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Recognizing the Reliability Non-coherence Components of Multiple Parallel Transmission Lines

***Abstract**. In order to describe the degree of the system reliability non-coherence feature, this paper proposes several new indices of reliability non-coherence probability, frequency and energy. This paper also presents a non-coherence component identification model for multiple parallel transmission lines with and without considering substation configurations. This method can be directly used to recognize the non-coherence components without evaluating the system reliability.*

***Streszczenie.** Zaproponowano szereg nowych wskaźników niezawodności niekoherentnych składników wielokrotnej równoległej linii transmisji. Pozwala to na rozpoznawanie składników niekoherentnych bez konieczności oceny całego systemu transmisji. (**Rozpoznawanie składników niekoherentnych w wielokrotnej równoległej linii transmisyjnej**)*

Keywords: reliability non-coherence feature, identification model, multiple parallel transmission lines, non-coherence indices
Słowa kluczowe: linia transmisyjna, składniki niekoherentne.

Introduction

Generally, adding a transmission line, circuit breaker or other component to a power system can improve the system reliability performance, which is the so-called reliability coherence phenomenon in power systems. However, in some cases, the reliability non-coherence phenomenon exists in power systems [1-4].

The reliability non-coherence refers to the fact that if one more component is added to a power system, the system reliability would not be improved, or even becomes worse. In other words, if one more component is out of service, system reliability at least would not be deteriorated or even becomes better. This component is called the reliability non-coherence component (RNC). Recognizing the RNCs and removing the RNC from a planning or operation power system can improve the system reliability and economy benefits.

A large number of power system reliability studies [5-9] have been done in developing power system reliability models and algorithms. However, there are only a few literatures discussing the reliability non-coherence phenomenon. The RNC does not occur in a generation system [10], because the generation capacity and reserve capacity will be reduced if a generating unit is out of service, and then the generation system reliability will be decreased. The possible reliability non-coherence feature in transmission system was presented in [2]. A simple system was used to illustrate the concept of reliability non-coherence in transmission systems in [3]. A case study for combinative structures of transmission lines and substation configurations was provided in [1], in which a double-line structure with tap-connection for supplying loads from two ends has lower reliability than a single-line structure with loop-in connection for supplying the same loads while both arrangements require the same number of other equipments. The non-coherence phenomenon occurs in a test power system with 23 generators, 24 transmission lines and 15 buses in [4] if the rated capacity of the transmission line L4 between buses 4 and 8 is changed. The transmission line L4 is a RNC when the transmission line L2 fails and the transmission lines L4 and L15 are both RNCs when the transmission line L9 fails, which indicates that the electrical parameters of components are important factors affecting the non-coherence feature of a power system.

The existence of RNCs not only increases the capital investment of equipments, but also reduces the system reliability performance. In other words, the reliability non-coherence phenomenon is negative for both the system economy and reliability. Recognizing of RNCs is, therefore, an important task in power system optimal planning and operation processes.

Substations are the energy transfer points between generation and transmission or between transmission and distribution. Based on the functional division in utilities, substations are generally parts of a transmission system [11]. In this paper, the existing condition and influencing factors of reliability non-coherence phenomenon in parallel transmission lines with and without considering substation configurations are analyzed.

Reliability evaluation models

A combinative transmission system containing substation configurations consists of various components, such as transmission lines, transformers, buses, breakers, reactors, and etc. In order to simplify the analysis process, the following assumptions have been made:

1) Power sources, transformers, and buses are assumed to be 100% reliable.
2) The parallel transmission lines have the same type (the length may be different), that is, they have the same rated capacity. Let C represent the rated capacity of one transmission line.
3) Breakers on the both ends of transmission lines have the same type, that is, they have the same reliability and electrical parameters.
4) The analysis process mainly focused on the active power. Therefore, the failure of reactors is not considered in the following models since the failure of reactors has little impact on the active power flows.
5) The probability of a simultaneous failure of more than two components is very small. Therefore, only one or two component failures are considered in the following models.

The reliability evaluation model for a parallel transmission line system consists of transmission line model, breaker model, and load model.

A. Component Model

A transmission line is represented using the two-state (up and down) model, and its availability A_L and unavailability U_L are:

(1) $$A_L=\mu_L/(\mu_L+\lambda_L)$$

(2) $$U_L=\lambda_L/(\mu_L+\lambda_L)$$

where μ_L and λ_L are the repair rate and failure rate of the transmission line.

Assuming that a breaker only has the short-circuit failure, a three-state reliability model in [3] for breaker is shown in Fig. 1.

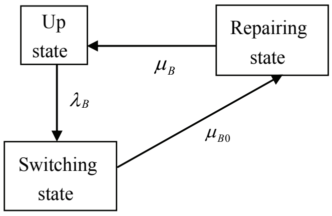


Fig.1. Three state model for breakers

The state probabilities A_B, U_{B1}, and U_{B2} for the up, repairing, and switching states in [2] and [3] can be obtained using the Markov equations associated with Fig. 1:

(3) $$A_B = \frac{\mu_{B0}\mu_B}{\mu_{B0}\mu_B + \mu_B\lambda_B + \mu_{B0}\lambda_B}$$

(4) $$U_{B1} = \frac{\mu_{B0}\lambda_B}{\mu_{B0}\mu_B + \mu_B\lambda_B + \mu_{B0}\lambda_B}$$

(5) $$U_{B2} = \frac{\mu_B\lambda_B}{\mu_{B0}\mu_B + \mu_B\lambda_B + \mu_{B0}\lambda_B}$$

where λ_B, μ_B and μ_{B0} are the failure rate, repair rate, and switching rate of circuit breaker, respectively.

B. Multiple Step Load Model

The load level has a considerable impact on the system reliability. When a multiple step load model is used, the annual reliability indices can be evaluated by summing each level system indices with the weighted probability of load level [2].

Assume that the probability of the ith load level is P_i:

(6) $P_i = T_i/8760$

where T_i is the time length of the ith load level in one year.

The annual system indices, such as LOLP (loss of load probability), EENS (expected energy not supplied) and LOLF (loss of load frequency), are:

(7) $$LOLP = \sum_{i=1}^{N} LOLP_i \cdot P_i$$

(8) $$EENS = \sum_{i=1}^{N} EENS_i \cdot P_i$$

(9) $$LOLF = \sum_{i=1}^{N} LOLF_i \cdot P_i$$

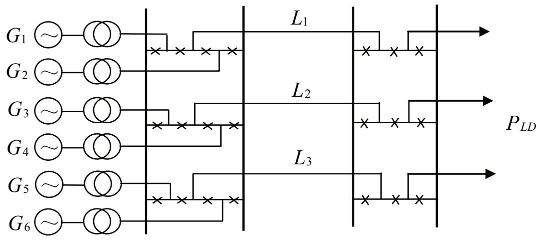
where $LOLP_i$, $EENS_i$, $LOLF_i$ are the system indices for the ith load level, and N is the number of load levels.

Reliability non-coherence identification of parallel transmission lines

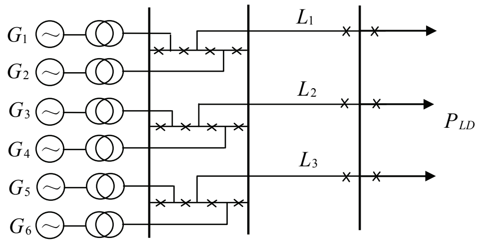
A. Considering Substation Configurations

Figs. 2 (a) and (b) show two parallel transmission line systems containing substation configurations. Both of the systems consist of six generating units and supply the load by three-circuit transmission lines. The one and one third breaker scheme is used for both of the systems as voltage step-up substation bus configuration at the source end of transmission lines, and the one and one half breaker scheme and single bus scheme are used as bus configuration at the load end of transmission lines for the two systems, respectively. It should be noted that there is very few practical parallel transmission systems using the single bus scheme and this scheme is only used for the comparison purpose of the non-coherence features among different schemes.

Basic reliability evaluation principles and n+2 Markov model can be used to evaluate the reliability of parallel transmission lines [3, 12]. The Reliability of parallel transmission lines considering substation configurations can be evaluated by the connectivity identification for each system state and the determination of the load points disconnected from the power sources.



(a) One and one third breaker and one and one half breaker scheme



(b) One and one third breaker and single bus scheme

Fig. 2 Structure of transmission lines and substation configurations

There are various adequacy indices [3], such as LOLP, LOLF, LOLE (loss of load expectation), and EENS, used to describe the reliability performance, and different indices usually reflect the reliability performance in different views. Therefore, a RNC of a system based on one of the indices will become a normal component while using other reliability indices.

The EENS index has a comprehensive characterization of the system LOLP and loss of load demand, and reflects a relatively more comprehensive performance of system reliability. Hence, the EENS index is used to recognize the RNC in the following study.

Assume that the non-coherence phenomenon occurs in a three-circuit transmission line (TCTL) system. This indicates that the reliability of a TCTL with one transmission line out of service, which becomes a double-circuit transmission line (DCTL), is better than the reliability of the original TCTL system. So

(10) $EENS_2 \leq EENS_3$

where $EENS_2$ and $EENS_3$ are the EENS index of the DCTL and the TCTL.

Because the EENS index is closely related to the rated capacity of generating unit, transmission line, load level, and component reliability parameters, the reliability non-coherence model cannot be analytically derived.

B. Without Considering Substation Configurations

The TCTL without considering substation configurations can be simplified as the system shown in Fig.3. Assume that the capacity of power sources is adequacy. The transmission capacity and probability are given in Table 1.

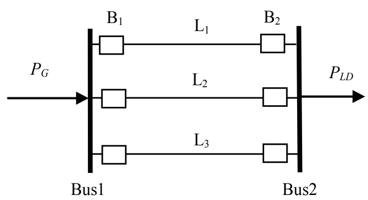


Fig.3. A three-circuit transmission line system

Table 1. The capacity and probability of three-circuit transmission line

Capacity	Probability
3C	$P_3(3C) = A_{L1}A_{L2}A_{L3}A_B^6$
2C	$P_3(2C) = (A_{L1}A_{L2}U_{L3} + A_{L1}U_{L2}A_{L3} + U_{L1}A_{L2}A_{L3})A_B^6 + 6A_{L1}A_{L2}A_{L3}A_B^5U_{B1} + 3A_{L1}A_{L2}A_{L3}A_B^4U_{B1}^2 + 2(U_{L1}A_{L2}A_{L3} + A_{L1}U_{L2}A_{L3} + A_{L1}A_{L2}U_{L3})A_B^5U_{B1}$
C	$P_3(C) = (A_{L1}U_{L2}U_{L3} + U_{L1}U_{L2}A_{L3} + U_{L1}A_{L2}U_{L3})A_B^6 + 4(U_{L1}A_{L2}A_{L3} + A_{L1}U_{L2}A_{L3} + A_{L1}A_{L2}U_{L3})A_B^5U_{B1} + 12A_{L1}A_{L2}A_{L3}A_B^4U_{B1}^2$
0	$P_3(0) = 1 - P_3(3C) - P_3(2C) - P_3(C)$

Based on (10), we can obtain:

Case1: $2C<P_{LD}\le 3C$

If all components of the DCTL are in service, the system can not meet the load demand and must be in the loss of load state. This indicates that the EENS of the DCTL is larger than that of the TCTL. Therefore, the TCTL has no non-coherence features.

Case 2: $C<P_{LD}\le 2C$

The occurrence condition of non-coherence phenomenon is

(11) $$P_{LD} \le P_{LD0}$$

where $P_{LD0} = C\,D_{L3}D_B^2E/L$;

$D_{L3}=\lambda_{L3}+\mu_{L3}$;

$D_B=\lambda_B\mu_{B0}+\mu_B\mu_{B0}+\mu_B\lambda_B$;

$E=(\mu_{L1}\lambda_{L2}+\lambda_{L1}\mu_{L2})\mu_{B0}\mu_B+4\mu_{L1}\mu_{L2}\mu_{B0}\lambda_B$;

$$L = \mu_{L1}\mu_{L2}\mu_{L3}\mu_B^2\mu_{B0}^3(\mu_B + 6\lambda_B) - D_{L3}D_B^2\mu_{L1}\mu_{L2}\mu_{B0}\mu_B + (\mu_{L1}\mu_{L2}\lambda_{L3} + \mu_{L1}\lambda_{L2}\mu_{L3} + \lambda_{L1}\mu_{L2}\mu_{L3})\mu_{B0}^3\mu_B^3$$

If $P_{LD}\le P_{LD0}$, the system is a reliability non-coherence system, otherwise, the system is a reliability coherence system. P_{LD0} is called the reliability non-coherence threshold load (RNTL).

Case 3: $P_{LD}\le C$

The occurrence condition of non-coherence phenomenon is

(12) $$A_B^2A_{L3} \ge 2/3$$

Generally, the availability A_B and A_{L3} of power system transmission lines and circuit breakers are close to 1. In many situations, equation (12) is always true. Hence, the system always remains the non-coherence feature.

Reliability non-coherence indices

The system load changes with time, and may be larger or less than the RNTL. The system non-coherence feature is not constant and changes with the load demands. In order to describe the non-coherence feature and impacts of non-coherence components on the system reliability, several new indices, such as reliability non-coherence probability, reliability non-coherence frequency, and reliability non-coherence energy, are presented in this paper.

1) Reliability Non-coherence Probability (RNP)

The index RNP is the occurrence probability of a power system in non-coherence state in a specified period.

(13) $$RNP = \sum_{i=1}^{M} P_i \sum_{j\in S} P_j$$

where M is the number of load levels, P_i the probability of the ith load level, S the set of non-coherence system state, and P_j the probability of the jth non-coherence system state.

Equation (13) indicates that the RNP is associated with the load levels and component failures.

2) Reliability Non-coherence Frequency (RNF)

The index RNF is the occurrence frequency of a power system in non-coherence state in a specified period. The frequency of a non-coherence system state is:

(14) $$f_j = P_j\sum_{k=1}^{T}\lambda_k$$

where f_j is the frequency of the jth non-coherence system state, λ_k is the departure rate of the kth component in state j and it can be a failure, repair, or switching rate, and T is the number of components. The RNF of the system is:

(15) $$RNF = \sum_{i=1}^{M} P_i \sum_{j\in S} f_j$$

3) Reliability Non-coherence Hours (RNH)

The index RNH is the occurrence hours of a power system in non-coherence state in a specified period.

(16) $$RNH=8760RNP$$

4) Reliability Non-coherence Energy (RNE)

The index RNE is the EENS reduction of a power system in non-coherence state in a specified period.

(17) $$RNE = \sum_{i=1}^{M} P_i\Delta EENS_i$$

where $\Delta EENS_i$ is the difference between the EENS of the original system and the EENS with the non-coherence components out of service for the ith load level.

The larger the RNE is, the better the reliability improvement of the system with removing the non-coherence components is.

Case studies

A. The TCTL Considering Substation Configurations

The parallel transmission lines considering substation configurations shown in Fig. 2 are used as examples to explain the proposed concepts, including the reliability non-coherence indices, the occurrence condition, and the influencing factors of non-coherence phenomenon.

Consider the systems shown in Fig. 2 with the rated voltage 500 kV, the rated capacity of one transmission line 1200 MW, and the rated capacity of one generating unit 550 MW. To simplify the analysis process, the three transmission lines are assumed to have the same reliability parameters. The reliability parameters of components are given in Table 2.

Table 2. The reliability parameters of components

Component	Failure rate [occ./year]	Repair rate [occ./year]	Switch rate [occ./year]
Breakers	0.03	95	8760
Transmission Lines	0.45	325	\

1) Constant load model

As mentioned earlier, the load level has an important effect on the system reliability performance and reliability non-coherence feature. The reliability indices of two system structures with transmission line L3 in or out of service are given in Table 3.

The single bus scheme shown in Fig. 2 (b) is a reliability coherence system if the load is larger than 1200 MW, while it is a non-coherence system if the load is less than 1200 MW. In other words, the system RNTL is close to the rated capacity of one transmission line. However, the one and one half breaker scheme shown in Fig.2 (a) is always a reliability coherence system for different load levels. Because any breaker can be removed for maintenance without any circuit interruptions, this scheme is much more reliable than the single bus scheme.

Similarly, the schemes of one and one third breaker, and double bus double breaker are always reliability coherence systems, which have the same reliability coherence property as that of one and one half breaker scheme.

Table 3. System reliability indices with L3 in or out of service for different load levels

Load [MW]	EENS of Fig.2 (a) [MWh/year]		EENS of Fig.2 (b) [MWh/year]	
	L3 in service	L3 out of service	L3 in service	L3 out of service
2000	161.68	19554.32	5928.10	29613.77
1500	90.83	7383.51	4427.62	13301.56
1201	72.77	117.25	3523.52	3549.08
1200	72.67	97.67	3520.50	3516.47
1000	60.56	77.46	2933.75	2930.39
800	48.45	61.97	2347.00	2344.31

2) Multiple step load model

Using the load model of IEEE RTS [13] and round technique [2], the yearly load can be divided into 15 steps. The probability of each load level is shown in Table 4.

Table 4. Load level step and its probability

Load level [%]	Probability
30	0.0029
35	0.0245
40	0.0683
45	0.1020
50	0.1231
55	0.1019
60	0.1046
65	0.1246
70	0.1001
75	0.0820
80	0.0817
85	0.0554
90	0.0222
95	0.0057
100	0.0007

Assume that the system peak loads are 2000 MW, 1500 MW and 1200 MW, respectively, and the system reliability indices and non-coherence indices of Fig. 2 (b) using the multiple step load model are given in Table 5. Table 5 shows that the smaller the peak load is, the larger the RNP, RNF and RNH are. However, the RNE increases first and then decreases due to different load levels and its probability distribution.

Table 5. System reliability indices and non-coherence indices for different peak load

Peak load [MW]	EENS [MWh/year]		RNP	RNF [occ/year]	RNH [h/year]	RNE [MWh/year]
	L3 in service	L3 out of service				
2000	3615.17	7619.17	0.000789	0.2239	6.91	1.77
1500	2704.02	2967.48	0.001475	0.4186	12.92	2.73
1200	2162.74	2160.21	0.001684	0.4780	14.75	2.54

B. The TCTL without Considering Substation Configurations

Fig. 3 is a typical TCTL without considering substation configurations. The reliability parameters of components are given in Table 2. The rated capacity of transmission line is 1200 MW.

1) Constant load model

Using (11), the system RNTL for the transmission L3 is 1204.77 MW. Table 6 shows that the TCTL is a coherence system when the system load is greater than 1204.77 MW, while the TCTL is a non-coherence system when the load is less than 1204.77 MW. This indicates that the system with transmission line L3 out of service can improve the system reliability when load level is less than the system RNTL 1204.77 MW.

The analysis above also shows that the system RNTL based on (11) can be directly used to judge whether a system is a reliability non-coherence system or not. In other words, the judging process does not need to evaluate the system reliability. The RNCs can be recognized by comparing the system load with the RNTL evaluated using (11).

Table 6. System reliability indices with L3 in or out of service for different load levels

Load level [MW]	EENS [MWh/year]		ΔEENS [MWh/year]
	L3 in service	L3 out of service	
2100	654.7	32025.2	-31370.5
1800	561.1	21419.1	-20858.0
1500	467.6	10813.0	-10345.4
1205	375.7	383.7	-8.0
1204.77	375.6	375.6	0
1204	375.3	348.4	26.9
1150	358.5	198.3	160.2

2) Multiple step load model

Using the multiple step load model given in Table IV, with the system peak loads of 2100 MW, 1900 MW and 1700 MW respectively, the system reliability indices and non-coherence indices of Fig. 3 are given in Table 7.

Table 7. System reliability indices and non-coherence indices for different peak load

Peak load [MW]	EENS [MWh/year]		RNP	RNF [occ/year]	RNH [h/year]	RNE [MWh/year]
	L3 in service	L3 out of service				
2100	402.2	6441.8	0.000843	0.2144	7.39	58.6
1900	363.9	3728.6	0.001099	0.2793	9.63	69.7
1700	325.6	1688.4	0.001460	0.3710	12.79	98.1

Table 7 shows that the smaller the peak load is, the larger the RNP, RNF and RNE are. For example, if the system peak load is 1700 MW, removing the transmission line L3 when system load is less than the system RNTL can reduce the EENS by 98.1 MWh/year. That is, the system EENS would be 227.5 MWh/year and improved by 30.1%. If the system peak load is less than the system RNTL, the system is always a reliability non-coherence system.

Conclusions

Using the reliability analytical model for parallel transmission line systems with and without considering substation configurations, this paper presents the existence conditions of reliability non-coherence features and derives a non-coherence component identification model. The proposed techniques can be directly used to judge whether a transmission line system has the con-coherence feature or not, which indicates that the judging process does not need evaluation of system reliability.

In order to describe the reliability non-coherence features, this paper proposes several new indices, such as reliability non-coherence probability (RNP), reliability non-coherence frequency (RNF), and reliability non-coherence energy (RNE).

This paper mainly focused on the reliability non-coherence features based on the EENS index. The analysis ideas and techniques can be extended to other reliability indices, such as LOLP and LOLF.

The following conclusions can be drawn from the analysis of reliability non-coherence for transmission lines:

The parallel transmission lines with the single bus scheme maybe a non-coherence system when system electrical and reliability parameters change. However, the schemes of one and one half breaker, one and one third breaker, and double bus double breaker are always coherence systems.

The system RNTL of the simplified transmission lines without considering substation configurations can be obtained by the non-coherence recognizing model. If the system load is larger than the system RNTL, the system is a coherence system. Otherwise, the system is a non-coherence system.

The non-coherence indices are closely related to the system peak load and the load probability distribution while considering the load curve in a given period. The larger the peak load is, the smaller non-coherence indices, such as RNP, RNF, and RNH, are.

According to the system RNTL and non-coherence indices, the non-coherence component in a system planning or operation process can be identified. Removing the non-coherence components from a system can improve the system reliability performance, which should bring the utilities many economic and social benefits in the optimal planning and operation processes.

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