Reliability Evaluation of UHVDC Transmission Systems with Hierarchical Connection Mode

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***Abstract*—Compared with the typical ultra HVDC (UHVDC) system, the inverters of the UHVDC system with the hierarchical connection mode (UHVDC-HCM) connect two receiving-end systems with different operation conditions, causing that the corresponding conversion units (CUs) at different terminals need to be differentiated in reliability modeling, and the spares should be set separately. A reliability model of the UHVDC-HCM system is proposed in this paper. The operating modes are classified by the capacities of the total system and the transmission powers to the two receiving-ends. Considering the independent spares of the components of the CUs at different terminals, the state space is derived. Two sets of indices are newly proposed to evaluate the system reliability more accurately. Based on the matrix description of the frequency & duration (F&D) method, the sensitivities of the reliability indices to the reliability parameters of the components are quantified. Numerical results validate the feasibility of the proposed model. The vulnerabilities are recognized by the sensitivity analysis, and the impact of different spare schemes on the reliability indices and sensitivities are compared. The proposed model and indices provide reference for the practical UHVDC-HCM projects.**

***Index Terms*—Frequency & Duration (F&D), Hierarchical connection, Reliability indices, Reliability model, Ultra HVDC (UHVDC).**

NOMENCLATURE

Abbreviations

HVDC	High-voltage DC.
UHVDC	Ultra HVDC.
HCM	Hierarchical connection mode.
HT, LT	High-terminal, low-terminal.
CU, CT	Conversion unit, converter transformer.
C&P, CS	Control & protection, converter station.
Val, SmR	Valve, smoothing reactor.
ACF, DCF	AC filter, DC filter.
PE	Pole equipment.
DCL	DC line.
Y, Δ	CTs' windings (Y/Y and Y/Δ).
F&D	Frequency & duration.
EA, BA	Energy availability, bipolar availability.
EOH	Equivalent outage hours.
EA-RH	EA of the receiving-end with higher voltage.
EA-RL	EA of the receiving-end with lower voltage.
MEA	Mismatch energy availability.
DA	Disconnection availability.
(U)BTA	(Un)balanced transmission availability.

Notations

λ, μ, γ	Failure, repair, and installation rates.
s	operating modes of UHVDC-HCM system.
$\boldsymbol{A}=[a_{ij}]$	Transition rate matrix before aggregation.
P, f, d	State probability, frequency, and duration.
$\boldsymbol{M}$	Equivalent matrix.
z	Reliability parameter.

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I. INTRODUCTION

RECENTLY, the UHVDC transmission system with the hierarchical connection mode (UHVDC-HCM) has been developed, and several UHVDC-HCM projects have been put into operation in China [1]. The inverter-side of the UHVDC-HCM system, as shown in Fig. 1, connects two receiving-end systems with different operation conditions [2]. Generally, the inverters at the high-terminal (HT) and the low-terminal (LT) connect the receiving-ends with the lower and higher voltages respectively [3-6]. Thus the components of the corresponding conversion units (CUs), such as the valve (Val), converter transformer (CT), and control & protection (C&P), need to be differentiated, and the spares should be set separately. Besides that, due to the independent reactive power control between the UHVDC and two receiving-end systems, the AC filters (ACFs) are also set independently [7].

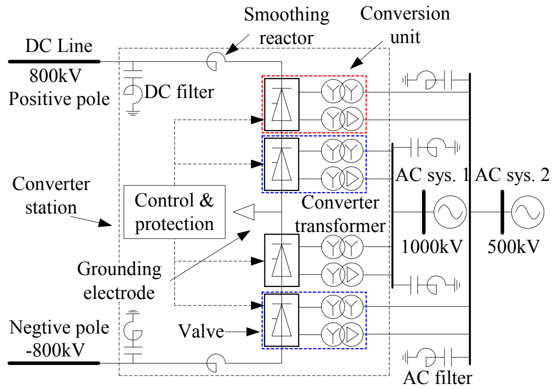

Fig. 1. Configuration of the inverter-side of UHVDC-HCM system

Considering the ±800kV Ximeng-Taizhou UHVDC-HCM project, the transmission distance of the project is 1619.7km, and the rated capacity and current are 10000MW and 6.25kA respectively. The voltage of the sending-end is 500kV, while in the converter station (CS) of the inverter-side, i.e. Taizhou station, half of the rated capacity are transferred to the receiving-ends with 1000kV and 500kV respectively [8]. Any outage of the components may lose the transmission powers to the two receiving-ends, causing a significant impact on the power system. Thus the reliability evaluation and vulnerability recognition of the UHVDC-HCM system may be conducive to the security operation of the power system [9-10].

However, up to now, not many literatures on the reliability evaluation are available for the UHVDC-HCM system, and the related researches are focused on the HVDC and typical UHVDC systems, with the method of the series-parallel configuration [11, 12], fault tree analysis (FTA) [13, 14], Monte Carlo sampling (MCS) [15, 16], and state enumeration [17, 18], etc. There are some problems for reliability evaluation based on these methods. For the series-parallel configuration, the availability of the total system is underestimated by multiplying availabilities of the series components due to the imaginary sates of common failures [19]. FTA has difficulty with the multiple-state components or to yield failure frequency/duration. MCS needs large calculation effort due to the requirement of the accuracy and non-effective samples [20].

By comparing the accuracy and calculation effort, the state space is the desirable choice. Due to the difficulty of drawing the complete state space of the UHVDC-HCM system directly, the reliability equivalence i.e. aggregation and combination, is applied. The author has proposed the matrix description of the frequency & duration (F&D) method in [21], where the manual lookup is substituted by the equivalent matrix for the state aggregation, with the merits of fascinating the reliability equivalence. Besides, the sensitivities of the reliability indices at the top layer to the reliability parameters at the lower layer are defined by the explicit function based on the matrix, which avoids the calculation efforts caused by the traditional method of continuously changing the parameters.

In this paper, considering the separate modeling and spares of the components of the inverters at different terminals, the reliability model of the UHVDC-HCM is newly proposed. The operation modes are classified by the capacities of the total system and the transmission powers to the two receiving-ends. Two sets of the indices are proposed to evaluate the system reliability more accurately. The reliability equivalence is derived based on the matrix description of the F&D method, and the vulnerabilities are recognized by the sensitivity analysis. Numerical results give the reliability indices with different spare schemes, and the sensitivity helps to quantify the impact of the components on the system reliability. The proposed model and indices provide reference for the practical UHVDC-HCM projects.

II. Structure and Operation Modes of UHVDC-HCM System

In general, the UHVDC-HCM system is classified by the CS and DC line (DCL). Due to the bulk capacity, each CS has 4 CUs, yielding 6 capacities of the total system, i.e. 100%, 75%, 50%, 2×25%, 25%, and 0. Reference [22] indicates that the outage of a CU reduces the capacity by 25%, and the outage of a pole equipment (PE) reduces the capacity by 50%. For the UHVDC-HCM system, since the special structure which is mentioned above, the ACFs of the inverters belong to the CUs, while the ACFs of the rectifiers belong to the PE. In addition, to reduce the 3rd order harmonics, a CU include 3 CTs of Y/Y windings and 3 CTs of Y/Δ windings [23], and different types need to be differentiated when considering the spares.

Considering the capacities of the total system and the transmission powers to the two receiving-ends, there are 8 operating modes for the UHVDC-HCM system:

1) Bipolar mode (s_1);

2) 3/4 bipolar mode with the outage of the HT converter (s_2): with the outage of one converter at HT, one pole is up while the other one is partially down. The transmission powers to the receiving-ends with the higher and the lower voltage are 50% and 25% of the rated capacities respectively;

3) 3/4 bipolar mode with the outage of the LT converter (s_3): one of the converters at LT is down, showing that the transmission powers to the receiving-ends with the higher and lower voltage are 25% and 50% of the rated capacities respectively;

4) Monopolar mode (s_4);

5) 1/2 bipolar mode with disconnection (s_5): the HT or LT converters are totally down to yield the disconnection between one of the receiving-end systems and UHVDC -HCM system;

6) 1/2 bipolar mode (s_6): two poles are partially down with the outage of the CUs at different terminals. For example, as shown in Fig. 1, the converters with the blue dotted box are outage, and the AC systems are all connected with the UHVDC-HCM system;

7) 1/2 monopolar mode (s_7);

8) Bipolar outage (s_8).

Table I shows the capacities of the positive and negative poles and the transmission powers to the two receiving-ends of each operating mode.

TABLE I
CAPACITIES AND TRANSMISSION POWERS OF DIFFERENT OPERATING MODES

Operating modes	System capacity	Capacity of different poles (positive/negative)	Transmission powers to the two receiving-ends (higher/lower)
s_1	100%	50%/50%	50%/50%
s_2	75%	25%/50% or 50%/25%	50%/25%
s_3	75%	25%/50% or 50%/25%	25%/50%
s_4	50%	0/50% or 50%/0	25%/25%
s_5	50%	25%/25%	0/50% or 50%/0
s_6	50%	25%/25%	25%/25%
s_7	25%	25%/0 or 0/25%	0/25% or 25%/0
s_8	0	0/0	0/0

III. Reliability Indices of UHVDC-HCM System

The reliability indices widely used for the HVDC and typical UHVDC systems are concerned with the capacity, probability and duration, such as the energy availability (EA), bipolar availability (BA), and equivalent outage hours (EOH), etc [24]. However, for the UHVDC-HCM, the powers transmitted to the two receiving-ends may not be well described by the existing reliability indices. For example, the energy availabilities of s_2 and s_3 are both 75%, but the transmission powers to the receiving-ends are different. In addition, the existing reliability indices do not include the disconnection probability between the UHVDC and AC systems.

This paper proposes 6 new reliability indices for the UHVDC-HCM systems, which may be classified to two sets: one is involved in the energy, while the other is involved in the probability. The indices involved in the energy include:

1) Energy availability of the receiving-end with higher voltage (EA-RH): the power transmitted to the receiving-end with higher voltage.

2) Energy availability of the receiving-end with lower voltage (EA-RL): the power transmitted to the receiving-end with lower voltage.

3) Mismatch energy availability (MEA): the difference of the transmission powers to the two receiving-ends.

The indices involved in the probability include:

1) Disconnection availability (DA): the probability of the disconnection between the AC systems and UHVDC system.

2) Balanced transmission availability (BTA): the probability of equal powers transmitted to the two receiving-ends.

3) Unbalanced transmission availability (UBTA): the probability of unequal powers transmitted to the two receiving-ends.

The expressions of the aforementioned reliability indices are given in Table II, where P_i is the probability of s_i.

TABLE II
EXPRESSION OF RELIABILITY INDICES

Indices	Expression
EA-RH (100%)	$100(\frac{1}{2}P_1+\frac{1}{3}P_2+\frac{2}{3}P_3+\frac{1}{2}P_4+\frac{1}{2}P_5+\frac{1}{2}P_6+\frac{1}{2}P_7)$
EA-RL (100%)	$100(\frac{1}{2}P_1+\frac{2}{3}P_2+\frac{1}{3}P_3+\frac{1}{2}P_4+\frac{1}{2}P_5+\frac{1}{2}P_6+\frac{1}{2}P_7)$
MEA (100%)	$100(\frac{1}{3}P_2+\frac{1}{3}P_3+P_5+P_7)$
DA	$P_5+P_7+P_8$
BTA	$P_1+P_4+P_6$
UBTA	$P_2+P_3+P_5+P_7$

IV. RELIABILITY EQUIVALENCE TO UHVDC-HCM SYSTEM

Due to the difficulty of drawing the complete state spaces of the UHVDC-HCM system, the reliability equivalence, which includes state aggregation and combination, is applied. The state space is aggregated by the F&D method based on the capacities of the total system and the transmission powers to the two receiving-ends, and the reduced state space is derived by combining the remaining states.

For the reliability equivalence to the UHVDC-HCM system, considering the independent spares of the inverters at different terminals, the CUs of the inverters at one terminal need to be aggregated before. With one spare, the state space of the Vals at one terminal is shown in Fig. 2 (a), where λ, μ, and γ are the failure rate, repair rate, and installation rate respectively. The top left and top right corners of the boxes are the state number and the aggregated capacity respectively. The aggregated state space is shown in Fig. 2 (b), where λ_{ij} and μ_{ij} are the equivalent failure rate and repair rate from state i to state j, and 1/2+ and 1/2– represent the outage of the Val in the negative and positive pole. Without the spare, the states 9-12 do not exist. The state space of the CTs can be derived similarly.

For the inverters, the state space of the CU is derived and aggregated by combining the Val, CT, C&P, and ACFs, while that of the rectifier is derived by combining the Val, CT, and C&P. With the aggregation of the CU and PE, the state space of the CSs is shown in Fig. 3 (a). Due to the separate modeling to the inverters at different terminals and the transmission powers to the receiving-ends, the red boxes are the increased states compared with the typical UHVDC system [21]. For example, the states 12 and 13 have the same capacity of the total system (50%), but different transmission powers to the two receiving-ends. Hence for the typical UHVDC system, the two states may be aggregated as one to simplify the complete state space, while should be differentiated for the UHVDC-HCM system.

The outages of the DCLs are not necessarily related to the CSs, thus combining the CSs at both stations and DCLs, the state space of the UHVDC-HCM system is given in Fig. 4. Compared with the typical UHVDC system, 13 states are increased, and for the final state space, which is shown in Fig 5 (b), due to the operating modes which are reclassified before, 2 states and 16 transition rates are increased.

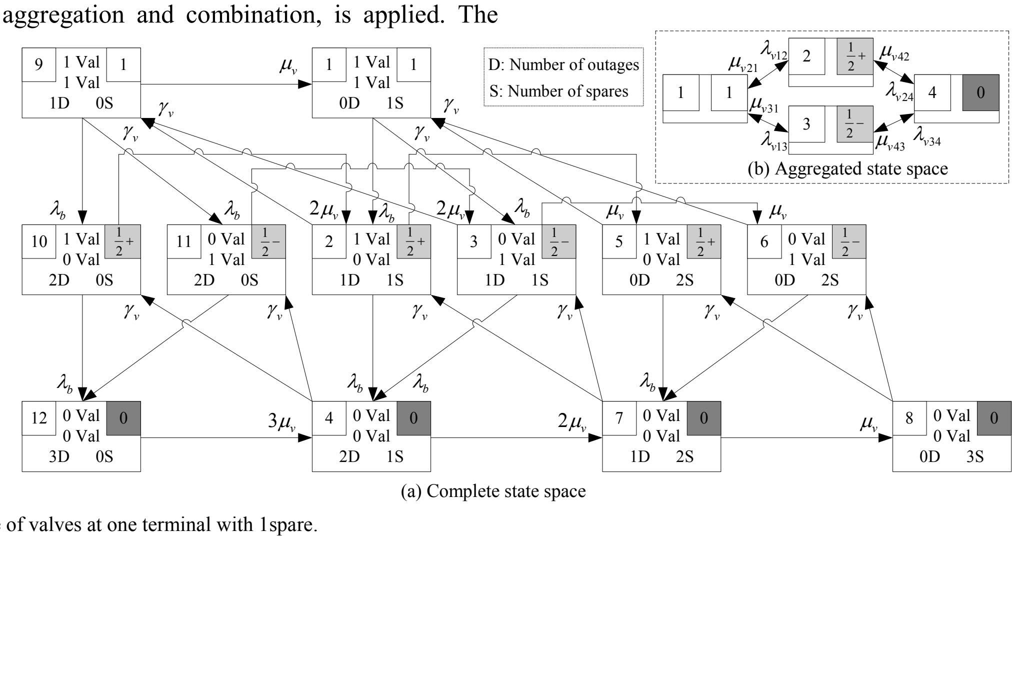

Fig. 2. State space of valves at one terminal with 1spare.

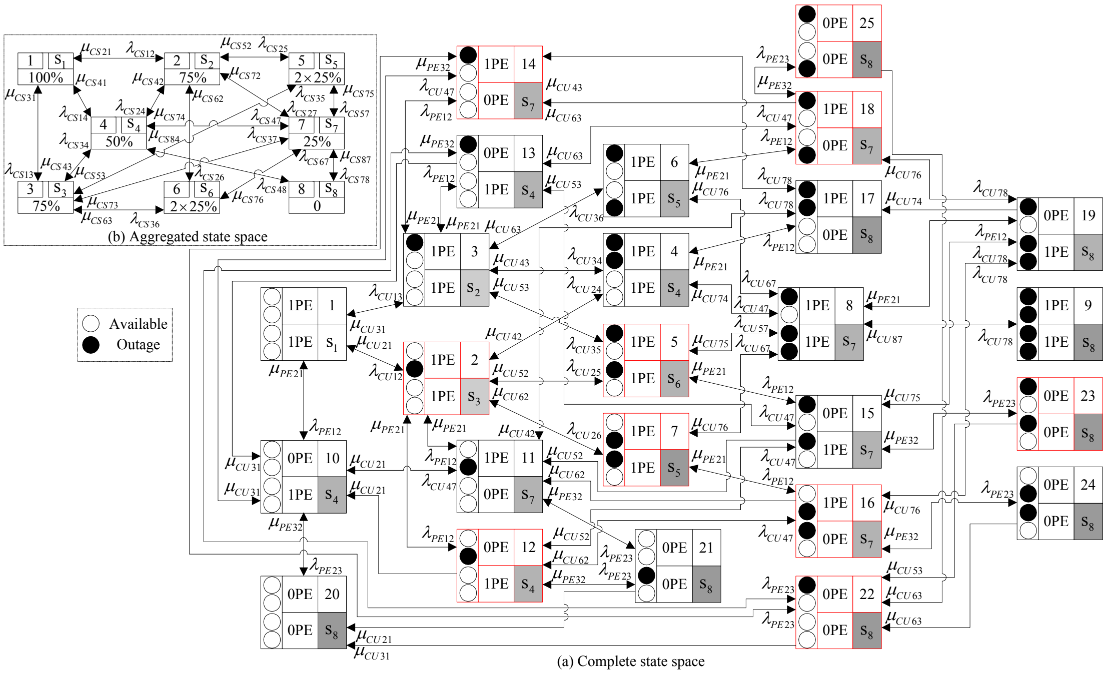

Fig. 3. State space of converter station.

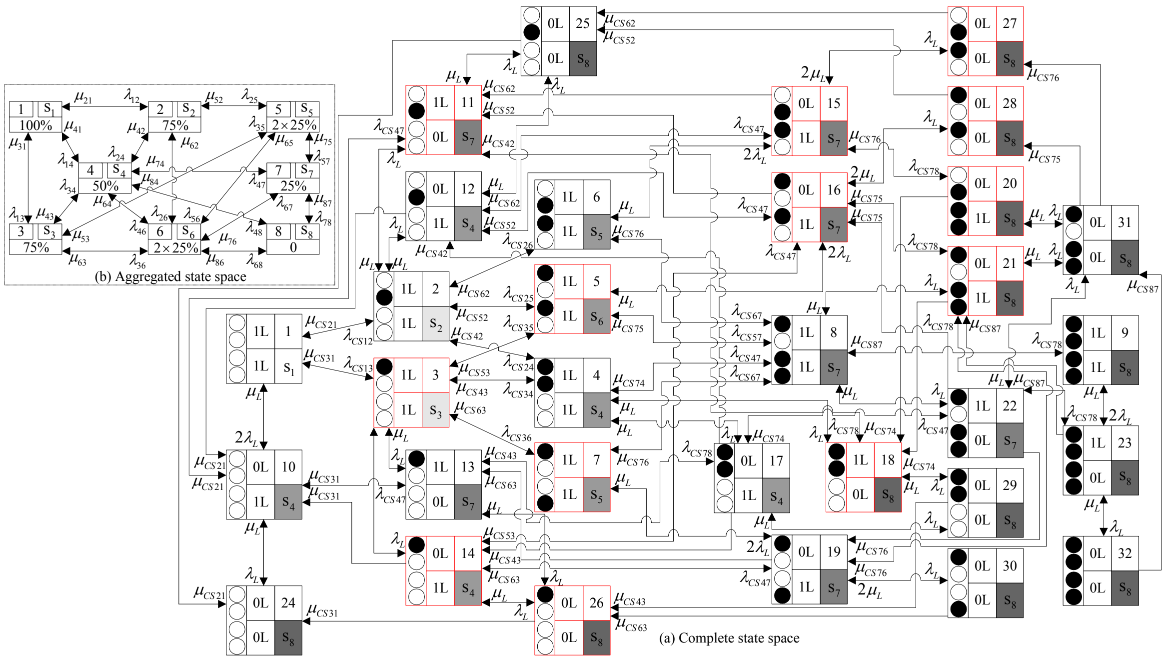

Fig. 4. State space of UHVDC-HCM system.

V. SENSITIVITY ANALYSIS BASED ON MATRIX DESCRIPTION OF F&D METHOD

In the matrix description of the F&D method, an equivalent matrix, $\boldsymbol{M}$, is introduced to substitute the manual lookup for the state aggregation. The column and row of the $\boldsymbol{M}$ denote the states before and after aggregation. For each row, the elements which equal to 1 indicate that the states have the same capacity and transmission powers to the two receiving-ends, thus can be aggregated, otherwise M_{ij} =0. For instance, the $\boldsymbol{M}$ of Fig. 2 is obtained by,

$$\boldsymbol{M}=\begin{bmatrix}1&0&0&0&0&0&0&0&1&0&0&0\\0&1&0&0&1&0&0&0&0&1&0&0\\0&0&1&0&0&1&0&0&0&0&1&0\\0&0&0&1&0&0&1&1&0&0&0&1\end{bmatrix} \quad (1)$$

Based on the equivalent matrix, the relationship of the state probability, $\boldsymbol{P}$, and the matrix of the transition frequency, $[f]$, before and after aggregation are given by,

$$[f'] = \boldsymbol{M}[f]\boldsymbol{M}^{\mathrm{T}} \quad (2)$$

$$\mathrm{diag}(\boldsymbol{P}') = \boldsymbol{M}\mathrm{diag}(\boldsymbol{P})\boldsymbol{M}^{\mathrm{T}} \quad (3)$$

where the superscript $'$ denotes the variables after aggregation.

The transition rates after aggregation, $\boldsymbol{A}'$, is solved by,

$$\boldsymbol{A}' = \mathrm{diag}(\boldsymbol{P}')^{-1}[f'] = (\boldsymbol{M}\mathrm{diag}(\boldsymbol{P})\boldsymbol{M}^{\mathrm{T}})^{-1}\boldsymbol{M}f\boldsymbol{M}^{\mathrm{T}} \quad (4)$$

For sensitivity analysis, with $\boldsymbol{D}$ given by $\boldsymbol{A}^{\mathrm{T}}$ and the last row replaced by [1, ⋯, 1], and $\boldsymbol{B}$ of $[0, \cdots, 0, 1]^{\mathrm{T}}$, the sensitivity of $\boldsymbol{P}$ to the reliability parameter, z, is defined by,

$$\frac{\partial \boldsymbol{P}}{\partial z} = \frac{\partial(\boldsymbol{D}^{-1}\boldsymbol{B})}{\partial z} = -\boldsymbol{D}^{-1}\frac{\partial \boldsymbol{D}}{\partial z}\boldsymbol{D}^{-1}\boldsymbol{B} \quad (5)$$

The sensitivity of transition rate matrix after aggregation, $\boldsymbol{A}'$, to z is given by (6), and together with (4) and (5), the sensitivity of $\boldsymbol{P}'$ to z is quantified.

$$\begin{aligned}\frac{\partial \boldsymbol{A}'}{\partial z} &= \frac{\partial((\boldsymbol{P}')^{-1}\boldsymbol{MPAM}^{\mathrm{T}})}{\partial z} \\ &= \frac{\partial(\boldsymbol{P}')^{-1}}{\partial z}\boldsymbol{MPAM}^{\mathrm{T}} + (\boldsymbol{P}')^{-1}\frac{\partial \boldsymbol{MPAM}^{\mathrm{T}}}{\partial z} \\ &= -(\boldsymbol{P}')^{-1}\frac{\partial(\boldsymbol{P}')}{\partial z}\boldsymbol{MPAM}^{\mathrm{T}} \\ &\quad +(\boldsymbol{P}')^{-1}\boldsymbol{M}(\frac{\partial \boldsymbol{P}}{\partial z}\boldsymbol{A} + \boldsymbol{P}\frac{\partial \boldsymbol{A}}{\partial z})\boldsymbol{M}^{\mathrm{T}}\end{aligned} \quad (6)$$

VI. Numerical Results

Due to the limited history, the multiple-year reliability data of the UHVDC-HCM project is unavailable. Thus the data of the HVDC system, as shown in Table III [25, 26], are applied in this paper, and the reliability parameters of the Val, CT, C&P, and ACF of the inverters at the HT and LT are set by considering the existing publication [27-29]. With the development of the UHVDC-HCM system, more accurate reliability parameters will be available to yield more practical conclusions by the proposed model.

TABLE III
Reliability Parameters of UHVDC System with HCM

Components	Failure rate (occ. per yr.)	Repair rate (occ. per yr.)	Installation time (hrs.)
Val (Rectifier)	0.1374	1460.000	6
Val (Inverter at HT)	0.08	876.00	6
Val (Inverter at LT)	0.355	1102.72	0.75
CT (Rectifier)	0.0126	290.5008	48
CT (Inverter at HT)	0.007	362.66	1
CT (Inverter at LT)	0.0664	79.45	40
C&P (Rectifier)	0.088	1158.12	–
C&P (Inverter at HT)	0.0774	2957.361	–
C&P (Inverter at LT)	0.200	1095.00	–
ACF (Rectifier)	0.200	876.00	–
ACF (Inverter at HT)	0.0607	1212.2	–
ACF (Inverter at LT)	0.396	652.72	–
DC filter	0.25	730	–
SmR	0.03	133.5366	–
DCL	4.7080	1101.890	–

A. Reliability Indices after Reliability Equivalence

Without considering the spare, the equivalent state space of the UHVDC-HCM system is shown in Fig. 5, and the transition rates among different operating modes are also given. It is found that s_5 and s_6 are both belong to the 1/2 bipolar mode in the typical UHVDC systems, and obviously the probabilities and transition rates of the two operating modes are different. Therefore, it is necessary to differentiate these two modes.

For schemes: (i) no spare, (ii) with 1 spare Val, (iii) with 2 spare Vals, (iv) with 1 spare Val and 1 spare CT, (v) with 1 spare CT, (vi) with 2 spare CTs, (vii) with 2 spare Vals and 2 spare CTs, the reliability indices are given in Fig. 6. It is found that with the spares:

1) EA is increased and EOH is decreased, showing that the system reliability is developed, and the change of EOH is more obvious than the others.

2) The spare of valve is more effective than the spare of CT. With the 1st spare, the system reliability is improved more obvious than the 2nd or more spare, showing that the spare schemes should be set by considering both reliability and economic.

3) Compared with the reliability indices of typical UHVDC system [21], EA is decreased by 1.079% and EOH is increased by 93%, which shows that the reliability of the UHVDC-HCM system is lower. But the advantages of enhancing the voltage support capability and obtaining a desirable power flow, which are not shown in the reliability indices, will gradually improve the reliability of the total power system.

4) BTA is increased while UBTA is decreased, and the difference between EA-RH and EA-RL is smaller, which shows that the spares contribute to the balanced transmission powers. Besides, the probability of the disconnection between the AC systems and UHVDC system is decreased by the spares, which is due to the spares may increase the availability of the total system.

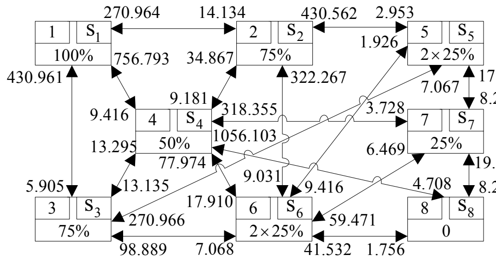

Fig. 5. Equivalent state space of UHVDC-HCM system

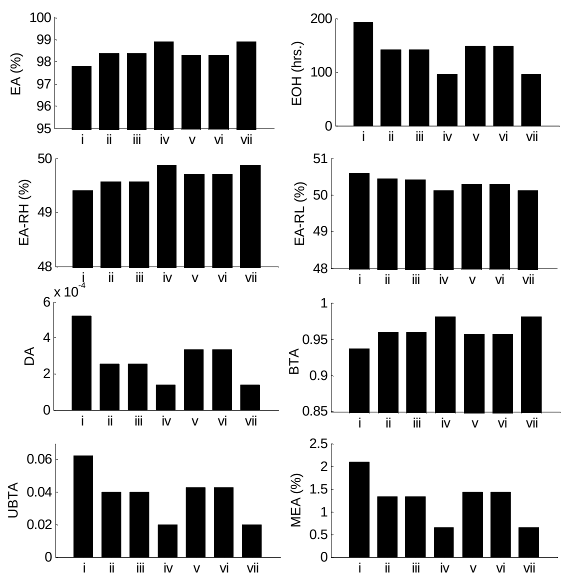

Fig. 6. Reliability indices of different spare schemes.

The probability, frequency, and average duration (*d*) of the operating modes with different spare schemes are given in Table IV. It is found that:

1) With the spares, the probabilities and frequencies of s_1 and s_4 are increased, while those of s_2, s_3, s_5, s_6, and s_7 are decreased. d_1 and d_4 have little difference, while the others are changed. Therefore, the spares schemes may be designed for different purposes, e.g. expecting the bipolar mode or avoiding the disconnection.

2) The probability of s_2 is higher than that of s_3, which is due to different failure rates of the inverter components at HT and LT. In this paper, the failure rates of Val, CT, C&P, and ACF of inverter at LT is higher than those at HT, causing the results mentioned above. With more actual reliability data, the corresponding conclusions will be more practical.

TABLE IV
RELIABILITY INDICES OF DIFFERENT CAPACITIES

Indices	Sch.	s1	s2	s3	s4	s5	s6	s7	s8
P	(i)	0.92551	4.825×10^{-2}	1.277×10^{-2}	1.148×10^{-2}	3.308×10^{-4}	1.463×10^{-3}	1.388×10^{-4}	5.171×10^{-5}
	(ii)	0.94807	3.273×10^{-2}	6.753×10^{-3}	1.147×10^{-2}	1.159×10^{-4}	7.231×10^{-4}	8.553×10^{-5}	5.153×10^{-5}
	(iii)	0.94813	3.268×10^{-2}	6.748×10^{-3}	1.147×10^{-2}	1.157×10^{-4}	7.214×10^{-4}	8.540×10^{-5}	5.154×10^{-5}
	(iv)	0.96846	1.357×10^{-2}	5.943×10^{-3}	1.161×10^{-2}	4.144×10^{-5}	2.762×10^{-4}	4.582×10^{-5}	5.231×10^{-5}
	(v)	0.94535	2.992×10^{-2}	1.212×10^{-2}	1.149×10^{-2}	1.906×10^{-4}	7.947×10^{-4}	9.507×10^{-5}	5.161×10^{-5}
	(vi)	0.94538	2.988×10^{-2}	1.212×10^{-2}	1.149×10^{-2}	1.903×10^{-4}	7.936×10^{-4}	9.499×10^{-5}	5.161×10^{-5}
	(vii)	0.96856	1.348×10^{-2}	5.939×10^{-3}	1.161×10^{-2}	4.111×10^{-5}	2.744×10^{-4}	4.564×10^{-5}	5.231×10^{-5}
f (occ. per yr.)	(i)	27.261	14.0950	5.8503	9.5403	0.2379	0.7451	0.05598	0.05776
	(ii)	27.925	14.0878	5.8163	9.5485	0.1462	0.5674	0.04872	0.05652
	(iii)	27.927	14.0875	5.8165	9.5486	0.1460	0.5669	0.04871	0.05652
	(iv)	28.525	13.9743	5.9180	9.5759	0.0826	0.3992	0.04749	0.05611
	(v)	27.845	13.9893	5.9545	9.5576	0.1768	0.5794	0.05010	0.05675
	(vi)	27.846	13.9891	5.9547	9.5577	0.1767	0.5791	0.05009	0.05674
	(vii)	28.528	13.9738	5.9185	9.5762	0.0823	0.3985	0.04750	0.05611
d (hrs.)	(i)	297.407	29.9868	19.1270	10.5397	12.1811	17.2007	21.7240	7.8425
	(ii)	297.407	20.3515	10.1707	10.5260	6.9482	11.1640	15.3771	7.9867
	(iii)	297.407	20.3190	10.1636	10.5263	6.9411	11.1476	15.3582	7.9871
	(iv)	297.407	8.5078	8.7971	10.6244	4.3922	6.0609	8.4513	8.1661
	(v)	297.407	18.7326	17.8324	10.5278	9.4407	12.0150	16.6227	7.9678
	(vi)	297.407	18.7092	17.8323	10.5278	9.4347	12.0045	16.6118	7.9681
	(vii)	297.407	8.4486	8.7898	10.6247	4.3745	6.0323	8.4163	8.1673

B. Sensitivity Analysis of UHVDC-HCM System

The reliability parameters of each component have different impacts on the system reliability, and the sensitivity analysis enables to recognize the vulnerability of the UHVDC-HCM system. Table V shows the sensitivities of the reliability indices to the failure rates of the components, where R denotes the components of the rectifier, showing that:

1) The impact of the components at different terminals on the system reliability are different, validating necessity of separate modeling to them.

2) The sensitivities of EA-RH and EA-RL to the components at the LT and HT are opposite numbers. Hence the components at different terminals may be used to modify the transmission powers to the two receiving-ends.

3) As the failure rates of the SmR, DCF, and ACF of the rectifier are increased, BTA is increased and UBTA is decreased, which are different from the others. For these components, the outage will result in the totally down of one pole, which is belong to the balanced operating, while for the others, the pole will be partially down.

TABLE V
SENSITIVITIES OF RELIABILITY INDICES TO FAILURE RATES

Component	EA	EOH	EA-RH	EA-RL	MEA	DA	BTA	UBTA
Val (R)	−1.71	149.65	3.50×10^{-2}	-3.58×10^{-2}	2.03	1.27×10^{-3}	-6.17×10^{-2}	6.17×10^{-2}
Val (LT)	−1.13	99.13	−0.70	0.70	1.41	3.58×10^{-4}	-4.28×10^{-2}	4.28×10^{-2}
Val (HT)	−2.14	187.54	1.39	−1.39	2.76	2.27×10^{-3}	-7.80×10^{-2}	7.80×10^{-2}
CT (R)	−5.50	481.70	0.15	−0.15	6.56	3.82×10^{-3}	-1.98×10^{-1}	0.20
CT (LT)	−9.77	855.96	−6.09	6.09	12.17	3.31×10^{-3}	-3.70×10^{-1}	0.37
CT (HT)	−1.69	148.18	1.10	−1.10	2.17	1.80×10^{-3}	-6.14×10^{-2}	6.14×10^{-2}
C&P (R)	−0.09	7.92	1.44×10^{-3}	-1.49×10^{-3}	0.11	7.04×10^{-5}	-3.28×10^{-3}	3.28×10^{-3}
C&P (LT)	−0.09	7.60	-5.37×10^{-2}	5.36×10^{-2}	0.11	2.73×10^{-5}	-3.28×10^{-3}	3.28×10^{-3}
C&P (HT)	−0.03	2.71	2.04×10^{-2}	-2.04×10^{-2}	4.18×10^{-2}	3.09×10^{-5}	-1.18×10^{-3}	1.18×10^{-3}
ACF (R)	−0.14	12.58	1.03×10^{-3}	-2.35×10^{-3}	6.46×10^{-3}	1.32×10^{-4}	2.96×10^{-5}	-4.29×10^{-5}
ACF (LT)	−0.07	6.13	-4.41×10^{-2}	4.41×10^{-2}	8.79×10^{-2}	1.69×10^{-5}	-2.66×10^{-3}	2.66×10^{-3}
ACF (HT)	−0.04	3.19	2.53×10^{-2}	-2.52×10^{-2}	4.94×10^{-2}	3.19×10^{-5}	-1.38×10^{-3}	1.39×10^{-3}
SmR	−1.87	163.81	1.37×10^{-2}	-3.38×10^{-2}	7.77×10^{-2}	1.68×10^{-3}	3.62×10^{-4}	-5.63×10^{-4}
DCF	−0.34	30.16	2.35×10^{-3}	-5.86×10^{-3}	1.52×10^{-2}	3.17×10^{-4}	6.79×10^{-5}	-1.03×10^{-4}
DCL	−0.09	7.69	6.00×10^{-4}	-2.40×10^{-3}	-3.44×10^{-3}	1.70×10^{-5}	9.86×10^{-6}	-2.78×10^{-5}

C. Impact of Parametric Changes and Different Spare Schemes on Sensitivity

In order to analyze the impact of the parametric changes on the sensitivity, the failures and repair rates of SmR, DCF, and ACF are changed, and the corresponding sensitivities are shown in Fig. 7. It is found that the sensitivities to the failure rates have little change, but remarkable to the repair rates. Therefore, the vulnerable components based on the failure rate are relatively determined, which provide reference to the practical UHVDC-HCM project.

The sensitivities of DA to the failure rates with different spare schemes are shown in Table VI, showing the following conclusions:

1) The sensitivities to the valves and CTs are more obviously by the spares, showing that the spares of one component may change the corresponding sensitivities.

2) The first spare has notable contribution to the sensitivities to the valves and CTs, while the 2nd has little effect.

3) The spare, either valve or CT, shows less contribution to the sensitivities to the components at the HT than those at the LT. Combined with the failure rates which are set in this section, the impact of the spare is larger with the increase of the failure rates.

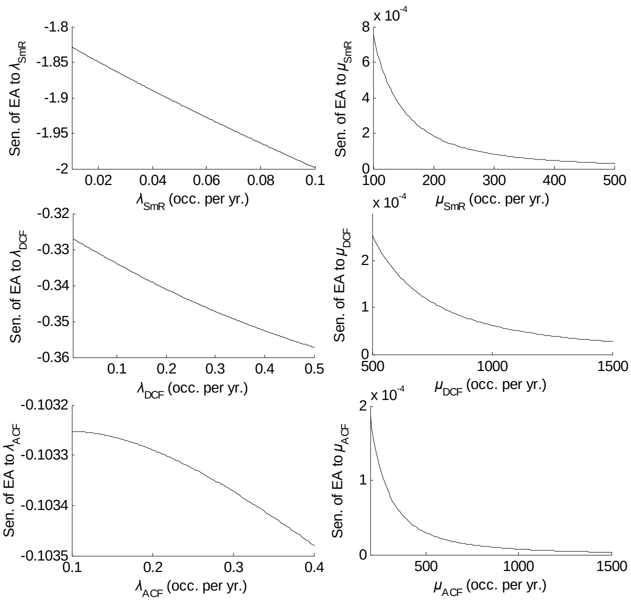

Fig. 7. Sensitivities with parametric changes.

TABLE VI
Sensitivities with Different Spare Schemes

Component	Spare Schemes						
	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)
Val (R)	1.27×10^{-3}	4.69×10^{-4}	4.68×10^{-4}	2.57×10^{-4}	9.10×10^{-4}	9.09×10^{-4}	2.55×10^{-4}
Val (LT)	3.58×10^{-4}	4.61×10^{-6}	3.03×10^{-6}	1.76×10^{-5}	3.56×10^{-4}	3.56×10^{-4}	1.62×10^{-5}
Val (HT)	2.27×10^{-3}	5.77×10^{-4}	5.74×10^{-4}	2.58×10^{-4}	1.45×10^{-3}	1.45×10^{-3}	2.56×10^{-4}
CT (R)	3.82×10^{-3}	2.63×10^{-3}	2.63×10^{-3}	9.43×10^{-4}	1.70×10^{-3}	1.70×10^{-3}	9.40×10^{-4}
CT (LT)	3.31×10^{-3}	2.09×10^{-3}	2.09×10^{-3}	5.01×10^{-4}	8.50×10^{-4}	8.40×10^{-4}	4.95×10^{-4}
CT (HT)	1.80×10^{-3}	1.28×10^{-3}	1.28×10^{-3}	5.78×10^{-7}	1.48×10^{-5}	1.46×10^{-5}	3.70×10^{-7}
C&P (R)	7.04×10^{-5}	4.77×10^{-5}	4.77×10^{-5}	2.64×10^{-5}	5.02×10^{-5}	5.01×10^{-5}	2.63×10^{-5}
C&P (LT)	2.73×10^{-5}	1.71×10^{-5}	1.71×10^{-5}	1.64×10^{-5}	2.73×10^{-5}	2.73×10^{-5}	1.63×10^{-5}
C&P (HT)	3.09×10^{-5}	2.17×10^{-5}	2.17×10^{-5}	8.47×10^{-6}	1.79×10^{-5}	1.79×10^{-5}	8.40×10^{-6}
ACF (R)	1.32×10^{-4}	9.32×10^{-5}	9.31×10^{-5}	6.13×10^{-5}	9.90×10^{-5}	9.89×10^{-5}	6.11×10^{-5}
ACF (LT)	1.69×10^{-5}	1.18×10^{-5}	1.18×10^{-5}	1.61×10^{-5}	2.07×10^{-5}	2.07×10^{-5}	1.62×10^{-5}
ACF (HT)	3.19×10^{-5}	2.51×10^{-5}	2.51×10^{-5}	1.03×10^{-5}	1.80×10^{-5}	1.80×10^{-5}	1.02×10^{-5}
SmR	1.68×10^{-3}	1.17×10^{-3}	1.17×10^{-3}	7.68×10^{-4}	1.28×10^{-3}	1.28×10^{-3}	7.66×10^{-4}
DCF	3.17×10^{-4}	2.25×10^{-4}	2.25×10^{-4}	1.49×10^{-4}	2.39×10^{-4}	2.39×10^{-4}	1.49×10^{-4}
DCL	1.70×10^{-5}	1.76×10^{-5}	1.76×10^{-5}	1.80×10^{-5}	1.75×10^{-5}	1.75×10^{-5}	1.80×10^{-5}

VII. Conclusion

In this paper, the reliability model of the UHVDC-HCM system is proposed based on the matrix description of the F&D method, which is summarized as follow:

1) Compared with the typical UHVDC system, the operation modes of the UHVDC-HCM system need to be classified based on the capacities of the total system and the transmission powers to the two receiving-ends.

2) For the reliability equivalence, the CUs of the inverters at different terminals need to be aggregated firstly, and the CU of the inverters is formed by the Val, CT, C&P, and ACF of the inverters, while the ACF of the rectifier belongs to the PE.

3) The proposed reliability indices can reflect the special structure and characteristics of the UHVDC-HCM system, such as the transmission powers to the receiving-ends and the disconnection probability between the UHVDC-HCM and AC systems.

4) The spares may improve the system reliability, and change the state probabilities, but the 2nd or more spares do not have the same influence as the first one. Thus the spare schemes need to be designed by considering both reliability and economic.

5) The sensitivities to the failure rates of the components are relative constant, which help to decide the vulnerabilities and corresponding countermeasures.

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