorithm is used to find the optimal maintenance strategies from a large class of possible maintenance scenarios.

However, the research above on maintenance strategy optimizations couldn't solve the problem essentially. Because if the reliability evaluation index system isn't adjusted, the scheduling and equipment department can't be unified. Preventive maintenance can improve power system availability and minimize related maintenance cost by arranging maintenance activities before system failure [20]. Therefore, this article proposes two novel reliability indexes which are called "Power Availability" and "Active Plan Energy Unavailability" from the perspective of preventive maintenance, and introduces the quantification evaluation method of HVDC outage risk expecting to utilize the guidance of reliability index system, to explore a new maintenance mode between scheduling and equipment department and to improve the reliability of the whole grid. Compared with the old maintenance mode, the new one, which shifts maintenance from passive to active, from emergency control to prevention, really implements the requirement of "Prevention First".

The paper is organized as follows: Section 2 presents the drawbacks of the reliability index of "Energy Availability" and defines the new index of "Power Availability". Section 3 provides a description on the quantified method for risk evaluation system of HVDC outage. Section 4 proposed the new index of "Active Planned Energy Unavailability" using the method proposed in section 3. Section 5 blend new indexes proposed in section 2 and 4 into the original reliability index system of HVDC to form the new one. Section 6 offers extensive explanations of the proposed index and risk evaluation system by using an application to China Southern Power Grid.

2. The New Index of Power Availability

In HVDC reliability index system, we regard Energy Availability as the core evaluation index of the HVDC equipment department. The reliability evaluation system is lack of index for encouraging the scheduling department to arrange maintenance initiatively. The Energy Availability is defined as following:

$$E_A = \left[1 - \left(T_f + T_s + T_d\right) / T_p\right] \times 100\% \tag{1}$$

$$T_f = \sum_{i=1}^{n_f} k_i t_i \tag{2}$$

$$T_s = \sum_{i=1}^{n_s} k_i t_i \tag{3}$$

$$T_d = \sum_{i=1}^{n_d} \frac{p_{di}}{p_m} t_i \tag{4}$$

where

E_A : Energy Availability,

T_f : forced outage hours,

T_s : scheduled outage hours,

T_d : derated capacity in service hours,

T_p : period hours,

n_f : times of forced outage,

n_s : times of scheduled outage,

n_d : times of derated capacity in service,

p_{di} : derated capacity in service of event i ,

p_m : rating transmission capacity of HVDC,

t_i : original outage hours of abnormal operation event i ,

k_i : discount factor of abnormal operation event i .

Based on the equations above, the Energy Availability can actually be expressed as following:

$$E_A = 1 - \left(\sum_{i=1}^{n_u} \tilde{k}_i t_i\right) / T_p , \tilde{k}_i = \left(p_m - \tilde{p}_i\right) / p_m \tag{5}$$

where:

$\tilde{k}_i$: the discount factor in abnormal operation event i ,

$\tilde{p}_i$: the available capacity for power transmission in abnormal operation event i and it can be defined as $\tilde{p}_i \in \left\{p_{di}, \frac{1}{2} p_m, p_m\right\}$.

Note that the discount factor $\tilde{k}_i$ could not distinguish the impacts of planned outage on the whole transmission system in different time. In other words, the same four hours of the HVDC outage, during the light load of HVDC in the evening and during the peak load in the moon, will have the same contribution to the Energy Availability due to the same the discount factor $\tilde{k}_i$. This is obviously unreasonable due to the different risk of the whole transmission system brought by HVDC outage under different load level.

Therefore, a new index named "Power Availability" is proposed by authors to improve the index of Energy Availability in literature [14]. It can reflect the HVDC system's ability of ensuring the actual transmission demand of the power grid, defined as follows:

$$O_A = 1 - \left(\sum_{i=1}^{n_u} w_i t_i\right) / T_p , w_i = \left(\tilde{p}_{i,m} - \tilde{p}_i\right) / \tilde{p}_{i,m} \tag{6}$$

where:

O_A : Power Availability,

w_i : the improved discount factor in abnormal operation event i ,

$\tilde{p}_{i.m}$: the expected demand for energy transmission of the HVDC system in the abnormal operation event i ,

n_u : the total number of abnormal operation event during period, which can be calculated as $n_u = n_f + n_s + n_d$.

$\tilde{p}_{i.m}$ can be calculated by averaging the value of maximum power transmission of HVDC during the periods which is close to the time of abnormal operation event. Equation (5), (6) shows that the equation of Power Availability is similar to Energy Availability, because they are made up of statistical data of equivalent outage hours. However, Compared with the Energy Availability index, the new index uses transmission power expected demands during the HVDC maintenance period rather than HVDC transmission capacity to reflect the real equivalent outage hours. The new index embodies the right timing chosen of the monopole outage maintenance arrangement. When the monopole planned maintenance occurs in the period of low load level and low demand of HVDC transmission power, w_i will be lower than k_i according to equation (5–6). Therefore, the corresponding equivalent outage hours will be reduced in the new index. It is more suitable for actual situation.

Using the new index to assess reliability can guide the HVDC operation department to applying for maintenance actively when operating personnel find the system hidden danger. It guides to arrange maintenance during the valley load of power grid under the lowest risk of the whole grid.

3. The Risk Evaluation System of HVDC Outage

If "Power Availability" can be added into the evaluation index system, it will be able to guide the equipment department to apply for maintenance initiatively. Yet, the scheduling department will face new challenges. Because there is no suitable risk analysis tool to quantify the effects that HVDC maintenance make on the whole grid reliability in order to arrange HVDC maintenance until now. In this section, the risk evaluation system is proposed using a quantified impact assessment of HVDC planned outage on the whole power system.

The quantified transmission system reliability methods have been researched for many years [13–16], but not quite utilized in HVDC maintenance planning. The two evaluation methods are enumeration and Monte Carlo simulation. Due to the request of computing speed, this paper chooses enumeration method to evaluate reliability. The following subsection will introduce the procedure of the risk evaluation system.

3.1. Suitable Reliability Indexes to Reflect System Risk

The literature [16] proposes a quantified impact assessment of the planned outage on operation reliability of the whole transmission system. However, it only chooses the index of the expected energy not supplied (EENS) to reflect the risk degree that it is not accurate enough. First, EENS could not reflect the difference between high load and light load power system, meaning that the same EENS in the transmission system with different load demand will have the same evaluation result. It is not reasonable. Through the analysis of all HVDC reliability evaluation indexes, we find that the index which mainly reflects the power system operation risk is the loss of load probability (LOLP) and security index (SI). Therefore, we choose those two indexes to represent the probability of occurrence and the consequence of the failures instead of EENS index. They are defined as follows:

1) Loss of Load Probability [6]

The index reflects the probability risk of load reduction occurring in grid under the specified failure set. The formula is as follows:

$$L_{LOLP} = \sum_{d \in S} I_f(x) P_d(x) \tag{7}$$

$$P_d(x) = \prod_{i=1}^{n_f} PF_k(x) \prod_{i=1}^{n-n_f} PF_{\tilde{k}}(x) \tag{8}$$

$$PF_k(x) = \lambda_k / (\lambda_k + \mu_k) = \lambda_k r_k / (\lambda_k r_k + 8760) \tag{9}$$

$$PF_{\tilde{k}}(x) = \mu_{\tilde{k}} / (\lambda_{\tilde{k}} + \mu_{\tilde{k}}) = 8760 / (\lambda_{\tilde{k}} r_{\tilde{k}} + 8760) \tag{10}$$

where:

S : fault set, $d \in S$,

$P_d(x)$: the probability of fault d under operation mode x , $k \in d$,

$PF_k, \lambda_k, \mu_k, r_k$: the unavailability, fault rate, repair rate and average repair time of fault component k , non-failure component $\tilde{k}$ is in a similar way,

$I_f(x)$: binary function which uses the system fault state as the independent variable, its expression is:

$$I_f(x) = \begin{cases} 1, \text{Having load shedding} \\ 0, \text{Don't have load shedding} \end{cases} \tag{11}$$

2) Security Index[3]

$$SI = \frac{L_{EENS}}{L_{\max}} \times 60 \tag{12}$$

$$L_{EENS} = \sum_{x \in \varphi} I_f(x) L_c(x) t(x) P(x) \tag{13}$$

where:

$L_{\max}$: the peak load of system,

$L_c(x)$: the minimum load shedding under the operation x,

$t(x)$: the duration from load shedding to power supply restored.

Second, putting all contingency evaluation result into one index will lead to situation that the single contingency result will cover the double or triple contingency result due to high frequency of one single contingency. It is not conform to trend that the scheduling department is concerning high-order failures increasingly. Moreover, scheduling departments use N-1 criterion, which means that any one single failure will not cause load shedding from the state with all elements in services, as checking method to ensure the safe and stable system operation at present. Therefore, the dispatching department's treatment must be fully considered. In order to make a difference between N-1 and other high-order contingency, this paper divides the risk evaluation indexes into three parts shown in the following text.

1) Risk index under N-1 fault

$$CIN1_i = \sum_{m \in \theta} W_{m1} \times \left(RI_{m1}(A) + RI_{m1}(B) \right) \tag{14}$$

where:

i : HVDC channel,

θ : grid reliability indexes set, this paper chooses LOLP and SI,

W_{m1} : the weight of index m under $N-1$ fault,

$RI_{m1}(A)$ and $RI_{m1}(B)$: the reliability indexes under $N-1$ fault when HVDC channel i is in normal operation and exit operation.

By definition, only if both index results of the operation A and B are zero, the evaluation index $CIN1_i$ of HVDC channel i will be zero.

2) Risk index under N-2,

$$CIN2_i = \sum_{m\in\theta} W_{m2} \times \frac{RI_{m2}(B) - RI_{m2}(A)}{RI_{m\bullet\max}(A)} \tag{15}$$

3) Risk index under N-3 and N-4 fault

$$CIN3,4_i = \sum_{m\in\theta} W_{m3,4} \times \frac{RI_{m3,4}(B) - RI_{m3,4}(A)}{RI_{m\bullet\max}(A)} \tag{16}$$

where:

W_{mk} : the weight of index m under $N-k$ fault, $k \in \{2,3,4\}$,

RI_{mk} : the reliability indexes under $N-k$ fault, $k \in \{2,3,4\}$,

$RI_{m.\max}(A)$: the maximum reliability indexes of the history for the normal operation of HVDC channel i .

The value of W_m should continue to be optimized based on the application. It depends on the importance of the LOLP and SI judging by scheduling department.

Those three risk indexes could not only ensure that the HVDC maintenance meet the N-1 criterion, but also ensure that the higher order contingency will not be covered by lower order contingency. We could draw up different threshold of each risk index to guide the HVDC planned maintenance. Meanwhile, this paper mainly analyzes the reliability indexes of the thermal stability. Depending on the demand of the risk evaluation, the dynamic security analysis including transient and voltage stability could also been involved for a comprehensive evaluation.

3.2. Selection of Contingency Set

According to the definition of risk indexes under different i-th order contingency, it is obvious that we could select only a small part of the original contingency which has larger contribution to the risk indexes to form the contingency set. It will sharply decrease the computing time. According to literature [15] and the calculation of this paper, the fault sets which largely impact the reliability index are on a parallel channel of HVDC. Particularly in CSG, the contingency set will be limited to those AC transmission lines of West-east power transmission project which are parallel with HVDC transmission system. Therefore, we can not only bring the lower probability and high risk of multiple failures which wasn't considered in the past reliability evaluation, but also reduce the fault set needed scanning significantly. It provides a probability for online application of scheduling department.

3.3. Evaluation of Failure System States

1) Contingency Analysis

The purpose of contingency analysis is to identify whether or not there is overloading, voltage violation and isolated island when there is some component failures. The basic two analysis methods are AC power-flow-based sensitivity and DC power-flow-based sensitivity methods. This paper chooses the latter method because it could provide fast and sufficiently accurate real power flow in the large power system.

2) Optimization Models for Load Shedding

If there is system problem following the component failures, an optimization model for load shedding is used to reschedule generation, alleviate power flow and voltage violations and avoid load shedding. If it is unavoidable, a load shedding linear optimization model should be utilized to minimize the total load curtailment.

To improve the calculation efficiency of reliability assessment of large power system, the authors propose an approach to local load shedding strategy by introducing a weighted factor α_i of each load bus i into the original objective function of linear programming model. The linear programming model based on DC power flow can be mathematically expressed as follows:

$$\min \sum_{i\in NL} \alpha_i C_i \tag{17}$$

subject to:

$$\mathbf{T}(S) = \mathbf{A}(S)(\mathbf{PG} - \mathbf{PD} + \mathbf{C}) \tag{18}$$

$$\sum_{i\in NG} PG_i + \sum_{i\in NL} C_i = \sum_{i\in NL} PD_i \tag{19}$$

$$PG_i^{\min} \le PG \le PG_i^{\max} \quad (i \in NG) \tag{20}$$

$$0 \le C_i \le PD_i \quad (i \in NL) \tag{21}$$

$$|T_k(\mathrm{S})| \le T_k^{\max} \quad (k \in L) \tag{22}$$

where:

S : system state following component failures,

$\mathbf{T}(S)$: real power flow vector in the outage state, $T_k(\mathrm{S})$ is its element,

$T_k^{\max}$: the upper limits of $T_k(\mathrm{S})$,

$\mathbf{A}(S)$: relation matrix between the real power flows and power injections in the outage state S ,

$\mathbf{PG}$: generation output vector, PG_i is its element,

$PG_i^{\min}$ and $PG_i^{\max}$: lower and upper limits of PG_i ,

$\mathbf{PD}$: load power vector, PD_i is its element,

$\mathbf{C}$: load curtailment vector, C_i is its element,

NG :set of generation buses,

NL :set of load buses,

L :set of circuits,

α_i : weighted factor of each load bus i which presents local load shedding scheme.

The value of weighted factor α_i depended on the electric distance between failure component and load bus *i*. Those load buses connected to the failure component *i* directly are defined as 1 degree buses. Then those load buses connected to 1 degree buses directly are defined as 2 degree buses. By that analogy, we could define N degree buses. There are positive correlation between the value of weighted factor α_i and the degree of load bus. In other words, when the load buses are quite far away from the failure component meaning the larger degree of load bus, weighted factor α_i should take larger value, otherwise, should take a smaller value.

3.4. The Risk Index Threshold of HVDC Planned Outage

Based on calculation of historical operation data and advices of dispatching department, risk indexes threshold that power grid allows bringing by HVDC outage could be summarized. Comparing the risk calculation result of the actual operation mode with those threshold standards, the planned maintenance outage suggestions could be easily obtained. Obviously, the threshold of CIN1, CIN2 and CIN3,4 will be different with each other. Moreover, the threshold standards are different for the different grids. Based on the definition of risk indexes and the procedure of HVDC reliability assessment, a computer program has been developed under the environment of Matlab2012a and applied in China Southern Power Grid (CSG). According to the historical operation data of CSG, the threshold of risk indexes can be concluded as shown in Table 1.

Of course, other HVDC transmission systems could also obtain the risk indexes threshold using the program developed by authors according to historical operation data and evaluation demand of the scheduling department. Once the threshold of risk index confirmed, the scheduling department could arrange HVDC planned maintenance by quantifying the impact that the HVDC system outage in the specified period made on system reliability.

Table1. The Risk Index Threshold of CSG HVDC Outage

HVDC System	Outage	CIN1_ threshold	CIN2_ threshold	CIN3, 4_ threshold
All HVDC System	Monopole	0	40	25
	Bipole	0	40	25

The judgment for maintenance of HVDC can be achieved basing on the overhaul criterion as shown in Table 1, which is helpful to optimize the actual maintenance strategy. When the risk indexes meet all of the following conditions, it could be recommended for the HVDC maintenance. The conditions are:

1) The risk evaluation result index CIN1=0;
2) The risk evaluation result index CIN2< CIN2 threshold;
3) The risk evaluation result index CIN3,4<CIN3,4 threshold;

In order to simplify the judgment for maintenance time of HVDC, it is proposed to split the judgment process into following three steps:

1) Firstly, if the evaluation result index CIN1 is not equal to zero, it is not necessary to judge other conditions and could directly draw the final conclusion of no HVDC maintenance.
2) Secondly, if the CIN1=0, it is suggested to compare the evaluation result index CIN2 with the CIN2 threshold. If the condition (2) as shown above is unsatisfied, it is not recommended for the HVDC maintenance too.
3) Finally, in the similar way, we could judge the condition (3). If all conditions are met by the evaluation result, the HVDC system could be suggested for planned maintenance.

4. The new index of Active Planned Energy Unavailability (APEU)

To reflect the value of the dispatching departments to actively arrange maintenance, this article proposes the concept of "Active Planned Outage Hours (APOH)", constructs "Active Planned Energy Unavailability (APEU)" index, in order to combine the maintenance arrangement with the guidance of the reliability index system perfectly. The outage time that is scheduling department actively arranged is called APOH. According to statistics of APOH during the period of the research time, it can further form APEU. In this section, there are extensive explanations of the definition and calculation method of the proposed indexes.

4.1. The Discriminant Conditions of Maintenance

Assuming that the time interval is T, t_f and t_e is the beginning and ending of T. According to the need of the precision of the evaluation, dispatching department calculate possible largest operation mode ($m_{max,i}, i = 1, 2, ..., k$, k is the total number of the operation mode) during the period. Assuming that $R(m,h)$ is the risk assessment result of HVDC channel h under the operation mode m, it can be obtained by HVDC shutdown the risk evaluation system. $I(R)$ is a binary function based on the results of the evaluation system, defined as follows:

$$I(R) = \begin{cases} 1, \text{Having maintenance condition} \\ 0, \text{Don't have maintenance condition} \end{cases} \quad (23)$$

The results of whether the HVDC transmission systems have the maintenance condition in time interval T can be calculated as equation 24:

$$C_J = \prod_{i=1}^{k} I\left(R\left(m_{\max,i}, h\right)\right) \quad (24)$$

If $C_J = 1$, that is, all of the operation mode having maintenance condition and the HVDC channel h could arrange maintenance; If $C_J = 0$, that is, there are at least one operation mode does not meet the maintenance condition, the maintenance of the HVDC channel is not recommended during the period of T.

4.2. Calculation Method of Active Planned Outage Hours (APOH)

Getting all periods of maintenance time as mentioned above together that can be actively arrange shutdown for dispatching department. Assuming that the research time is d and the length of d is 1 day, it can be divided into 24 hours, expressed as $T(d,k), 0 \le k \le 23$. Each interval can be represented as $[t_{start}(d,k), t_{end}(d,k)]$ .Assuming that $m_{\max}(T(d,k))$ is the biggest operation mode during all time periods, the valid period time H which complies with the standards of the maintenance of the HVDC system can be calculated as follows:

$$\begin{cases} H = [t_{start}(d,n), t_{end}(d,m)] \\ \prod_{k=n}^{m} I(R(m_{\max}(d,k),h)) = 1 \\ n \le m, \text{且} \ n,m = \{i \mid 0 \le i \le 23\} \end{cases} \quad (25)$$

In the equation (25), n and m is the beginning and the ending of H.

Assuming that there are r periods of shutdown time and the i-th period is expressed as H_i, the set of all shutdown time is $S_d = \{H_i \mid i = 1, 2, ..., r\}$. If the dispatching department arrange H_i to maintenance in the actual operation, $\sum_{i=1}^{m} H_i$ is called "Active Planned Outage Hours".

4.3. Active Planned Energy Unavailability (APEU)

Energy availability is the core of the current reliability evaluation index, and it can be divided into Planned Outage and Forced Outage which including derated capacity in service. Based on the definition of "Active Planned Outage Hours", the Planned Outage can be divided in two parts, one is Passive Planned Outage (PPO) and the other is Active Planned Outage (APO). PPO means the outage that the operation department applies to the dispatching department due to equipment defects; APO symbolizes that the dispatching department take the initiative to arrange maintenance under the precondition of system reliability allowance. Obviously, APO is the Planned Outage currently using.

Based on the definition above, this article divides Planned Energy Unavailability (PEU) into Passive Planned Energy Unavailability (PPEU) and Active Planned Energy Unavailability (APEU). According to the statistical data of the whole year, the calculations expresses as the following formula:

$$PPEU = \frac{PPOH}{PH} \times 100\% \quad (26)$$

$$APEU = \frac{APOH}{PH} \times 100\% \quad (27)$$

where PPOH and APOH are Passive and Active Planned Outage Hours respectively; PH is Period Hours during the research.

Table 2. Reliability Index System of HVDC Transmission System

Reliability index	Evaluation Object	Evaluation Nature	Guidance
Active Planned Energy Unavailability	Dispatching department	Encouragement	The higher the better
Forced Outage Times	Equipment department	Punishment	The lower the better
Forced Energy Unavailability			
Passive Planned Energy Unavailability			
Power Availability			
Energy Availability	Power Grid Corporation	Statistical analysis	The higher the better
Energy Utilization			

5. A New Reliability Index System for HVDC Assessment

Blend new indexes proposed in section 2 and 4 into the original reliability index system of HVDC, the range of use and the assessment objects will not only be limited to the equipment department, but also involve the dispatching department and power grid corporations. A new reliability index system of HVDC is shown in the Table 2. The guiding role of the new reliability index system is mainly reflected in:

- Using "Active Planned Energy Unavailability" to reflect the job value of scheduling department. The power grid corporation can take incentive measures to encourage the scheduling department to arrange maintenance during the valley load as much as possible. The scheduling departments assess the system risk comprehensively by calculation and initiatively arrange maintenance on the premise of guaranteeing the system reliability redundancy, in order to find the best balance of planned maintenance and power system reliable operation. It also reflects the level of power network operation;
- Using Forced Outage Times, Forced Energy Unavailability, Passive Planned Energy Unavailability and Power Availability to evaluate the equipment department. In fact, it puts forward higher requirements on equipment department. They need to do the daily inspection, state detection and make dynamic equipment maintenance plan more carefully. Once finding equipment hidden defects, the equipment department should find the most suitable period using the maintenance risk evaluation system, and apply to scheduling department for maintenance. Once the maintenance plan approved, they should increase the intensity of equipment maintenance and eliminate the equipment defect quickly, in order to ensure the healthy operation of HVDC. If they cannot do the job well leading force outage or equipment damage, the result will be reflected in the Forced Energy Unavailability or Passive Planned Energy Unavailability. It requires the equipment department more meticulous and more careful.
- Energy Availability and Energy Utilization are the comprehensive results of five indexes above. It can be used for statistical analysis to power grid corporations.

6. Case Study

This section uses the 500 kV equivalent network of China Southern Power Grid as a simulation case to illustrate the value of new index in the guiding role of maintenance. The authors have a detailed example analysis of "Power Availability" index in the literature [14]. The following text will explain the HVDC outage risk index mainly.

The grid contains 8 circuits of 500 kV HVDC transmission line, 51 power plants, 357 circuits of 500 kV and 25 circuits of 220 kV AC transmission lines. The fault set includes: all of the N-1 faults and multiple fault considered to 4-order (N-4), which is in parallel with HVDC or close to the rectifier or the inverter station. The current equipment maintenance is separated into four categories [21]: planned maintenance, temporary maintenance, emergency maintenance and post-fault maintenance. Planned maintenance, referring to the monthly schedule maintenance, belongs to the maintenance schedule for a long time. However, the temporary and emergency maintenance requires at least 1-3 days before submitting an application, belonging to the maintenance of a short time. In this paper, the risk evaluation system of HVDC has a better guidance of both.

If the dispatching departments receive the emergency repair application of monopole outage in "Gaopo-Zhaoqing HVDC" on April 1, firstly, they will divide the load curve into 24 hours and taking the

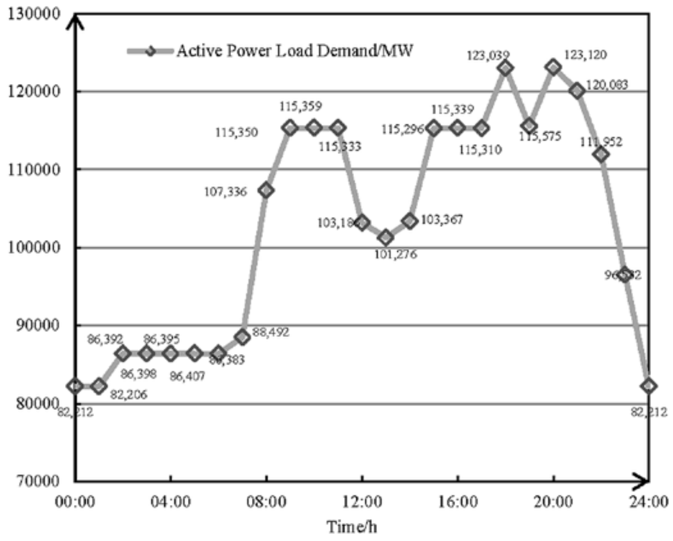

Fig.1. Biggest Forecasting Active Power Load Demand in Each Hour on April, 1

Table 3. The Evaluation results of Gaopo-Zhaoqing HVDC System During the Period of [20:00-21:00]

Operation modes	N-1			N-2			N-3,4		
	LOLP	SI	CIN1	LOLP	SI	CIN2	LOLP	SI	CIN3,4
Maximum of history	0	0	——	1.40E-07	5.62E-07	——	1.85E-10	4.4538E-09	——
Normal operation	0	0	——	1.40E-07	3.11E-07	——	8.908E-11	5.7892E-10	——
Monopole outage	0.000352	0.001465	0.091%	4.88E-07	3.51E-06	409.18%	1.688E-10	2.4751E-09	42.84%

Table4. Comparison of Evaluation Results During Three Periods

Duration	CIN1	CIN2	CIN3, 4	Whether or not be outage
[00:00-01:00]	0%	0%	0%	yes
[08:00-09:00]	0%	75.42%	23.48%	no
[20:00-21:00]	0.09%	409.18%	42.84%	no

biggest operation modes in each hour to form green lines in Figure 1. Then input the data of green line into the software developed by authors to calculate the reliability indexes (LOLP, SI) and outage risk indexes (CIN1, CIN2, CIN3,4), in order to obtain the advice of outage. The results of system peak load period [20:00-21:00] shows in Table 3. Comparing with the results of valley load period [00:00-01:00] and the waist load period [08:00-09:00], the results show in Table 4.

The Figure1 shows that the power grid in [20:00-21:00] is in the highest load level. During this period, HVDC power transmission is higher than other periods, and the effect on the system reliability is more obvious, so the shutdown risk significantly higher than the other two periods. CIN1>0 illustrate that the power flow is so heavy that power system cannot satisfy the rule of N-1, so it isn't recommended outage.

Because the period [00:00-01:00] is in the morning, the system has the minimum load, HVDC operates in a light load and AC transmission lines are with high transmission redundancy. Therefore, the risk is so low that HVDC outage almost has no visible influence on the system reliability. Hence, it can arrange shutdown maintenance.

During the waist load period [08:00-09:00], although the grid can satisfy the rules of N-1, system risk value as high as 75% is nearly two times higher than the threshold that the power grid can accept under N-2 fault. Moreover, the risk index is close to the threshold under N-3, 4 faults. Therefore, this period is not recommended to arrange maintenance.

Similarly, we can calculate the risk value of other periods to draw the Figure 2. The Figure 2 shows that system highest risk period is

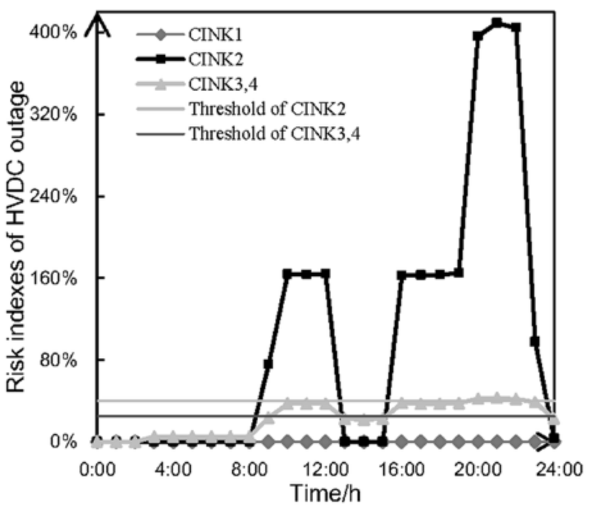

Fig. 2. Risk indexes of Gaopo-Zhaoqing HVDC system on April, 1

at the peak load time [20:00-21:00], while the lowest risk is at valley load [00:00-01:00]. It illustrates that the risk value of HVDC outage is positively related to the system load level.

Moreover, Figure 2 shows that the allowed shutdown periods are [00:00-00:08], [12:00-15:00] and [23:00-24:00]. The long period time for "Gaopo-Zhaoqing HVDC" monopole shutdown overhaul is [00:00-8:00]. We can also calculate the risk value of the last day to get longer continuous outage time, facilitating maintenance which needs a longer time to repair. [12:00-15:00] is the shorter period. Although the risk index of CIN3, 4 is approximate to threshold, the probability of 3 order and 4 order failure is low. The scheduling department can decide whether or not to arrange maintenance after weighing the pros and cons.

According to the maintenance periods provided by scheduling department, the equipment department makes a final choice after taking all factors into consideration, such as weather, personnel, length of repair time and maintenance during day or night. On actual operation, scheduling department will adjust operation mode after arranging the HVDC shutdown, such as reducing the generator output of Yunnan and Guizhou province and increasing generator output of Guangdong province, to reduce transmission power of HVDC. Therefore, the actual risk value is lower than the calculation.

This method is also suitable for the maintenance schedule of longer duration, as long as increasing assessment time ranges appropriately. For lasting for several days or even weeks maintenance, we can use the biggest daily operation mode or the biggest weekly operation mode as a unit to analysis the grid risk value.

7. Conclusion

This paper proposes two novel indexes to improve the original reliability index system of HVDC from the perspective of preventive maintenance. It gives theoretic support to promote the HVDC maintenance mode from the aspects of reliability index and evaluation algorithm. The new reliability index system is proposed from the perspective of grid benefit maximization, balancing short-term and long-term interests effectively, balancing equipment efficiency and system efficiency. The proposed index of "Power Availability" could reflect the impacts of planned maintenance which is arranged in different time on the whole transmission system. "Active Planned Outage Hours (APEU)" is put forward from a higher point of management which will boost the connectivity and cooperation between scheduling department and equipment department to find a good balance between maintenance and security operation. The proposed risk evaluation system provides a tool for scheduling department to choose suitable time to arrange HVDC maintenance. This paper using the risk based approach to arrange HVDC maintenance planning is a pioneering work.

Currently, the risk based approach could only be used to assessing the impact of HVDC outages make on the power system reliability. However, it can be expanded to the risk evaluation of AC transmission line maintenance in the future, thereby realizing the general algorithm of outage risk assessment and maintenance timing chosen for AC and DC transmission line. Moreover, when the integration and sharing of operation mode analysis software, the reliability assessment software and scheduling on-line analysis software on the basic data platforms could be achieved, the comprehensive guidance for the power grid maintenance will be truly realized.

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