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Modelling and Simulation of an Adaptive Protection Scheme for a Distribution Feeder with Solar Photovoltaic Integration in Zambia

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***Abstract* – The increasing integration of inverter-based solar photovoltaic (PV) generation into medium-voltage (MV) distribution networks has introduced significant protection coordination challenges. Traditional overcurrent protection schemes, originally designed for radial feeders with unidirectional power flow and predictable fault current levels, become ineffective due to the limited and controlled fault current contribution of PV systems, leading to relay blinding, mis-coordination, nuisance tripping, and delayed fault clearing. This paper presents the modelling and simulation of an adaptive protection scheme for 11 kV and 33 kV distribution feeders with integrated solar PV, modelled after the ZESCO Limited network in Zambia. Detailed system models were developed using MATLAB/ Simulink, SolidWorks, and Power World Simulator to evaluate fault behaviour under varying solar penetration levels. An adaptive protection algorithm dynamically adjusts relay settings, including pickup current and time multiplier setting (TMS), based on real-time system conditions such as load variation, fault levels, and PV output. Simulation results demonstrate that the proposed scheme improves relay coordination, reduces fault clearing time, and enhances system reliability compared to conventional fixed-setting protection methods. The study confirms that adaptive protection is a practical and essential solution for enabling higher solar penetration in Zambian distribution networks.**

***Keywords* – Adaptive Protection, Solar PV Integration, Distribution Feeders, Overcurrent Relays, Power System Simulation, Zambia.**

I. Introduction

The global electric power sector is undergoing rapid structural transformation driven by renewable energy penetration, decentralisation of generation, and smart grid evolution. Historically, power systems were designed around centralised synchronous generation plants supplying electricity through hierarchical transmission and distribution networks to passive end-users [1], [2]. Protection coordination strategies were therefore developed under assumptions of predictable short-circuit levels, unidirectional power flow, and relatively stable system configurations.

However, the rapid integration of distributed energy resources (DERs), particularly solar photovoltaic (PV) systems, has fundamentally altered the operating characteristics of distribution networks. Solar PV systems are increasingly embedded directly within medium-voltage (MV) distribution feeders, converting formerly passive radial networks into active systems capable of bidirectional power flow [3], [4]. Unlike conventional synchronous generators, inverter-based PV systems exhibit limited and controlled fault current contribution, significantly affecting relay performance [5], [6].

In Zambia, electricity generation has historically relied heavily on hydropower. Climate variability and recurrent drought conditions have exposed vulnerabilities in energy security. As part of national energy diversification strategies, solar PV installations have expanded significantly within distribution networks operated by ZESCO Limited [7], [20]. These feeders were originally designed as radial networks with passive load assumptions, operating at 11 kV and 33 kV.

The integration of inverter-based solar PV into radial feeders introduces several technical challenges: reduced fault current magnitude, bidirectional power flow, relay blinding and sympathetic tripping, and loss of coordination margins. Studies have confirmed that inverter-based distributed generation fundamentally alters feeder fault characteristics, potentially compromising traditional overcurrent protection [8], [9], [19]. As solar penetration increases, static relay settings become inadequate to guarantee selectivity and reliability [10].

Adaptive protection schemes have emerged as a promising solution for active distribution networks [11], [12], [17], [18], [22]. By dynamically adjusting relay settings in response to real-time system conditions, adaptive protection enhances reliability while maintaining coordination. This paper investigates the modelling and simulation of an adaptive protection scheme for ZESCO representative feeders, evaluating the limitations of static protection and proposing adaptive strategies for weak radial systems typical of Zambia.

II. Problem Formulation and Research Objectives

A. *Protection Challenges of Solar-Integrated Feeders*

Traditional overcurrent protection schemes were designed under assumptions of high and predictable fault current levels, unidirectional power flow, and stable network configurations [13]. The integration of solar PV systems violates these assumptions in three primary ways.

First, inverter-based PV systems provide limited fault current contribution, typically 1.1 to 2.0 per unit (p.u.) of rated current, compared to 5–8 p.u. for conventional synchronous machines [5], [14]. This reduced magnitude leads to relay blinding, where the grid-side relay sees only a fraction of total fault current because the downstream PV source feeds the fault locally, causing potential under-reach or failure to trip.

Second, bidirectional power flow can result in incorrect relay operation and failure of fuse-recloser coordination [8], [15]. Sympathetic tripping may also occur, where a PV plant feeds back into a healthy feeder during a fault on an adjacent feeder, causing unnecessary disconnection.

Third, in weak radial feeders typical of Zambia characterised by long radial configuration and high impedance these issues are further exacerbated. As solar penetration increases, static relay settings become wholly inadequate, leading to reduced reliability, increased fault clearing time, and potential system instability [16].

B. *Research Objectives*

The specific objectives of this study are:

(1) To model and simulate a solar-integrated MV distribution feeder and analyse the impact of PV penetration on fault characteristics;

(2) To design and implement an adaptive protection scheme that dynamically adjusts relay settings based on real-time operating conditions;

(3) To evaluate and compare the performance of adaptive protection against conventional schemes in terms of

coordination, sensitivity, and fault clearing time.

III. Theoretical Framework and Mathematical Modelling

A. *Feeder Impedance and Load Flow Model*

The distribution feeder is represented by its per-unit equivalent impedance:

$$Z_{feeder} = R_{line} + jX_{line} \ pu \quad (1)$$

Load flow with solar PV injection is modelled using the Newton–Raphson method. The net active and reactive power injections at bus i are:

$$P_i = P_{load,i} - P_{PV,i} \ ; \ Q_i = Q_{load,i} - Q_{PV,i} \quad (2)$$

B. *Short-Circuit Analysis*

For a three-phase fault at bus k, the fault current is:

$$I_f = \frac{V_{preF}}{Z_{th,k}} \ pu \quad (3)$$

For a single line-to-ground (SLG) fault, symmetrical components are applied. With solar PV integration, the total fault current becomes a superposition of grid and inverter contributions. The inverter fault current is bounded.

$$I_{inv,fault} \ \epsilon [1.1, 2.0] \ pu \quad \textit{(IEEE Std 1547-2018)} \quad (4)$$

This limitation reduces the total fault current seen by upstream relays, compromising detection sensitivity.

C. *IEC Overcurrent Relay Model*

The relay operating time follows the IEC standard inverse-time characteristic:

$$t = TMS \times \left(\frac{k}{PSM^{\alpha} - 1} \right) \quad (5)$$

Where TMS is the time multiplier setting, $PSM = \frac{I_{fault}}{I_{pickup}}$ is the plug setting multiplier, and k, α are curve constants (IEC Standard Inverse: k = 0.14, α = 0.02). Coordination between primary and backup relays requires a minimum coordination time interval (CTI):

$$CTI = t_{backup} - t_{primary} \geq CTI_{min} \ (CTI_{min} \ \textit{Typically 0.3–0.4 s}) \quad (6)$$

Under high solar penetration, reduced PSM values collapse CTI margins, causing mis-coordination.

D. *Adaptive Protection Framework*

The adaptive algorithm selects relay setting groups based on the real-time solar penetration level λ:

$$S_{active} = \begin{cases} S_1, & \lambda < 0.3 \\ S_2, \lambda \leq \lambda < 0.6 \\ S_3, & \lambda \geq 0.6 \end{cases} \quad (7)$$

Each setting group $\{I_{pickup}, TMS\}$ *is pre-optimised to satisfy* $CTI_{adaptive} \geq CTI_{min}$ under the corresponding penetration band. Dynamic recalculation of PSM and TMS eliminates the blinding effect and restores high spee-

-d fault clearance.

The sensitivity index is given by:

$$SI = \frac{I_{fault,min}}{I_{pickup}} \tag{8}$$

and must satisfy $SI > 1.2$, for reliable relay operation. Adaptive settings ensure that this condition is met across all penetration levels.

IV. System Modelling and Simulation Methodology

A. *System Under Study*

The system modelled is a radial MV distribution feeder representative of ZESCO Limited networks in Zambia, operating at 11 kV and 33 kV. It comprises a utility grid source, a 33/11 kV step-down transformer, distribution line segments modelled with impedance parameters, multiple load buses (residential and industrial), an inverter-based solar PV system integrated at selected feeder buses, and overcurrent relays with circuit breakers at strategic locations.

Three software platforms were employed in a complementary manner: MATLAB/Simulink for dynamic time-domain simulation and adaptive protection algorithm implementation; Power World Simulator for steady-state load flow analysis and system visualisation; and SolidWorks for three-dimensional physical visualisation of system components.

B. *MATLAB/Simulink Subsystem Models*

The complete MATLAB/Simulink model integrates seven interconnected subsystems. The Grid/Utility Source Subsystem models the three-phase voltage source with associated impedance and a step-down transformer providing balanced voltage supply at 33 kV, stepping down to 11 kV distribution level.

The Solar PV Generation Subsystem consists of a PV array converting solar irradiance to DC energy, a DC-DC boost converter for voltage regulation, a Maximum Power Point Tracking (MPPT) controller using the Perturb-and-Observe technique, and a PWM-controlled inverter synchronised to the grid. This subsystem limits fault current contribution to the 1.1-2.0 p.u. range consistent with IEEE 1547-2018.

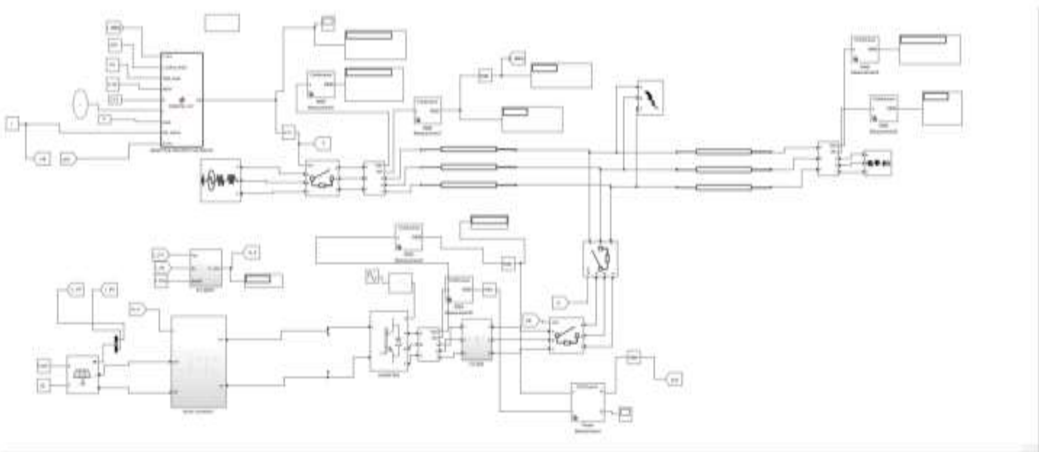

Fig. 1. Complete MATLAB/Simulink simulation system.

The Distribution Feeder Subsystem models line segments using RL impedance parameters and multiple load buses. The Fault Simulation Subsystem introduces controlled three-phase, SLG, line-to-line, and double line-to-ground faults at specified locations and times. The Measurement Subsystem captures real-time voltage and current signals for relay input. The Adaptive Protection Subsystem, implemented using MATLAB Function blocks, processes these measurements and dynamically adjusts relay parameters. The Circuit Breaker Subsystem isolates faulted sections upon receiving trip signals.

C. *Simulation Parameters*

Table 1 summarises the key MATLAB/Simulink simulation parameters, and Table 2 presents the Power World Simulator parameters.

Table 1. Matlab/Simulink Simulation Parameters for Adaptive Protection Analysis.

Parameter	Value	Unit
System Voltage	11	kV
Grid Voltage	33	kV
System Frequency	50	Hz
Solar PV Capacity	100	kW
Transformer Rating	33/11	kV
Relay Characteristic	IEC Standard Inverse	–
Pickup Current Setting	1.2	p.u.
Time Multiplier Setting (TMS)	0.2	–
PV Fault Current Contribution	2.0	p.u.
Simulation Time	5	s
Sampling Time	50×10^{-6}	s
Total Feeder Load	500	kW
Load Power Factor	0.85 lagging	–
Fault Resistance	0.001	Ω

Table 2. Power World Simulator Parameters for Load Flow and Protection Coordination Analysis.

Parameter	Value	Unit
Network Configuration	Radial Distribution Feeder	–
Number of Buses	6	–
Slack Bus Voltage	1.0	p.u.
Minimum Bus Voltage	0.52	p.u.
Active Power Flow	2.0	MW
Reactive Power Flow	1.0	Mvar
Solar PV Penetration Level	20	%
Load Flow Method	Newton–Raphson	–

Parameter	Value	Unit
Protection Method	Adaptive Overcurrent	–
Supply Configuration	Utility Grid + Solar PV	–

V. Simulation Results and Discussion

A. *Load Flow Analysis - Power World Simulator*

The Power World Simulator load flow results show that active power flows from the utility source toward connected load buses through the radial feeder. The sending-end bus voltage is maintained at 1.0 p.u., while downstream buses experience a gradual reduction to approximately 0.52 p.u. under heavily loaded conditions, confirming the effect of cumulative line impedance.

The integration of the solar PV distributed generation unit provides local power support to nearby load buses, reducing feeder loading and minimising power transfer from the main utility source. Consequently, transmission losses decrease and voltage stability improves. The results also reveal bidirectional power flow when solar generation exceeds local load demand a condition that directly challenges conventional unidirectional relay assumptions.

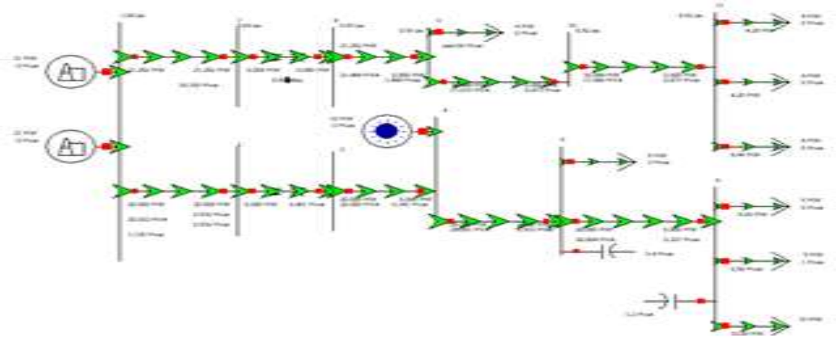

Fig. 2. Load flow analysis (Power World Simulator).

B. *Conventional protection baseline (no PV integration)*

Before PV integration, a three-phase symmetrical fault was applied to the feeder. Fault current escalated instantaneously to a sustained peak from a single direction the grid utility. Because no distributed generation exists downstream, the fault current is uniform along the feeder to the fault point. The conventional IEC inverse time relay operated correctly, accurately computing trip time based on a predictable, unidirectional fault contribution. Phase voltages suffered a severe symmetrical sag approaching near zero at the fault location, while line currents showed a large symmetrical increase with standard inductive load phase shift.

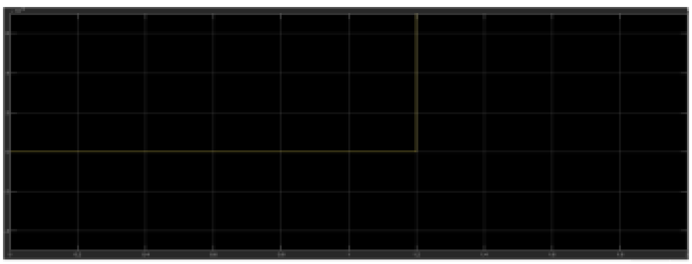

Fig. 3. Fault clearing time conventional protection (no PV integration).

Fig. 4. Voltage and current waveforms conventional protection (no PV integration).

C. *Post-Integration Fault Behaviour (with Solar PV)*

Following baseline assessment, the solar PV plant was integrated and the identical fault was simulated. The inverter based resource fundamentally altered the fault topology: the fault site was fed from two sources simultaneously the upstream utility grid and the downstream solar PV farm.

The grid-side relay experienced a reduced percentage of total fault current because the downstream PV source fed the fault locally, demonstrating the relay blinding phenomenon. Current waveforms reflected the limited fault-current capability of the PV inverters, while voltage recovery profiles became highly dynamic due to reactive power support (fault ride through) injected by the inverter. Under certain conditions, healthy feeders adjacent to the faulted section experienced sympathetic tripping from PV back feed.

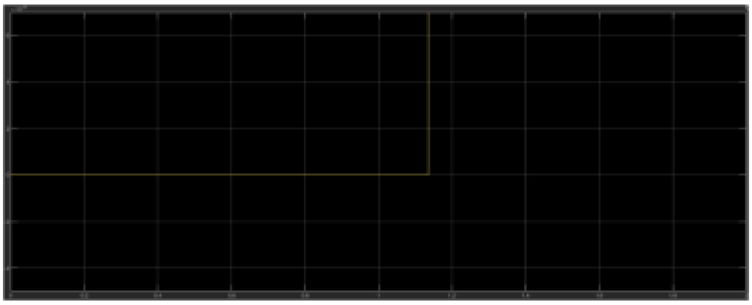

Fig. 5. Fault clearing time post-PV integration (relay blinding effect).

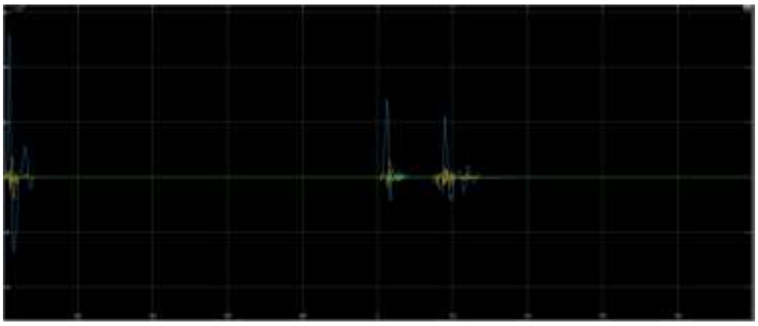

Fig. 6. Voltage and current waveforms post-PV integration (with solar PV).

D. *Adaptive Protection Performance*

The implemented adaptive protection scheme continuously monitored the altered voltage and current signatures. By dynamically recalculating PSM and TMS based on real-time solar output whether the PV plant was online or offline the adaptive relay successfully eliminated the blinding effect and restored high-speed, reliable fault clearance despite complex post-integration waveforms.

The scheme correctly identified the operating state based on solar penetration level λ and selected the corresponding pre-optimised setting group, ensuring that CTI margins were maintained and SI > 1.2 across all tested fault conditions.

E. *Comparative Performance Analysis*

Table 3 presents a structured comparison between conventional fixed setting protection and the proposed adaptive scheme across key performance indicators.

Table 3. Comparative Performance Analysis: Conventional Versus Adaptive Protection.

Performance Parameter	Conventional Protection	Adaptive Protection
Relay Coordination	Poor under high PV penetration	Improved
Relay Sensitivity	Reduced	Improved
Fault Clearing Time	Increased	Reduced
Voltage Stability	Moderate	Improved
Transmission Losses	Higher	Reduced
Power Quality	Moderate	Improved
System Reliability	Lower	Higher
Response to Changing Conditions	Fixed / Static	Dynamic / Adaptive

The comparative analysis confirms that adaptive protection outperforms conventional methods across all evaluated indicators. Conventional overcurrent protection, relying on fixed relay settings, becomes ineffective as fault current levels and power flow directions change under distributed generation integration. The adaptive scheme overcomes these limitations through dynamic parameter adjustment, resulting in measurable improvements in relay sensitivity, coordination accuracy, and fault clearing performance.

F. *Discussion*

The results obtained in this study are consistent with, and extend, findings reported in similar adaptive protection investigations on inverter dominated feeders [17], [18], [22]. The fault current limitation observed for the simulated PV inverter (1.1–2.0 p.u.) corroborates the relay blinding mechanism reported for comparably configured feeders [8], [15], and confirms the IEEE 1547-2018 interconnection limit assumed in Section III-B. Unlike several of these prior studies, which were validated on relatively strong, well-interconnected networks, the present work specifically targets the long, high-impedance radial feeders characteristic of ZESCO Limited's distribution system [20], where upstream fault current and voltage support are inherently limited. This explains why the voltage sag observed at the fault point in the conventional baseline case (Section V-B) approached near-zero, and why maintaining the sensitivity index constraint (SI > 1.2) proved more demanding than has been reported for stronger-grid case studies.

The dynamic recalculation of PSM and TMS across setting groups S1–S3, selected according to the real-time penetration level λ, allowed the relay to track the migration of fault current contribution from the grid to the PV source, directly counteracting the blinding effect quantified in Section V-C. Because each setting group is pre-optimised so that CTI ≥ CTImin, the scheme preserves coordination margins even as penetration approaches the highest tested band ($\lambda \geq 0.6$), a condition under which the conventional fixed-setting relay in the baseline case was shown to mis-coordinate and produce sympathetic tripping on a healthy adjacent feeder.

From a practical standpoint, the comparative results in Table 3 indicate that the benefits of adaptive protection are not confined to fault-clearing speed alone: the improved voltage stability and reduced losses observed in Section V-A suggest that the real-time monitoring infrastructure required for adaptive relaying could also support ZESCO Limited's broader voltage regulation and loss-reduction objectives, reinforcing the case made elsewhere for prioritising monitoring upgrades in weak-grid utilities [16]. The present study is nonetheless limited to simulation-based validation using representative feeder parameters; as discussed in Section VII, hardware-in-the-loop testing and field trials remain necessary before the scheme can be recommended for full-scale deployment.

VI. Conclusions

This paper has presented the modelling and simulation of an adaptive protection scheme for medium voltage distribution feeders with integrated solar PV generation in Zambia, targeting ZESCO Limited 11 kV and 33 kV networks. The following conclusions are drawn:

(1) Solar PV inverters limit fault current contribution to 1.1-2.0 p.u., far below the 5-8 p.u. of synchronous generators, causing relay blinding, mis-coordination, sympathetic tripping, and delayed fault clearance in conventional fixed-setting schemes.

(2) Load flow analysis confirms bidirectional power flow and progressive voltage reduction along the radial feeder, particularly under high PV penetration conditions.

(3) The proposed adaptive protection algorithm, based on real time monitoring of solar output and dynamic recalculation of PSM and TMS, successfully eliminates relay blinding and restores reliable fault clearance across all tested penetration levels.

(4) Comparative simulation results confirm measurable improvements in relay coordination, sensitivity, fault clearing time, voltage stability, power quality, and overall system reliability over conventional protection.

(5) Adaptive protection is a technically validated, practically deployable solution for enabling higher renewable energy penetration in Zambia's distribution networks without wholesale infrastructure replacement.

Future work should focus on hardware-in-the-loop experimental validation, integration of SCADA and IEC 61850 [21] communication protocols, inclusion of battery energy storage systems, and application of machine learning techniques for enhanced adaptive relay decision-making under highly dynamic operating conditions.

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