Postprint: Gaussian Algorithm-Based Refined Modeling of Nonlinear Coupling Dynamic Characteristics of Gas in HVDC Smoothing Reactors

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Abstract

With numerous HVDC transmission projects integrated into AC systems in recent years, AC/DC hybrid power grids have been significantly impacted. The operational status of DC systems, particularly the performance of their control and protection systems, has become a critical factor affecting the security and stability of AC/DC hybrid power grids. Maloperation of gas protection in smoothing reactors triggered by system faults represents one of the key non-electrical quantity factors leading to DC system lockout. This paper conducts a detailed study and analysis of the equipment principles and characteristics of smoothing reactor gas protection, employs Gaussian regression algorithm to achieve refined modeling and decoupling of the nonlinear coupling characteristics between mechanical vibration of smoothing reactor gas protection and impulse current, while maintaining compatibility with electromagnetic transient algorithms. Through pure electromagnetic transient simulation of AC/DC power grids based on actual engineering control and protection case studies of the East China Power Grid using ADPSS at the State Grid Simulation Center, the nonlinear fast-response dynamic characteristics of how dynamic variations in electrical quantities such as fault impulse currents in AC/DC power grids influence non-electrical quantities like mechanical vibration acceleration of smoothing reactor gas protection can be described in detail. This provides key technical means for accident analysis, fault replay, prevention, and equipment improvement regarding multiple incidents of DC lockout caused by maloperation of smoothing reactor gas protection in practical engineering, holds significant practical importance for further enhancing the multi-dimensional accuracy of practical DC engineering simulation, and offers valuable insights for detailed modeling of other nonlinear electrical equipment.

Full Text

Preamble

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HVDC Smoothing Reactor Gas Relay Non-linear Coupled Dynamic Characteristics Detailed Model Based on Gaussian Algorithm

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ABSTRACT: In recent years, as numerous HVDC projects have been integrated into AC systems, they have brought significant impacts to AC-DC hybrid power grids. The operational condition of DC systems, particularly the performance of control and protection systems, has become a critical factor affecting the security and stability of AC/DC hybrid power grids. System failures causing smoothing reactor gas relay malfunctions represent one of the main non-electrical quantity factors leading to DC blocking. This paper analyzes the principles and characteristics of smoothing reactor gas relay equipment, models and decouples the nonlinear coupling characteristics between mechanical vibration and DC shock current using Gaussian regression algorithm, which is compatible with electromagnetic transient simulation algorithms. Using the proposed model for pure electromagnetic simulation in an actual engineering example of East China power grid AC/DC system, the model can describe in detail the nonlinear rapid dynamic response characteristics of how electrical factors such as AC/DC power grid fault shock current dynamically change affect the non-electrical quantity of smoothing reactor gas relay mechanical vibration acceleration. It provides key technical means for analyzing, reproducing, preventing, and improving equipment in practical engineering accidents where smoothing reactor gas relay malfunctions caused DC blocking. This work is of important practical significance for further improving the multi-dimensional accuracy of HVDC practical engineering simulation and provides a methodology for detailed modeling of other nonlinear electrical-related equipment.

KEY WORDS: HVDC; Commutation Failure; Smoothing Reactor Gas Relay; Non-Electrical Quantity; Non-linear Dynamic Characteristics

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Abstract

With the large-scale integration of HVDC transmission projects into AC systems in recent years, significant impacts have been imposed on AC-DC hybrid power grids. The operational status of DC systems, especially the performance of their control and protection systems, has become a crucial factor influencing the security and stability of AC-DC hybrid grids. System faults triggering malfunctions of smoothing reactor gas protection constitute one of the important non-electrical causes of DC system blocking. This paper conducts a detailed investigation and analysis of the equipment principles and characteristics of smoothing reactor gas relays. The Gaussian regression algorithm is employed to perform refined simulation and decoupling of the nonlinear coupling dynamic characteristics between mechanical vibration and shock current, which is compatible with electromagnetic transient algorithms. Based on the ADPSS pure electromagnetic transient actual engineering control and protection calculation example of East China power grid from the State Grid Simulation Center, AC-DC grid pure electromagnetic simulation can be performed, enabling detailed description of the nonlinear rapid response dynamic characteristics of how electrical quantities such as fault shock currents in AC-DC grids dynamically change affect the non-electrical quantity of smoothing reactor gas relay mechanical vibration acceleration. This provides key technical means for accident analysis, fault reproduction, prevention, and equipment improvement for multiple incidents in practical engineering where false operation of smoothing reactor gas protection led to DC blocking. It holds important practical significance for further improving the multi-dimensional accuracy of practical HVDC engineering simulation and provides a methodology for detailed modeling of other nonlinear electrical-related equipment.

Keywords: HVDC; Commutation Failure; Smoothing Reactor Gas Protection; Non-Electrical Quantity; Non-linear Dynamic Characteristics

HVDC transmission, with its advantages in long-distance, large-capacity power delivery and asynchronous grid interconnection, has played a crucial role in China' s "West-to-East Power Transmission and National Grid Interconnection"strategy [1-3]. China has constructed multiple large-capacity, long-distance ultra/ultra-high voltage DC transmission corridors. Currently, over twenty DC transmission projects have been completed and put into operation nationwide, with the highest voltage level of $±$800kV and maximum transmission capacity of 8 million kW [4-6]. Simultaneously, to implement China' s air pollution prevention and control action plan, the State Grid will plan and construct four ultra-high voltage DC transmission channels, forming the world' s DC transmission system with the largest power, highest voltage level, most concentrated 落点, and most complex structure of AC-DC hybrid power grid.

With the large-scale integration of HVDC transmission projects into AC systems in recent years, significant impacts have been imposed on AC-DC hybrid power grids, particularly the receiving-end grids [7-11]. The operational status of DC systems, especially the performance of their control and protection systems, has become a crucial factor influencing the security and stability of AC-DC hybrid grids. In recent years, multiple accident cases have occurred where normal AC grid operations and faults, combined with improper control and protection system strategies for certain components, led to abnormal DC power fluctuations or even blocking, causing significant impacts on the grid. These include incidents where smoothing reactor and other component protections caused DC blocking after AC faults, seriously affecting the security, stability, and normal operation of both sending and receiving-end grids. For example, on July 5, 2013, a single-phase fault in the Shanghai AC grid caused a 500kV DC smoothing reactor gas relay operation at a receiving-end station in East China, leading to DC monopolar blocking. On February 7, 2010, a UHV 800kV DC system in East China experienced two commutation failures, with the smoothing reactor heavy gas operation at the receiving-end converter station Unit II, causing Unit II DC blocking, etc. These accidents have always been difficult to simulate in detail and reproduce for analysis because existing DC simulations focus on electrical quantities and lack refined simulation of critical non-electrical quantities like smoothing reactor gas relays that can directly block DC, making accident reproduction and simulation analysis challenging [12-15].

On the other hand, detailed characteristic modeling of HVDC smoothing reactor gas protection involves complex nonlinear dynamic coupling relationships between electrical and non-electrical quantities, representing a difficulty in refined AC-DC grid simulation. With the expansion of DC system scale and closer coupling between AC and DC systems, DC system blocking has enormous impact on grid security and stability. The fact that the interaction response characteristics between critical non-electrical quantity factors like smoothing reactor gas relays that frequently cause DC system blocking and AC-DC grids remain in a fuzzy state is unacceptable to various departments in State Grid engineering operations. Based on a State Grid special science and technology project, this paper employs technical procurement methods to obtain high-commercial-value internal smoothing reactor gas relay data from Shenyang Transformer Company, conducts detailed research and analysis of smoothing reactor gas relay equipment principles and characteristics, uses the Gaussian algorithm to perform refined simulation and decoupling of the nonlinear coupling dynamic characteristics between mechanical vibration and shock current, implements modeling and programming in ADPSS, and ensures compatibility with electromagnetic transient DC engineering algorithms. Using the ADPSS pure electromagnetic transient actual engineering control and protection calculation example of East China power grid from the State Grid Simulation Center, AC-DC grid pure electromagnetic simulation can be performed, enabling detailed description of the nonlinear rapid response dynamic characteristics of how electrical quantities such as fault shock currents in AC-DC grids dynamically change affect the non-electrical quantity of smoothing reactor gas relay mechanical vibration acceleration.

2. Smoothing Reactor Gas Relay Characteristics Analysis

DC smoothing reactor gas protection operates with rapid sensitivity and can respond sensitively to various fault types including inter-layer and inter-turn short circuits of windings, internal faults of bushings, core faults, internal winding breaks, oil level drops, and insulation deterioration [15]. The DC smoothing reactor gas relay equipment structure mainly consists of a shell, top cover, and switching device [15]. The shell is made of weather-resistant cast aluminum alloy with flange connections. The shell has a glass observation window for viewing the internal switching system and reading the volume of accumulated gas through its scale values. The glass observation window is protected by a rotatable metal cover [15]. The top cover components include a wiring cover, junction box, inspection button, inspection valve, etc., with the junction box having two cable outlets [15]. At the field installation, the bellows connecting the smoothing reactor gas relay to the oil conservator is a flexible connection, while the connection to the oil tank is a rigid pipe connection, forming a cantilever structure.

[Figure 1: see original paper] 3D simulation diagram of receiving end fault station

[Figure 2: see original paper] Smoothing Reactor Gas Relay Field structure diagram

Since July 3, 2012, a receiving-end 500kV station in East China experienced dozens of bipolar commutation failures. The transient currents caused by commutation failures varied, resulting in different vibration accelerations of the smoothing reactor gas relay. Modeling and simulation of the electrical dynamic correlation characteristics of the smoothing reactor gas relay vibration acceleration are required.

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3. Smoothing Reactor Gas Relay Characteristics Modeling

Based on the Gaussian algorithm [16-17], the following model is established for DC smoothing reactor gas relays. Mechanical vibration acceleration (viba) can be calculated through dynamic correlation characteristics of transient shock current (I). Applying the Gaussian algorithm to quantitative analysis models not only simplifies model parameters but also improves model interpretability [16-17], while being compatible with electromagnetic transient integration algorithms.

Where l, e, and g are Gaussian coefficients to be determined. Taking logarithms on both sides: ln(a) (I)]

Calculate partial derivatives:

Expand to obtain:

From the above calculations, the DC smoothing reactor gas relay vibration characteristic model can be established and implemented in ADPSS.

The comparison between calculated values from the proposed model (equations 1-13) and measured data under different equipment type parameters is shown below. It can be observed that the vibration acceleration of DC smoothing reactor gas relays exhibits different types of nonlinear correlation with transient shock current, which is related to equipment type, model, and structure, but shows similar model dynamic variation characteristics. As transient shock current increases, the growth rate of vibration acceleration gradually decreases. The vibration magnitude caused by current increase varies with different dynamic characteristics, and changing equipment structure can alter the dynamic characteristics between transient shock current and smoothing reactor gas relay vibration acceleration.

[Figure 3: see original paper] Smoothing Reactor Gas Relay I Model Calculation Comparison Waveform

[Figure 4: see original paper] Smoothing Reactor Gas Relay II Model Calculation Comparison Waveform

Comparison of gas resistance test data and model effects under different parameters

Parameter descriptions in the table: - **SSE (Sum of Squares due to Error)**: The sum of squares of errors between fitted data and original data at corresponding points. - **R-square (Coefficient of Determination)**: Defined as the ratio of SSR to SST, where SSR is the sum of squares of the regression (sum of squared differences between predicted data and original data mean), and SST is the total sum of squares (sum of squared differences between original data and mean). - **RMSE (Root Mean Squared Error)**: Also called the fitting standard deviation of the regression system, which is the square root of MSE. - **MSE (Mean Squared Error)**: The mean of squared errors between predicted data and original data at corresponding points. - **Adjusted R-square**: The adjusted coefficient of determination, where R-square can be used to evaluate the quality of regression equations. When comparing regression equations with different numbers of independent variables, the influence of the number of independent variables in the equation must also be considered.

7.5 Accident Case Analysis

The July 5 accident was caused by an AC system fault leading to DC commutation failure. The resulting series of chain reactions caused the smoothing reactor gas protection to operate at a 500kV DC receiving-end station in East China. In the ADPSS simulation case, a single-phase ground fault on the receiving-end AC bus causes DC commutation failure. The base capacity is 100 MVA. At time 2s, a phase-A single-phase ground fault occurs in the ADPSS DC receiving-end inverter side near area, with fault duration of 100ms. The primary system of the DC model uses detailed actual engineering data provided by the State Grid Dispatching Center, and the DC control system logic comes from the domestically produced control system authorized by the engineering winning bidder. The overall case has been verified through multi-faceted comparison between the State Grid Simulation Center and actual engineering, making the research results practically significant for engineering scientific research.

[Figure 5: see original paper] HVDC detail system

The figure shows that the fault conduction relationship is intuitively displayed through overall waveforms. The fault originates from the AC system fault, triggering DC commutation failure. The DC transient shock current caused by commutation failure generates mechanical forces that create vibration in the smoothing reactor body and gas relay. Simultaneously, the cantilever structure of the smoothing reactor gas relay and oil conservator amplifies the vibration, causing escalation of smoothing reactor gas relay mechanical vibration acceleration. When vibration acceleration exceeds mechanical tolerance, the stability of the baffle contact setting threshold decreases. Pressure wave flow impacts the baffle installed in flowing insulating oil. When the flow velocity of pressure wave flow exceeds the baffle' s action sensitivity, the baffle moves in the direction of pressure wave flow [15], forcibly pushing the float to the setting position and causing contact operation, which sends a trip signal and leads to false operation of heavy gas in the smoothing reactor.

[Figure 6: see original paper] HVDC Smoothing Reactor Gas Relay Fault Conduction Waveforms

[Figure 7: see original paper] HVDC inverter side AC current

[Figure 8: see original paper] HVDC inverter side AC voltage

[Figure 9: see original paper] HVDC inverter side active power

[Figure 10: see original paper] HVDC blocking filter delay removal signal

[Figure 11: see original paper] HVDC inverter side reactive power

The figures demonstrate that the transient shock current triggered by the AC system fault caused false operation of the smoothing reactor gas protection, leading to blocking of DC pole I converter valve. After 300ms, pole I filters were removed, causing impact on active and reactive power of both sending and receiving-end AC systems. The preliminary fault reproduction conducted using the proposed model combined with engineering examples can relatively detailedly demonstrate and analyze the dynamic characteristics of key equipment and the fault conduction process and transient shock impact in AC-DC 联动 faults.

Conclusion

This paper has detailedly investigated and analyzed the equipment principles and characteristics of DC smoothing reactor gas relays. The Gaussian algorithm was employed to model the electrical correlation dynamic characteristics of the non-electrical equipment (smoothing reactor gas relay) that has repeatedly caused DC blocking in actual engineering. The model was implemented through programming on the domestically developed ADPSS platform and is compatible with DC electromagnetic transient engineering calculations. Based on the East China power grid case from the State Grid Simulation Center and State Grid Dispatching Center, a preliminary fault reproduction of the July 5 accident was conducted. This research is significant for studying the fault conduction characteristics of blocking faults involving non-electrical quantities in complex large-scale AC-DC power grids. It achieves an important functional 填补 for future prevention, control, and improvement of related faults in both theoretical and simulation aspects, holds important practical significance for further improving the multi-dimensional accuracy of DC engineering simulation, and provides a methodology for detailed modeling of other nonlinear electrical-related equipment such as MCSR.

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