Analytic of VSC-HVDC Interconnected Power Systems from a Perspective of Frequency Security

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Abstract. In the interconnected power systems with VSC-HVDC (Voltage Source Converter-High Voltage Direct Current) transmission links, the failures of VSC-HVDC system can cause large power imbalance for both sending-end and receiving-end power systems. In this paper, the reliability model of the VSC-HVDC system is developed based on series-parallel structure recognition. The frequency dynamics of the power systems are characterized considering the frequency regulation of the power systems in response to the power imbalance arise from the component failures. Moreover, the Monte Carlo simulation method is applied to analyze the frequency dynamics in different contingencies. The indices measuring the frequency stability and the reliability of the interconnected power systems are introduced.

Nomenclature

| Symbol | Description |
|--------|-------------|
| λ, μ | equivalent failure and repair rates of the subsystem, respectively. |
| λ_1, μ_1 | failure and repair rates of component i in the subsystem, respectively. |
| ΔV_{DC} | DC voltage variation of the VSC-HVDC |
| Δf_f | RE system frequency deviation |
| r_1, r_1 | control gain parameters in the VSC-support framework |
| Δf_s | equivalent frequency deviation for the SE system |
| ΔPS | initial power imbalance in the SE and RE systems, respectively. |
| ΔPR | normal transmission power of HVDC system during operation period i |
| P_{SI} | sum of the normal power output of committed generators suffering from failures in both AC systems, respectively. |
| P_{RI} | percentage of the remaining transmission power capacity and overload rate of HVDC, respectively. |
| ω_s | set of possible failure scenarios |
| ω_s | probability of scenario s during period i |
| TS | durations of frequency abnormal of SE and RE systems for scenario s respectively |
| TS_i | durations of PFR and SFR of the SE system for scenario s, respectively |
| TS_i | durations of PFR and SFR of the RE system for scenario s, respectively |
| TR | energy reductions caused by generation tripping and load shedding respectively in the SE system for scenario s; |
| TR | energy reductions caused by generation tripping and load shedding respectively in the SE system for scenario s; |
| LSR | energy reduction caused by load shedding in the RE system for scenario s. |

In Figure 1, the failure and repair rates of CS, and MS, respectively.
1. Introduction

The VSC-HVDC system has several advantages including the ability to connect weak AC power systems and offer reactive power support, and better controllability [1].

With the wide deployment of VSC-HVDC systems, it poses a challenge for guaranteeing the frequency stability and of the interconnected power systems [2]. Considering the significant impacts of the possible failures of VSC-HVDC, several studies have been conducted on the reliability modeling of the VSC-HVDC, which mostly focus on component-level analysis. In [3], the reliability model of converter valves in VSC-HVDC systems is developed considering the internal structure and functions. In [4], the reliability of high power IGBT modules is analyzed. There also exist some studies analyzing the system-level reliability of the power systems considering the VSC-HVDC application. In [5], the reliability model and analytical reliability evaluation of VSC-HVDC systems are proposed, where the effect of different converter topologies is studied. A combined reliability model of VSC-HVDC connected offshore wind farms is proposed in [6].

Frequency stability is an important field of power system security and reliability [7]. Considering the low inertia effect of the HVDC transmission system, several studies have been conducted on analyzing the frequency stability of the power systems with HVDC. In [8], the cost-efficient contingency reserve allocation scheme for combined HVDC and AC power systems is studied. The provision of virtual inertia from energy storage systems in HVDC interconnected systems is discussed in [9]. In [10], the frequency stability of SE power systems with given control strategies is studied. In addition, the ability of HVDC system for providing frequency support is investigated. Reference [11] proposes a HVDC control scheme which involves only local measurements and actions, to provide frequency support. In [12], a VSC-HVDC control scheme based on power synchronization control is proposed, considering the loss of external AC interconnector or local generation. Reference [13] studies the overload capacity of VSC-HVDC for the provision of frequency services.

However, few studies have been conducted on the reliability evaluation of the interconnected power systems with the consideration of the frequency dynamics. As innovative contributions, this paper proposes a framework for reliability evaluation of interconnected power systems with VSC-HVDC links, considering the impact of not only possible failures but also the low inertia characteristic of the VDC-HVDC.

2. Reliability model of the VSC-HVDC system

The bipolar VSC-HVDC system with two 12-pulse converters consists of the following components: AC filter (ACF), breaker (Brk), converter transformer (CT), converter valve (CV), converter protection and control system (PC), DC filter (DCF) and DC transmission line (DCL)[5].

Considering that the component failures have various impacts on the HVDC transmission capacity, the whole VSC-HVDC system is divided into two kinds of subsystems, namely monopole system (MS) and converter system (CS). The failure and repair rates [3] of the subsystem can be expressed as:

\[ \lambda_s = \sum_i \lambda_i \]

\[ \mu_s = \frac{\sum_i \lambda_i \mu_i}{\sum_i \lambda_i} \]

Each pole of the bipolar VSC-HVDC system is modeled as a series-parallel structure, consisting of two parallel CSs in series of one MS. Hence, the breakdown of one CS will cause partial failure of the pole, while the breakdown of one MS can lead to total failure of the pole. Consequently, each pole is of three possible states, including perfect working state, partial fail state (one CS fails) and total fail state (both CSs fails or/and the MS fails). Subsequently, the whole VSC-HVDC system can be regarded as a multi-state model, which can achieve different performance levels corresponding to different transmission capacities. Assuming that each pole shares the capacity equally and the two CSs in one pole are also with the same capacity, there are five possible states for the transmission
capacities for all contingencies: 1) Intact. The HVDC system works ideally without any component failures. 2) 75% rated. One pole suffers from a partial failure while the other works well, causing a 25% loss in capacity. 3) 50% rated. Two kinds of operation modes are associated with a 50% rated capacity. One is that one pole totally fails, while the other is normal. The second is that both poles partially fail. 4) 25% rated. One pole partially fails and the other totally fails. 5) Total failure. Both poles totally fail.

In the following paragraphs, the unipolar state space model is firstly developed. Then two separate unipolar models are aggregated to build the reliability model of the bipolar system.

Each pole consists of two CSs and one MS. Hence, there are eight subsystem state combinations for the pole. The eight-combination space model of the pole is shown in Figure 1, in which shaded subsystems represent those at failure state.

According to the state space model, the probability of each combination can be calculated by solving a set of differential equations [5].

![Figure 1. Unipolar state space model for VSC-HVDC system.](image)

Note that different subsystem state combinations can lead to the same capacity of the pole. Hence, the eight subsystem state combinations are aggregated to three states for the pole, including normal state (N), partial failure state (P) and total failure state (F). In Figure 1, the states of the pole in different combinations are shown in the top-right corner of the corresponding block.

3. Reliability model for power systems interconnected by VSC-HVDC

The reliability model for power systems interconnected by VSC-HVDC is developed in this section. The frequency dynamics of both SE and RE systems under each contingency are formulated based on the primary frequency response (PFR) and secondary frequency response (SFR) and a support strategy.

3.1. Frequency support strategies under system contingencies

When there is a failure of the VSC-HVDC system leading to the transmission capacity reduction, power imbalances, and frequency deviation may occur in both the SE and RE power systems. Fortunately, the temporary-overload capability of the converters of the VSC-HVDC system can be exploited to mitigate the power imbalance and frequency disturbance [14]. When some parts of the VSC-HVDC system encounters outages, the converters still working can increase their power capacity fast to offset the loss to an extent. Such frequency support strategy of the VSC-HVDC system includes the following two parts: 1) When the VSC-HVDC system is at 75% capacity, the transmission power of the remaining converters will increase by 10%. 2) When the capacity of the VSC-HVDC system decrease to 50% or below, the power capacity of the remaining converters will increase by 15%.

The adjustment of the transmission capacity of the VSC-HVDC system can also be used to support the power system suffering generator outages. The frequency support strategy in response to the generator outages include the following parts:
When generator failure occurs in the RE system, a two-step frequency-voltage control mechanism of the HVDC system is activated. Firstly, the frequency deviation is measured based on which the DC voltage will be adjusted. Then, the DC voltage variation will be converted to produce an equivalent frequency deviation signal for the SE system. The relationship between frequency and voltage during the control process is given by [11]:

$$\Delta V_{DC} = r_f \Delta f$$

$$\Delta f_r = r_f \Delta V_{DC}$$

(3)

(4)

Figure 2. Control diagram of support strategy for generator failures (SE to RE).

Based on the frequency deviation signal $\Delta f_r$, the generators in the SE system increase the power output which will be transmitted to the RE system. The control diagram is illustrated by Figure 2. $Sat_a(x)$ is a saturation block representing the power transmission limit of the HVDC systems.

When generator failure occurs in the SE system, the support strategy is like the strategy mentioned above with the two-step frequency-voltage control mechanism. In this case, the generators in the RE system will increase the power output, and therefore the HVDC system can reduce its transmission power for relieving the power imbalance in the SE system.

3.2. Frequency dynamics of the power systems

For characterizing the system frequency dynamics, the power imbalance should be formulated at first. Considering the possible failures of the generators and the VSC-HVDC system, the initial power imbalance during operation period $t$ can be formulated as:

$$\Delta P_{S_i} = -P_{S_i}^G + (1-c_i) P_{r_f}^f r_f c_i P_f^r$$

$$\Delta P_{R_j} = -P_{R_j}^G - (1-c_i) P_{r_f}^f + r_f c_i P_f^r$$

(5)

$c_i \in C = \{1, 0.75, 0.5, 0.25, 0\}$

Setting $\Delta P_{S_i}$ and $\Delta P_{R_j}$ as inputs of the frequency response model, then the frequency deviation of AC power systems, $\Delta f_s$ and $\Delta f_r$, can be obtained. If the frequency support strategy for generator outages is considered, extra power will be added to the input.

There are many possible scenarios for the generator outages and HVDC system failures. Thus, Monte Carlo (MC) simulation method [15] is adopted here to sample the possible scenarios based on the performance distribution probability of the HVDC system and the generators. The states of the HVDC system and generators are specified in each scenario. The convergence condition is that the ratio of the standard deviation and the variance of the target variable is less than or equal to 0.01. [15]
4. Formulation of reliability indices

In this section, four reliability indices are used to evaluate the reliability of interconnected systems.

4.1. Expected abnormal frequency duration (EAFD)

EAFD evaluates the expected duration of abnormal system frequency (beyond the under/over-frequency limit). EAFD is calculated as:

$$EAFD = \sum_{i} \sum_{s \in \Omega} p_{i,s}(TS_{i,s} + TR_{i,s})$$

4.2. Expected number of frequency insecurity (ENFI)

The initial rate of change of frequency (RoCoF) is the slope of the frequency right after the happening of the contingency. RoCoF can be calculated by [15]:

$$RoCoF = \left. \frac{d|\Delta f|}{dt} \right|_{t=0} = \frac{\Delta P}{2H}$$

The largest frequency deviation, i.e., the maximum value of $|\Delta f|$ during the frequency response process, should not exceed the RoCoF. Otherwise, the frequency stability incident occurs.

ENFI can be evaluated as the sum of the probabilities of the frequency instability scenarios:

$$ENFI = \sum_{i} \sum_{s \in \Omega} p_{i,s}(IS_{i,s} + IS_{r,s})$$

The security indicators $IS_{i,s}$ and $IS_{r,s}$ equal to 0 if the frequency dynamics is secure and 1 if it is not.

4.3. Accumulated frequency deviation expectation (AFDE)

In order to evaluate the extent of the frequency deviation, we define AFDE as:

$$AFDE = \sum_{i} \sum_{s \in \Omega} p_{i,s} \left( \int_{0}^{TS_{i,s} + TR_{i,s}} |\Delta f_{i,s}| dt + \int_{0}^{TR_{i,s} + TR_{r,s}} |\Delta f_{r,s}| dt \right)$$

The severity of system frequency insecurity is affected by two aspects, namely, the frequency deviation amplitude and the abnormal frequency duration. Here, through the temporal integral of abnormal frequency which is defined as AFDE, the above two aspects are synthesized and the system frequency is comprehensively evaluated.

4.4. Expected energy curtailment (EEC)

The control ability of frequency response is limited by the reserve capacity. So the system frequency cannot be restored to nominal if the reserve capacity is not able to cover the power imbalance. Under such circumstance, load shedding and generator tripping are required for under-frequency and over-frequency cases respectively. It should be noted that the generator tripping is an emergency measure when the Automatic Generation Control (AGC) or other generation dispatching measures fail to restore the system frequency. EEC is proposed to evaluate the reduction of such kind of load shedding and generator tripping, which is defined as:

$$EEC = \sum_{i} \sum_{s \in \Omega} p_{i,s}(GCS_{i,s} + LSS_{i,s} + LSR_{i,s})$$

The energy reduction $GCS_{i,s}$, $LSS_{i,s}$, and $LSR_{i,s}$ can be calculated by the integral of load shedding/generator tripping over the time of period $i$.

5. Case study

A modified two-area RTS-79 system is used for case study [15]. The VSC-HVDC system reliability parameters are referred to [16]. The generator and load parameters of the frequency response are derived from [7]. The nominal frequency is 50 Hz, the RoCoF limit is 0.6 Hz/s, the over/under frequency limits are 50.5 and 49.5 Hz respectively. $r_{r}$ and $r_{l}$ are 0.8 and 0.7 Hz/V respectively.
5.1. Results of reliability indices
In this case, the transmission capacity of the VSC-HVDC system is 700 MW and the length of the transmission line is 300 km. The primary and secondary reserve capacities are both set as 10% of the demand. The reliability model of the VSC-HVDC system is obtained, the parameters of which are shown in Table 1. The reliability evaluation results of the interconnected power system are shown in Table 2. In the following tables, occ is the abbreviation of occurrence. By comparing the reliability indices without and with frequency support strategies, it can be concluded that frequency support strategies enhance the system reliability.

![Table 1. Reliability evaluation of HVDC system.](image)

| Capacity (%) | Probability | Frequency(occ/yr) |
|--------------|-------------|------------------|
| 100          | 0.987191    | 10.5366          |
| 75           | 0.009461    | 10.1664          |
| 50           | 0.003318    | 0.4969           |
| 25           | 2.938E-5    | 0.0319           |
| 0            | 1.228E-6    | 2.804E-4         |

![Table 2. Basic result of reliability indices calculation.](image)

|                      | EAFD(hr/year) | ENFI(occ/yr) | AFDE(Hzs/yr) | EEC(MWh/yr) |
|----------------------|---------------|--------------|--------------|-------------|
| Without support strategies |               |              |              |             |
| SE                   | 0.469         | 52.170       | 1379.205     | 1423.050    |
| RE                   | 1.511         | 80.637       | 2108.430     | 2619.970    |
| Total                | 1.981         | 132.807      | 3487.635     | 4043.020    |
| With support strategies |              |              |              |             |
| SE                   | 0.286         | 28.682       | 914.275      | 927.265     |
| RE                   | 0.695         | 51.671       | 1058.353     | 1531.948    |
| Total                | 0.981         | 80.354       | 1972.628     | 2459.217    |

5.2. Effect of VSC-HVDC
The percentage of VSC-HVDC power supply to the RE system power is increased from 15% to 45%. The simulation result is proposed in Figure 3.

![Figure 3. Effect of HVDC penetration on reliability indices.](image)
It can be seen that the four indices are increased with higher penetration of the VSC-HVDC. While the increase trend of AFDE, ENFI and EEC are similar, EAFD rises in a quite different way. There is a sharp rise in EAFD right when HVDC penetration is larger than 39.876% while the change rate is quite slow at other points. The main reason is that when HVDC penetration exceeds 39.876%, the final frequency deviation caused by contingencies with high probability is right larger than 0.2 Hz after the SFR. This will result in a significant rise in EAFD according to its definition. The simulation result shows that in this case, the increase of HVDC penetration will bring negative effect on the system frequency reliability and may require more reserve capacity in AC power systems.

6. Conclusions

This paper proposed a framework for reliability evaluation of the power systems interconnected by VSC-HVDC. The proposed method simultaneously captures the effects of the possible failures and low inertia characteristics on power system reliability, which can be easily expanded to study multi-end interconnected systems and the power systems with different frequency control strategies.

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