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Original Research Article

Distance Protection Performance on Long EHV Lines in Desert Conditions: Effects of Temperature, Sag, and Impedance Drift

Humayun[1*]
[1]Research Scholar

***Corresponding Author**
Humayun
Research Scholar

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Abstract: Distance protection is a primary protection scheme for long extra-high-voltage transmission lines, but its performance can be significantly affected by harsh desert operating conditions. In desert regions, EHV lines are exposed to high ambient temperature, intense solar radiation, low humidity, wind variation, sand contamination, and wide daily thermal cycles. These factors influence conductor temperature, sag, resistance, line impedance, and the apparent impedance measured by distance relays. As conductor temperature increases, resistance rises and the relay impedance locus may shift, creating risks of under reach, overreach, delayed tripping, incorrect zone coordination, and inaccurate fault location. Long EHV lines are also affected by distributed capacitance, shunt compensation, mutual coupling, load encroachment, and high-resistance faults, which further complicate relay performance. This paper examines the influence of temperature, sag, and impedance drift on distance protection behavior in desert environments. It presents a technical review of operating challenges and proposes an adaptive protection framework based on conductor temperature monitoring, dynamic line rating data, weather sensors, relay event records, and periodic setting validation. The study concludes that environment-aware distance protection improves dependability, security, selectivity, and resilience of EHV transmission systems operating under severe desert conditions and supports reliable future grid operation.

Keywords: Distance Protection, EHV Transmission Lines, Desert Conditions, Conductor Temperature, Conductor Sag, Impedance Drift, Apparent Impedance, Relay Reach, Adaptive Protection, Dynamic Line Rating.

1. INTRODUCTION

Extra-high-voltage (EHV) transmission lines form the backbone of bulk power transfer in desert regions, where generation sources, industrial loads, cities, renewable plants, and interconnection points are often separated by long geographical distances. These lines operate at 220 kV, 380 kV, 400 kV, 500 kV, or higher and their reliability is linked to power-system security. Because a fault on a long EHV corridor can disturb stability, protection systems must identify the faulted section quickly, isolate it selectively, and avoid unnecessary tripping of healthy circuits. Among protection schemes, distance protection remains one of the common methods for overhead transmission lines because it estimates the electrical distance to a fault by measuring voltage and current at the relay location and calculating apparent impedance.

The basic principle of distance protection appears simple, but its performance on long desert EHV lines is technically complex. A distance relay compares the measured apparent impedance with predetermined relay zones, Zones 1, 2, and 3. Zone 1 provides fast primary protection for most of the protected line, Zone 2 gives delayed protection for the remaining section and part of the adjacent line, and Zone 3 provides remote backup. These settings are calculated from line parameters, fault studies, and coordination requirements. If the actual line condition differs from the assumed model, the relay may misjudge the fault position. This can result in underreach, overreach, delayed tripping, loss of selectivity, incorrect backup operation, or inaccurate fault location.

Desert environments make this issue important because overhead conductors are exposed to high ambient temperature, intense solar radiation, hot wind, low humidity, sand contamination, and daily thermal variations. These factors affect conductor temperature and therefore conductor resistance. IEEE Std 738-2023 explains a numerical method for relating bare overhead conductor temperature to electrical current and weather conditions, showing that line thermal behavior depends on more than load current alone. When conductor temperature rises, resistance increases and the resistive component of line impedance changes. On a long EHV line, even a moderate resistance change can shift the apparent impedance trajectory seen by the relay, during high-resistance ground faults, remote-end faults, or heavy loading. This temperature-driven impedance drift reduces the margin between dependable tripping and secure restraint.

Conductor sag is another important desert-condition factor. As conductor temperature increases, the conductor expands and the mid-span sag becomes larger. Sag is usually discussed in relation to clearance, thermal rating, and public safety, but it also has protection relevance. Changes in conductor position may alter conductor-to-ground distance, phase geometry, mutual coupling with parallel circuits, capacitance, and zero-sequence behavior. NERC notes that real-time line capacity is limited by conductor heating and sagging, and that dynamic line rating tools use ambient temperature, conductor temperature, wind speed, and solar irradiation to estimate safe transmission capacity. These same measurements can support protection engineers by indicating whether relay setting assumptions remain valid under actual desert operating conditions.

The research problem addressed in this paper is that many distance relay settings are still based on nominal or conservative line parameters, while long desert EHV lines operate under continuously changing thermal, mechanical, and electrical conditions. The mismatch between static relay settings and dynamic line behavior becomes critical as transmission corridors are loaded closer to their limits, renewable generation is connected through long lines, and utilities attempt to maximize existing network capacity. Dynamic line rating is increasingly discussed as a grid-enhancing technology because it can adjust line ratings according to up-to-date weather and conductor conditions. However, if operating limits become dynamic while protection settings remain static, a coordination gap may appear between power-system operation and protection dependability.

Therefore, this paper examines distance protection performance on long EHV lines under desert conditions with specific focus on temperature, sag, and impedance drift. It reviews the mechanisms by which environmental stress modifies conductor resistance, apparent impedance, relay reach, zone coordination, load encroachment, and fault-location accuracy. The paper also presents an adaptive protection direction based on conductor temperature monitoring, weather-based line rating data, phasor measurements, relay event records, and periodic setting validation. The purpose is not to replace conventional relay-setting studies but to improve them by adding environment-aware validation. Such an approach can help utilities maintain fast, selective, secure, and dependable protection for EHV transmission corridors operating in severe desert climates and future high-loading grid conditions.

2. LITERATURE REVIEW

Distance protection has been widely used for the protection of high-voltage and extra-high-voltage transmission lines because it provides fast fault detection by measuring the apparent impedance between the relay location and the fault point. The relay calculates impedance from the measured voltage and current and compares it with predefined operating zones. If the apparent impedance falls inside the relay characteristic, the relay initiates tripping according to the selected zone and time delay. Hoq (2023) explains that distance protection is commonly applied to transmission lines because it can operate using local voltage and current measurements and does not always require communication with the remote terminal. However, because distance protection is based on apparent impedance, any variation in line parameters, fault resistance, source infeed, or system operating condition can affect the relay decision.

Recent studies have shown that conventional distance protection faces increasing challenges in modern transmission networks. Hernández-Santafé *et al.*, (2025) discuss that fault resistance can significantly affect the apparent impedance seen by distance protection, and this effect is influenced by current contribution from the remote line end and pre-fault load flow conditions. This is important for long EHV lines because remote-end infeed and heavy loading can shift the impedance locus and cause underreach or overreach. High-resistance faults are particularly difficult because the additional resistive component may move the measured impedance outside the intended relay zone, even when the fault is physically located inside the protected section.

The literature also identifies renewable-energy integration and converter-interfaced generation as major factors affecting distance relay performance. Paladhi and Pradhan (2021) proposed an adaptive distance protection method for lines connected to converter-interfaced renewable plants. Their work shows that converter control behavior can change fault-current characteristics and reduce the accuracy of conventional impedance-based fault detection. Although their study focuses on renewable plant connections, the finding is relevant to long desert EHV corridors because many desert power networks are increasingly connected to solar and wind generation plants through long transmission lines. In such conditions, the relay may not receive a traditional fault-current response, and the calculated impedance may no longer represent the actual fault distance accurately.

Mazibuko *et al*., (2024) reviewed the impact of transmission-line compensation and renewable-energy-source integration on protection schemes. Their review highlights that series compensation, shunt compensation, and renewable integration can change the behavior of distance relays and require adaptive protection methods. This is highly relevant for long EHV lines because compensation devices are often used to improve voltage control, increase transfer capability, and manage reactive power. However, these devices can introduce additional impedance effects, voltage inversion, current inversion, subsynchronous components, and protection coordination difficulties. Therefore, fixed relay settings may not be sufficient when line operating conditions and network topology vary significantly.

Temperature-dependent conductor behavior is another major area in the literature. IEEE Std 738-2023 provides a standard numerical method for calculating the current-temperature relationship of bare overhead conductors under steady or time-varying current and weather conditions. The standard confirms that conductor temperature depends not only on current but also on weather conditions such as ambient temperature, wind, and solar heating. This is directly related to desert EHV protection because conductor resistance increases as conductor temperature rises. Since distance relays use impedance-based measurements, a change in conductor resistance can contribute to impedance drift, especially during high-load periods, high ambient temperature, and intense solar radiation.

Dynamic line rating literature further supports the need to consider real-time environmental effects. Dynamic line rating uses measured or forecasted weather and conductor conditions to estimate the actual thermal capacity of an overhead line. The Federal Energy Regulatory Commission noted in 2024 that dynamic line ratings can reflect solar heating, wind speed, wind direction, and other forecastable weather inputs when determining transmission line ratings. This is important because the same environmental variables that affect line rating also affect conductor temperature, sag, and resistance. Therefore, dynamic line rating data can support protection engineers by showing whether actual operating conditions remain within the assumptions used for relay setting calculations.

NERC's 2024 reliability insight on grid-enhancing technologies also explains that dynamic line rating systems use data such as ambient temperature, conductor temperature, wind speed, and solar irradiation to estimate real-time transmission capacity. It also notes that overhead line capacity is limited by conductor heating and sagging. These points are especially important in desert conditions, where low wind speed, high solar radiation, and high ambient temperature can cause conductor temperature and sag to increase. From a protection perspective, sag is not only a mechanical-clearance issue; it may also affect line geometry, mutual coupling, zero-sequence impedance, and fault-location accuracy.

Cybersecurity and data reliability are also emerging concerns in dynamic and adaptive protection applications. Idaho National Laboratory (2024) notes that dynamic line rating deployments may collect field data such as wind speed, wind direction, ambient air temperature, solar radiation, and line current. While such data can improve operational awareness, protection schemes that depend on external measurements must ensure data integrity, sensor accuracy, communication reliability, and secure integration with control-center systems. For desert EHV lines, this means adaptive relay settings should not be changed blindly based on uncertain field data. Instead, environmental measurements should be validated and used with conservative engineering limits.

Overall, the reviewed literature shows that distance protection performance is influenced by apparent impedance accuracy, fault resistance, remote-end infeed, renewable integration, compensation devices, conductor temperature, sag, and real-time weather conditions. However, many studies focus separately on adaptive relaying, renewable integration, line thermal rating, or high-resistance faults. Limited attention is given to the combined effect of desert temperature, conductor sag, and impedance drift on long EHV distance protection. This creates a clear research gap. The present paper addresses this gap by linking desert environmental conditions with relay reach performance, zone coordination, fault-location accuracy, and adaptive setting validation. The review indicates that future protection systems for desert EHV corridors should combine conventional relay-setting principles with environment-aware monitoring, dynamic line rating data, and periodic impedance validation.

3. AIM AND OBJECTIVES OF THE STUDY

The main aim of this study is to examine the performance of distance protection on long extra-high-voltage transmission lines operating in desert conditions, with special attention to the effects of temperature, conductor sag, and impedance drift. The study focuses on how harsh environmental and operating conditions can change the electrical and mechanical behavior of overhead lines and how these changes can influence relay reach, tripping accuracy, fault-location reliability, and protection coordination. Since distance relays operate by measuring apparent impedance, any variation in line resistance, reactance, conductor geometry, or fault current contribution can affect the relay decision. Therefore, the aim is to develop a clear technical understanding of these influences and present a practical protection framework suitable for utilities managing long EHV corridors in hot desert regions.

The first objective is to explain the operating behavior of distance protection on long EHV transmission lines. This includes the function of Zone 1, Zone 2, and Zone 3 protection, the role of apparent impedance measurement, and the importance of correct relay setting calculation. This objective is necessary because the performance of distance protection depends on the accuracy of line parameters and the ability of the relay to distinguish between internal faults, external faults, heavy load conditions, and abnormal system swings.

The second objective is to analyze the impact of desert temperature on conductor resistance and apparent impedance. In desert regions, overhead conductors are exposed to high ambient temperature, direct solar radiation, and heavy loading during peak demand periods. These conditions increase conductor temperature, which increases resistance and changes the impedance value seen by the relay. This objective helps identify how thermal variation can create underreach, overreach, delayed operation, or reduced fault-location accuracy.

The third objective is to examine the effect of conductor sag on distance protection performance. Sag increases when the conductor heats and expands. Although sag is mainly considered a mechanical and clearance issue, it can also influence electrical parameters by changing conductor height, phase spacing behavior, coupling with nearby circuits, and zero-sequence impedance. This objective evaluates how sag-related changes may affect relay measurement, ground-fault detection, and the reliability of protection on long lines crossing remote desert corridors.

The fourth objective is to study impedance drift as a combined outcome of temperature variation, sag, line loading, fault resistance, mutual coupling, shunt compensation, and system topology changes. Impedance drift is important because the relay setting is usually based on assumed line data, while the real line operates under variable conditions. This objective aims to connect individual environmental and electrical factors into one protection-performance problem.

The fifth objective is to identify the major protection risks associated with fixed relay settings in desert EHV systems. These risks include Zone 1 underreach, Zone 2 overreach, Zone 3 maloperation, load encroachment, poor high-resistance fault sensitivity, incorrect ground-distance compensation, and inaccurate fault location. By identifying these risks, the study supports better relay-setting review and maintenance planning.

The sixth objective is to propose an adaptive protection approach for improving distance protection performance. This approach includes conductor temperature monitoring, weather sensors, dynamic line rating data, phasor measurement units, relay event records, fault recorder analysis, and periodic setting validation. The purpose is not to replace conventional protection principles but to strengthen them with real-time environmental awareness.

The study is guided by three research questions. First, how do desert temperature and solar heating influence the apparent impedance measured by distance relays on long EHV lines? Second, how does conductor sag contribute to relay reach error, ground-fault measurement uncertainty, and fault-location deviation? Third, how can adaptive monitoring and setting validation improve protection dependability and security under changing desert operating conditions?

The significance of this study lies in its practical value for transmission utilities, protection engineers, system planners, and asset managers. As desert power networks expand and renewable-energy projects increase, long EHV lines are expected to carry higher power flows under more variable operating conditions. A better understanding of temperature, sag, and impedance drift can help utilities reduce unwanted trips, prevent delayed fault clearing, improve outage response, and maintain reliable bulk power transfer. This study therefore contributes to safer, smarter, and more resilient EHV transmission protection in desert environments for present networks and future expansion planning requirements.

4. METHODOLOGY

This study adopts a structured technical review methodology to evaluate how distance protection performs on long extra-high-voltage transmission lines operating under desert conditions. The methodology connects environmental exposure, conductor behavior, line-parameter variation, and relay operating performance into one integrated assessment framework. Since the topic involves both protection engineering and overhead-line thermal behavior, a review-based approach is suitable for identifying the mechanisms through which high temperature, conductor sag, and impedance drift influence relay dependability, security, selectivity, and fault-location accuracy.

The first stage of the methodology is problem identification. Long EHV lines in desert regions are selected as the main study context because they are exposed to severe ambient conditions and are often used for bulk power transfer across remote corridors. The key problem considered is the mismatch between fixed relay settings and variable line behavior. Conventional distance relay settings are normally calculated using standard line impedance, assumed conductor temperature, selected fault cases, and network configuration. However, in desert operation, the actual conductor temperature may rise significantly because of solar radiation, high ambient temperature, heavy loading, and low cooling wind. This causes a change in conductor resistance and creates impedance drift, which may affect the apparent impedance measured by the relay.

The second stage is literature and standards review. Recent technical studies, relay application guides, dynamic line rating documents, and conductor-temperature standards are reviewed to identify accepted principles and current research gaps. IEEE Std 738-2023 is considered relevant because it provides methods for calculating the relationship between conductor current, temperature, and weather conditions. Dynamic line rating literature is also considered because it explains how ambient temperature, wind speed, solar irradiation, conductor temperature, line tension, and sag are used to estimate real-time line capacity. These sources support the argument that the physical condition of an overhead line is dynamic and should be considered during protection performance evaluation.

The third stage is parameter identification. The main variables are grouped into environmental, mechanical, electrical, and protection-related categories. Environmental variables include ambient temperature, solar radiation, wind speed, wind direction, sand contamination, and daily thermal cycling. Mechanical variables include conductor sag, tension, clearance, and conductor position. Electrical variables include positive-sequence impedance, zero-sequence impedance, resistance, reactance, shunt capacitance, mutual coupling, load current, fault resistance, source strength, and remote-end infeed. Protection variables include relay zone reach, relay characteristic, ground compensation factor, load encroachment logic, power swing blocking, communication-assisted tripping, and fault-location algorithm.

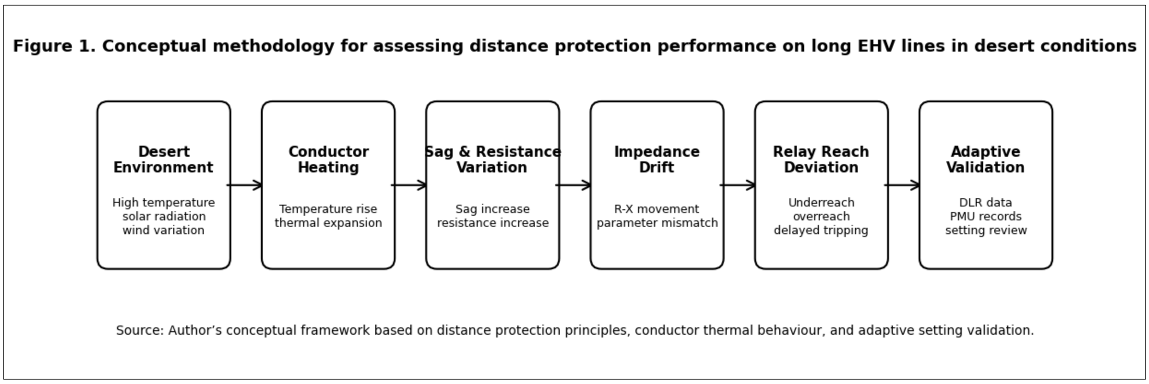
The fourth stage is conceptual modelling of impedance drift. In this stage, the study explains how conductor temperature changes resistance using the standard resistance-temperature relationship. The change in resistance is then linked to apparent impedance movement on the R-X plane. The analysis considers that the relay does not directly measure physical distance; it measures voltage-current ratio. Therefore, any factor that changes the voltage-current relationship can change the relay's interpretation of fault location. This stage also explains how sag can modify line geometry, ground-return behavior, mutual coupling, and zero-sequence impedance, particularly in long corridors and parallel-line arrangements.

The fifth stage is relay performance assessment. The protection impact is evaluated in terms of five performance indicators: dependability, security, selectivity, speed, and fault-location accuracy. Dependability refers to the ability of the relay to trip for internal faults. Security refers to the ability of the relay to avoid tripping for external faults or non-fault conditions. Selectivity means isolating only the faulted section. Speed refers to clearing the fault within the required time. Fault-location accuracy refers to the relay's ability to estimate the fault point correctly for maintenance and restoration. Each indicator is assessed against desert-condition stressors.

The sixth stage is development of an adaptive protection framework. The framework proposes that distance relay settings should be periodically validated using actual or estimated conductor temperature, dynamic line rating data, weather-station measurements, phasor measurement unit data, relay disturbance records, and fault reports. The purpose is not to change settings continuously without control, but to create a supervised engineering process where setting groups, alarms, or operating limits can be adjusted when the line condition exceeds the assumptions used in the original setting study.

Table 1: Methodological variables used in the study

Category	Main variables	Protection relevance
Environmental	Ambient temperature, solar radiation, wind, sand, humidity	Changes conductor heating and cooling assumptions
Mechanical	Sag, tension, clearance, conductor position	Affects geometry, coupling, and fault exposure
Electrical	Resistance, reactance, sequence impedance, fault resistance	Alters apparent impedance and relay reach
Protection	Zone reach, relay characteristic, ground factor, blocking logic	Determines tripping accuracy and coordination
Monitoring	DLR data, PMU data, weather sensors, event records	Supports adaptive validation and setting review



Source: Author's conceptual framework based on distance protection principles, conductor thermal behaviour, and adaptive setting validation.

5. Distance Protection Principles for Long EHV Lines

Distance protection is based on the principle that the electrical impedance between a relay location and a fault point is approximately proportional to the physical length of a line. The relay measures phase voltages and line currents through voltage transformers and current transformers, calculates apparent impedance, and compares the measured value with preset operating characteristics on the resistance-reactance plane. When the measured impedance falls within a selected protection zone, the relay initiates tripping according to the zone logic and time delay. This method is widely used on long EHV overhead lines because it provides high-speed primary protection and coordinated backup protection without requiring direct measurement of the fault location.

A typical distance protection scheme uses three main zones. Zone 1 is normally set to cover most of the protected line, but not the full length, in order to avoid overreach into the next line section. It usually operates instantaneously because it is intended to clear faults that are clearly internal. Zone 2 is set to cover the remaining part of the protected line and a portion of the adjacent line. It operates with a time delay to coordinate with remote-end protection. Zone 3 provides remote backup for faults beyond the adjacent bus and is set with a longer delay. In long EHV systems, these zones must be coordinated with line differential protection, pilot-aided schemes, breaker-failure protection, auto-reclosing, and system stability requirements.

The apparent impedance measured by a distance relay is affected by the fault type. For three-phase faults, the relay mainly uses positive-sequence impedance. For phase-to-phase faults, the measured loop impedance is based on the involved phases. For single-line-to-ground faults, the relay must compensate for zero-sequence current because the ground-return path changes the apparent impedance. The ground distance element uses a residual compensation factor, called the k-factor. If the zero-sequence impedance or mutual coupling is not accurately represented, the ground-distance element may overreach or underreach. This issue becomes important on long EHV lines, especially where parallel circuits share the same corridor.

Long EHV lines also differ from short lines because their electrical behavior is more distributed. Line charging current, shunt capacitance, Ferranti effect, and reactive-power compensation influence voltage and current distribution along the line. Shunt reactors may be installed to control overvoltage during light-load conditions, while series capacitors may be used to improve power transfer capability. These devices can improve system operation but complicate distance protection because they change the impedance seen by the relay during faults. Protection engineers must consider compensation, source impedance ratio, load flow direction, remote infeed, and weak-infeed conditions during setting calculation.

Relay characteristics are selected according to application requirements. Mho characteristics are naturally directional and offer good security during heavy load, but they may have limited resistive reach for high-resistance faults. Quadrilateral characteristics provide independent resistive and reactive reach settings and are often preferred when fault resistance is expected to be significant. Modern numerical relays may include load encroachment blocking, power swing blocking, directional supervision, memory polarization, adaptive setting groups, and communication-assisted tripping. These functions improve performance, but they also require accurate configuration and periodic testing.

On long desert EHV lines, distance protection must operate under changing line conditions. High conductor temperature increases resistance, sag changes line geometry, and heavy loading moves the apparent impedance closer to the load region. As a result, the security margin between normal load and fault impedance may reduce. A remote high-resistance ground fault may appear outside the intended tripping zone, while an external fault may appear inside a backup zone if the relay setting is too aggressive. Therefore, fixed settings based only on nominal impedance may not always represent the actual operating condition.

The basic protection principle remains reliable when supported by correct modelling, suitable zone coordination, and regular validation. For long EHV corridors, relay setting studies should include different loading levels, conductor temperatures, source conditions, fault resistances, compensation states, and line outage scenarios. Event records and fault-location data should also be reviewed after actual disturbances. In desert networks, distance protection should be treated as a dynamic performance function rather than a static setting exercise. This approach helps maintain dependable, secure, and selective fault clearing under normal and severe environmental conditions.

6. Impact of Desert Temperature on Conductor Resistance and Apparent Impedance

Desert temperature has a direct influence on the electrical behavior of long EHV overhead transmission lines because conductor resistance is temperature dependent. In normal relay-setting studies, line impedance is commonly calculated from reference values supplied by the conductor manufacturer or utility line database. These values are usually based on a standard temperature, such as 20°C or another selected design condition. However, in desert regions, the actual conductor temperature can rise far above the reference value because of high ambient temperature, direct solar radiation, heavy load current, low wind cooling, and long exposure during peak demand hours. This difference between reference temperature and actual operating temperature changes the resistive component of line impedance.

The relationship between conductor resistance and temperature can be expressed as $R_2 = R_1 [1 + \alpha(T_2 - T_1)]$, where R_1 is the resistance at reference temperature, R_2 is the resistance at operating temperature, α is the temperature coefficient of the conductor material, T_1 is the reference temperature, and T_2 is the actual conductor temperature. When T_2 increases, R_2 also increases. For EHV lines, reactance is normally larger than resistance, but resistance variation is still important because distance relays measure apparent impedance, not only reactance. The effect becomes more visible on long lines, ground faults, high-resistance faults, and heavily loaded corridors.

Apparent impedance is calculated by the relay from measured voltage and current. During a fault, the relay expects the apparent impedance to fall within a particular zone according to the fault distance. If conductor resistance has increased due to desert heating, the impedance locus may shift on the resistance-reactance plane. This shift can affect Zone 1, Zone 2, and Zone 3 performance. Zone 1 may underreach if the relay sees the fault as farther than it actually is. Zone 2 may experience coordination problems with the next line section. Zone 3 may become vulnerable to load encroachment or unwanted backup operation during stressed system conditions.

Desert temperature also affects daily protection performance. In the morning, conductor temperature may be close to the assumed setting condition. During the afternoon, solar radiation and ambient temperature increase conductor heating. At the same time, electricity demand may rise because of cooling loads, increasing current and Joule heating. In the evening, load may remain high while conductor cooling may be slow. Therefore, the line impedance seen by the relay is not constant across the day. A setting that appears secure under mild conditions may have reduced margin during peak desert operation. This practice is especially valuable for 380 kV and 500 kV corridors where small percentage errors can represent long physical distances and extended repair searches.

High temperature also interacts with fault resistance. Single-line-to-ground faults in desert areas may involve dry soil, sand, tower footing resistance, flashover paths, or arcing faults. These conditions can add significant resistance to the fault loop. When increased conductor resistance and fault resistance occur together, the apparent impedance moves further into the resistive direction. If the relay's resistive reach is not adequate, especially for mho characteristics, the relay may fail to detect the fault within the expected zone.

For this reason, protection studies for desert EHV lines should not rely only on nominal line impedance. They should include conductor-temperature scenarios, peak-load cases, seasonal temperature profiles, and high-resistance fault simulations. Dynamic line rating measurements, weather sensors, and conductor temperature estimation can help utilities compare actual operating conditions with relay-setting assumptions. By including temperature-dependent resistance in setting validation, utilities can reduce underreach, improve fault-location accuracy, and maintain reliable distance protection during severe desert operation in remote locations.

7. Effect of Conductor Sag on Relay Performance

Conductor sag is an important operating factor for long EHV overhead lines in desert environments. Sag refers to the vertical displacement of the conductor between two supporting towers. It increases when conductor temperature rises, because the conductor expands and loses mechanical tension. In desert corridors, sag can become more significant during high ambient temperature, strong solar radiation, low wind cooling, and heavy current loading. Although sag is usually treated as a clearance and mechanical safety issue, it also has a direct and indirect influence on distance protection performance.

The first protection impact of sag is related to line geometry. Distance relay settings are calculated using line impedance values derived from conductor size, spacing, height, transposition, earth-return path, and tower arrangement. When sag increases, the conductor height above ground changes along the span. This can slightly modify capacitance, ground-return effects, and zero-sequence impedance. For phase faults, the impact may be limited, but for single-line-to-ground faults, the ground-return path and zero-sequence parameters are more sensitive. If the relay compensation factor is based on fixed zero-sequence data, actual sag-related variation may contribute to ground-distance reach error.

The second impact is mutual coupling. Many long EHV desert routes use double-circuit lines or parallel corridors to transfer bulk power. When sag changes conductor position, the electromagnetic relationship between adjacent circuits can also change. During ground faults, mutual zero-sequence coupling may cause the relay to measure an apparent impedance that differs from the actual line impedance to the fault. This can lead to underreach, overreach, or incorrect directional decision, especially when one circuit is out of service, lightly loaded, or grounded for maintenance.

The third impact is fault exposure. Excessive sag reduces clearance between the conductor and ground, vehicles, temporary construction equipment, sand dunes, or nearby structures. In desert areas, flashover can occur during dust storms, contamination, high wind, or abnormal clearance reduction. Such faults may be intermittent or high resistance. A high-resistance flashover can move the apparent impedance in the resistive direction, making it difficult for Zone 1 or Zone 2 elements to detect the fault quickly.

Sag also affects fault-location accuracy. Numerical relays estimate fault distance using stored impedance per kilometer. If actual conductor geometry and impedance differ from the stored model, the estimated distance may be inaccurate. On a short line, this error may be acceptable, but on a long EHV line, even a small percentage error can create several kilometers of uncertainty. This delays patrol, repair, and restoration in remote desert areas.

Therefore, sag should be included in protection performance studies. Utilities should compare relay settings with thermal rating studies, dynamic line rating records, conductor temperature estimates, and line survey data. Where sag variation is high, adaptive setting validation, wider resistive reach, improved ground compensation, and event-record analysis should be applied. Considering sag in distance protection improves selectivity, dependability, operating security, maintenance planning, emergency response, and restoration efficiency during severe desert loading conditions across remote high-voltage transmission corridors and substations in practice today.

8. Impedance Drift and Relay Reach Errors

Impedance drift refers to the change between the line impedance assumed during relay setting calculation and the actual impedance experienced during operation. On long EHV lines in desert conditions, this drift can occur because of conductor temperature rise, sag variation, load changes, fault resistance, mutual coupling, shunt compensation, and network topology changes. Distance relays depend on apparent impedance measurement, so any deviation in actual line parameters can influence relay reach and operating accuracy.

The most direct cause of impedance drift is temperature-dependent resistance. When the conductor becomes hotter, its resistance increases. This changes the resistive component of the line impedance and shifts the apparent impedance point on the R-X plane. In normal operation, the change may appear small, but during faults it can become important because the relay must decide quickly whether the measured impedance belongs inside or outside a protection zone. On long EHV lines, even a small impedance percentage error can represent a long physical distance.

Relay reach error appears mainly as underreach or overreach. Underreach occurs when the relay fails to operate for a fault inside its intended zone because the apparent impedance appears greater than expected. This may happen during remote-end faults, high-resistance ground faults, weak infeed conditions, or high conductor temperature. Underreach is dangerous because it delays fault clearing and transfers operation to backup protection. Overreach occurs when the relay operates for a fault outside its intended zone because the measured impedance appears lower than expected or enters the relay characteristic incorrectly. Overreach reduces security and may disconnect healthy lines.

Impedance drift also affects zone coordination. Zone 1 must remain secure and should not trip beyond the protected line. Zone 2 must cover the remote end but coordinate with adjacent line protection. Zone 3 must provide backup without tripping during heavy load or power swings. If impedance drift is not considered, these margins can become weak. This is especially important in desert systems where high load, solar generation variation, and long transmission corridors create changing power-flow patterns.

Fault-location accuracy is another concern. Numerical relays estimate fault distance using stored impedance values. If actual impedance differs because of temperature and sag, the estimated fault location may be wrong. In remote desert areas, this increases patrol time and restoration delay. Therefore, impedance drift should be included in relay-setting reviews through temperature-based line models, event-record analysis, dynamic line rating data, PMU measurements, and periodic validation. Managing impedance drift improves relay dependability, security, selectivity, and restoration performance.

9. Desert-Specific Fault Conditions Affecting Distance Relays

Desert environments create fault conditions that differ from those considered in standard transmission-line protection studies. Long EHV lines crossing desert corridors are exposed to dry soil, high tower-footing resistance, sand contamination, wind-blown dust, extreme heat, and limited moisture. These conditions can affect the nature of faults and the apparent impedance measured by distance relays. In many cases, desert faults are not solid metallic faults with low resistance. They may be high-resistance, intermittent, or arcing faults, especially when flashover occurs through dust, polluted insulators, temporary structures, sand accumulation, or reduced clearance caused by conductor sag.

High-resistance ground faults are particularly challenging for distance protection. When fault resistance is added to the fault loop, the apparent impedance moves further in the resistive direction on the R-X plane. If the relay characteristic has limited resistive reach, such as a traditional mho element, the relay may fail to detect the fault in Zone 1 or may operate only after delayed backup protection. Quadrilateral characteristics usually provide better resistive coverage, but they must be carefully coordinated to avoid load encroachment during heavy desert loading.

Dust and sand contamination also influence fault behavior. Insulator pollution may reduce surface insulation strength, especially during humidity changes, fog, or light moisture after long dry periods. A contaminated insulator may produce leakage current and partial discharge before developing into a flashover. These evolving faults may not create stable fault current immediately, making the relay measurement less predictable. Arcing faults can further distort voltage and current waveforms, causing apparent impedance to fluctuate near relay boundaries.

Desert corridors may also experience faults linked to mechanical and environmental exposure. High wind can move conductors, increase galloping risk, or bring temporary objects near energized conductors. Sandstorms can reduce visibility and delay field inspection after tripping. In remote areas, long patrol distances make accurate relay fault location very important. If temperature, sag, and impedance drift have already affected relay calculations, the reported fault distance may be inaccurate, increasing restoration time.

Another concern is weak infeed or renewable-connected desert networks. Solar plants connected through long EHV lines may contribute limited or controlled fault current through power-electronic converters. This can reduce the current seen by the relay and affect directional or distance element operation. Therefore, desert-specific fault studies should include high-resistance ground faults, contaminated-insulator flashovers, variable source strength, renewable infeed, extreme loading, and sag-related clearance faults. Including these cases improves relay dependability, security, coordination, and restoration performance.

10. Adaptive Protection Framework for Desert EHV Lines

An adaptive protection framework is required for long EHV lines in desert regions because fixed relay settings may not fully represent actual operating conditions. The proposed framework combines conventional distance protection principles with real-time or periodically updated information about conductor temperature, weather, sag, loading, and relay performance. The purpose is not to allow uncontrolled automatic setting changes, but to support supervised and validated protection decisions that improve dependability, security, selectivity, and fault-location accuracy.

The first component of the framework is environmental monitoring. Weather stations, line sensors, and dynamic line rating systems can provide data on ambient temperature, solar radiation, wind speed, wind direction, and conductor temperature. These values help engineers estimate whether the line is operating close to or beyond the conditions assumed during relay setting calculation. When conductor temperature is high, resistance increases and the apparent impedance may shift; therefore, relay reach margins should be reviewed against peak desert conditions.

The second component is electrical monitoring. Phasor measurement units, digital fault recorders, disturbance records, and relay event files should be used to compare measured voltage, current, impedance, and fault-location data with study results. If repeated events show impedance deviation, poor fault-location accuracy, or relay operation near zone boundaries, the relay settings should be reassessed. This creates a feedback loop between actual field performance and protection engineering studies.

The third component is adaptive setting validation. Modern numerical relays can store multiple setting groups for different operating conditions, such as normal loading, high-temperature operation, line-compensated operation, weak-infeed conditions, or special renewable-generation dispatch. However, setting-group changes must be controlled through approved logic, communication security, engineering review, and operational procedures. Incorrect adaptive switching can create more risk than fixed settings.

The fourth component is simulation and testing. Utilities should perform short-circuit studies, load-flow studies, electromagnetic transient simulations, and relay test-set validation using desert-specific scenarios. These scenarios should include high-resistance ground faults, conductor temperature variation, sag-related clearance faults, shunt reactor operation, mutual coupling, renewable infeed, and maximum load. Relay characteristics such as mho, quadrilateral, load encroachment, and power swing blocking should be checked under each scenario.

Finally, the framework requires periodic review. Protection settings should be updated after line uprating, tower modification, conductor replacement, new generation connection, compensation installation, or repeated relay misoperation. Through monitoring, validation, simulation, engineering governance, and review, adaptive protection can make distance relays more reliable for desert EHV transmission corridors.

11. DISCUSSION AND PRACTICAL IMPLICATIONS

The discussion shows that distance protection on long EHV lines cannot be treated as a purely static relay-setting issue, especially in desert environments. Traditional distance relay settings are normally calculated from nominal line impedance, standard conductor data, selected fault cases, and assumed system operating conditions. However, desert transmission corridors operate under high ambient temperature, intense solar radiation, variable wind cooling, heavy loading, and wide daily thermal cycles. These conditions change conductor temperature, resistance, sag, and the apparent impedance measured by the relay. As a result, the actual relay operating condition may differ from the original setting study.

One important implication is the risk of relay reach error. Higher conductor temperature increases resistance and may shift the impedance locus in the R-X plane. When this occurs during remote-end faults or high-resistance ground faults, Zone 1 may underreach and fail to clear an internal fault instantaneously. Zone 2 and Zone 3 may also face coordination problems if the measured impedance enters or leaves the relay characteristic unexpectedly. Therefore, protection engineers should consider conductor-temperature variation when reviewing distance protection settings for long desert EHV lines.

Another implication is the importance of fault-location accuracy. Long desert lines often pass through remote areas where inspection and repair require significant time. If relay fault-location estimation is affected by impedance drift, sag, mutual coupling, or fault resistance, maintenance teams may search the wrong section of the line. This increases outage duration and restoration cost. Therefore, relay event records, digital fault recorder data, and actual patrol findings should be compared after every major fault to improve the line model used in protection studies.

The practical value of adaptive protection is also clear. Weather sensors, dynamic line rating systems, conductor-temperature monitoring, and PMU measurements can help utilities understand when the line is operating outside the assumed protection-setting envelope. However, adaptive protection must be applied carefully. Relay setting changes should be supervised by engineering rules, cybersecurity controls, operational approval, and periodic testing. Poorly controlled adaptive schemes may create unwanted trips or hidden protection gaps.

For utilities, the recommended practice is to combine conventional distance protection with environment-aware validation. Protection studies should include peak desert temperature, maximum loading, high-resistance faults, renewable infeed, shunt compensation, mutual coupling, and sag-related clearance cases. This approach improves relay dependability, security, selectivity, and restoration performance. It also supports more resilient EHV transmission operation as desert networks expand and carry increasing power flows.

12. CONCLUSION

Distance protection remains a vital protection scheme for long EHV overhead transmission lines because it provides fast fault detection, selective tripping, and reliable backup protection. However, this paper shows that its performance can be significantly affected when the protected line operates in severe desert conditions. High ambient temperature, intense solar radiation, low wind cooling, sand contamination, and heavy loading increase conductor temperature and resistance. At the same time, thermal expansion increases conductor sag and may influence line geometry, clearance, mutual coupling, and zero-sequence behaviour. These changes contribute to impedance drift, which affects the apparent impedance measured by the relay.

The main protection concern is that fixed relay settings may not fully represent actual operating conditions. Temperature-driven resistance increase, high-resistance ground faults, sag-related clearance faults, renewable infeed, shunt compensation, and changing system topology can produce underreach, overreach, delayed tripping, load encroachment, and inaccurate fault location. These risks are more serious on long desert EHV corridors because small impedance errors can represent several kilometres of physical distance and can delay fault inspection and restoration.

The study concludes that desert EHV protection should be supported by environment-aware validation. Protection engineers should include conductor temperature variation, maximum loading, high-resistance faults, mutual coupling, sag conditions, and renewable generation scenarios in relay-setting studies. Modern tools such as dynamic line rating data, weather sensors, conductor-temperature estimation, phasor measurement units, digital fault recorders, and relay event records can strengthen setting review and field performance evaluation.

An adaptive protection framework is therefore recommended, but it must be applied with engineering supervision, cybersecurity controls, testing, and operational approval. Properly implemented, adaptive validation can improve dependability, security, selectivity, and fault-location accuracy. Overall, reliable distance protection for long desert EHV lines requires coordination between protection engineering, line thermal monitoring, asset management, and real-time system operation under future high-demand desert grid expansion planning.

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