PROTECTION METHODOLOGY FOR DISTRIBUTED GENERATION WITH RESPECT TO TRANSIENT INSTABILITY

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ABSTRACT

This paper presents a protection methodology for distributed generation (DG) with respect to transient instability, using the Enugu distribution network as a case study. A detailed ETAP model of the network was developed, incorporating an integrated microgrid consisting of photovoltaic systems, diesel generation, and battery energy storage. The study investigates the impact of DG on both steady-state and dynamic system performance. Analyses conducted include load flow studies, transient stability simulations under various fault conditions, and protection coordination assessments. Both conventional and adaptive overcurrent protection schemes were evaluated at increasing DG penetration levels. Case studies, including three-phase faults at selected buses, demonstrate that properly coordinated primary relays can effectively isolate faults. For instance, OCR-8 at Bus 602 successfully cleared a fault without unnecessary backup relay operation. Results show that DG integration significantly alters the magnitude and direction of fault currents, making conventional static relay settings inadequate. This necessitates the use of adaptive protection schemes incorporating directional elements and dynamic relay settings to maintain selectivity and prevent mis-operations. This work contributes by developing a reproducible ETAP-based model of a DG-integrated distribution network, quantifying the impacts of DG on protection and transient stability, and demonstrating that optimized relay settings can restore coordination. The study highlights adaptive relaying as an effective solution for enhancing protection performance. It is recommended that utilities conduct detailed ETAP-based protection studies prior to DG integration, deploy adaptive relays on feeders with high DG penetration, and that regulatory standards be updated to ensure proper protection coordination and system stability.

Keywords: Distributed Generation, ETAP, Microgrid, Protection, Stability, Photovoltaic.

1.0 INTRODUCTION

Nigeria's electricity sector continues to experience a significant generation deficit, resulting in an unreliable power supply that adversely affects industrial productivity, commercial activities, and socio-economic development. Frequent power outages and voltage instability have increased the dependence on alternative energy sources such as diesel generators and renewable energy systems, leading to higher operating costs and environmental concerns (Sambo *et al*., 2012; Oyedepo, 2012). To address these challenges, the integration of distributed generation (DG), particularly renewable energy-based microgrids incorporating solar photovoltaic (PV), wind, and small-scale hydro systems, has gained considerable attention as a viable solution for enhancing power system performance. Distributed generation provides localized electricity production close to load centers, thereby reducing transmission losses, improving voltage profiles, increasing energy efficiency, and enhancing the overall reliability and resilience of distribution networks (Obi *et al*., 2022; Shahbazitabar *et al*., 2021; Marković *et al*., 2023).

Despite these benefits, the increasing penetration of distributed generation significantly alters the operating characteristics of conventional distribution systems, which were originally designed for unidirectional power flow from centralized generating stations to consumers. The integration of DG introduces bidirectional power flow, changes in fault current magnitude and direction, increased network complexity, protection coordination challenges, and transient stability concerns. These issues can lead to relay maloperation, nuisance tripping, delayed fault clearance, and reduced system security if conventional protection schemes are maintained without appropriate modifications (Nwajuonye *et al*., 2021; Fayazi *et al*., 2021; Li *et al*., 2021). Consequently, the design and implementation of adaptive protection strategies have become increasingly important to ensure that protection systems remain reliable and selective under varying operating conditions associated with DG integration.

Recent developments in power electronics and intelligent control techniques have further improved the operational performance of inverter-based distributed generation systems. Advanced converter control strategies enable DG units to respond more effectively to disturbances, thereby improving voltage regulation, frequency stability, and transient performance during system faults and switching operations. At the same time, adaptive protection schemes capable of dynamically adjusting relay settings according to changing network conditions have demonstrated significant improvements in maintaining protection coordination and minimizing unnecessary outages in modern active distribution networks (Idam *et al*., 2026; Ahmed *et al*., 2022; Chae *et al.,* 2021).

Beyond the Nigerian context, the rapid integration of distributed energy resources (DERs) has become a global trend driven by decarbonization policies, increasing electricity demand, and the transition toward smart grids. High penetration of photovoltaic systems, wind generation, battery energy storage systems (BESS), and electric vehicles has fundamentally transformed conventional passive distribution networks into active distribution systems characterized by bidirectional power flow, variable fault current levels, and increased operational complexity. These developments have created significant challenges in voltage regulation, protection coordination, power quality, and transient stability across power systems worldwide (Hatziargyriou *et al*., 2021; Shahbazitabar *et al*., 2021; Marković *et al*., 2023). Consequently, utilities increasingly employ adaptive protection schemes, intelligent electronic devices (IEDs), communication-assisted relaying, and advanced distribution management systems to ensure reliable and secure network operation under varying distributed generation conditions. Therefore, the operational challenges observed in the Enugu distribution network are consistent with those reported in modern active distribution networks globally, thereby demonstrating the broader applicability of the proposed protection methodology.

In this context, accurate modelling and simulation tools are essential for evaluating the impact of distributed generation on power system protection and stability before practical implementation. Electrical Transient Analyzer Program (ETAP) provides a comprehensive platform for conducting load flow analysis, short-circuit studies, protection coordination, and transient stability assessments under different operating scenarios.

Therefore, this study develops an ETAP-based protection methodology to evaluate protection coordination and transient stability in a distributed generation-integrated distribution network. The objective is to investigate the influence of DG on relay coordination and system dynamic performance while proposing suitable protection measures that enhance the reliability, stability, and operational security of modern distribution networks in accordance with established industry standards and best practices (IEEE, 2020; International Energy Agency, 2021).

2.0 SUMMARY OF THE REVIEWED LITERATURE

Early studies established the foundation of distributed generation (DG) by highlighting its technical and economic benefits to modern power systems. Pepermans *et al.* (2005) described DG as an effective means of improving system efficiency, reducing transmission losses, enhancing voltage regulation, and increasing the reliability of electricity supply. Similarly, Dulău *et al.* (2014) examined the effects of DG on electric power systems and noted that while DG improves network performance, it also alters fault current levels and power flow patterns, thereby creating new challenges for conventional protection systems.

In the Nigerian context, Nwajuonye *et al.* (2021) demonstrated that integrating distributed generation into distribution networks significantly enhances system reliability and operational efficiency by improving voltage profiles and reducing feeder losses. Likewise, Obi *et al.* (2022) investigated the application of distributed generation in the Onitsha distribution network and reported improvements in power supply quality and network performance, emphasizing the suitability of DG for addressing persistent electricity supply challenges in Nigeria.

Recent research has focused on overcoming the operational challenges introduced by higher levels of DG penetration. Li *et al.* (2021) examined protection issues in active distribution networks and showed that adaptive relay coordination is necessary to accommodate varying fault current levels and bidirectional power flow. Similarly, Bisheh *et al*. (2021) proposed an adaptive protection coordination scheme capable of maintaining relay selectivity under changing network configurations, thereby improving the reliability of DG-integrated distribution systems.

In addition to protection coordination, the dynamic performance of distributed generation has received considerable attention. Idam *et al.* (2026) demonstrated that advanced cascade controller techniques significantly improve the transient response and stability of power electronic converters used in inverter-based DG systems, thereby enhancing system performance during disturbances and fault conditions.

Although previous studies have separately investigated the benefits of distributed generation, adaptive protection, and transient stability enhancement, relatively few have combined protection coordination and transient stability assessment within a single modelling framework. This study addresses this gap by employing ETAP to perform an integrated evaluation of protection coordination and transient stability in a distributed generation-integrated distribution network, thereby providing a comprehensive assessment of system reliability and protection performance.

3.0 METHODOLOGY

The Enugu 33/11 kV distribution network, operated by the Enugu Electricity Distribution Company (EEDC), was selected as the case study because it represents a typical radial distribution system with increasing distributed generation (DG) penetration. Utility data, including bus voltages, load demands, transmission line parameters, transformer ratings, and existing protection settings, were used to develop the network model in ETAP Version 19.0.

A hybrid DG system comprising photovoltaic (PV) arrays, diesel generators, and battery energy storage systems (BESS) was modelled and integrated into the network through appropriate transformers and power electronic converters at the Point of Common Coupling (PCC). The DG system was evaluated under both grid-connected and islanded operating conditions to investigate its impact on network performance.

The ETAP model consisted of the utility source, 33/11 kV transformers, busbars, radial feeders, distribution lines, load centres, and the integrated hybrid DG system. The modelling approach followed established ETAP-based studies on Nigerian distribution networks (Nwajuonye *et al*., 2021; Obi *et al*., 2022). The single-line diagrams of the base network, hybrid DG system, and integrated system are presented in Figs. 1–3.

Load flow, short-circuit, transient stability, and protection coordination analyses were performed under pre- and post-DG operating conditions. Three-phase, line-to-line, and single-line-to-ground faults were simulated to evaluate the effects of DG on voltage profile, power flow, fault current level, relay coordination, and transient stability. Protection coordination was achieved using Time–Current Characteristic (TCC) curves, while an adaptive protection strategy was assessed by considering changes in DG penetration, power flow direction, and fault current contribution. Similar ETAP-based adaptive protection approaches have also been reported by Palayil *et al.* (2022).

3.1. Short-Circuit Analysis Standard

Short-circuit studies were performed in ETAP Version 19.0 using the IEC 60909 standard for three-phase, line-to-line, and single-line-to-ground fault calculations. The IEC 60909 methodology provides standardized procedures for calculating initial symmetrical short-circuit currents while accounting for the different fault current contributions from synchronous rotating machines and inverter-based distributed energy resources. The diesel generator was modelled as a synchronous generator with transient reactance characteristics, whereas the photovoltaic system and battery energy storage system were represented using inverter-based models with limited fault current contribution in accordance with IEC 60909 recommendations. The calculated fault currents formed the basis for relay coordination, transient stability assessment, and protection performance evaluation throughout this study.

3.2 Case Study Description

The Enugu 33/11 kV distribution network, operated by the Enugu Electricity Distribution Company (EEDC), was selected as the case study to evaluate the impact of distributed generation (DG) on transient stability and protection coordination. The network serves residential, commercial, institutional, and industrial consumers through a radial distribution system, making it suitable for assessing the influence of DG on system operation. Like many Nigerian distribution networks, the system experiences voltage instability, equipment overloading, frequent faults, and protection coordination challenges. The integration of distributed energy resources, particularly photovoltaic systems and diesel generators, introduces bidirectional power flow and varying fault current levels, which can affect the performance of conventional overcurrent protection (Obi *et al*., 2022; Nwajuonye *et al.,* 2021).

A hybrid DG system was integrated into the network, and load flow, short-circuit, transient stability, and protection coordination analyses were performed using ETAP Version 19.0. The developed model was used to evaluate the effects of DG integration on voltage profile, fault current, relay coordination, and overall system stability under different operating conditions.

Table 1: Load data for 11kV Network

ID	Rating (kVA)	Rated kV
Apostles4	129	11
CCB Okpala AVE5	71.3	11
Colliery Ave. Ridge Way3	271	11
Constitution rd5	289	11
Coporate Affairs Comm5	53.2	11
Court Ave5	257	11
DylicSuites& Garden2	56	11

Eco Bank10	55.6	11
Eco Bank11	32.6	11
Enugu Sport Club5	293	11
Farm asso. NIG LTD5	31.4	11
Federal Inland rev5	43	11
Federal Morgage Bank5	36.2	11
Federal Radio House5	143	11
Fidelity Bank5	49	11
First Bank5	104	11
GLO Switch Yard5	267	11
GLO/ETB okpala AVE5	46.7	11
Govt.printig press5	155	11
High street5	286	11
Hse Dev Authority2	95.6	11
Justice Nwobodo5	39.1	11
Keystone Bank5	35.8	11
Load38	23.8	11
MODOTELS NIG LTD5	162	11
Mr Biggs5	359	11
Mrs Lolo AGu2	87.3	11
MTN NIG5	15.6	11
NCFC5	108	11
NEPA Ogui Office5	53.2	11
New A.G Office5	49	11
NPC1	236	11
Police Comm State House 5	33.7	11
Prime & Power LTD 5	66.3	11
Railway Gate4	96.4	11
Railway Goodshed4	266	11
RCCG 6 HQ2	107	11
Safari garden5	131	11
Skye bank3	44.8	11
Stanbic IBTC5	43.1	11
State CID5	200	11
Station Road5	303	11
Texaco FST5	33	11
UBA bank5	41	11
UBA Bank 20 Okpara AVE2	43.8	11
UBA Station Road5	79.1	11
Union Bank2 okpara AVE2	216	11
Union Bank5	207	11

Table 2: Distribution line parameter for 11kv distribution Network

Conductor type	AAC
Voltage	11Kv
Area	100mm^2

Table 3: Distribution line parameter for 33kv distribution Network

Conductor type	ACSR
Voltage	33kV
Area	250mm^2

Table 4: Transformer parameters

KVA Rating	62.5MVA
Primary Voltage	132Kv
secondary Voltage	33Kv
Frequency	50Hz

Table 5: Transformer Electrical Parameers

Parameter	Value
Rated Capacity	62.5 MVA
Primary Voltage	132 kV
Secondary Voltage	33 kV
Vector Group	Dyn11
Percentage Impedance	12.5%
Frequency	50 Hz
Grounding	Solidly grounded neutral

3.3 Distributed Generation Integration and Network Modelling

A hybrid distributed generation (DG) system comprising photovoltaic (PV) arrays, diesel generators, and battery energy storage systems (BESS) was developed and integrated into the Enugu 33/11 kV distribution network at the Point of Common Coupling (PCC). The DG units were interconnected through power electronic converters and transformers to facilitate both grid-connected and islanded modes of operation.

The network was modelled in ETAP Version 19.0 using utility data, including bus voltages, load demands, line parameters, transformer ratings, and existing protection settings. The base distribution model comprised the utility source, 33/11 kV transformers, busbars, radial feeders, distribution lines, and load centres. A standalone hybrid DG model was first developed and validated before integration with the existing network. The modelling approach follows established ETAP-based studies on Nigerian distribution systems (Nwajuonye *et al*., 2021). The single-line diagrams of the base network, hybrid DG system, and integrated network are presented in Figures 1–3.

3.34 Distributed Generation Parameters

The hybrid distributed generation system consisted of a photovoltaic (PV) array, a synchronous diesel generator (Gen24), and a battery energy storage system (BESS). The photovoltaic unit was rated at 2 MW, while the diesel generator had a rated capacity of 1.5 MW (1.875 MVA, 0.8 power factor). The battery energy storage system was rated at 500 kW/1 MWh to provide voltage support and transient power balancing during network disturbances. The PV inverter operated under constant active power with voltage-reactive power (Volt-VAR) control, whereas the diesel generator employed IEEE Type-1 automatic voltage regulator (AVR) and governor models available within ETAP. The BESS inverter employed droop-based active and reactive power control to support voltage regulation during transient events.

3.5 Protection Coordination

Protection coordination was evaluated using ETAP by simulating three-phase, line-to-line, and single-line-to-ground faults under pre- and post-DG operating conditions.

Overcurrent relays and circuit breakers were coordinated using Time–Current Characteristic (TCC) curves to ensure selective fault clearance, with the relay nearest the fault operating as the primary protection while upstream relays provided backup protection. To address variations in fault current magnitude and power flow introduced by DG integration, an adaptive protection strategy was investigated by considering changes in DG penetration level, fault current contribution, and power flow direction. The proposed scheme was validated through fault simulations at different network locations, and its performance was assessed using voltage profile, fault current level, relay operating time, selectivity, and transient stability indices.

3.6 Adaptive Protection Implementation.

The adaptive protection strategy adopted in this study was implemented within the ETAP simulation environment using multiple predefined relay-setting groups rather than a real-time communication-assisted protection architecture. Different distributed generation (DG) operating conditions, including grid-connected operation, islanded operation, and varying DG penetration levels, were simulated individually. For each operating condition, ETAP recalculated the network fault current levels, after which appropriate relay pickup currents and time dial settings were manually updated to establish an optimized relay setting group. Protection coordination was then evaluated separately for each operating scenario. This offline adaptive coordination approach has been widely adopted for evaluating protection performance under changing network conditions before practical implementation (Ustun *et al*., 2021; Choudhary *et al*., 2022).

Consequently, the proposed adaptive protection methodology represents an offline adaptive relay coordination approach in which relay parameters are modified according to anticipated network operating conditions. No IEC 61850 communication network, GOOSE messaging, relay-to-relay communication, or automatic online relay group switching was modelled in this study. Instead, the objective was to evaluate how adaptive relay settings can restore coordination under changing DG operating conditions before field implementation. Similar approaches have been reported in the literature, where adaptive relay setting groups are evaluated using ETAP or equivalent power system simulation platforms prior to field deployment (Horowitz & Phadke, 2022; Blackburn & Domin, 2015). The single-line diagram of the modelled Enugu distribution network is shown in Figure 1 while the single-line diagram of the hybrid DG system is illustrated in Figure 2.

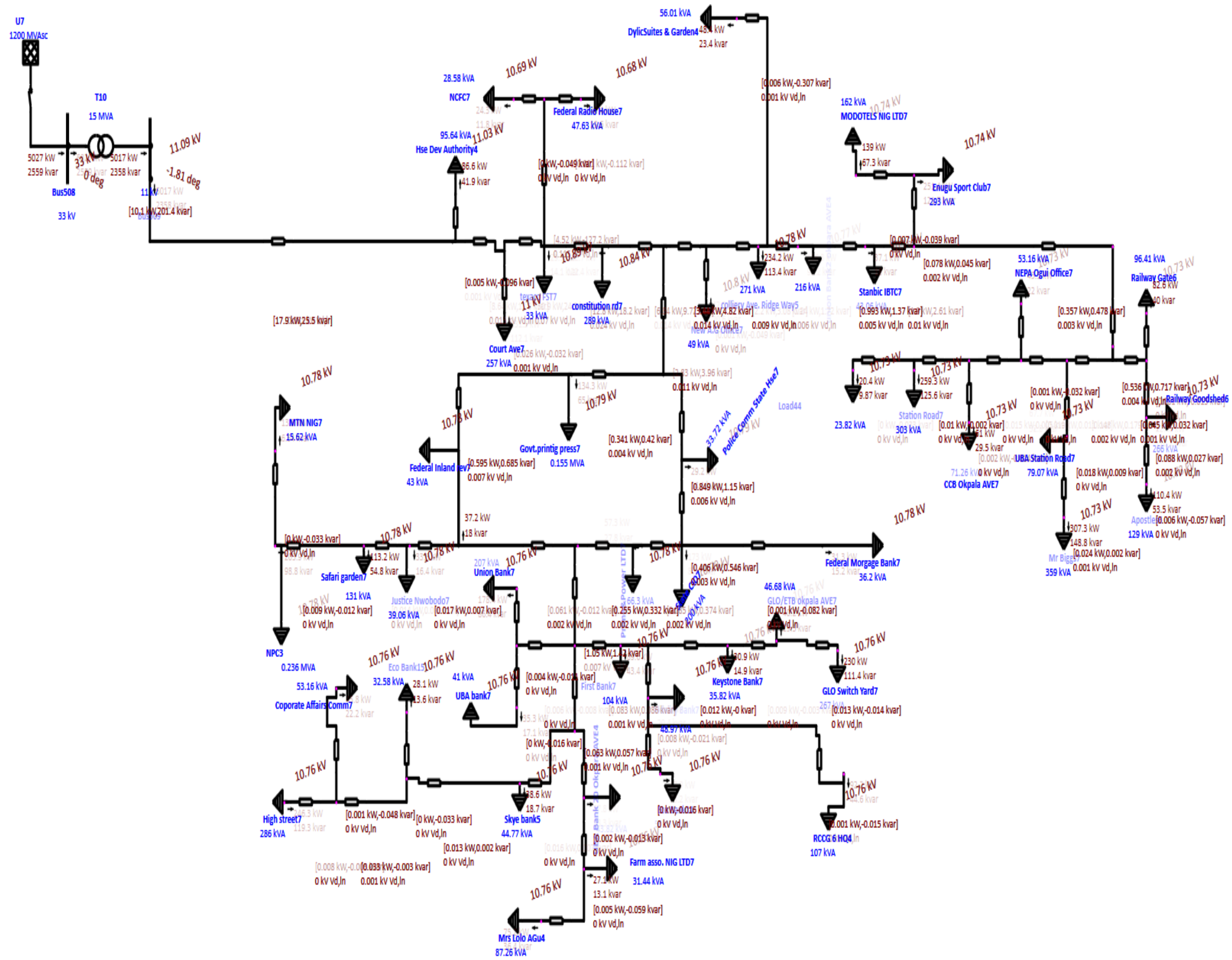

Figure1: One line diagram of the Enugu Kingsway distribution network

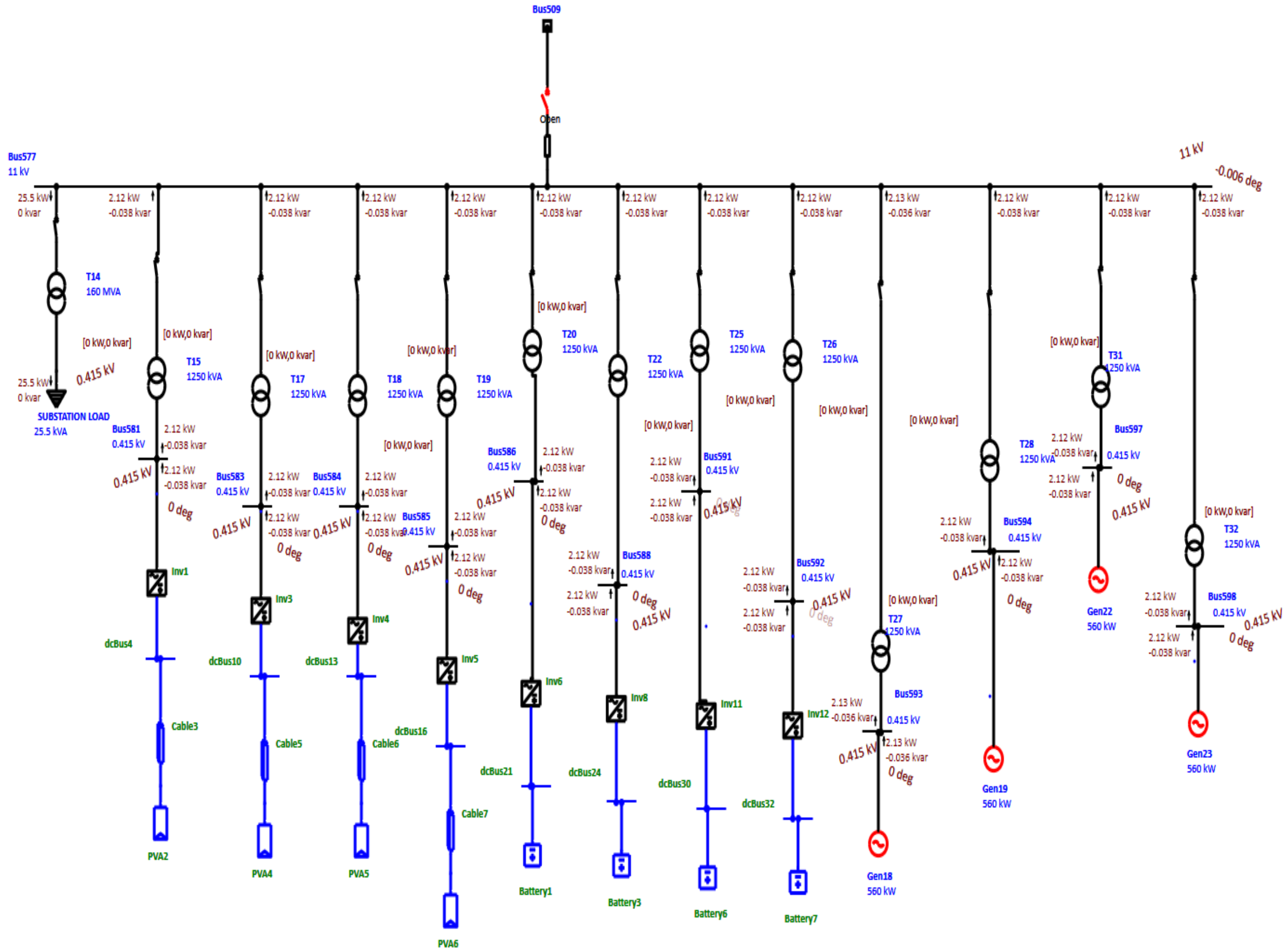

Figure 2: One line diagram of the hybrid distributed generation (DG) system

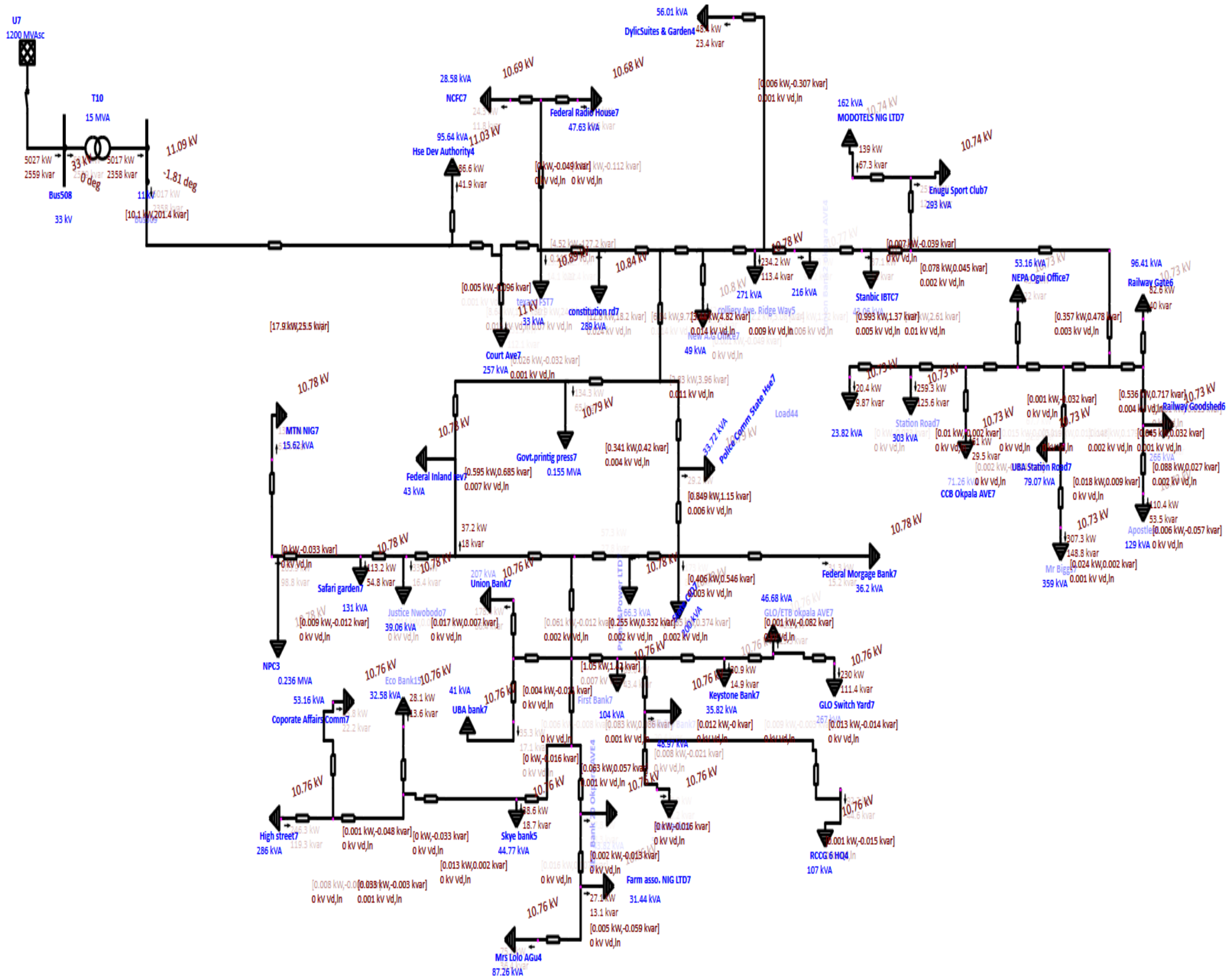

Figure 3: Model of the Integration of The Hybrid DG with the Distribution Network

3.7. Relay Operating Characteristics

Overcurrent relay coordination was performed using the IEC Standard Inverse Time-Current Characteristic (IDMT) curve implemented in ETAP. The relay operating time was calculated using

$$t = \frac{0.14 \times TMS}{\left(\frac{I_f}{I_p}\right)^{0.02} - 1}$$

where
t= relay operating time
TMS=time multiplier setting
I_f = Measured fault current (A)

I_p = Relay pickup current (A)

Relay settings were selected to ensure selective operation between primary and backup protection while maintaining a coordination time interval (CTI) of approximately 0.30 s under all simulated fault conditions.

Table 6. Overcurrent Relay Coordination Settings Used in the ETAP Simulation

Relay	Curve Type	Pickup Current (A)	Time Multiplier Setting	Coordination Time Interval (s)
OCR-8	IEC Standard Inverse	320	0.15	0.30
OCR-7	IEC Standard Inverse	360	0.20	0.30
OCR-6	IEC Standard Inverse	420	0.25	0.30
OCR-5	IEC Standard Inverse	480	0.30	0.30

4.0 RESULTS AND DISCUSSION

4.1 Load Flow Analysis

Figures 4–8 below present the load flow results for the base network, standalone DG system, and the integrated DG network. The base case showed acceptable voltage regulation with bus voltages ranging from 0.971–1.000 p.u., while feeder currents reached 288.7 A and the maximum line loss was 50.92 kW. In the standalone DG mode, the microgrid maintained a regulated voltage of 0.415 kV with negligible line losses (0.0074 kW) and reduced current flow (8.30 A). Following DG integration, the distribution network maintained an acceptable voltage profile while approximately 3.1 MW of power was supplied through the DG feeders. Although the utility grid continued to provide most of the reactive power demand, DG improved local power sharing and reduced feeder loading. Overall, the load flow results demonstrate that DG integration enhances voltage support and improves power distribution while maintaining satisfactory operating conditions.

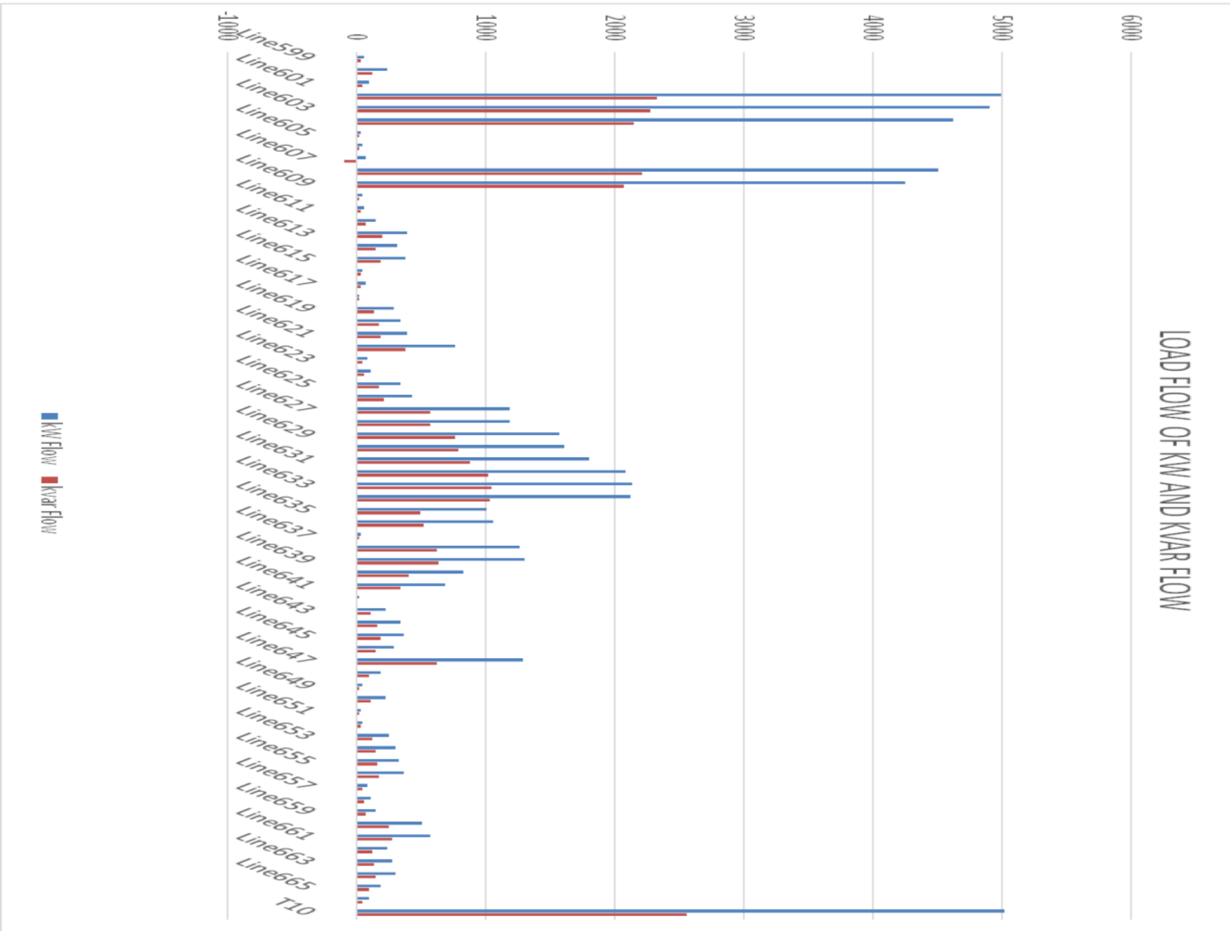

Figure 4: Base Case Load Flow Analysis Result of Kw and Kvar Flow

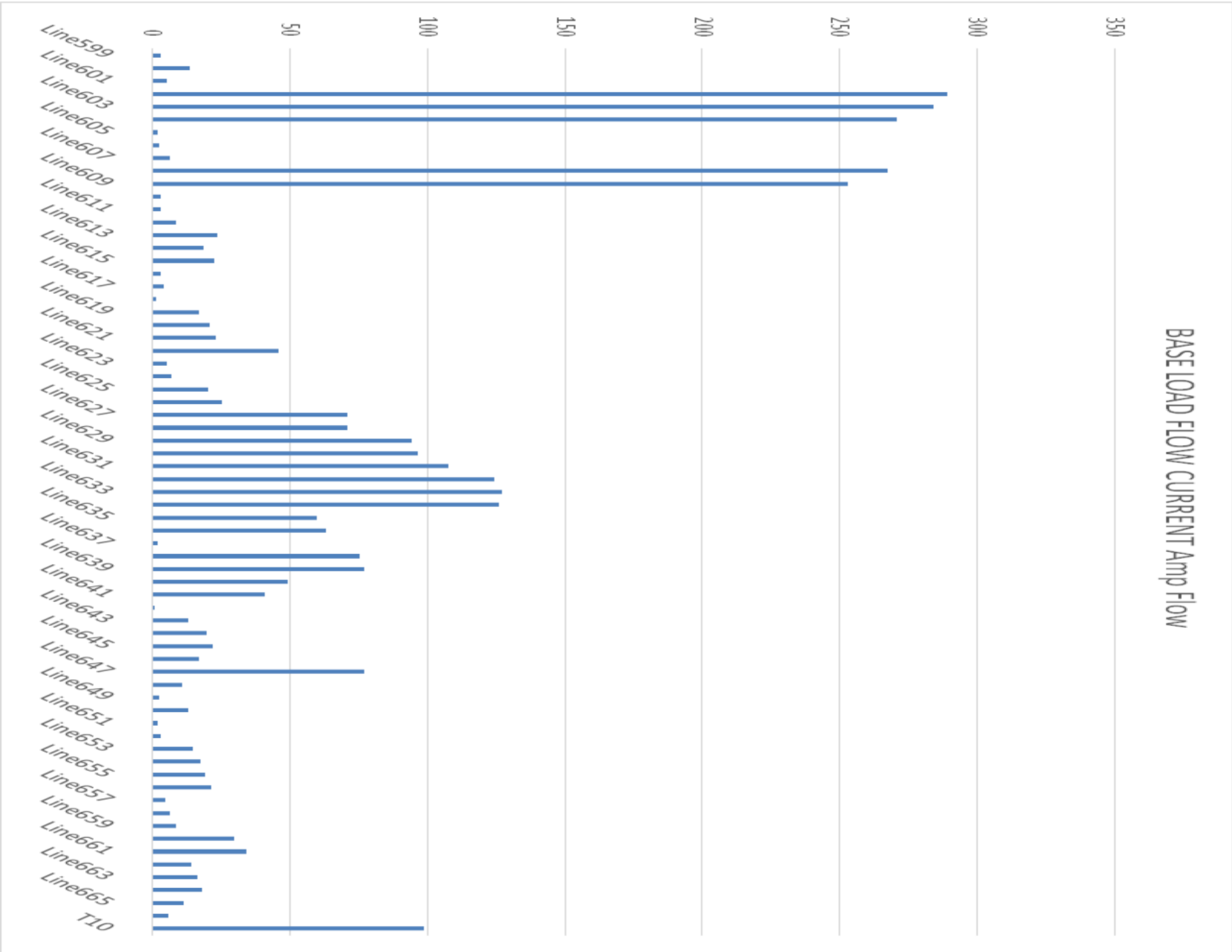

Figure 5: Base Case Load Flow Analysis Result of Current flow

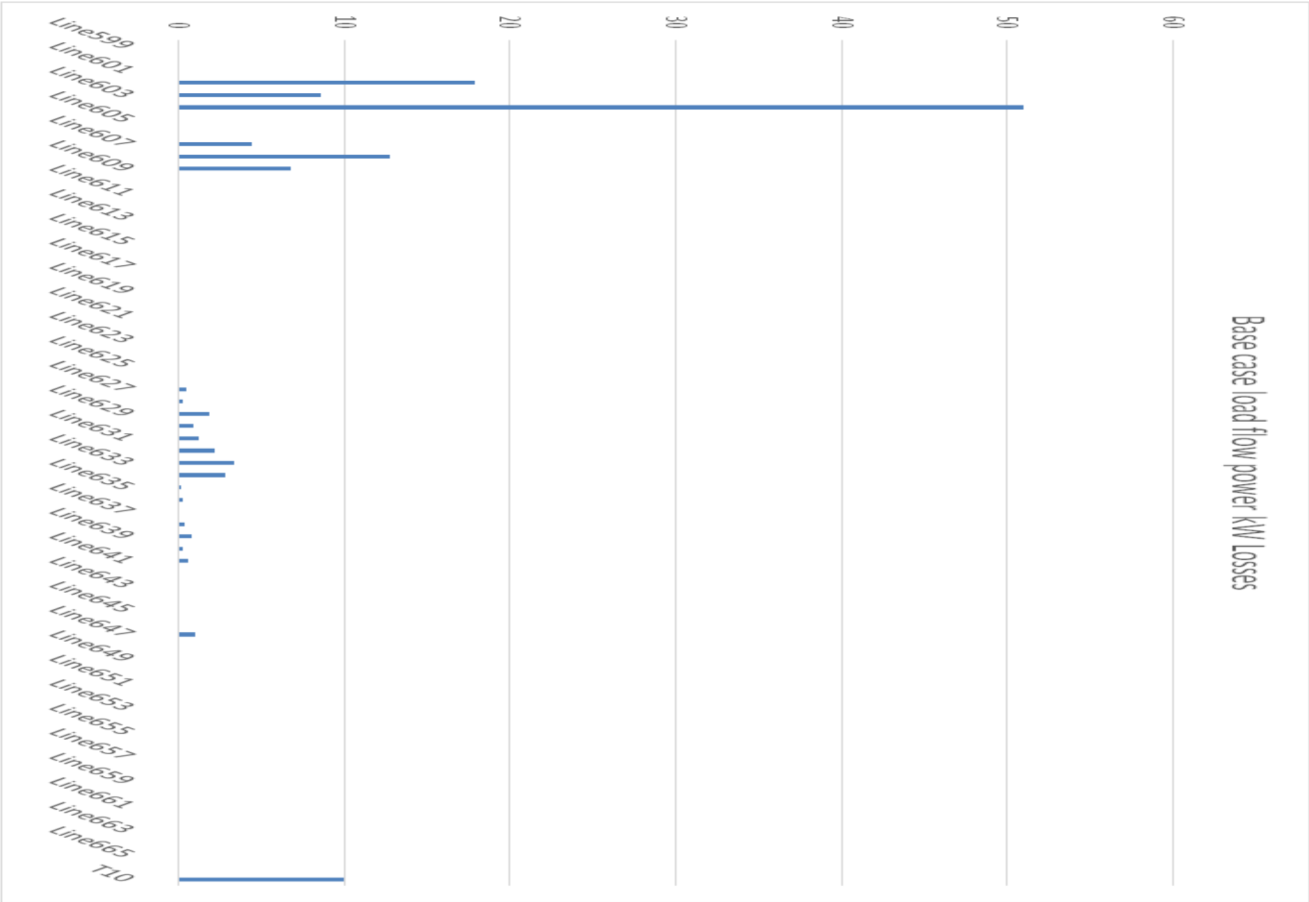

Figure 6: Base Case Load Flow Analysis Result of the base case power losses

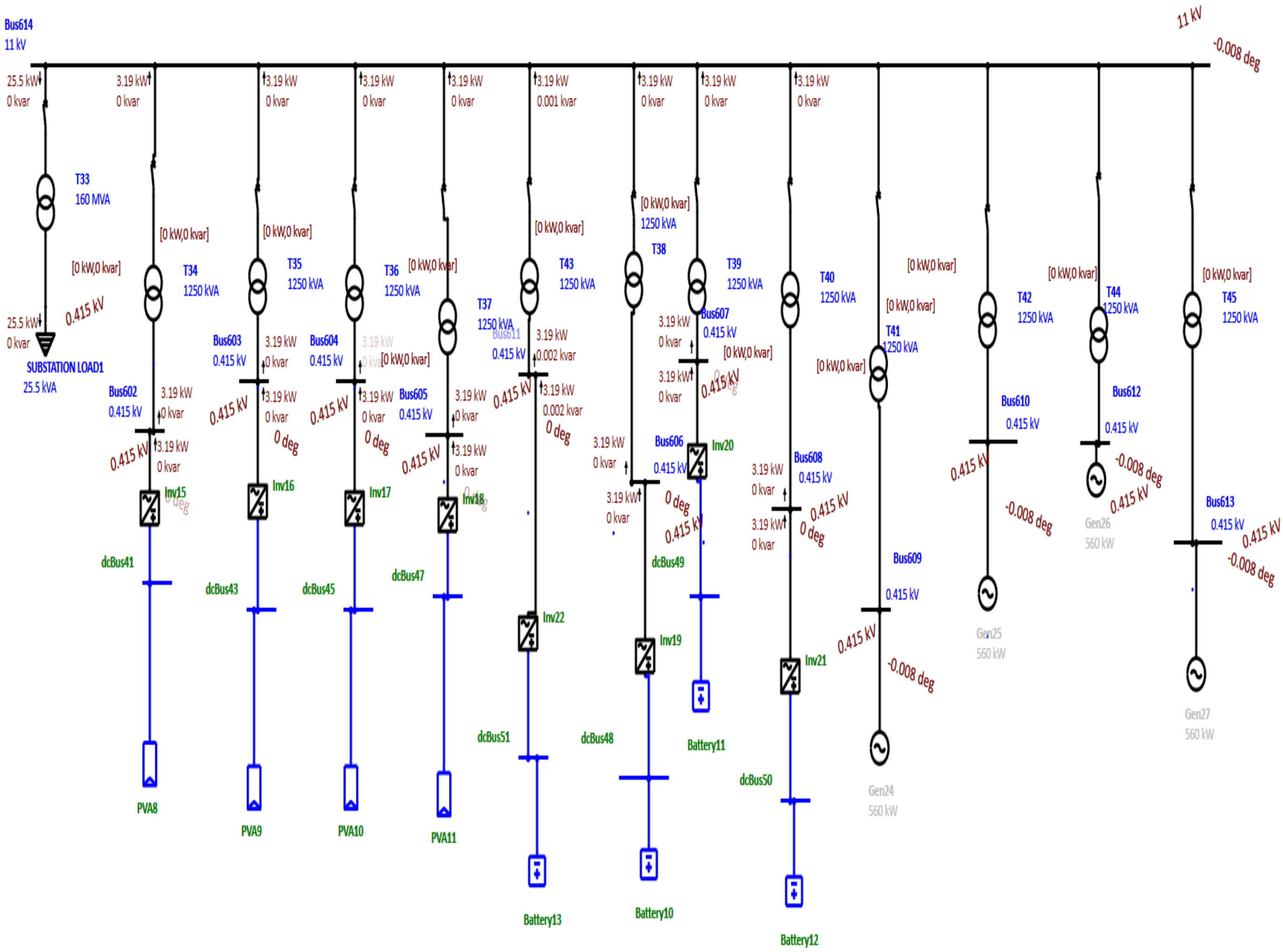

Figure 7: Base Case Load Flow Analysis Result of the hybrid distributed generation without the diesel generator

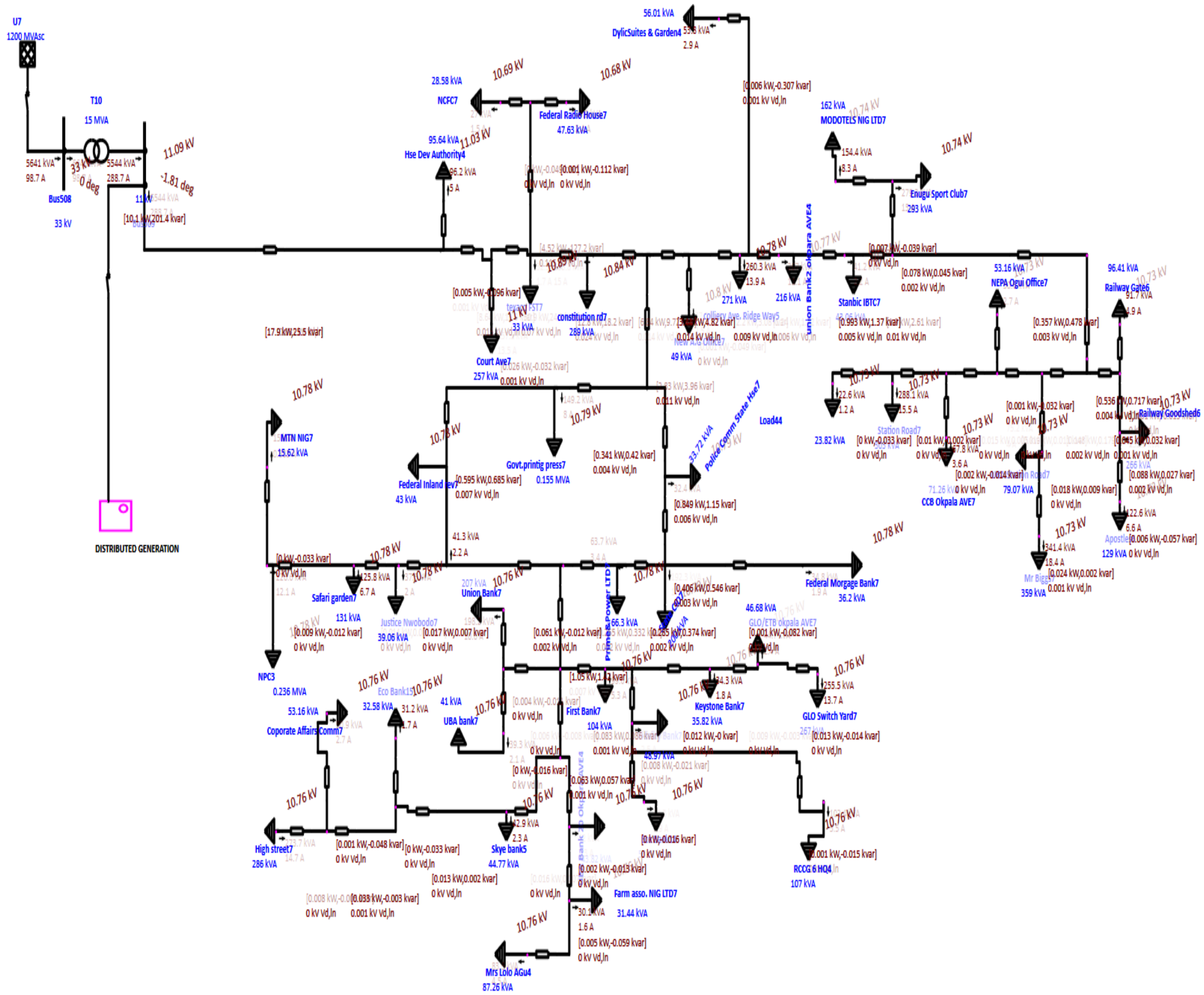

Figure 8: Integrated load flow of Enugu distribution station

4.2 Transient Stability Analysis

Transient stability was evaluated using a 20 s ETAP simulation under single-line-to-ground and three-phase fault conditions (Figures 9–16).

Following fault initiation, Generator 24 exhibited rotor angle oscillations, speed deviation and increased stator current. The protection system successfully isolated the fault, preventing loss of synchronism. After fault clearance, generator speed, mechanical power and current reduced to zero because the generator was disconnected by the protection system. Although stability was preserved, generator tripping reduced the available generation, indicating the importance of faster fault clearing and improved fault ride-through capability.

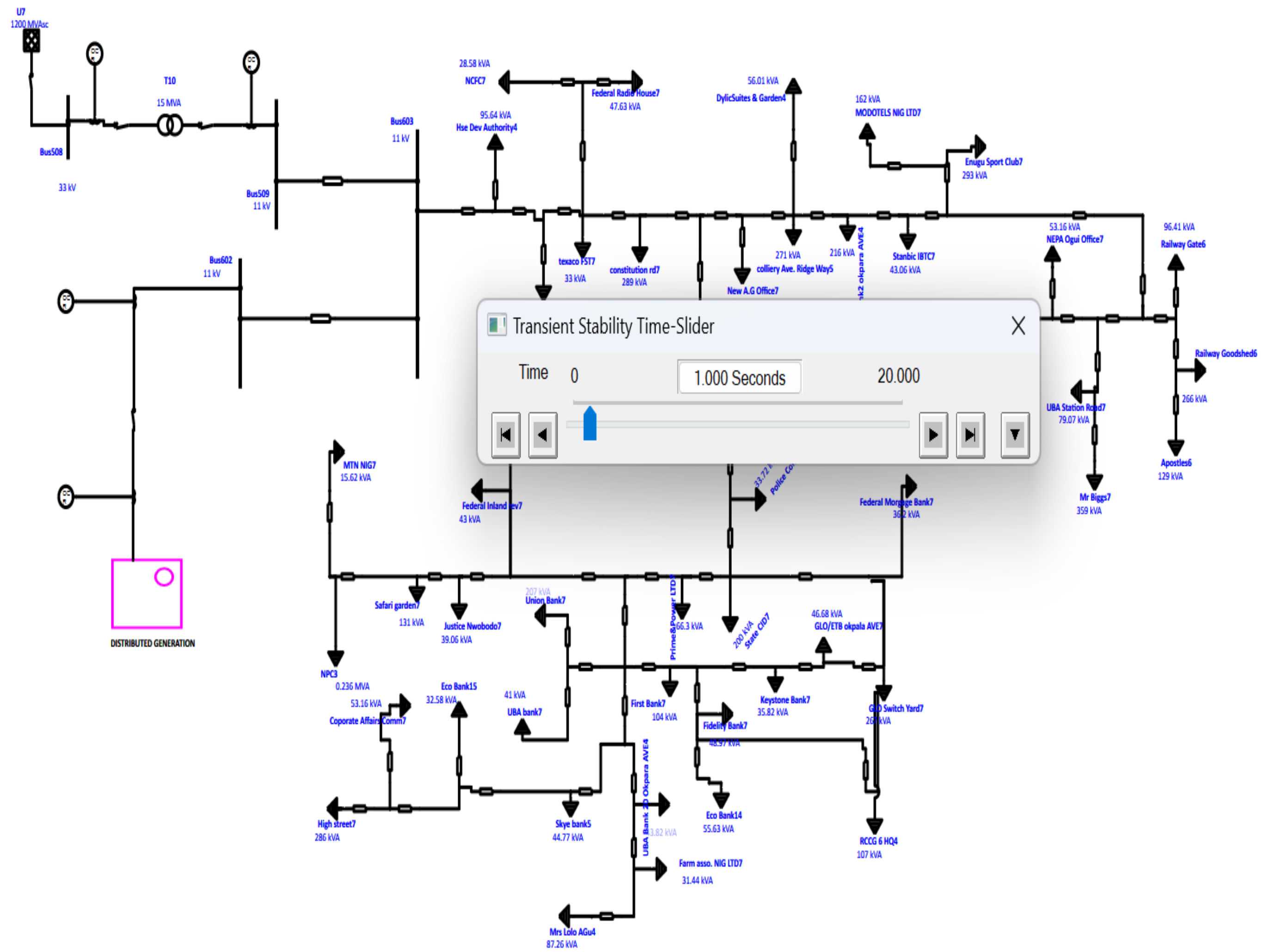

Figure 9: Single line diagram before the impact of fault

4.2.1 Single-Line to Ground Fault (SLG) Circuit Breaker Response

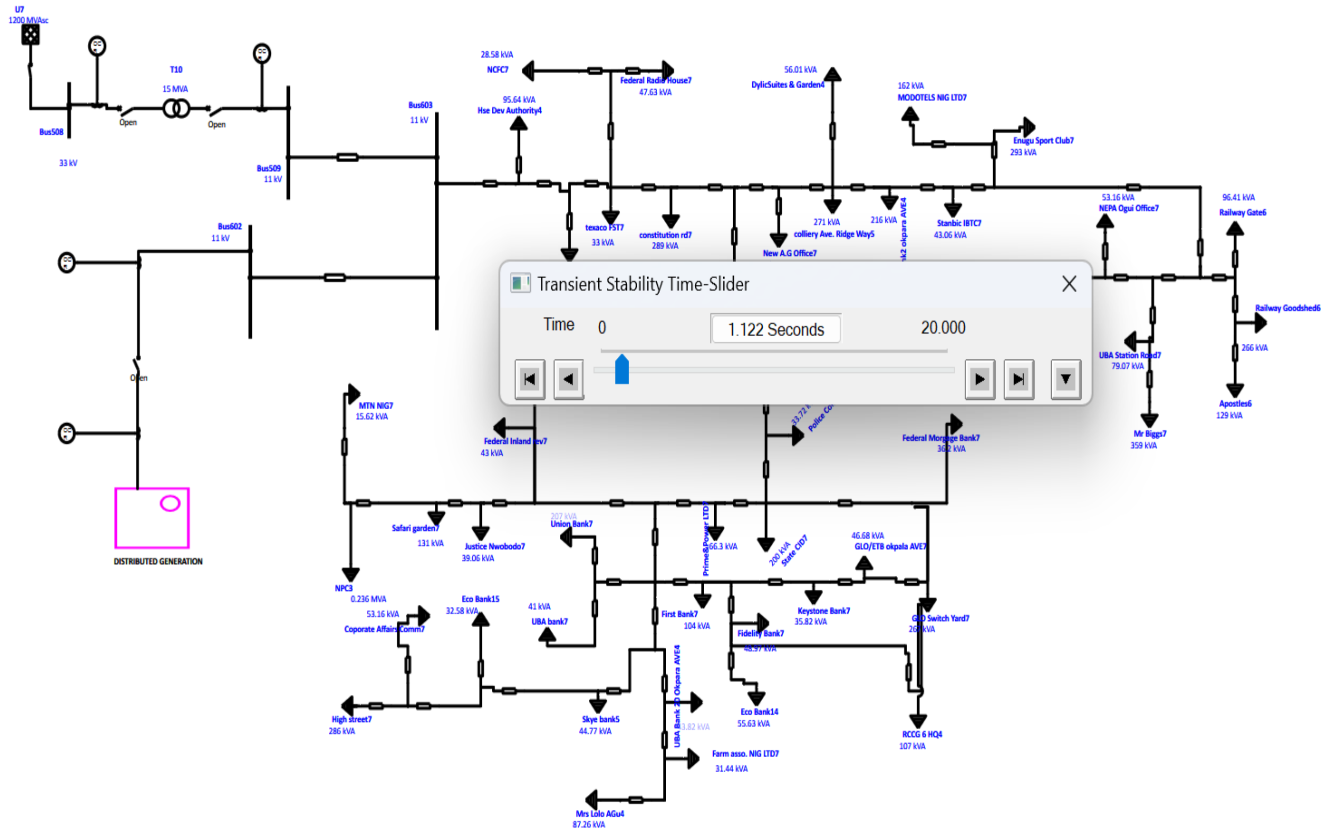

Figure 10: Enugu network responding to the impact of single line to ground fault

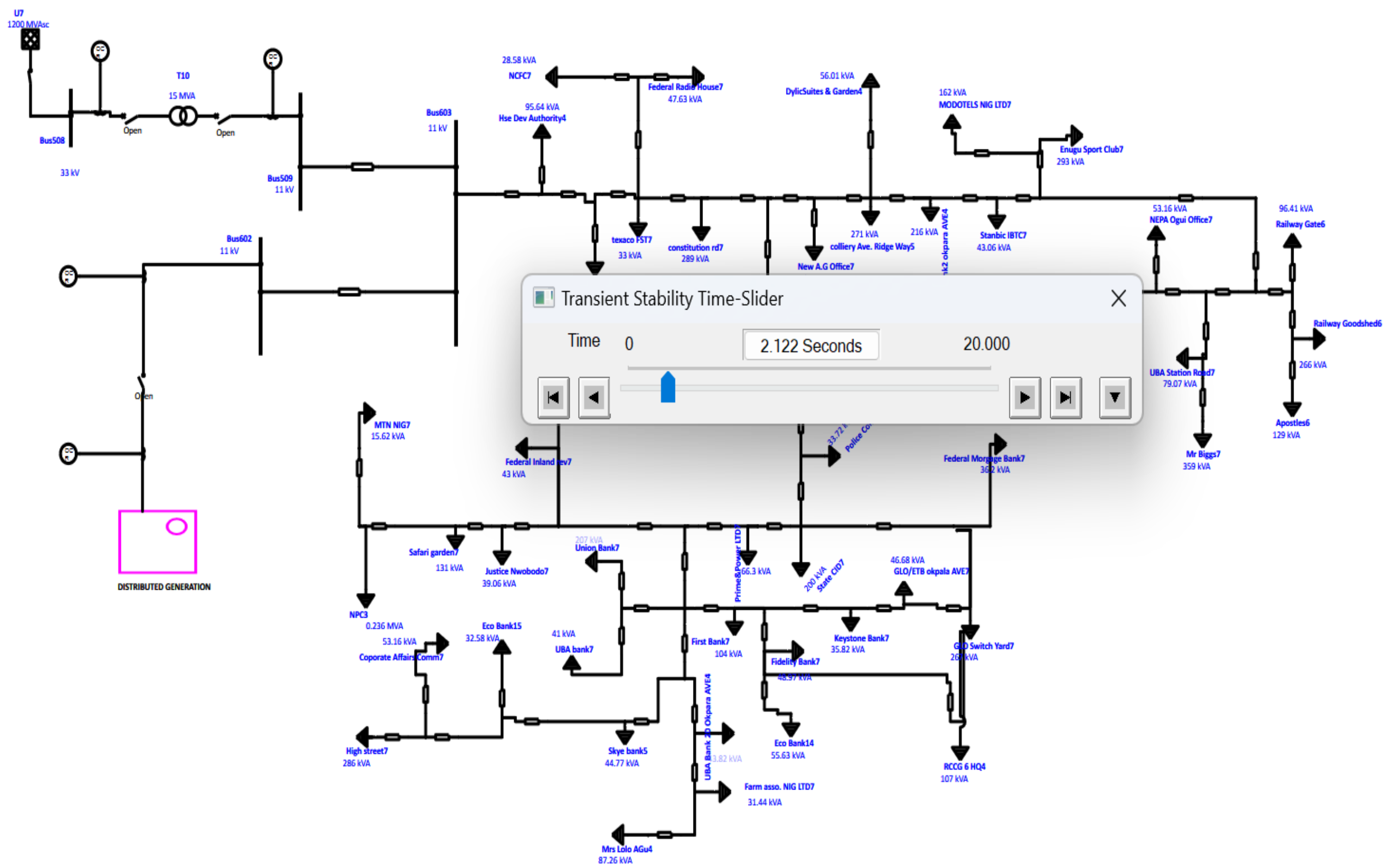

Figure 11: Three-Phase Fault Circuit Breaker Response

4.3 Protection Coordination Performance

Protection coordination results (Figures 17–20) confirmed satisfactory relay selectivity under different fault locations. For a three-phase fault at Bus 602, OCR-8 detected and cleared the fault through CB-23, while backup relays remained inactive because the primary relay operated within the coordination interval. Similar selective operation was observed for faults at Buses 603, 509 and 508, where the nearest relay-circuit breaker combination isolated only the faulted section.

The results demonstrate that the proposed relay coordination strategy provides reliable fault isolation while minimizing unnecessary feeder outages.

4.4 Protection Coordination Performance Result

Following the transient stability analysis, this section evaluates the performance of the proposed protection schemes and their influence on the overall reliability of the Enugu distribution network with integrated DG. The assessment focuses on overcurrent relay operation, protection coordination.

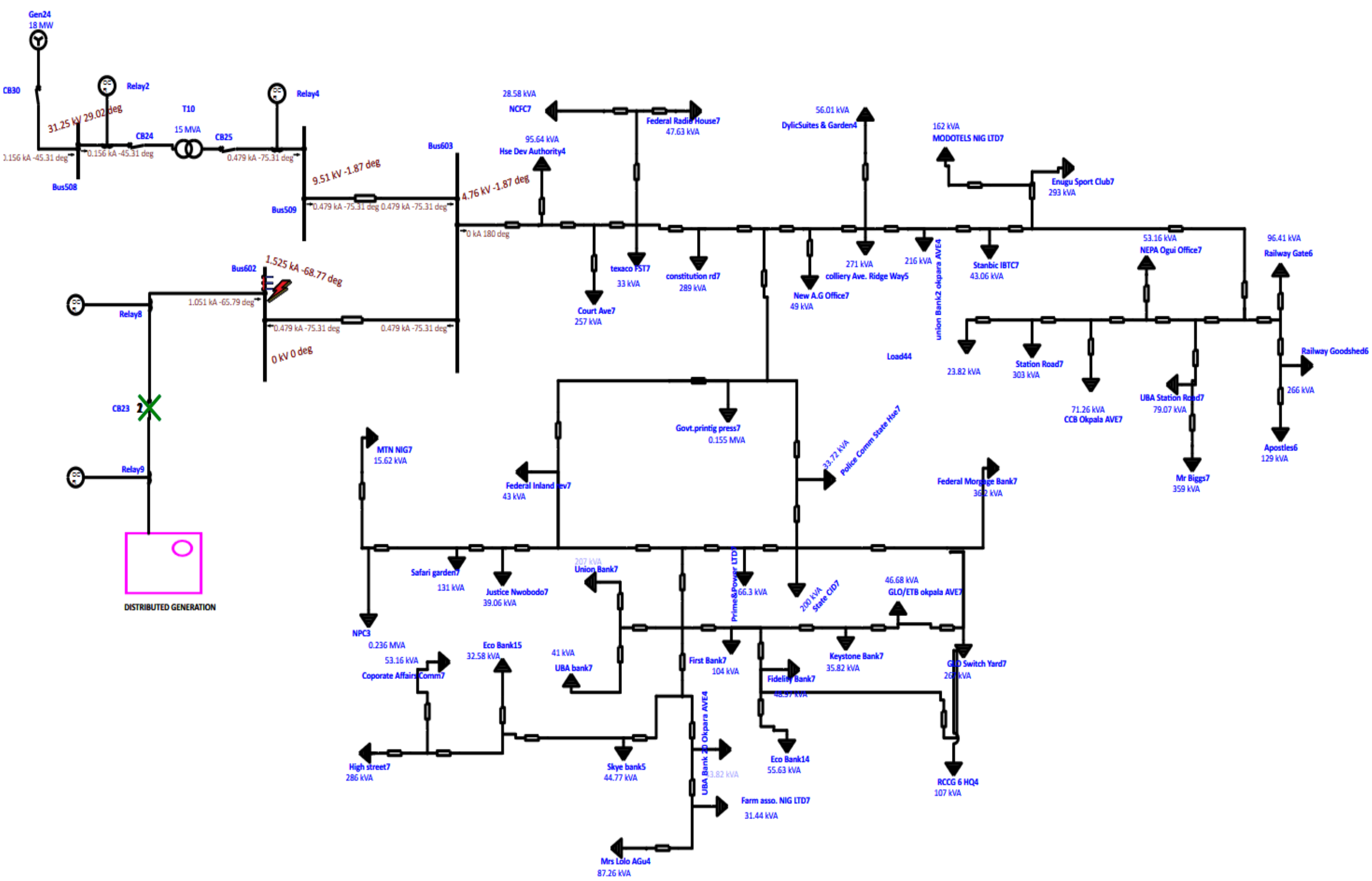

Figure 11: Three-Phase Fault on Bus 602

From the protection coordination assessment, a three-phase fault was introduced on Bus 602 of the Enugu distribution network which is the bus that is attached with the distributed generation in service. The primary protection device, Overcurrent Relay OCR-8, linked to Circuit Breaker CB-23, detected the fault and operated according to its programmed settings. OCR-8 was configured with a CO2 short time inverse curve and a pickup setting of 0.08 × CT (equivalent to 8 A primary and 0.4 A relay current) with a time dial of 0.5. Additionally, the instantaneous element was set to trip at 10 × CT (equivalent to 1000 A primary and 50 A relay current) with an intentional delay of 0.01 seconds. This configuration ensured that the fault was detected and cleared promptly.

Upon fault detection, OCR-8 issued a trip command to CB-23, which opened to isolate the faulted section of integrated network. This isolation prevented the fault from escalating into upstream buses such as Bus 603 and Bus 509. Backup protection—OCR-2 for CB-24 and OCR-4 for CB-25 remained inactive because the primary protection cleared the fault well within the designed grading margin of 0.4 seconds, ensuring selectivity and avoiding unnecessary outages in healthy feeders.

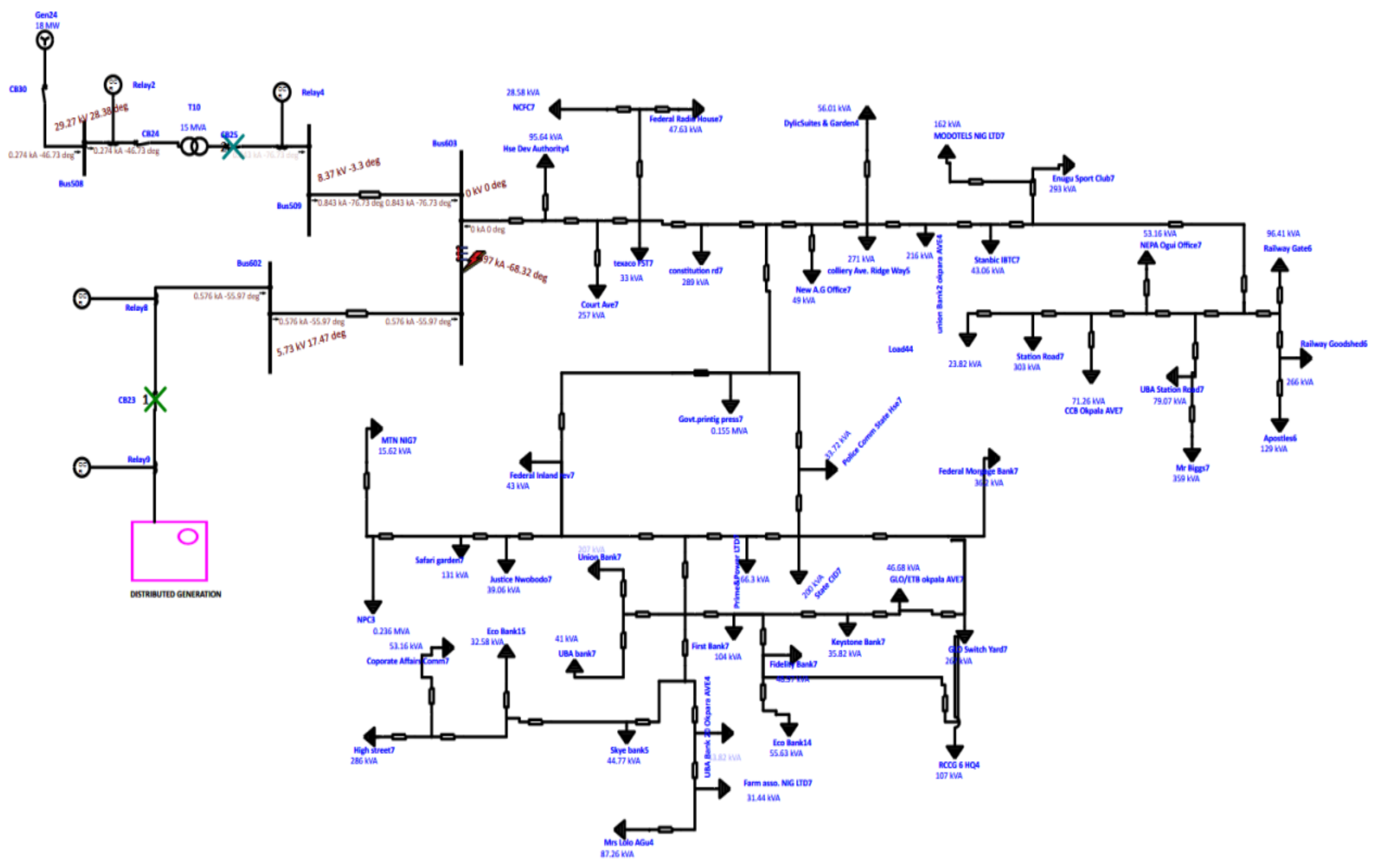

Figure 12: Three-Phase Fault on Bus 603

Similarly, when the three-phase symmetrical fault occurred on bus 603, the circuit breakers CB23 and CB25 which are controlled by overcurrent relays 8 and 4 and are closer to the faulty bus responded by isolating the faulty bus from other buses.

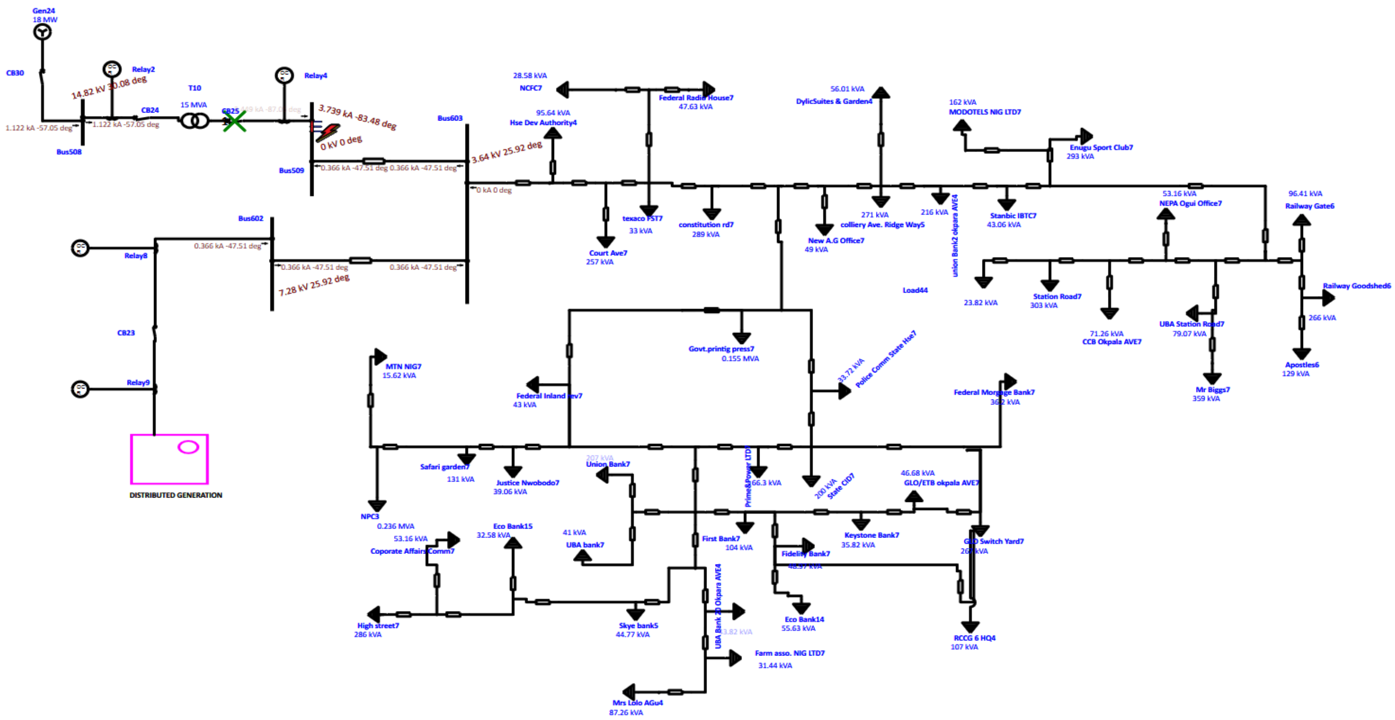

Figure 13: Three-Phase Fault on Bus 509

Similarly, when the three-phase symmetrical fault occurred on bus 603, the circuit breakers CB23 and CB25 which are controlled by overcurrent relays 8 and 4 and are closer to the faulty bus responded by isolating the faulty bus from other buses

To isolate the fault on bus 509, the overcurrent relay OCR 4 activated the circuit breaker CB 25 that is the circuit breaker and the overcurrent relay that are closest to the faulty bus.

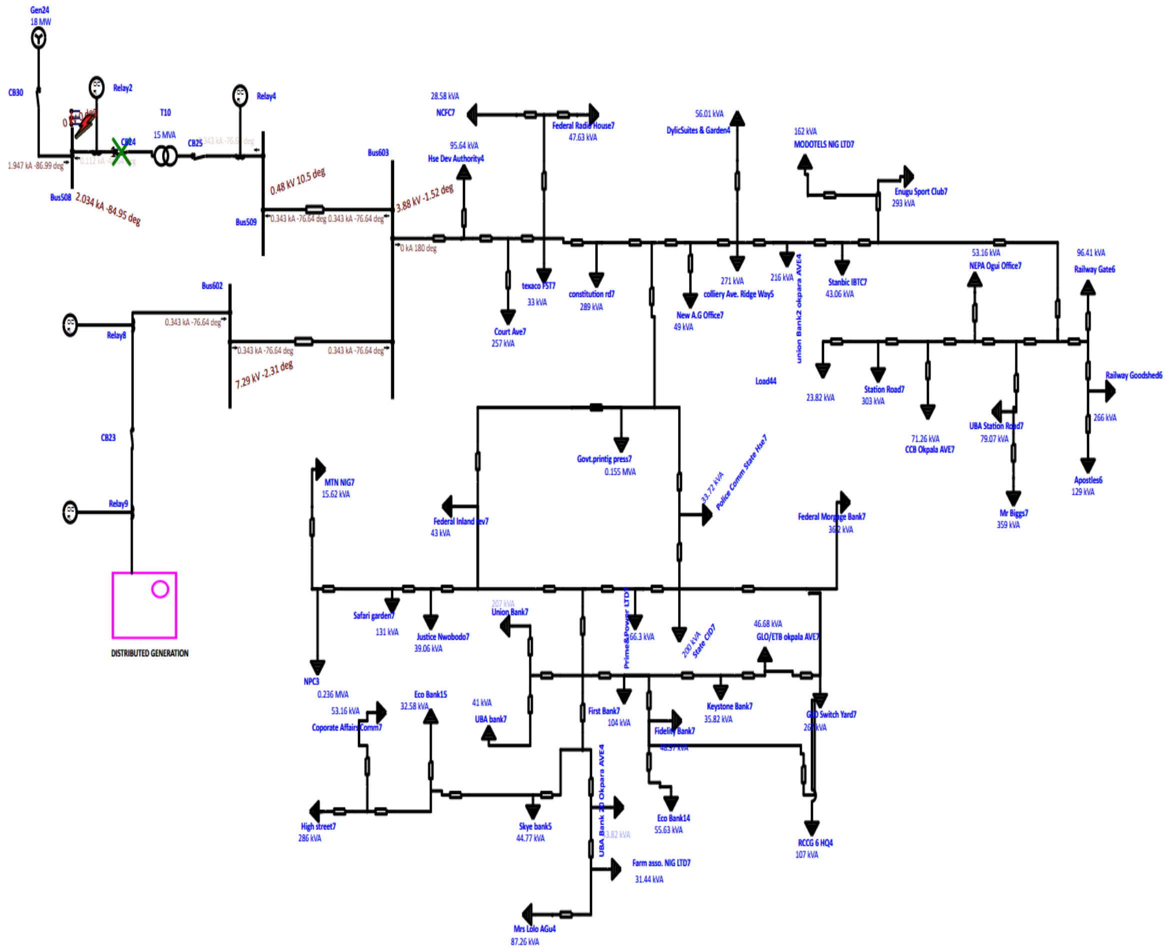

Figure 14: Three-Phase Fault on Bus 508

Protection coordination was further verified using ETAP Time-Current Characteristic (TCC) plots. The coordination curves confirmed that OCR-8 operated within its designated primary protection zone for faults at Bus 602, while the operating times of upstream backup relays remained outside the coordination time interval, thereby preventing unnecessary backup operation. The minimum coordination time interval between primary and backup relays was maintained at approximately 0.30 s throughout the simulated fault scenarios, satisfying recommended relay coordination practice and confirming proper discrimination between successive protection devices.

5.0 DISCUSSION

The results indicate that integrating distributed generation improves voltage regulation, local power supply and overall network performance. However, DG alters fault current magnitude and power flow direction, reducing the effectiveness of conventional overcurrent protection. The adaptive protection scheme-maintained relay selectivity and ensured reliable fault clearance under varying operating conditions, consistent with the findings of Bisheh *et al* (2021) and Nguyen *et al.* (2021). Following fault clearance at approximately 4.5 s, Generator 24 was disconnected by the protection system, causing generator speed, mechanical power, and stator current to decrease to zero. Although the protection system successfully prevented loss of synchronism, removal of the generator reduced the locally available generation capacity. Consequently, the utility grid compensated for the lost generation through increased power import while the remaining distributed energy resources continued supporting local loads. Because the disconnected generator represented only a relatively small proportion of the total system generation, the network maintained acceptable frequency stability and remained operational without cascading instability. These findings agree with Nwajuonye *et al.* (2021), Taberi *et al.,* and Obi *et al.* (2022) on voltage improvement through DG integration, while extending previous studies by incorporating transient stability and adaptive protection assessment. The observed stable inverter response also supports the findings of Idam *et al*. (2026) regarding improved converter dynamics under transient conditions Nevertheless, the event demonstrates that unnecessary generator tripping may reduce operational resilience and increase dependence on the upstream grid. Future implementations should therefore incorporate fault ride-through (FRT) capability and adaptive protection strategies capable of distinguishing temporary disturbances from permanent faults, thereby minimizing unnecessary distributed generation disconnection while maintaining system security.

6.0 CONCLUSION

This study developed an ETAP-based protection methodology for a DG-integrated Enugu distribution network. The results show that hybrid DG improves voltage profile, enhances local power support and maintains transient stability during network disturbances. However, DG modifies fault current characteristics, making conventional relay settings inadequate. The proposed adaptive protection approach restored relay coordination and improved protection reliability, demonstrating its suitability for modern DG-integrated distribution systems

7.0 RECOMMENDATIONS

Adaptive overcurrent protection should be adopted for distribution networks with high distributed generation (DG) penetration to ensure reliable system protection. Relay settings should be reviewed periodically following DG installation to maintain proper protection coordination. Detailed ETAP protection studies should also be performed before integrating DG to evaluate its impact on the network and optimize protection settings. Furthermore, intelligent monitoring and communication-assisted protection systems should be deployed to enhance network reliability and support the development of future smart distribution networks.

REFERENCES

Ahmed, A., Nadeem, T. B., Naqvi, A. A., Siddiqui, M. A., Khan, M. H., Zahid, M. S. B., & Ammar, S. M. (2022). Investigation of PV utilizability on university buildings: A case study of Karachi, Pakistan. Renewable Energy, 195, 238–251. https://doi.org/10.1016/j.renene.2022.06.006

Ansari, M., & Ansari, M. (2021). Mitigating the impact of distributed generations on relay coordination using fault current limiters. arXiv preprint, arXiv:2106.12406.

Bisheh, H., Fani, B., &Shahgholian, G. (2021). A novel adaptive protection coordination scheme for radial distribution networks in the presence of distributed generation. International Transactions on Electrical Energy Systems, 31(3), e12779. https://doi.org/10.1002/2050-7038.12779

Bui, D. M., Le, P. D., Nguyen, T. P., & Nguyen, H. (2021). An adaptive and scalable protection coordination system of overcurrent relays in distributed-generator-integrated distribution networks. Applied Sciences, 11(18), 8454. https://doi.org/10.3390/app11188454

Chae, W., Lee, J.-H., Kim, W.-H., Hwang, S., Kim, J.-O., & Kim, J.-E. (2021). Adaptive protection coordination method design of remote microgrid for three-phase short circuit fault. Energies, 14(22), 7754. https://doi.org/10.3390/en14227754

Dulău, L. I., Abrudean, M., &Bică, D. (2014). Effects of distributed generation on electric power systems. Procedia Technology, 12, 681–686.

Fayazi, H., Fani, B., Moazzami, M., &Shahgholian, G. (2021). An offline three-level protection coordination scheme for distribution systems considering transient stability of synchronous distributed generation. International Journal of Electrical Power & Energy Systems, 131, 107069. https://doi.org/10.1016/j.ijepes.2021.107069

Gutierrez-Rojas, D., Nardelli, P. H. J., Mendes, G., &Popovski, P. (2020). Review of the state-of-the-art on adaptive protection for microgrids based on communications. arXiv preprint, arXiv:2007.13479.

Idam, E. O., Muoghalu, C. N., & Achebe, P. N. (2026). Performance response improvement of power electronics converter using cascade controllers. International Journal of Modern Research in Electrical and Electronic Engineering, 10(1).

Institute of Electrical and Electronics Engineers. (2020). IEEE Standard 1547-2018: IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces. IEEE.

International Energy Agency. (2021). World Energy Outlook 2021. International Energy Agency. https://www.iea.org/

Li, X., Wang, Y., Zhang, H., & Chen, Z. (2021). Protection challenges and adaptive relay coordination in active distribution networks with distributed generation. IEEE Access, 11, 45120–45134.

Marković, M., Bossart, M., & Hodge, B.-M. (2023). Machine learning for modern power distribution systems: Progress and perspectives. Journal of Renewable and Sustainable Energy, 15(3), 032301. https://doi.org/10.1063/5.0147592

Nwajuonye, R. O., Okonkwo, I. I., &Iloh, J. P. (2021). Distribution network reliability and efficiency enhancement using distributed generation. Journal of Engineering Research and Reports, 21(3), 55–71. https://doi.org/10.9734/JERR/2021/v21i317452

Obi, P. I., Okonkwo, I. I., &Ogba, C. O. (2022). Power supply enhancement in Onitsha distribution network using distribution generations. Nigerian Journal of Technology, 41(2), 318–329. https://doi.org/10.4314/njt.v41i2.14

Oyedepo, S. O. (2012). Energy and sustainable development in Nigeria: The way forward. Energy, Sustainability and Society, 2, Article 15. https://doi.org/10.1186/2192-0567-2-15

Pepermans, G., Driesen, J., Haeseldonckx, D., D'haeseleer, W., &Belmans, R. (2005). Distributed generation: Definition, benefits and issues. Energy Policy, 33(6), 787–798.

Sambo, A. S., Garba, B., Zarma, I. H., &Gaji, M. M. (2012). Electricity generation and the present challenges in the Nigerian power sector. Journal of Energy and Power Engineering, 6(7), 1050–1059.

Shahbazitabar, M., Abdi, H., Nourianfar, H., Anvari-Moghaddam, A., Mohammadi-Ivatloo, B., &Hatziargyriou, N. (2021). An introduction to microgrids, concepts, definition, and classifications. In Microgrids (pp. 3–16). Springer. https://doi.org/10.1007/978-3-030-59750-4_1

Waqar, A., Hussain, B., Ahmad, S., Yahya, T., &Sarwar, M. (2019). A communication-less protection strategy to ensure protection coordination of distribution networks with embedded distributed generation.arXiv preprint, arXiv:1906.07571.

Hatziargyriou, N. (Ed.). (2021). *Microgrids: Architectures and Control* (2nd ed.). Wiley.

Shahbazitabar, M., Abdi, H., Nourianfar, H., Anvari-Moghaddam, A., Mohammadi-Ivatloo, B., & Hatziargyriou, N. (2021). *Microgrids: Concepts, Definition and Classification.*

Marković, M., Bossart, M., & Hodge, B. M. (2023). *Machine Learning for Modern Power Distribution Systems.*

Blackburn, J. L., & Domin, T. J. (2015). *Protective Relaying: Principles and Applications* (4th ed.). CRC Press.

Choudhary, A., Singh, M., & Gupta, R. (2022). Adaptive overcurrent relay coordination in active distribution networks with distributed generation integration. *Electric Power Systems Research*, **203**, 107640.

Horowitz, S. H., & Phadke, A. G. (2022). *Power System Relaying* (5th ed.). Wiley.

Ustun, T. S., Aghniaey, S., & Hussain, S. M. S. (2021). Adaptive protection for smart distribution networks with high penetration of distributed energy resources. *Renewable and Sustainable Energy Reviews*, **143**, 110889