Journal of Innovation and Development
ISSN: 2958-4752 | Vol. 11, No. 1, 2025

Application of Anti-Voltage Sag Technology and Traveling Wave Fault Location in Oilfield Power Grids

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Abstract: With the expansion of power system scales and increasing load complexity, voltage sags ("flicker") and line faults pose severe challenges to industrial production and grid security. Anti-voltage sag technology effectively mitigates equipment shutdowns caused by voltage fluctuations through core measures such as contactor delayed release protection and UPS/DC-BANK systems, ensuring power supply reliability in continuous production scenarios like oilfields. Traveling wave fault location technology leverages the high-frequency transient characteristics of fault-induced traveling waves to achieve rapid and precise fault localization in transmission and distribution lines, significantly reducing fault diagnosis time. This paper systematically analyzes the principles and typical applications of these two technologies: anti-voltage sag technology reduces unplanned downtime risks in oilfield distribution networks through multi-level protections (e.g., low-voltage motor retrofitting, high-voltage equipment delayed tripping, and system-level fast bus transfer devices); traveling wave fault location combines dual-terminal methods, wavelet transforms, and intelligent algorithms to achieve sub-1% localization errors in complex scenarios such as HVDC lines and multi-branch cable networks. Research demonstrates that these technologies enhance grid resilience from "prevention to recovery" perspectives. Future advancements in intelligent coordination (e.g., digital twins and edge computing) could further optimize the efficiency of power system fault management, providing critical technical support for smart grid development.

Keywords: Anti-voltage sag technology; raveling wave fault location; oilfield distribution network; transmission and distribution line fault analysis.

1. Introduction

The rapid evolution of new power systems and the deep transformation of energy structures have introduced multidimensional challenges to power system stability and fault management. On one hand, large-scale renewable energy integration, high penetration of power electronic devices, and the complexity of hybrid AC/DC grids have increased grid volatility and vulnerability. Transient issues like voltage sags (commonly termed "flicker") and harmonic disturbances frequently cause unplanned shutdowns of critical industrial equipment. For example, a single flicker event in petrochemical plants can result in economic losses exceeding millions of RMB [1]-[2]. On the other hand, the extensive coverage and harsh operating environments of transmission and distribution lines lead to inefficiencies in fault localization. Traditional impedance-based methods, affected by time-varying line parameters and load fluctuations, often exhibit errors exceeding 5%, failing to meet modern "minute-level" fault recovery demands [3]-[4].In this context, anti-voltage sag technology and traveling wave fault location have emerged as core solutions for grid resilience. The former enhances motor tolerance to voltage sags to over 300 ms through dynamic compensation mechanisms like contactor delayed release and DC-BANK systems, effectively avoiding cascading shutdowns [5]-[6]. The latter leverages the high-frequency transient characteristics and near-light-speed propagation of traveling waves, combined with distributed monitoring and intelligent algorithms, to achieve sub-kilometer localization accuracy in complex scenarios like HVDC lines, reducing fault diagnosis time by over 60% [7]. This paper constructs a technical framework for these technologies, focusing on "problem-oriented analysis, technical interpretation, and collaborative optimization." It first examines the anti-voltage sag requirements and implementation pathways in oilfield distribution networks, then explores adaptive improvements for traveling wave fault location in hybrid AC/DC grids, and finally proposes a collaborative application paradigm under smart grid frameworks to enhance fault prevention, rapid localization, and recovery efficiency.

2. Principles of Anti-Voltage Sag Technology and Its Application in Oilfield Distribution Networks

2.1. Basic Principles of Anti-Voltage Sag Technology

Voltage Sag refers to the situation where the root mean square value of the grid voltage drops to 10%-90% of the rated value within a short period (from 0.5 cycle to 1 minute), usually accompanied by a phase jump. In the industry, it is called "momentary voltage drop" [8]-[9]. Its causes include external disturbances such as lightning strikes, short-circuit faults in transmission lines, and grid voltage imbalance caused by the switching of adjacent large-capacity equipment (such as electric arc furnaces); internal system faults such as grounding faults, inrush currents of transformers, and impact of starting currents of motors; and fluctuations in new energy sources such as local voltage instability caused by the intermittency of the output of distributed power sources such as photovoltaic power generation and wind power generation.

There are three core protection mechanisms in anti-momentary voltage drop technology, namely contactor delayed release, dynamic support of UPS/DC-BANK, and fast transfer device (FBT). Contactor delayed release means reducing the contactor release voltage threshold (e.g., from 75% to 50% of the rated voltage) or installing a delay module (such as the FS - MD series) to keep the contactor in the closed state for 200 - 300 ms during the voltage sag, thus preventing shutdown caused by short - term voltage drops.The UPS provides millisecond - level backup AC power for control circuits such as PLC and DCS to ensure the operation of sensitive equipment. The DC - BANK continuously monitors the DC bus voltage of the frequency converter in real - time (the threshold is usually 650V) and activates the energy - storage capacitor bank within 3 - 5 ms to provide 0.5 - 2 seconds of DC support.Based on the prediction of bus residual voltage decay and the synchronization capture algorithm, the fast transfer device (FBT) can complete the switching of the backup power supply within 100 ms.

2.2. Analysis of the Demand for Anti-momentary Voltage Drop in the Power Distribution Network of Oilfields

As a continuous production scenario, the power distribution network of oilfields needs to ensure the stable operation of key equipment such as oil pumps and water injection systems. In terms of the requirements for production continuity, a single shutdown of an oil pump can lead to an imbalance in the wellhead pressure, an interruption in crude oil transportation, and even trigger secondary accidents such as liquid accumulation in the wellbore.

The characteristics of the momentary voltage drop risks in the power grid of oilfields are concentrated in three aspects: Firstly, there are frequent external disturbances. Since most of the power grids are located in remote areas, long-distance overhead lines are vulnerable to lightning strikes (accounting for more than 35%) and salt spray corrosion, which often trigger instantaneous short circuits or grounding faults. Secondly, the dynamic impact of the load is significant. High-power water injection pumps and compressors are started and stopped more than 50 times a day, causing the bus voltage fluctuation rate to exceed ±10%. Thirdly, the complexity of extreme environments is prominent. Harsh conditions such as deserts and oceans accelerate the insulation aging of equipment, resulting in the failure rate of lines above 6kV being 2 to 3 times higher than that in inland areas. The superposition of multiple risks greatly increases the instability of the system operation.

In response to the above requirements, the anti-momentary voltage drop technology needs to construct a two-tier protection system of "equipment tolerance - system reconstruction": at the low-voltage side, an anti-momentary voltage drop contactor (release threshold ≤ 50%Ue) and DC-BANK DC support (maintenance time ≥ 500ms) are used; at the high-voltage side, low-voltage delayed tripping (action time 0.5-1.5s) and a fast transfer device with linkage of optical differential protection (switching time ≤ 100ms) [10] are configured to form a protection system that is suitable for the characteristics of the power grid in oilfields.

2.3. The Specific Application of Anti-momentary Voltage Drop Technology in Oilfields

For the low-voltage motors in oilfields (such as oil transfer pumps and water injection pumps), a collaborative protection scheme of anti-momentary voltage drop contactors and UPS is adopted. By optimizing the release voltage threshold (≤ 50% of the rated voltage) or installing a delay module (such as the FS-MD series), the anti-momentary voltage drop contactor can maintain the main circuit in the closed state for 200-300 ms when the voltage drops. This can improve the anti-momentary voltage drop ability of the low-voltage motor to more than 300 ms and reduce the tripping rate by 65% [11]. The UPS provides 20-100 ms of dynamic power support for the control circuits (PLC and DCS). For example, in the case of Lanzhou Petrochemical, the power-off tolerance time of the control circuit is extended to 500 ms, avoiding the interruption of logic signals [12]. The two form a "dual redundancy of main control" protection system. The synergistic effect of maintaining the closed state of the main circuit and the control logic is remarkable. After the application in an offshore oilfield, the number of shutdowns of low-voltage motors due to momentary voltage drops has decreased by 82%, effectively ensuring the stability of continuous production.

For the high-voltage motors in oilfields (such as compressors and main oil pumps), a collaborative strategy of low-voltage delayed tripping and bus residual voltage locking is adopted. By setting a tripping delay of 0.5 to 1.5 seconds, the duration of the momentary voltage drop (usually < 500 ms) can be avoided. After a 35kV water injection station configured a 0.8-second delay, the mis-tripping rate of high-voltage motors decreased from 45% to 8%. At the same time, the residual voltage locking logic is introduced. When the bus residual voltage is higher than 60% of the rated value, the tripping signal is automatically locked to avoid misoperation during the voltage recovery period. In combination with the linkage of the fast transfer device, the bus recovery time is compressed to 150 ms [13], effectively balancing the equipment protection requirements and the system's ability to quickly restore power.

For the variable frequency drive equipment in oilfields (such as variable frequency water injection pumps), a collaborative technology of DC-BANK DC support and low-voltage ride-through is adopted. The DC-BANK monitors the voltage in real time by connecting energy-storage capacitor banks in parallel on the DC bus side. When a voltage drop (with a threshold of 650V) is detected, it can be switched in within 3-5 ms and provide a DC energy buffer for 0.5-2 seconds. Cases show that its anti-momentary voltage drop ability is improved to 500 ms, avoiding shutdown [14]. At the same time, the low-voltage ride-through function is upgraded. By using IGBT dynamic adjustment, the bus voltage fluctuation is controlled within ±10%, and a software current-limiting algorithm is used to reduce the torque impact, enabling the frequency converter to continuously operate for 2 seconds at 80% of the rated voltage [15]. The collaboration of the two achieves dual guarantees of energy buffering and dynamic adjustment during voltage sags, significantly improving the anti-momentary voltage drop ability of the equipment and the reliability of continuous operation. After the transformation of an oilfield, the number of unplanned shutdowns of variable frequency equipment has decreased by 90% annually, saving more than 3 million yuan in maintenance costs per year [16].。

The power grid of the oilfield achieves collaborative protection by deploying a fast transfer device (FBT) and an intelligent power management system. Based on the optical differential protection signal, the fast transfer device can complete the switching of the backup power supply within 100 ms after detecting a line fault (the action conditions are that the voltage difference ≤ 10% and the phase difference ≤ 15°). After the transformation of a 6kV busbar, the power supply recovery time is shortened from 5 minutes to 30 seconds [17].The intelligent power management integrates a wavelet transform voltage sag prediction model and an adaptive control strategy, and dynamically switches the power supply mode of the UPS/DC-BANK. For example, a certain intelligent module reduces the power consumption of the contactor by 40% and the DC switching delay ≤ 10 ms [18].In the linkage of the two, the fast transfer device ensures rapid power restoration, and the intelligent system optimizes energy distribution and the response to voltage sags. Collaboratively, the power grid's tolerance time for momentary voltage drops is increased to more than 1 second, and the risk of system-level shutdowns is reduced by 85%, significantly enhancing the continuity of power supply [10].

3. The Principle of Traveling Wave Fault Location Technology and Its Application in the Fault Analysis of Transmission and Distribution Lines

3.1. The Basic Principle of Traveling Wave Fault Location

The generation of traveling wave signals occurs when a short circuit or lightning strike fault happens in the transmission and distribution lines. The sudden change in the voltage and current at the fault point will excite high-frequency transient traveling wave signals (ranging from 1kHz to 1MHz), which propagate towards both ends of the line at a speed close to the speed of light (0.95 to 0.98 times the speed of light). During the propagation process, the traveling wave experiences reflection and refraction at positions with discontinuous impedance, such as branch points and terminals, resulting in waveform distortion.

The traveling wave fault location methods are mainly divided into the single-ended method and the double-ended method. The single-ended method calculates the fault distance by using the time difference between the initial traveling wave of the fault and the reflected wave. This method does not require synchronization at the opposite end, but it is vulnerable to subsequent reflection interference. In complex networks, the positioning error can reach up to 3%. The double-ended method calculates the distance by synchronously collecting the time difference of the arrival of traveling waves at both ends. It relies on GPS/B code clock synchronization. When the synchronization error is ≤ 1us, the positioning accuracy is better than 0.1%, making it suitable for long-distance transmission lines.

3.2. The Demand for Fault Location of Transmission and Distribution Lines

The rapid and accurate location of faults in transmission and distribution lines is a core requirement for ensuring the reliability of the power grid. According to statistics, a single high-voltage line fault that is not dealt with in a timely manner can lead to power outages lasting several hours, and the economic losses can reach the level of millions of yuan [19]. With the increase in the cable rate in cities (overhead lines are gradually being replaced by underground cables), the traditional manual inspection is inefficient, and there is a need to rely on automation technologies to achieve fault isolation and restoration within minutes [20].。

The traditional impedance method has significant limitations in the fault location of power lines: Firstly, the measurement based on power frequency voltage/current has low sensitivity to high-resistance faults (such as the deterioration of cable insulation), and the positioning error often exceeds 5% [21]. Secondly, the line reactance, transition resistance, and load fluctuations (especially with the access of distributed power sources) are likely to cause the mismatch of the distance measurement equation. Simulations show that a 10% load fluctuation can triple the error [22]. In addition, in the hybrid lines of cables and overhead lines, due to the sudden change in wave impedance and the fact that traditional algorithms cannot correct the wave velocity differences, the positioning results are prone to failure [23]. The traditional impedance method faces bottlenecks in accuracy and adaptability in complex scenarios, and it is necessary to integrate the traveling wave method, intelligent algorithms (such as wavelet denoising and modulus analysis), and the collaboration of multi-source data to construct a highly robust positioning system that is suitable for multi-branch/hybrid lines [24].

3.3. The Application of Traveling Wave Fault Location in the Fault Analysis of Transmission and Distribution Lines

For high-voltage direct current (HVDC) lines, due to their long transmission distances (usually exceeding 1000 kilometers) and the influence of frequency-dependent parameters on the wave velocity, the errors of traditional traveling wave fault location are significant. Therefore, distributed monitoring and wave velocity correction technologies are adopted. The former involves deploying monitoring terminals every 50-100 km along the conductors to collect traveling wave current waveforms in real time. By combining single-ended and double-ended algorithms, the long-distance attenuation is reduced. For example, in the case of a lightning strike fault on a ±500 kV line, the positioning error is reduced from ±2 km to ±200 m [25]. The latter dynamically calculates the line distribution parameters (R, L) based on the time difference of the arrival of double-ended traveling waves and the current amplitude, and corrects the wave velocity model in real time. For instance, in the Yazhong-Jiangxi ±800 kV project, the joint correction by multiple methods enables the fault location accuracy to reach ±0.3% [26]. In addition, the inverse traveling wave fault location technology uses the àtrous algorithm to accurately calibrate the wavefront, avoiding the interference of the frequency-dependent reflection coefficient, and achieves an error of less than 0.5% in hybrid conductor lines, effectively solving the problem of high-precision location under long distances and multi-factor interference.

In multi-branch overhead lines, due to multiple reflections of traveling waves, the misjudgment rate of the traditional single-ended or double-ended method is as high as 30%. To address this issue, a collaborative solution combining the three-terminal traveling wave method and the branch judgment matrix is proposed.The three-terminal traveling wave method adds a third monitoring point and uses the Pearson correlation coefficient (with a threshold > 0.9) to analyze the waveform similarity for identifying the fault section. For example, in a 220kV line, the Hilbert-Huang Transform (HHT) is used to extract the instantaneous frequency characteristics, and after combining with sampling error correction, the positioning error is less than 1% [27].The branch judgment matrix constructs a fault location vector based on the wave velocity difference between the zero-mode and the first-mode. By forming a feature vector from the ratio of the distance measurement results of each monitoring terminal to the inherent length of the line, and screening the terminal data that meet the threshold ($|\Delta L/L| < 5\%$). PSCAD simulations show that this method can achieve an error of less than 100m in complex branch networks without the need for GPS synchronization [28].These two technologies respectively improve the positioning accuracy and anti-interference ability in multi-branch scenarios through topological expansion and feature screening.

For cable lines, due to the distributed capacitance (approximately 200 pF/m), the attenuation rate of traveling waves is relatively high (0.2 dB/km), and it is necessary to improve the fault location accuracy by extracting high-frequency features. Wavelet transform uses the cubic B-spline wavelet to decompose the traveling wave signal, and extracts the high-frequency components above 100 kHz to accurately calibrate the wavefront. For example, in the case of a single-phase grounding fault of a 10 kV cross-linked polyethylene (XLPE) cable, the fault location error is less than 50 m [29]. The joint time-frequency analysis combines the Wigner-Ville distribution (WVD) and the short-time Fourier transform (STFT) to capture the time-frequency mutation characteristics of traveling waves. For instance, in a 35 kV overhead-cable hybrid line, the Hilbert-Huang Transform (HHT) is used for adaptive decomposition of the frequency band and correction of the wave velocity attenuation model, reducing the error from 5% to 1% [30]. In addition, the zero-mode wave velocity correction technology based on wavelet multi-frequency band analysis can eliminate the instability of the ground-mode wave velocity, achieving an error of less than 100 m in single-phase grounding faults of the distribution network, comprehensively solving the constraints on the positioning accuracy caused by the high-frequency attenuation of cables and the wave velocity differences in hybrid lines.

Due to the complex branches and unbalanced three-phase loads in the distribution network, the traditional double-ended fault location method is limited. Therefore, a fusion scheme of the improved single-ended method and deep learning is proposed. The improved single-ended method realizes fault location by eliminating the influence of the zero-mode wave velocity, based on the arrival time of the first wavefront of the line-mode traveling wave (triggered by high-voltage pulse injection) and the stable line-mode wave velocity (298 m/μs), with an error of less than 100 m [31]. The deep learning technology further enhances the anti-interference ability [32]. The Long Short-Term Memory (LSTM) network extracts accurate wavefront timestamps from the noisy traveling waves, increasing the signal-to-noise ratio by ≥ 20 dB. The Convolutional Neural Network (CNN) dynamically compensates for the changes in wave velocity, and in the simulation of a 10 kV line, the error is less than 0.5%. At the same time, combined with the digital twin model, it predicts the propagation path of traveling waves, and simultaneously completes the identification and location of lightning strike/non-lightning strike fault types. Through the full-chain optimization of "signal processing - parameter correction - intelligent diagnosis", this technical system significantly improves the efficiency and accuracy of fault handling in complex distribution network scenarios.

4. Conclusions

(1) The comprehensive anti-momentary voltage drop technology, through the hierarchical protection and rapid switching mechanism, has significantly improved the ability of the oilfield power system to resist voltage sags and ensured the continuous operation of key equipment. The traveling wave fault location technology, relying on high-precision signal processing (such as wavelet transform and EMD-SVD decomposition) and multi-terminal collaborative measurement, has achieved rapid location of faults in complex lines (with an error of less than 1%). It performs particularly well in scenarios of hybrid lines and multi-branch lines. The combination of these two technologies can effectively shorten the fault recovery time (from the hour level to the minute level) and reduce production losses, providing technical guarantees for industrial scenarios with high reliability requirements, such as oilfields.

(2) In the future, it is necessary to further optimize the adaptability of the traveling wave front identification algorithm and the anti-momentary voltage drop device to meet the challenges of extreme working conditions and new types of power electronic devices.

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