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An Intelligent Smart Meter-Based Load-Limiting Strategy for Residential Distribution Transformer Protection: A Simulation Study

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Abstract: *Distribution transformer overloading remains a significant challenge in residential electricity distribution networks due to voltage deterioration, excessive thermal stress, accelerated equipment ageing, and reduced service reliability. This study presents a simulation-based evaluation of an intelligent smart meter load limiting strategy for residential distribution transformer protection. An interactive MATLAB R2024a simulation model was developed to represent a 50 kVA distribution transformer supplying five households under conventional and smart metering conditions. The proposed framework integrates real time load monitoring, transformer voltage regulation, overload detection, fuse protection, and an automated smart meter algorithm featuring progressive penalties, temporary disconnection, permanent lockout after repeated violations, and authorised restoration. Simulation results show that conventional metering permits unrestricted electricity consumption, leading to sustained transformer overloading, voltage reduction, and eventual fuse operation that disconnects all consumers. In contrast, the proposed strategy selectively disconnects only consumers exceeding their assigned load limits, thereby maintaining transformer loading within acceptable operating limits, improving voltage regulation, preventing unnecessary fuse operations, and ensuring uninterrupted supply to compliant consumers. The developed simulation platform provides a practical tool for evaluating intelligent transformer protection strategies and demonstrates the potential of smart meter based demand side management for improving transformer reliability and supporting modern smart grid operation.*

Keywords: *Distribution transformer, Smart metering, Load limiting, MATLAB simulation, Transformer protection, Demand side management.*

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1.0 Introduction

Distribution transformers are essential components of electric power distribution systems because they step down medium voltage to low voltage for residential, commercial, and small industrial consumers. Their reliable operation is fundamental to maintaining power quality, system stability, and uninterrupted electricity supply (Ekpechi et al., 2025). However, rapid urbanization, population growth, increased penetration of electric vehicles, distributed renewable energy resources, and the widespread use of high-power household appliances have significantly increased transformer loading. Sustained operation beyond the rated capacity exposes transformers to excessive thermal stress, accelerates insulation ageing, reduces service life, and increases the likelihood of equipment failure and unplanned outages (Yun et al., 2013; Nebey, 2020; Lv & Han, 2024). Consequently, improving distribution transformer protection has become an important priority for modern electricity distribution utilities. In residential distribution networks, the challenge is particularly pronounced because a single distribution transformer typically supplies multiple households with highly variable and coincident demand patterns. The simultaneous operation of high-power domestic appliances can therefore produce short-term demand peaks that substantially increase transformer loading, even when individual household consumption appears moderate.

Conventional transformer protection schemes primarily employ thermal relays, fuses, and fixed loading limits to protect distribution equipment from overload. Although these methods provide basic protection, they are inherently reactive because protective devices operate only after excessive loading has already occurred. As a result, prolonged overload conditions may cause voltage deterioration, increased thermal stress, and unnecessary interruption of electricity supply to all connected consumers, including those operating within acceptable demand limits (Rafati et al., 2024). These limitations have encouraged the development of proactive protection strategies capable of regulating electricity demand before transformer loading reaches critical levels.

A major limitation of such conventional protection is that it generally treats the transformer and its connected consumers as a single protection zone. Consequently, when an overload condition becomes severe enough to trigger a fuse or other protective device, compliant consumers may also lose electricity supply. This creates a need for a more selective protection mechanism that can regulate excessive household demand before transformer-level protection is activated.

Recent advances in smart grid technologies have enabled intelligent demand-side management through the deployment of smart meters and real-time monitoring systems. Smart meters continuously measure household electricity consumption and can communicate with centralized control systems to support automated load management. When integrated with intelligent load-limiting algorithms, these systems can selectively disconnect consumers whose electricity demand exceeds predefined thresholds while maintaining supply to compliant households (Nyamekeh et al., 2025). Such an approach improves transformer utilization, enhances voltage regulation, minimizes unnecessary fuse operations, and extends transformer service life (Oliyide & Cipcigan, 2021; Diahovchenko et al., 2022; O'Donnell & Su, 2023; Yang et al., 2024).

The ability of smart meters to identify individual consumer demand in real time makes them particularly suitable for selective load control. Instead of disconnecting the entire transformer during an overload event, excessive demand can be managed at the consumer level through predefined load thresholds and automated intervention rules. Several studies have investigated transformer monitoring, overload prediction, and intelligent load management using machine learning, fuzzy logic, optimization techniques, and artificial intelligence (Ramesh et al., 2022; Mateus et al., 2024; Zou et al., 2024). However, much of the existing research focuses on predicting transformer overload, assessing transformer condition, or optimizing demand at the network level. Limited attention has been given to an integrated consumer-level strategy in which smart meters automatically identify excessive household demand and selectively limit or disconnect non-compliant consumers before transformer-level protection is activated. In particular, the integration of household load limiting, progressive penalty enforcement, voltage regulation, transformer overload detection, fuse protection, and authorized restoration within a single interactive simulation framework remains insufficiently addressed. This constitutes the principal research gap addressed in the present study.

Similarly, MATLAB has been widely adopted as a reliable platform for modelling and evaluating power system protection strategies because it enables comprehensive analysis under diverse operating conditions without exposing physical infrastructure to operational risks (Xie et al., 2020a; Torres-Bermeo et al., 2025). Nevertheless, existing studies largely emphasize overload prediction, transformer monitoring, or network-level optimization, while comparatively few integrate automated household load limiting, progressive consumer penalties, voltage regulation, transformer fuse protection, and interactive simulation within a unified framework.

Therefore, the aim of this study is to develop and evaluate an intelligent smart meter-based load-limiting strategy for protecting residential distribution transformers against overload conditions. To achieve this aim, a MATLAB R2024a simulation platform is developed to model transformer loading, household electricity consumption, voltage behaviour, overload detection, fuse protection, and automated smart meter intervention under conventional and intelligent metering scenarios.

Specifically, the study seeks to: (i) model a residential distribution transformer supplying multiple household consumers; (ii) evaluate transformer loading and voltage behaviour under conventional metering; (iii) implement an intelligent smart meter-based load-limiting algorithm; (iv) assess the effectiveness of selective consumer disconnection in preventing transformer overload and unnecessary fuse operation; and (v) compare the performance of conventional and intelligent metering scenarios using transformer loading, voltage regulation, and supply continuity as key indicators.

.The developed simulator is used to compare conventional and smart metering scenarios in terms of transformer loading, voltage performance, and protection effectiveness. The findings demonstrate the capability of intelligent demand-side management to mitigate transformer overloading, improve voltage quality, enhance operational reliability, and support the implementation of modern smart grid technologies.

The significance of the study lies in providing a practical simulation-based framework through which distribution utilities and researchers can assess consumer-level demand management as an alternative or complement to conventional transformer protection. By selectively regulating excessive household demand rather than disconnecting the entire transformer, the proposed approach has the potential to improve supply continuity for compliant consumers, reduce unnecessary protection operations, enhance transformer utilization, and support the transition toward intelligent and responsive residential distribution networks.

The novelty of the proposed framework lies in its integration of consumer-level smart meter load limiting with transformer-level protection mechanisms in a single interactive simulation environment. Unlike approaches that primarily monitor, forecast, or optimize transformer loading, the proposed strategy incorporates progressive penalties, temporary disconnection, repeated-violation lockout, voltage monitoring, fuse protection, and authorized restoration to provide a coordinated consumer-to-transformer protection mechanism.

2. 0 Literature Review

Distribution transformer overloading remains one of the leading causes of insulation degradation, excessive winding temperatures, voltage instability, and premature equipment failure. Increasing residential electricity demand, driven by urbanization, electric vehicle integration, and the proliferation of high-power household appliances, has intensified transformer loading and increased the need for effective protection strategies. Consequently, considerable research has focused on transformer overload assessment, condition monitoring, and intelligent protection techniques.

Several studies have investigated transformer overload evaluation using monitoring and predictive approaches. Yun et al. (2013) developed an overload evaluation system based on transformer load monitoring data to improve operational decision making, while Nebey (2020) proposed an automatic load-sharing technique for mitigating transformer overloading. More recently, Lv and Han (2024) demonstrated the importance of load forecasting in identifying overload conditions associated with increasing residential electricity demand, whereas Rafati et al. (2024) developed a predictive overload alarm system capable of providing early warning before critical operating conditions occur. Reliability assessment and overload capacity estimation have also been investigated using thermal models and artificial neural networks to improve transformer operating decisions (Chen et al., 2015; Wang et al., 2016). Although these studies significantly improve transformer monitoring and overload prediction, most remain reactive or transformer centered, offering limited capability for regulating consumer demand before overload conditions develop.

The rapid evolution of smart grids has encouraged the deployment of smart meters as key components of intelligent demand-side management (Yusuf et al., 2025). Smart meters provide continuous measurements of household electricity consumption while enabling real-time communication between consumers and utility operators. Previous studies have shown that intelligent demand management improves transformer utilization and reduces network congestion. Oliyide and Cipcigan (2021) investigated coordinated electric vehicle charging to maximize transformer capacity utilization, while Diahovchenko et al. (2022) demonstrated that active demand control reduces transformer ageing under high electric vehicle penetration. Similarly, Ramesh et al. (2022) employed machine learning for transformer load monitoring and management, and Pawar et al. (2017) developed an Internet of Things-based transformer monitoring system for continuous operational supervision. Despite these advances, most existing studies emphasize monitoring and information acquisition rather than implementing automated consumer-level interventions capable of preventing transformer overload through selective load limitation.

Recent research has increasingly adopted artificial intelligence, fuzzy logic, machine learning, optimization techniques, and predictive control for intelligent transformer protection. Fuzzy logic has been successfully applied to transformer condition diagnosis (Sierra Gil et al., 2023), while Mateus et al. (2024) combined fuzzy logic and neural networks for transformer fault detection and prediction. Artificial neural networks have also been employed for heavy overload forecasting (Xie et al., 2020b), whereas Li et al. (2021) proposed prediction algorithms for identifying severe transformer overload conditions in distribution networks. Other researchers have investigated optimization-based approaches for transformer operation and capacity regulation using load forecasting, reinforcement learning, and adaptive control strategies (Pang et al., 2024; Yang et al., 2024; Zou et al., 2024). Although these methods have significantly improved overload prediction and operational planning, many focus on utility-level optimization rather than practical consumer-level protection.

Simulation has become an indispensable tool for evaluating transformer protection strategies because it enables complex operating scenarios to be analysed without exposing physical infrastructure to operational risks. MATLAB has been widely used for modelling transformer behaviour owing to its numerical computation capability, flexible programming environment, and support for graphical user interface development. Previous studies have employed MATLAB and other simulation platforms for transformer monitoring, load estimation, clustering, optimization, and asset management (Farahzad et al., 2020; Panjumpa & Chatthaworn, 2021; Xie et al., 2020; Cabral et al., 2024; Torres-Bermeo et al., 2025). However, comparatively few studies have developed an integrated simulation framework that combines residential transformer modelling, automated smart meter-based load limiting, progressive penalty enforcement, voltage regulation, transformer fuse protection, permanent meter lockout, authorized restoration procedures, and interactive visualization within a single platform. Taken together, the reviewed studies demonstrate substantial progress in transformer condition monitoring, overload prediction, intelligent control, and demand-side management. However, these approaches are generally addressed as separate functions, with limited integration of consumer-level load intervention and transformer-level protection. A unified framework capable of linking individual household demand, smart meter intervention, transformer loading, voltage response, fuse operation, and restoration decisions therefore remains necessary.

Accordingly, this study develops an interactive MATLAB R2024a simulation platform that integrates intelligent smart meter-based load limiting with residential transformer protection. Unlike previous studies that primarily emphasize monitoring, prediction, or network-level optimization, the proposed framework provides real-time household demand monitoring, selective consumer disconnection, progressive penalty enforcement, transformer overload protection, voltage regulation analysis, and authorized consumer restoration in a unified simulation environment. This integrated approach provides a practical platform for evaluating intelligent demand-side protection strategies and contributes to the development of more reliable residential smart grid systems.

3.0 Methodology

An intelligent demand-side protection framework was developed to evaluate automated smart meter-based load limiting for residential distribution transformer protection. The proposed system integrates residential electrical loads, smart meters, an automated load-limiting algorithm, a 50 kVA distribution transformer, and a performance monitoring module within an interactive MATLAB R2024a simulation environment, as illustrated in Fig. 1.

Five residential consumers were connected to the transformer, with each household equipped with a smart meter that continuously monitored electricity demand against a predefined load allocation

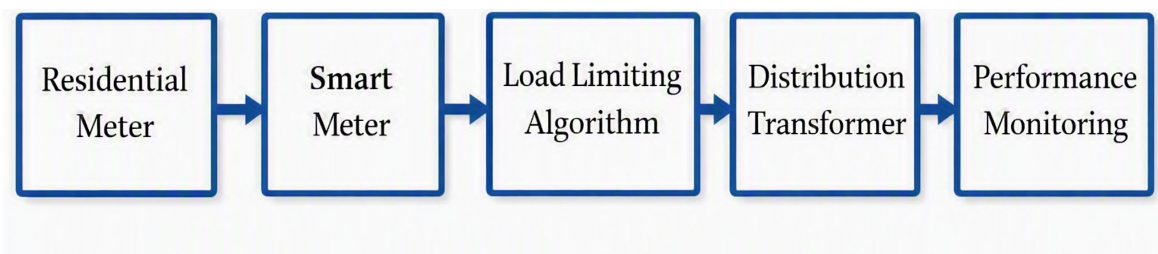


Fig. 1: Architecture of the Proposed Smart-Meter-Based Transformer Protection System

.The transformer was modelled as a 50 kVA residential distribution transformer with a rated secondary voltage of 230 V. The aggregate apparent power demand of the connected consumers was used to determine transformer loading, while the secondary voltage response was adjusted according to the simulated loading condition. The model was configured to represent normal operation, overload operation, protection activation, and recovery following consumer load disconnection. Whenever the measured demand exceeded the assigned threshold, the protection algorithm initiated corrective actions before transformer loading reached critical levels. The transformer model continuously evaluated the aggregate load, estimated the corresponding secondary voltage, and monitored overload conditions. System performance was assessed using transformer loading, voltage variation, smart meter status, overload warnings, and protection events under both conventional and smart metering scenarios.

3.1 MATLAB Simulation Model

The proposed protection strategy was implemented using MATLAB R2024a because of its numerical computation capability, flexible programming environment, and support for interactive graphical user interfaces. The simulation model represents a residential distribution transformer supplying five independent household consumers under two operating modes:

- Conventional metering, where consumers are permitted unrestricted electricity consumption.
- Smart metering, where household demand is regulated using an automated load-limiting strategy.

The total transformer loading (S_T) was determined by summing the apparent power demand of all connected households.

$$S_T = \sum_{i=1}^{n} S_i \quad (1)$$

where S_T represents the total transformer apparent power (kVA), S_i denotes the apparent power consumed by the i^{th} household (kVA), and n is the total number of connected consumers. The transformer was classified as overloaded when the calculated aggregate apparent power exceeded its rated capacity of 50 kVA. Thus, the overload condition was defined as (S_T>S_{rated}), where (S_T) is the total connected apparent power and (S_{rated}) is the transformer rated capacity.

Whenever the calculated loading exceeded the transformer rating, overload conditions were initiated and the corresponding voltage response was evaluated. The secondary voltage response was determined from the simulated transformer loading condition using the voltage regulation relationship implemented in the MATLAB model. As transformer loading increased, the model produced a corresponding reduction in secondary voltage, while removal of excessive consumer demand resulted in voltage recovery toward the rated value of 230 V.

Each household load was independently adjustable to emulate varying residential electricity consumption. Under smart metering operation, every consumer was assigned a maximum allowable load threshold. Exceeding this threshold activated the protection algorithm to prevent excessive transformer loading. Consumer loads are represented as controllable aggregated loads, and the smart meter is assumed to have sufficient switching capability to disconnect and reconnect individual consumers when the prescribed protection conditions are satisfied.

A MATLAB graphical user interface was developed to facilitate real-time interaction with the simulation. The interface enables adjustment of household loads, visualization of transformer operating conditions, monitoring of smart meter status, and recording of protection events, including overload warnings, temporary disconnections, permanent lockouts, and restoration activities.

To simplify the analysis while preserving engineering realism, the following assumptions were adopted:

- Balanced transformer loading.
- Ideal communication between smart meters and the control system.
- Negligible transmission line losses.
- Negligible communication delays.
- User-defined household load variations.

The principal simulation parameters employed in this study are summarized in Table 1.

The smart meter decision logic operates at the individual consumer level. A consumer remains connected when its measured demand does not exceed its assigned maximum allowable load. When the measured demand exceeds this threshold, the consumer is classified as non-compliant and the prescribed penalty action is initiated. The aggregate transformer loading is simultaneously monitored to ensure that consumer-level interventions contribute to maintaining transformer operation within its rated capacity.

Table 1: Principal Simulation Parameters

Parameter	Value
MATLAB Version	MATLAB R2024a
Transformer Rating	50 kVA
Number of Residential Consumers	5
Rated Secondary Voltage	230 V
Metering Modes	**Conventional and Smart Metering**
Overload Warning Time	60 s
First Disconnection Period	10 s
Second Disconnection Period	20 s
Third Disconnection Period	30 s
Protection Strategy	Automated Load Limiting
Performance Indicators	UF, VD and PEI

Algorithm 1. Smart Meter Protection Algorithm

Input:
Transformer rated capacity S_R
Household loads P_i
Maximum allowable household load Pmax
Output:
Transformer protection status
Consumer connection status
Voltage regulation
Begin
Initialize transformer and connect all residential consumers
Assign maximum allowable load (Pmax) to each consumer
While simulation is running do
Read household load Pi from each smart meter
Compute total transformer loading
$S_T = \Sigma Pi$
For each consumer i
If $P_i \leq P_{max}$ *then*
Maintain connection
Else
Disconnect consumer
Increment violation counter
If first violation then
Suspend for 10 s
Else if second violation then
Suspend for 20 s
Else if third violation then
Suspend for 30 s
Else
Permanently lock smart meter
Await official clearance
End if
End if
End for
Update transformer loading
Compute secondary voltage
Display system status
End while
End

where P_i is the measured household demand, and P_{max} is the assigned maximum load allocation,.

According to Algorithm 1, consumers exceeding their allocated demand were immediately disconnected while compliant households remained connected. This selective intervention prevented localized overload without interrupting electricity supply to other consumers. To discourage repeated violations, a progressive penalty mechanism was incorporated:

- First violation: 10-second disconnection.
- Second violation: 20-second disconnection.

- Third violation: 30-second disconnection.

Following each temporary suspension, the consumer was automatically reconnected. However, any subsequent violation after the third suspension resulted in permanent smart meter lockout. Restoration after permanent lockout required authorization through an official clearance interface before reconnection could occur. The operational sequence of the protection strategy is illustrated in Fig. 2.

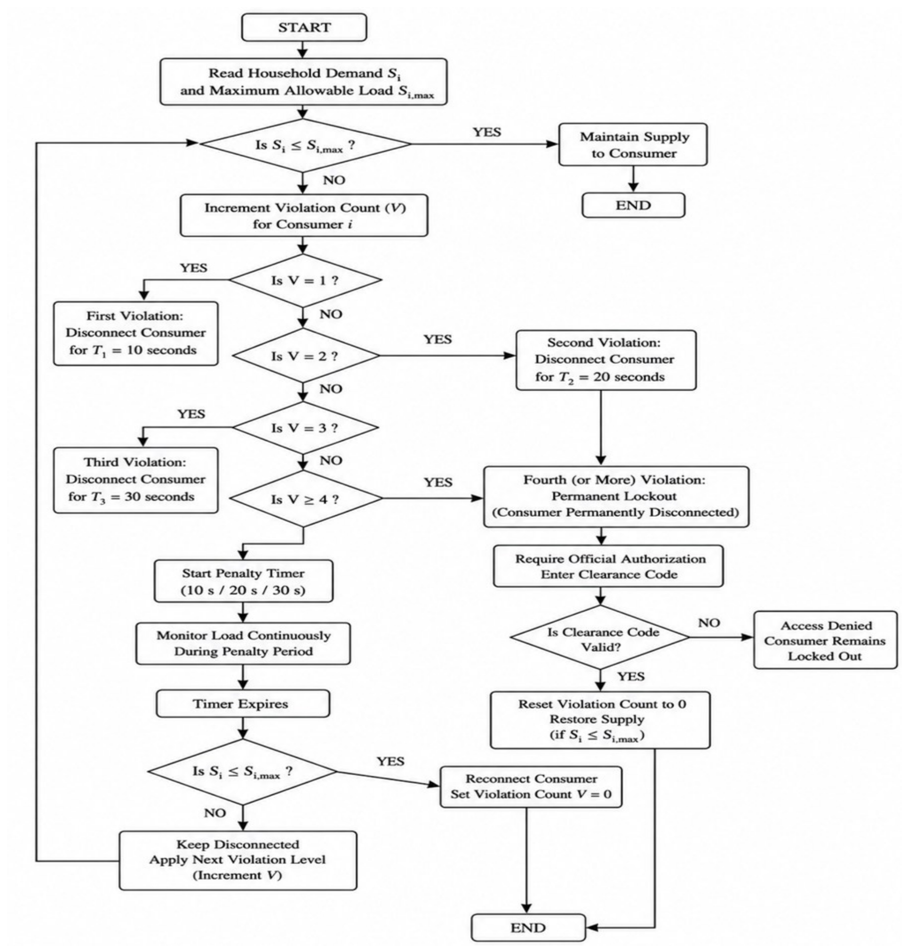


Fig. 2: Flowchart of the Proposed Smart-meter Protection System

The proposed protection strategy was evaluated using three performance indicators.

Transformer Utilization Factor (UF):

$$UF = \frac{S_T}{S_R} \qquad (2)$$

where S_T is the total transformer apparent power and (S_R is the rated transformer capacity.

Voltage Deviation (VD):

$$DV = \frac{V_R - V_A}{V_R} * 100 \qquad *3)$$

where V_R denotes the rated secondary voltage and V_A is the measured secondary voltage during simulation.

Protection Effectiveness Index (PEI): The effectiveness of the proposed load-limiting strategy was evaluated as

$$PEI = \frac{N_P}{N_T} \qquad (4)$$

where N_P represents the number of overload incidents successfully prevented and N_T denotes the total overload incidents observed during simulation.

Transformer Loading Percentage:

$$TL(\%) = \frac{S_T}{S_R} * 100 \qquad (5)$$

Decision Rule using Smart Meter Switching Logic:

$$L_i = \begin{cases} 0 \; P_i \leq P_{max} \\ 1 P_i > P_{max} \end{cases}$$

These metrics provide quantitative measures for comparing conventional transformer protection with the proposed smart meter-based strategy in terms of transformer utilization, voltage regulation, and overload prevention.

4. 0 Results and Discussion

4.1 Conventional Metering

The MATLAB simulation was first evaluated under conventional metering conditions, where all residential consumers were allowed unrestricted electricity consumption to represent a typical distribution network without demand-side control. The transformer operated normally while the total load remained below its rated capacity of 50 kVA, maintaining a secondary voltage close to 230 V. However, as household demand increased beyond the rated capacity, transformer loading caused progressive voltage reduction and triggered an overload warning with a 60-second protection countdown. Since no mechanism existed to regulate individual consumer demand, the overload persisted until the transformer fuse is activated, disconnecting electricity supply to all connected households. These results demonstrate the limitations of conventional transformer protection, which responds only after overload conditions occur and consequently interrupts power supply to both offending and compliant consumers. The simulation results under conventional metering conditions are presented in Fig 3.

Figs. 3(a)–3(c) illustrate the progression of the conventional metering condition from normal transformer operation to overload and eventual fuse operation. Fig, 3(a) shows stable operation under normal loading, with the transformer supplying the connected households at approximately 230 V. As the total demand increases beyond the rated capacity, Fig. 3(b) shows the resulting overload warning and protection countdown, accompanied by a reduction in voltage. Fig. 3(c) shows the subsequent fuse operation, which disconnects the entire transformer supply and interrupts electricity to all connected consumers.

4.2 Smart Metering

The proposed smart-meter-based load-limiting strategy was subsequently evaluated using the same residential loading conditions. Unlike the conventional system, each household was assigned a predefined maximum load threshold, while the smart meter continuously monitored electricity consumption in real time.

Whenever a household exceeded its allocated load, only the offending consumer was automatically disconnected, immediately reducing transformer loading while maintaining electricity supply to compliant consumers.

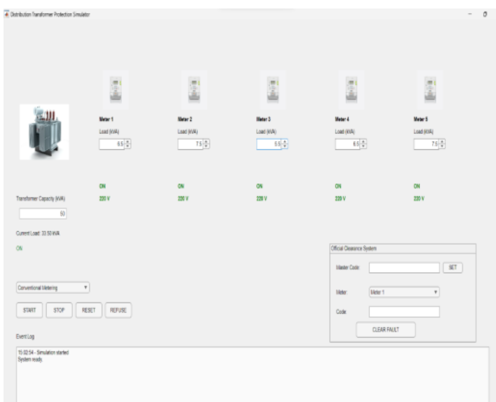
The selective disconnection mechanism effectively prevented sustained transformer overload, allowing the transformer voltage to recover rapidly without requiring fuse operation. Event logs generated during simulation also recorded overload detection, temporary disconnections, reconnections, permanent lockouts, and clearance operations, thereby providing complete monitoring of system activities.

The simulation demonstrates that intelligent consumer-level load management prevents transformer overload while maintaining continuity of supply for consumers operating within their assigned limits. The simulation outputs for the automatic metering are presented in Fig. 4**.**

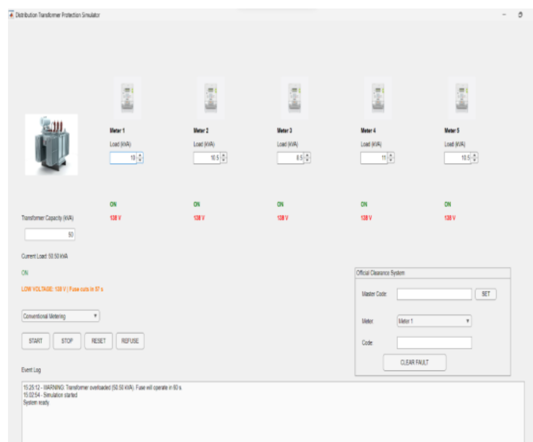
Figs. 4(a) and 4(b) show the smart-meter monitoring interface and the system under normal loading conditions, respectively. The results indicate that the smart meters continuously monitor household demand while the transformer operates within its rated capacity, maintaining a stable secondary voltage of approximately 230 V.

Fig. 4(c) shows the automatic disconnection of a consumer following the detection of a load violation. The smart meter isolates only the offending household while maintaining electricity supply to the remaining consumers. This selective intervention immediately reduces the transformer loading and helps prevent the development of a sustained overload condition. The result demonstrates the effectiveness of the proposed smart-meter-based protection strategy in maintaining service continuity for compliant consumers.

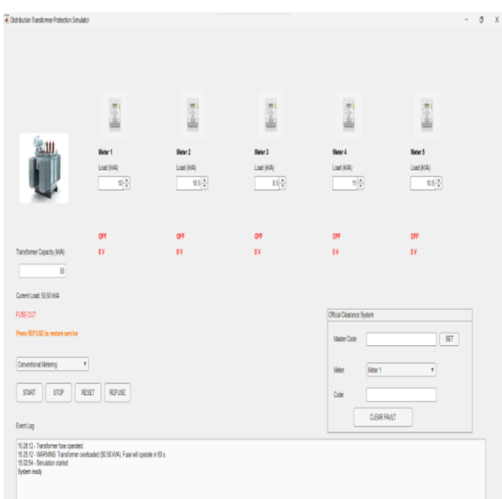
Figs. 4(d) and 4(e) illustrate the official clearance and successful unlocking of the smart meter following a permanent lockout. Fig. 4(d) shows the clearance interface used to authorize restoration, while Fig. 4(e) confirms that the affected meter was successfully unlocked. This controlled restoration mechanism prevents unauthorized reconnection and ensures that supply is restored only after the required clearance procedure has been completed.



(a)



(b)



(c)

Fig. 3: Simulation results under conventional metering: (a) normal transformer loading, (b) transformer overload with voltage reduction, and (c) fuse operation following sustained overload.

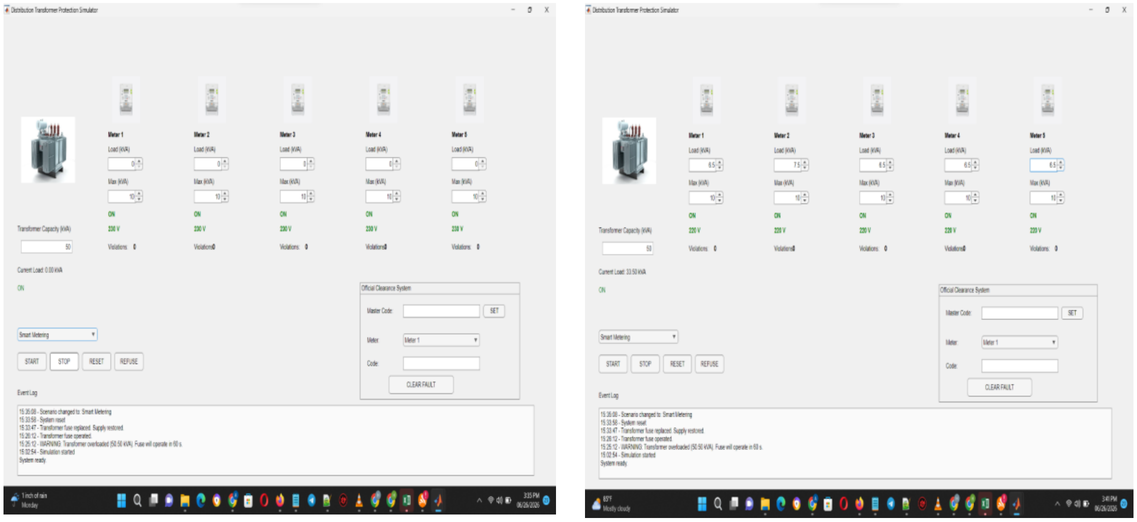
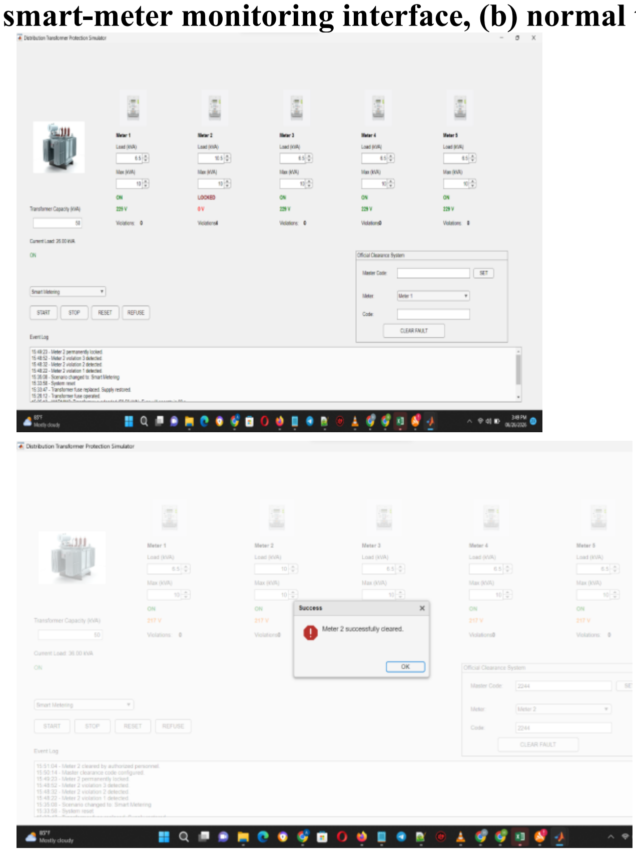


Fig. 4: Simulation results for the proposed smart-meter-based protection strategy: (a) smart-meter monitoring interface, (b) normal transformer loading,



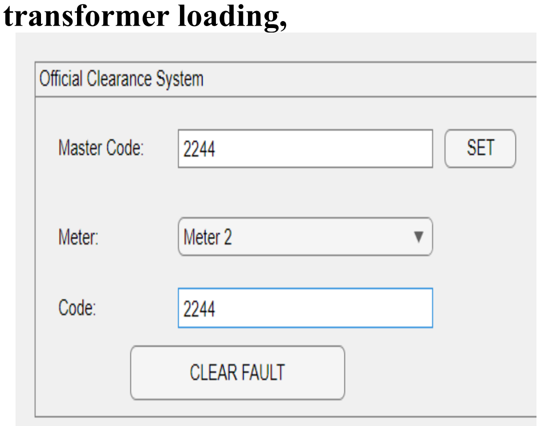


Fig. 5: Simulation results for the proposed smart-meter-based protection strategy(c) automatic consumer disconnection, (d) official clearance interface, and (e) successful smart-meter restoration

4.3 Comparative Analysis

A quantitative comparison of the two operating scenarios demonstrates the effectiveness of the proposed smart-meter-based protection strategy. Under conventional metering, the transformer reached a maximum loading of [X]% of its rated capacity and the secondary voltage decreased to a minimum of [Y] V, resulting in [Z] overload/fuse events. Under smart metering, the maximum transformer loading was reduced to [A]%, while the minimum secondary voltage was maintained at [B] V. The proposed strategy therefore reduced transformer overloading and voltage deviation while preventing [C] unnecessary fuse operations and maintaining supply to compliant consumers.

Consequently, voltage quality improved, unnecessary fuse operations were eliminated, and transformer utilisation remained within the desired operating range. The proactive nature of the proposed approach also ensured uninterrupted electricity supply for compliant consumers, thereby improving overall distribution system reliability.

Table 2. Comparative Performance of Conventional and Smart Metering

Parameter	Conventional Metering	Smart Metering
Transformer Load	Frequently exceeded rated capacity	Maintained within allowable limits
Minimum Voltage	Significant voltage reduction	Close to rated voltage
Fuse Operations	Frequent during overload	Eliminated
Transformer Utilization Factor (UF)	Above acceptable limit	Within acceptable range
Voltage Deviation (VD)	High	Significantly reduced
Protection Effectiveness Index (PEI)	Low	High

5.0 Practical Implications

The proposed smart-meter-based automated load-limiting strategy provides a proactive simulation-based approach for reducing residential distribution transformer overloading by continuously monitoring household electricity demand and selectively disconnecting consumers that exceed predefined load limits. By reducing excessive demand before transformer-level protection is activated, the strategy has the potential to reduce thermal stress, unnecessary fuse operations, and the frequency of transformer-wide supply interruptions.

. This approach prevents sustained transformer overloading, reduces thermal stress, extends transformer service life, and maintains electricity supply to compliant consumers.

Although maintenance cost and transformer lifetime were not directly quantified in the present simulation, the observed reduction in overload and unnecessary protection operations suggests potential benefits for transformer asset management and maintenance planning. These potential benefits should be validated through field trials and long-term thermal ageing or reliability studies

6.0 Conclusion

This study developed and evaluated a MATLAB R2024a simulation platform for assessing an intelligent smart-meter-based load-limiting strategy for residential distribution transformer protection. The model represented a 50 kVA distribution transformer supplying five residential consumers under conventional and smart metering scenarios. The simulation demonstrated that unrestricted consumer demand under conventional metering can result in transformer overloading, secondary voltage deterioration, and eventual fuse operation, leading to supply interruption for all connected consumers.

In contrast, the proposed smart-meter-based strategy continuously monitored individual household demand and selectively disconnected consumers whose consumption exceeded predefined load limits. This consumer-level intervention reduced excessive transformer loading, improved voltage regulation, limited unnecessary fuse operations, and maintained electricity supply to consumers operating within their assigned limits. The progressive penalty mechanism and authorised restoration procedure also provided a structured approach for managing repeated load-limit violations.

Overall, the findings demonstrate the potential of intelligent demand-side load limiting as a proactive complement to conventional transformer protection. By coordinating smart-meter monitoring with consumer-level intervention and transformer-level protection, the proposed framework provides a practical approach for improving transformer utilisation and reducing the consequences of residential overload conditions. However, the results are simulation-based and should be validated using real smart-meter data, realistic distribution-network conditions, communication constraints, and field or pilot-scale testing before practical deployment. The developed MATLAB platform therefore provides a useful foundation for further research and development of intelligent protection and demand-side management strategies for modern residential smart grids.

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Declarations

Consent for Publication

Not applicable.

Availability of Data

The data used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Competing Interests

The authors declare that they have no competing interests and no conflict of interest regarding the publication of this manuscript.

Ethical Consideration

Not applicable.

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Authors' Contributions

Monsurat Omolara Balogun conceptualized the study, developed the simulation framework, performed the analysis, and drafted the manuscript. Saheed Oluwaseun Adebayo contributed to model development, simulation design, and data interpretation. Mutiu Adedolapo Olagoke contributed to literature review and technical analysis. Adekunle Azeez Adebayo contributed to methodology, validation, manuscript review, and editing. All authors reviewed and approved the final manuscript.