Postprint Analysis of DC Power Modulation Effects on Power Angle Stability of Heilongjiang Power Grid

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Abstract

Taking the Heilongjiang power grid as the research object, when a fault occurs in the AC transmission corridor delivering power southward to the Jilin and Liaoning power grids, the power flow originally directed toward Jilin and Liaoning will be diverted to converge at Zhalute along the Hanan-Huamin direction, increasing the equivalent impedance of the power flow corridor and introducing power angle stability issues to the Heilongjiang power grid. This paper employs power modulation of the Zhaqing HVDC link to enhance the power angle stability of the Heilongjiang power grid, proposes the utilization of Prony analysis for parameter tuning of the DC modulator, and investigates the impact of modulation gain variations on system stability. The research findings offer valuable reference for improving power angle stability in actual power grid operations.

Full Text

Preamble

Analysis of DC Power Modulation Effects on Rotor Angle Stability of Heilongjiang Power Grid

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Abstract

When faults occur in the AC transmission corridors that deliver power from Heilongjiang to Jilin and Liaoning provinces, the power flow originally destined for these provinces gets redirected along the Hanan-Huamin route to Zhalute, increasing the equivalent impedance of the transmission path and creating rotor angle stability issues for the Heilongjiang power grid. This paper utilizes the power modulation capability of the Zhaqing HVDC link to improve the rotor angle stability of the Heilongjiang grid, proposes using Prony analysis for parameter tuning of the DC modulator, and discusses how variations in modulation gain affect system stability. The research results provide valuable reference for improving rotor angle stability in actual power grid operations.

Keywords: HVDC transmission, Heilongjiang power grid, DC power modulation, Prony analysis, angle transient stability

1 Introduction

Due to the reverse distribution of energy resources and load centers in Northeast China, wind and thermal power both require external transmission, making the construction of UHV DC transmission corridors a crucial approach for optimizing resource allocation. Following the commissioning of the Zhaqing UHV DC project, the main transmission pattern of the Northeast power grid has changed, with power converging from the north, east, and south toward the Zhalute converter station and nearby substations. While this has alleviated power flow pressure on the 500 kV AC transmission lines between Heilongjiang-Jilin and Jilin-Liaoning provinces, the original AC transmission still carries a significant portion of the power flow. If an N-1 fault occurs in the inter-provincial AC transmission, excess power will surge toward the Zhalute converter station, posing serious rotor angle stability problems for the Heilongjiang power grid. How to leverage the flexible active power control capability of HVDC systems to adapt to fault characteristics and enhance the security and stability of the Heilongjiang grid has become an urgent issue.

HVDC converters consist of numerous power electronic devices and typically possess a long-term overload capacity of 1.1 pu and a short-term overload capability of 1.5 pu for 3 seconds. During large disturbances, utilizing this short-term overload capacity to rapidly modulate the DC power injected into the AC system can compensate for power imbalances between sending and receiving ends during transient processes, thereby improving transient angle stability. DC power modulation is classified into large-signal modulation and small-signal modulation. Large-signal modulation can achieve amplitude variations of 20%-50% of DC power, aiming to enhance transient stability, such as emergency DC power support. Small-signal modulation typically only varies 3%-10% of DC power, focusing on improving dynamic stability and suppressing power oscillations. Currently, by quickly absorbing or compensating for power deficits, the acceleration area is reduced and the deceleration area increased, achieving the goal of improving system angle stability.

As shown in [Figure 1: see original paper], in an AC-DC transmission system, if an N-1 fault occurs on an AC line, the equivalent impedance XΣ increases, potentially causing angle stability issues at the sending-end system. Using sending-end system electrical quantities as input signals to the power modulator, the output modulation signal is combined with the power control command to regulate DC output power, thereby improving system angle stability. The HVDC control system is illustrated in [Figure 2: see original paper].

Extensive research has been conducted on using DC power modulation to enhance power system stability [1-13]. When system faults occur, the grid structure, operating mode, fault location, type, and severity determine what control method, modulation signal [14-16], and modulation law [17-19] the HVDC system should adopt to improve transient stability margins, requiring careful study and extensive simulation. Although numerous papers have analyzed DC modulation issues, parameter selection for modulators often relies on engineering experience without detailed, in-depth investigation.

This paper uses Heilongjiang power grid operational data from 2018 in PSASP to study the impact of DC power modulation on system angle stability, employs Prony analysis for modulator parameter tuning, and analyzes angle stability under different gain conditions.

2.1 DC Power Modulation Principle

The principle of DC power modulation involves adding a DC power modulator to the HVDC transmission system control unit. When the system experiences large disturbances, the modulator responds to excess power or power deficits in the faulted system to improve transient stability. In [Figure 2: see original paper], the power setpoint Pdref and power modulation signal PMOD are summed and divided by DC voltage Ud to obtain the current order signal, which then passes through Voltage Dependent Current Order Limiting (VDCOL) and Current Control Amplifier (CCA) to output the rectifier firing angle for converter valve control.

2.2 DC Power Modulator Model

For stability issues caused by N-1 faults, either power or frequency can be selected as the modulation input signal. Since active power variations differ across lines, using line active power change ΔP as an input requires establishing dedicated signal transmission routes from monitoring points to the DC converter station. However, using bus frequency signals or frequency change Δf allows direct measurement at converter station buses without dedicated signal transmission lines, making it more convenient. This paper selects the rectifier station bus frequency as the modulation input signal.

The DC power modulator structure is shown in [Figure 3: see original paper].

The term s/(1 + sTd) acts as a differentiator, primarily extracting signal variation trends to achieve better dynamic control effects. Larger Td values result in smaller phase lead of the output, affecting damping performance, but if Td is too small, it cannot accurately reflect the unavoidable time delay in actual measurement circuits. After comprehensive consideration, Td is selected in the range of 0.1–1 s. The combination of 1/(1 + sTf) and s/(s +) forms a band-pass filter combining low-pass and high-pass filtering, which maximizes amplitude at a specific frequency band while suppressing other bands, where Tf is the filter time constant and   is the lead compensation factor. The term (s^2As + B)/(s^2 + Cs + D) represents a notch filter with parameters A, B, C, D, which are generally not used for control in engineering applications (typically set as A = B = C = D). K is the modulation gain; PMIN is the sum of DC power and lower modulation limit; PMAX is the sum of DC power and upper modulation limit; and PMOD is the output power modulation signal.

3.1 Prony Analysis Method

Prony analysis constructs a mathematical model using a linear combination of exponential functions to describe equally spaced sampled data, providing an algorithm that can directly estimate frequency, damping factor, amplitude, and initial phase of given signals. Because Prony analysis can extract signal characteristics, it is widely used in power system analysis [20]. The Prony algorithm can fit measured system signals using a linear combination of exponential terms:

$$y(n) = \sum_{i=1}^{p} b_i z_i^n = \sum_{i=1}^{p} A_i e^{j\theta_i} e^{(\alpha_i + j2\pi f_i)\Delta tn}$$

where n = 0 to N-1, N is the number of data points in y(n); p is the model order; A__i is the mode amplitude; __i is the mode initial phase; __i is the mode damping factor; f__i is the mode frequency; and Δt is the time interval.

The accuracy of Prony analysis results is closely related to parameter selection, including sampling frequency, time length, and model order. Improper parameter selection may yield inaccurate results.

(1) Sampling frequency f__p: To ensure sampling frequency exceeds twice the highest signal frequency and suppress spectral aliasing, sampling is typically performed at four times the highest signal frequency. Excessively high sampling frequency may deteriorate fitting performance and reduce accuracy.

(2) Time length T__p: During system faults, an appropriate time segment of the modulation signal is selected based on fault initiation and clearance times. The time length should not be too large, as this may prevent identification of rapidly decaying components, causing information loss and hindering result analysis.

(3) Model order p: Since power system dynamic processes have very high order, reduced-order models are generally used for approximation. The typical Prony order selection method starts with a large initial order L, much greater than the actual number of exponential terms in the signal, to obtain L exponential components. Then the optimal subset of p components is selected to approximate the observed data in a least-squares sense. The order p that minimizes the sum of squared errors is used for Prony analysis.

3.2 Modulation Parameter Selection

Modulator parameter settings significantly impact performance. While previous literature often relied on engineering experience, this paper proposes parameter selection based on Prony analysis.

Under any fault condition without modulation, the spectrum of the rectifier-side bus frequency signal contains several energy-concentrated frequency bands, whereas normal operation signals contain only a single low-energy frequency component. Very low-frequency components in the spectrum can be considered DC components, which from a signal perspective do not affect system stability. By performing Prony analysis on the rectifier-side bus frequency signal, the main frequency bands and parameters can be identified to complete modulator parameter selection.

From a frequency domain perspective, the main frequency of the output DC modulation power should match the main oscillation frequency of the bus frequency signal to achieve good modulation effects. This can be understood as the fault causing a significant increase in energy in a particular frequency band of the bus frequency signal, and the DC supplementary signal providing power support at the same frequency to reduce power oscillations in that band. From a time domain perspective, the output DC modulation power should provide positive modulation when bus frequency rises and stop or provide negative modulation when frequency falls, thereby improving the angle stability of grid synchronous generators.

The parameter selection process based on Prony analysis is as follows:

(1) **Determine Prony analysis time length**: Based on fault initiation and clearance times, determine the sampling time length for bus frequency Prony analysis. Overly long or short sampling times cause information loss. System critical clearing time is typically 0.2–0.3 s, so signals 0.6–1 s after fault occurrence are generally sampled.

(2) **Determine Prony analysis sampling frequency and order**: During system N-1 faults, the highest frequency in bus frequency signals ranges between 20–25 Hz. Sampling is typically performed at four times the highest signal frequency, yielding a sampling period of 0.01 s. Software automatic order determination is used to establish the order.

(3) **Perform Prony analysis**.

(4) **Determine modulator parameters from analysis results**: The band-pass filter formed by 1/(1 + sTf) and Ks/(s +) has the transfer function:

$$D(s) = \frac{(1 + sTf)(s + \varepsilon)}{K}$$

Its logarithmic amplitude-frequency characteristic is:

$$L(\omega) = 20\lg K + 20\lg\omega - 20\lg\sqrt{1 + T_f^2\omega^2} - 20\lg\sqrt{\omega^2 + \varepsilon^2}$$

When « :

$$L(\omega) = 20\lg K + 20\lg\omega - 20\lg\varepsilon$$

When » 1/Tf:

$$L(\omega) = -20\lg\omega + 20\lg K + 20\lg T_f$$

When « « 1/Tf:

$$L(\omega) = 20\lg K$$

Based on Prony analysis results, obtain the maximum amplitude frequency f1d and the secondary maximum frequency f2d. When [f2d, f1d] [/2 , 1/2 Tf], the band-pass filter maximizes amplitude in this frequency band while suppressing other bands.

4.1 Simulation Background

The Heilongjiang power grid is located at the northernmost part of the Northeast grid. Its structural schematic is shown in [Figure 4: see original paper]. It connects to the Jilin grid through four 500 kV AC lines. After commissioning the Zhaqing UHV DC project, the external transmission capacity of the Northeast grid has significantly improved. Heilongjiang’ s power is partly collected at Zhalute for delivery to East China, and partly flows to Jilin and Liaoning grids. Among the four 500 kV inter-provincial AC corridors, the heavily loaded Hanan-Hexin line experiences an N-1 fault that redirects power flow originally destined for Jilin and Liaoning along the Hanan-Huamin direction to Zhalute. Although power flow on the Tianshui-Zhalute and Changsheng-Zhalute lines also decreases, the overall situation shows excess power surging into Zhalute and reduced flow on the Lishu-Puhe line. For the Heilongjiang grid itself, if stability control measures are inadequate during faults on heavily loaded inter-provincial corridors, rotor angle stability issues can arise, causing severe economic losses. This study utilizes the flexible power control capability of the Zhaqing UHV

DC transmission to adapt to fault characteristics and improve the rotor angle stability of the Heilongjiang grid.

4.2 Simulation Cases

A three-phase short-circuit ground fault is set on the 500 kV Hanan-Hexin AC corridor between Heilongjiang and Jilin at 5 s, cleared after 0.2 s. DC power modulation is used to improve Heilongjiang grid rotor angle stability, and the impact of different modulation gains is observed and compared. Before discussing gain variation effects, modulator parameters are first set based on Prony analysis. The time segment from 5–5.8 s is selected (Prony analysis time length Tp = 0.8 s) with a sampling period of 0.01 s. The results are shown in , and the spectrum is shown in [Figure 5: see original paper].

From the analysis results, f1d = 24.10313 Hz and f2d = 21.79885 Hz are obtained. Therefore, = 136.276 and Tf = 0.0066 are set. Taking Td = 0.5 and K = 4000, the rotor angle curves of the nearby Xinhua generator and remote Hegang generator are observed with and without power modulation, as shown in [Figure 6: see original paper] and [Figure 7: see original paper]. The results demonstrate significant improvement in first-swing stability after modulation.

A three-phase short-circuit ground fault is set on the 500 kV inter-provincial AC corridor between Heilongjiang and Jilin. Partial generators from each region of the Heilongjiang grid are selected to observe their rotor angle curves, as shown in [Figure 8: see original paper], with a critical clearing time of 0.23 s. Under the same fault duration, DC power modulation is applied, and the rotor angle curves are shown in [Figure 9: see original paper]. The modulation improves the critical clearing time of synchronous units.

4.3 Influence of Different Modulation Gains on Angle Stability

The above analysis shows that using Prony analysis on bus frequency signals to determine filter time constant Tf and lead compensation factor effectively improves Heilongjiang grid angle stability. This section discusses the influence of modulation gain K on system angle stability under the same fault background, using the nearby Xinhua unit and remote Hegang unit as examples, with a fault at 5 s cleared after 0.2 s.

From the equation, when n is large and the sampling time segment is small, any frequency component in can be represented by a continuous-time function:

$$F(t) = Ae^{j\theta}e^{(\alpha+j\omega)t}$$

The DC power modulator transfer function is:

$$G(s) = \frac{(1 + sTd)(1 + sTf)(s + \varepsilon)}{(s^2 + As + B) + (Cs + D)}$$

The output is:

$$PMOD(s) = F(s)G(s)$$

Different modulation gains have varying effects on synchronous unit angle stability. Small gains provide limited stability improvement, while excessive gains cause overshoot, potentially worsening AC system instability rather than improving it. Based on first-swing characteristics of remote and nearby units under different gains, remote units show better stability improvement after modulation.

During DC modulation, considering the DC system's overload capability PMOD 0.1Pd, the logarithmic amplitude-frequency characteristic yields:

$$20 \lg PMOD(\omega) \leq 20 \lg 0.1Pd$$

Substituting the amplitude and damping factor data corresponding to the maximum frequency f1d and secondary maximum frequency f2d into the equation yields K 5287.

The influence of different modulation gains K on first-swing stability is shown in , with Xinhua unit rotor angle curves under different gains shown in [Figure 10: see original paper]. discusses the impact of different modulation gains on unit critical clearing times.

5 Conclusion

This paper analyzed DC power modulation principles and studied the impact of Zhaqing UHV DC power modulation on system angle stability when inter-provincial AC system three-phase short-circuit ground faults occur in the Heilongjiang grid. Simulation results verify that DC frequency modulation significantly improves the angle stability of the Heilongjiang grid.

Modulator parameters were set based on Prony analysis, and simulation results validated the effectiveness of this parameter setting approach, providing guidance for stability control in actual Northeast power grid operations. The gain K range was limited based on DC overload capability, and the influence of different modulation gains on modulation effectiveness was discussed. The results show that different gains have varying effects on system stability: small gains provide limited improvement, while excessive gains cause overshoot, potentially worsening AC system instability.

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Note: Figure translations are in progress. See original paper for figures.