

# Performance of Voltage-Driven Protection Systems in Renewable-Dominated Networks: A Case Study of the Lusaka 132 kV Transmission Network

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**Abstract** - The global transition toward renewable energy generation is significantly altering the behaviour of modern power systems. Voltage-driven protection systems, particularly distance protection, were originally designed for networks dominated by synchronous generators with high short-circuit levels and stable voltage characteristics (Kundur, 1994; Anderson, 1999). The increasing penetration of inverter-based resources (IBRs) such as solar photovoltaic generation introduces new operational conditions including reduced system strength, limited fault current contribution, and dynamic control interactions during faults.

This paper investigates the performance of voltage-driven protection systems under increasing renewable penetration using the Lusaka 132 kV transmission network as a case study. A detailed network model was developed in DigSILENT PowerFactory and analysed under progressive photovoltaic penetration levels ranging from 0% to 100%. Both RMS and electromagnetic transient simulations were conducted to evaluate relay performance during single-line-to-ground and three-phase faults.

Results demonstrate that increasing renewable penetration reduces fault current magnitude, distorts impedance trajectories, and increases the risk of relay under-reach and delayed tripping (He et al., 2019; Gordon et al., 2022). Several mitigation strategies including battery energy storage systems, static VAR compensation, adaptive protection, and communication-assisted protection schemes are evaluated. The findings highlight the importance of modern protection strategies capable of maintaining reliable protection performance in renewable-dominated power systems.

## Keywords

Renewable Energy Integration; Distance Protection; Inverter-Based Resources; Weak Grid; EMT Simulation; Power System Protection

## 1 INTRODUCTION

Power systems worldwide are undergoing a significant transformation driven by the integration of renewable energy sources such as solar photovoltaic (PV) and wind generation. This transition is motivated by the need to reduce greenhouse gas emissions, enhance energy security, and support sustainable development. However, the rapid integration of renewable generation introduces important technical challenges for power system operation and protection (CIGRE, 2019).

Zambia is currently expanding solar photovoltaic generation to complement hydropower resources, making the evaluation of protection system performance under renewable penetration increasingly important for the national grid.

Traditional power system protection schemes were developed for networks dominated by synchronous generators. These machines provide high fault current contributions, strong voltage support, and predictable dynamic behaviour during disturbances (Kundur, 1994). Protection devices such as distance relays and directional overcurrent relays rely on these characteristics to detect and isolate faults quickly and selectively.

Inverter-based renewable resources behave fundamentally differently from synchronous machines. During fault conditions, grid-following inverters typically limit their fault current contribution to approximately 1.1–1.3 per unit in order to protect converter

components (IEEE PSRC, 2022). As renewable penetration increases, synchronous generation is displaced, resulting in declining short-circuit levels and reduced system strength.

These changes can significantly affect protection system performance. Reduced fault current magnitude alters impedance measurements used by distance relays and may lead to under-reach or delayed operation. In addition, fast control dynamics in inverter-based resources may distort voltage and current signals used for relay polarisation (He et al., 2019).

Despite extensive international research on renewable integration and protection challenges, relatively limited studies have focused on African transmission networks. Zambia is currently increasing solar PV deployment to complement hydropower generation, particularly in the Lusaka region. This makes the Lusaka 132 kV transmission network a suitable case study for investigating the behaviour of protection systems in renewable-dominated environments.

## 2 LITERATURE REVIEW

Conventional protection philosophies were developed for systems dominated by synchronous generation. Under these conditions, fault currents are relatively high and voltage waveforms remain stable during disturbances. Distance protection schemes therefore operate reliably by calculating the apparent impedance between the relay location and the fault using voltage and current measurements (Anderson, 1999).

The increasing penetration of inverter-based resources significantly alters these assumptions. Converter-interfaced generation typically operates as a controlled current source with strict current limiting characteristics during faults. As a result, fault current magnitudes may be substantially lower than those expected in conventional power systems (CIGRE, 2019).

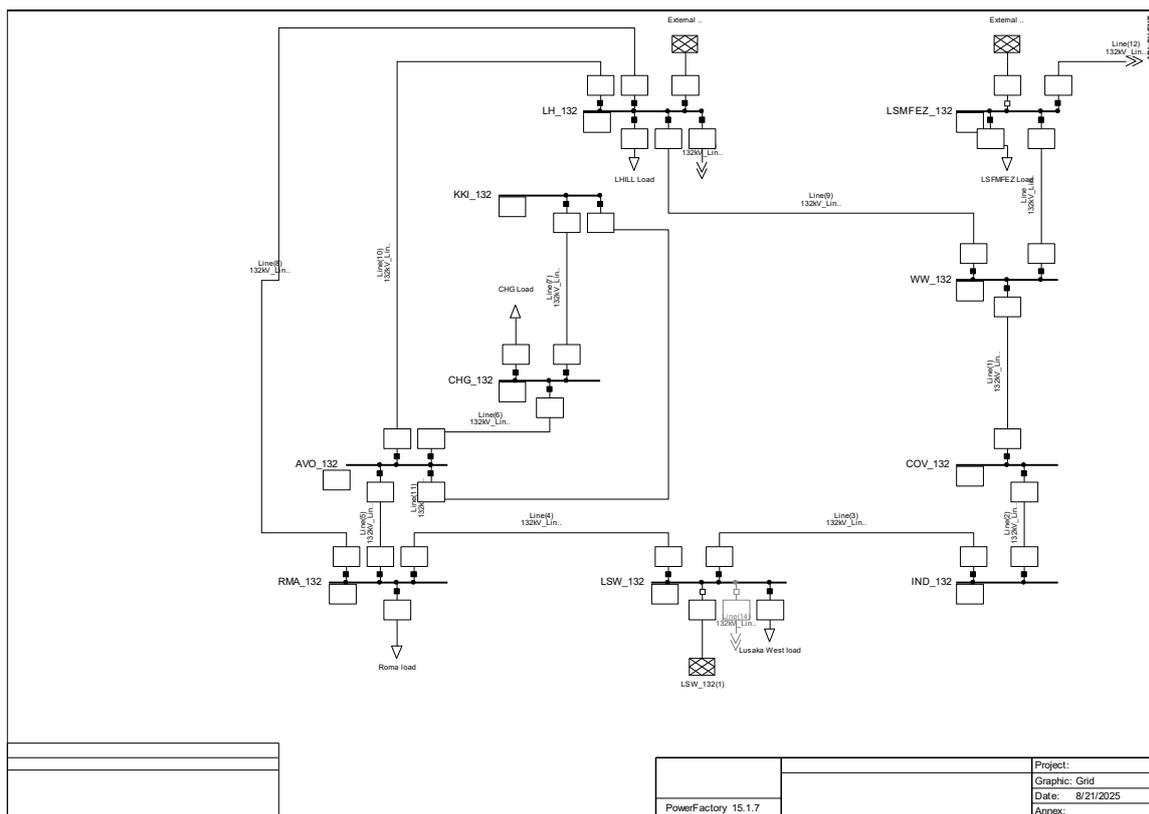
Several studies have demonstrated that declining short-circuit levels can affect distance relay performance. He et al. (2019) showed that reduced system strength increases the likelihood of relay under-reach and measurement errors in impedance calculations. Gordon et al. (2022) reported similar observations in weak grid studies conducted on renewable-dominated networks.

In addition to reduced fault current levels, inverter control systems introduce complex dynamic behaviour during disturbances. Phase-locked loop (PLL) instability, harmonic distortion, and converter current limiting may distort relay measurement signals and affect directional polarisation (IEEE PSRC, 2022).

These challenges have led researchers to investigate alternative protection strategies including adaptive relaying, communication-assisted protection schemes, and dynamic voltage support technologies such as synchronous condensers and battery energy storage systems (Nikmehr et al., 2021). These approaches aim to improve protection reliability under varying system operating conditions.

## 3 METHODOLOGY

This study adopted a simulation-based approach to evaluate the behaviour of voltage-driven protection systems in the Lusaka 132 kV transmission network. A detailed model of the transmission network was developed using DIGSILENT PowerFactory. The model includes transmission lines, transformers, load models, and photovoltaic generation sources connected at selected network nodes. The simplified single line diagram of the Lusaka 132 kV transmission network used in this study is shown in **Figure 1**.



**Figure 1:** Single Line Diagram of the Lusaka 132kV Network

Renewable penetration levels were increased progressively to represent future grid scenarios. Simulation cases were developed for photovoltaic penetration levels of 0%, 25%, 50%, 75%, and 100% of the generation contribution to the Lusaka network.

Fault studies were performed for both single-line-to-ground faults and three-phase faults at selected locations along protected transmission lines. Relay performance was evaluated based on trip time, zone operation, and impedance trajectory behaviour.

Two simulation domains were used. RMS simulations were conducted to analyse steady-state behaviour and general protection performance trends. Electromagnetic transient simulations were then performed to capture fast dynamic phenomena associated with inverter control behaviour including current limiting, harmonic distortion, and PLL response.

#### 4 RESULTS AND ANALYSIS

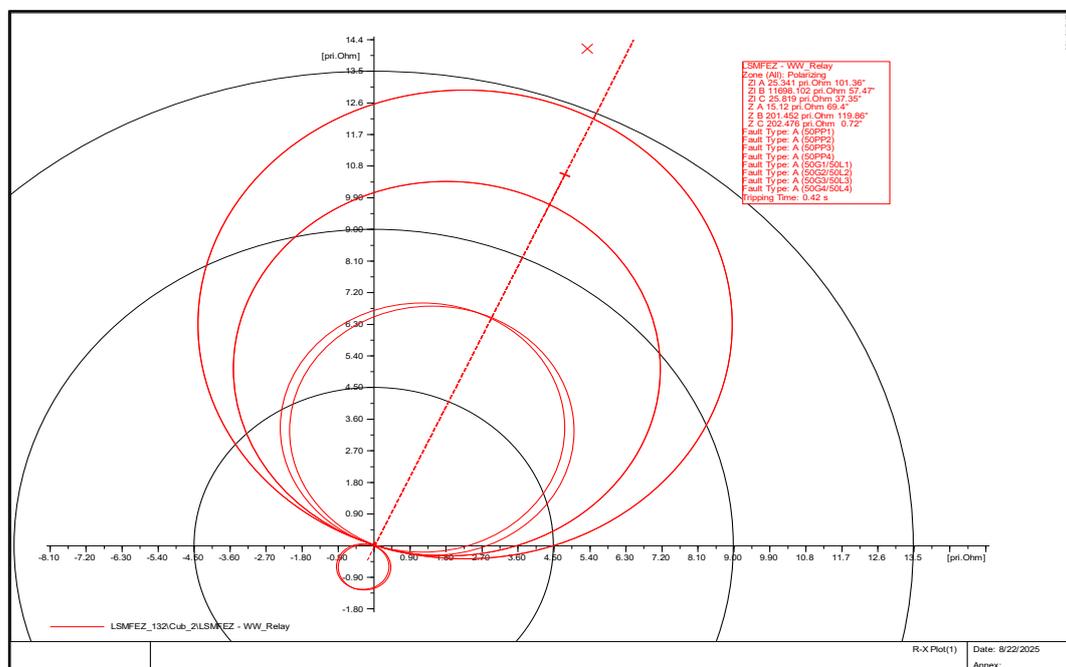
Simulation results show a progressive degradation in distance relay performance as photovoltaic penetration increases. Under the base case scenario dominated by synchronous generation, the network exhibits high fault current levels and stable voltage behaviour. Distance relays operate correctly within their intended protection zones and trip times remain consistent with coordination requirements.

**Table 1:** Distance relay response to PV Penetration sweeps for both single line to ground and three phase line fault.

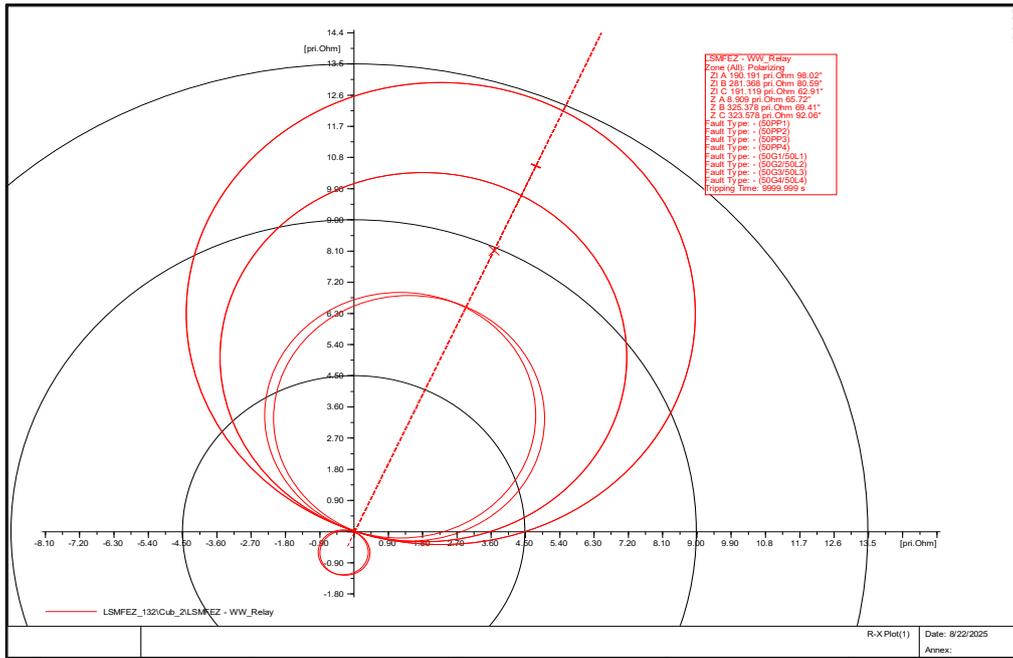
PV Penetration (%)	Fault Type	Fault Location (Line %)	Fault Resistance ( $\Omega$ )	Relay Zone Triggered	Relay Trip Time (s)
100%	L-G	90%	15.688 $\Omega$	No zone operated	No trip operated
			15.896 $\Omega$		

			With LH infeed at remote end		
100%	3 Phase	90%	8.110 Ω	No zone operated	No trip operated
			8.196 Ω		
			With LH infeed at remote end		
75%	L-G	90%	16.336 Ω	Zone 2	0.420s
75%	3 Phase	90%	8.174 Ω	Zone 2	0.420s
50%	L-G	90%	15.811 Ω	Zone 2	0.420s
50%	3 Phase	90%	8.141 Ω	Zone 2	0.420s
25%	L-G	90%	15.434 Ω	Zone 2	0.420s
25%	3 Phase	90%	8.122 Ω	Zone 2	0.420s
0%	L-G	90%	15.154 Ω	Zone 2	0.420s
0%	3 Phase	90%	8.185 Ω	Zone 2	0.420s

As photovoltaic penetration increases, the displacement of synchronous generation results in declining short-circuit levels. The apparent impedance measured by the relay increases and impedance trajectories move closer to the protection boundaries. In Figures 2 and 3 below, the impedance plots for the extreme cases of the trip / no trip thresholds are presented in the X-R plane.



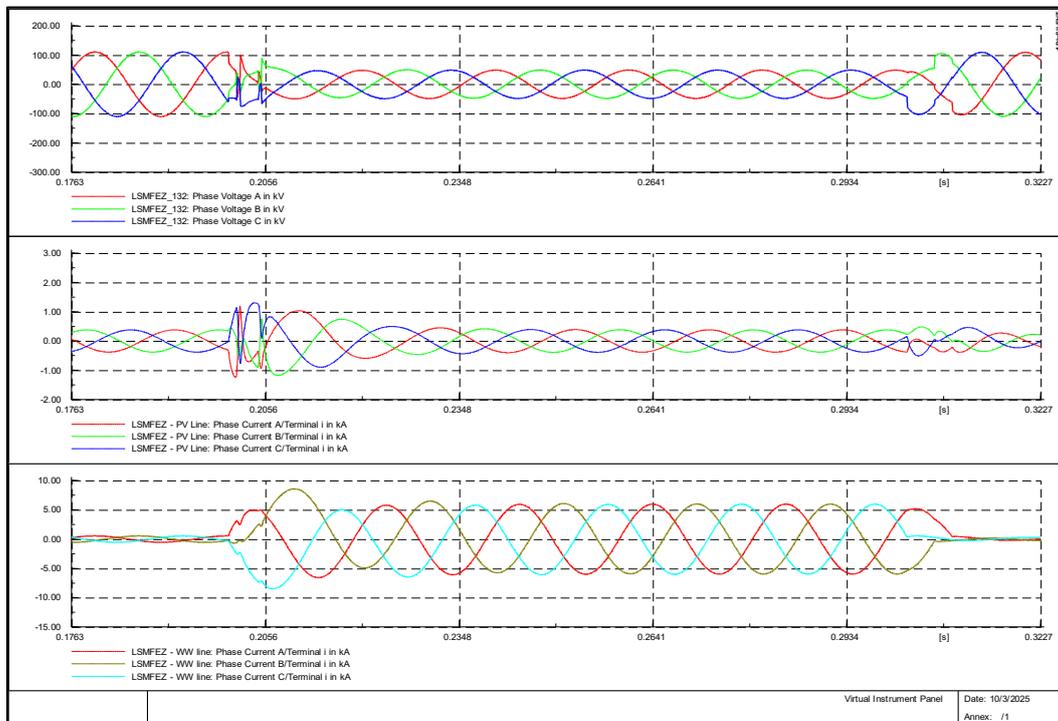
**Figure 2:** Impedance plot of applied fault, with relay characteristic and fault impedance plotted on the X/R plane. Notable is the correct trip operation.



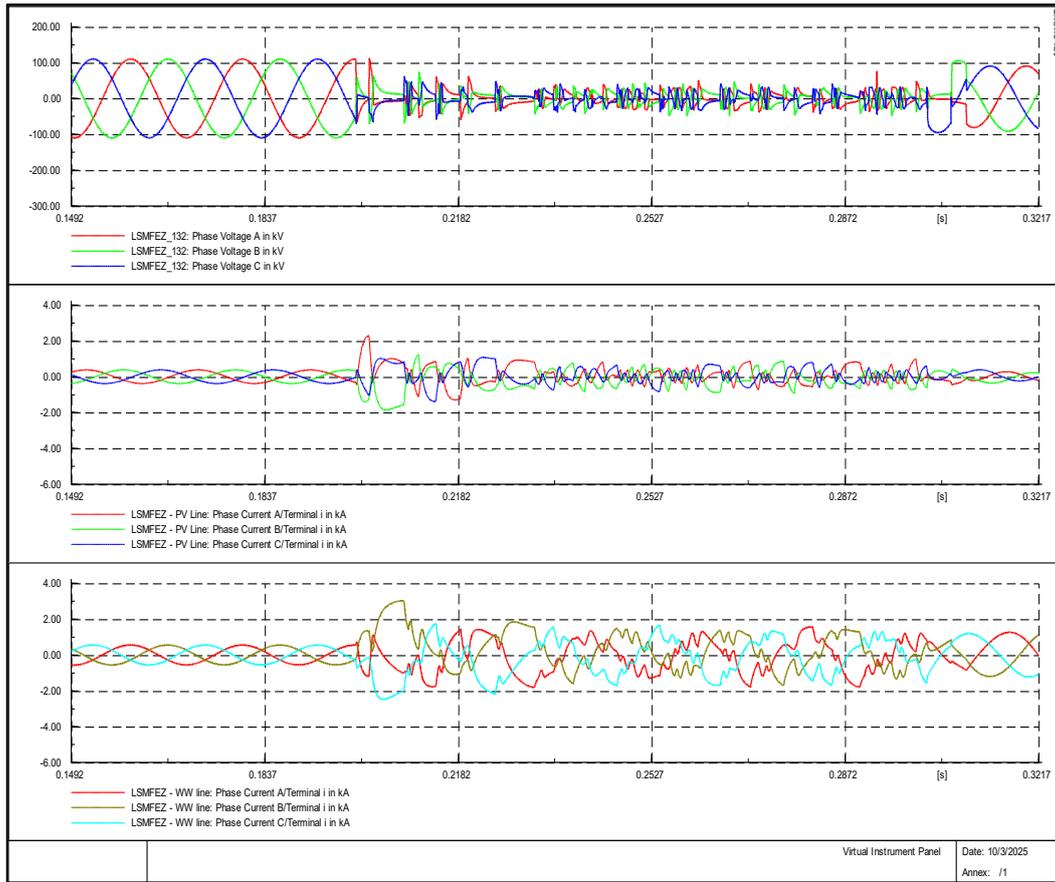
**Figure 3:** Impedance plot of applied fault, with relay characteristic and fault impedance plotted on the X/R plane. Notable is the no trip operation.

At high renewable penetration levels, the system begins to exhibit weak grid characteristics. Voltage depressions during faults become deeper and voltage recovery becomes slower. These conditions distort the voltage and current signals used by distance relays to calculate apparent impedance.

Electromagnetic transient simulations reveal additional phenomena not visible in RMS analysis. Inverter current limiting behaviour and phase-locked loop dynamics introduce waveform distortion during fault events.



**Figure 4:** EMT results for the *three* phase to ground fault with 0% PV penetration. Notable in the third trace of the LSMFEZ – WW line current is the sustained and undistorted fault current.



**Figure 5:** EMT results for the *three*-phase fault with 100% PV penetration. Notable in the first trace of phase voltage is the collapse of the 132kV LSMFEZ busbar voltage at fault inception, the highly distorted fault current contribution from the LSMFEZ – PV line in trace two, an effect evident on the LSMFEZ – WW line current in trace three upon which the distance relay performance can be analysed.

### 5 MITIGATION STRATEGIES

Several mitigation strategies were investigated to improve protection performance in renewable-dominated networks. Dynamic voltage support technologies such as battery energy storage systems and static VAR compensators can improve voltage stability during fault conditions, thereby improving relay measurement accuracy.

Adaptive protection schemes that modify relay settings based on system operating conditions also provide improved protection performance under varying renewable penetration levels.

Communication-assisted protection schemes such as line differential protection were identified as robust alternatives to conventional voltage-driven protection systems. These schemes rely on current comparison between line terminals rather than local voltage measurements and are therefore less sensitive to changes in system strength.

**Table 2:** Mitigation Strategy Comparison

Strategy	Single-Phase Faults	3-Phase Faults	Overall Effectiveness
BESS	Partial	Good	Moderate
Capacitor	Poor	Poor	Low
SVC	Excellent	Excellent	Best
FRT tuning	Limited	Limited	Limited
Adaptive Distance	Poor	Poor	Low
Line Differential	Excellent	Excellent	Best

## 6 CONCLUSION

The increasing penetration of inverter-based renewable generation fundamentally alters power system behaviour and introduces new challenges for conventional protection schemes. This study demonstrates that declining short-circuit levels and inverter control dynamics significantly affect the performance of voltage-driven protection systems.

Simulation results show that increasing photovoltaic penetration leads to reduced fault current levels, distorted impedance trajectories, and increased risk of relay under-reach. EMT analysis further highlights dynamic phenomena such as inverter current limiting and waveform distortion that influence relay measurement accuracy.

The results highlight the need for modern protection approaches including adaptive protection schemes, communication-assisted protection, and dynamic voltage support technologies to ensure reliable protection performance in renewable-dominated power systems.

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