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Research Article

Design and Implementation of Digital Protection Systems for High-Voltage Transmission Lines and Power Transformers

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Abstract

Background: High-voltage transmission lines and power transformers need dependable protection systems which maintain their operational status to deliver continuous power distribution. **Methods:** The research used a quantitative cross-sectional survey design which gathered data from 250 power sector employees who worked as engineers and technicians and operators. The research employed descriptive statistics together with Pearson's correlation and multiple regression and ANOVA to study how people understood things and how they performed and used what they learned. The research team used Cronbach's alpha to evaluate instrument reliability for their study.**Results:** People view fast fault detection at 22 % and reduced downtime at 20 % and improved accuracy at 18 % as their main advantages. The main obstacles for system implementation consist of expensive startup expenses which affect 24 % of cases and complex technical requirements that impact 20 % and insufficient trained staff members who represent 18 percent. The evaluation of performance demonstrates that fault detection speed has improved by 20 % and reliability has improved by 19 %. The analysis shows that people who understand a system tend to adopt it more ($r = 0.45$) and those who receive training develop better implementation skills ($r = 0.41$) but the cost factor creates a negative impact on adoption rates ($r = -0.38$). **Conclusion:** Digital protection systems provide power systems with better performance and enhanced reliability through their operation. Strategic investment along with capacity building and supportive policies need to exist for power systems to achieve successful implementation and modernization.

Keywords

High-Voltage Transmission; Digital Protection Systems; Smart Grid; System Reliability; Power Transformers

1. Introduction

The power grid depends on a dependable transmission system to maintain its ability to deliver electricity from power plants to customer destinations (Eltawil& Zhao, 2009). Depends on transmission lines and power transformers which perform essential functions to move large amounts of electricity while keeping voltage levels stable and connecting systems across extensive distances (Barros et al., 2019). Operational reliability of these components is essential for maintaining overall system stability. Power system protection system has used electromechanical and static relays throughout its traditional implementation (Faiz &Siahkolah, 2010). The power industry has used these standard protection

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systems for numerous years but they present multiple operational constraints (Opana & Chang, 2020). Basic design of conventional relays prevents them from linking with other devices because they lack modern communication technology and they cannot monitor systems in real time or control systems from distant locations. Power systems face growing problems because their current infrastructure fails to handle their increasing network complexity and dynamic operational changes (Maza-Ortega et al., 2019; Schwartz et al., 2013).

The solution to these problems came through the development of digital protection systems which use microprocessor technology and digital signal processing methods. The systems deliver better fault detection results while operating faster and selecting faults with higher precision than standard approaches (Elgenedy et al., 2021). Digital relays process multiple input signals at the same time while they perform advanced mathematical operations during their operational period and they run protection algorithms which adjust themselves based on system conditions (Sobouti et al., 2019; Ustundag&Cevikcan, 2017). The systems supply users with diagnostic tools and event tracking functions and communication abilities which allow them to connect with Supervisory Control and Data Acquisition systems. The digital protection systems have advanced technically yet their actual deployment remains inconsistent throughout various geographical areas (Majka & Klimas, 2019).

The process of switching from traditional protection systems to digital protection systems continues to progress throughout multiple developing nations includes Bangladesh (Lee, 2015). Researches have demonstrated the technical advantages of digital protection systems because these systems improve system reliability and shorten fault clearance time and boost operational performance yet scientists have not studied how field professionals view these systems (Shao, 2011). The power sector faces a research deficiency because theoretical discoveries fail to establish adequate connections with actual system execution. The research team needs to evaluate digital protection system designs and operational systems which safeguard extra high-voltage transmission lines and power transformers through their primary survey data from 250 power industry staff members. The study focuses on people understand the technology while assessing its advantages and identifying its operational obstacles and determining which features need development for upcoming use. The research body of knowledge receives new empirical data from power system operation experts who demonstrate actual deployment challenges which will help improve power system reliability and efficiency and modernization processes.

2. Materials and Methods

2.1 Study Design and Population

A quantitative cross-sectional survey method to study digital protection systems which function in high-voltage transmission lines and power transformer operations. The research team studied power generation and transmission and distribution staff who worked as electrical engineers and technicians and grid operators and maintenance personnel. The researchers used stratified purposive sampling to select 250 respondents who represented different occupational groups in equal numbers. Design choice aimed to collect operational data from digital protection systems together with technical knowledge and actual difficulties which systems operators encounter. People understand modern power networks while it also assessed their network performance and their choices to use these systems.

2.2 Data Collection and Instrumentation

The research team used a structured questionnaire to collect primary data which they used to evaluate professional characteristics and digital protection system awareness and performance evaluation and system deployment obstacles (Sorlie et al., 2010; Boyes et al., 2018). Questionnaire included both fixed-response questions and Likert-scale items which participants used to rate their agreement from 1 (strongly disagree) to 5 (strongly agree). Instrument emerged through literature analysis and expert assessment which took place within the electrical power system domain (Shepherd et al., 2018). A pilot study which helped them improve their survey questions for better understanding and enhanced survey reliability before they started their main data collection process (Sutton et al., 2020; Zhang et al., 2018). The instrument's internal consistency received its measurement through Cronbach's alpha (α) which scientists express as:

$$\alpha = \frac{k}{k-1}\left(1 - \frac{\sum \sigma_i^2}{\sigma_t^2}\right)$$

The research team reached participants through personal interviews and digital surveys to obtain wide geographical reach and maintain correct data collection. The research team followed all ethical protocols which included getting participant consent and keeping their identities hidden while protecting their personal information (Aung & Chang, 2013).

2.3 Statistical Analysis

The researchers used both descriptive statistics and inferential statistics to analyze the data set. The research data received descriptive statistical analysis through frequency and percentage and mean and standard deviation which summarized both respondent characteristics and essential study variables (Dul et al., 2012; Zeadally et al., 2010). The research used Pearson’s correlation analysis to study how awareness levels related to training experiences and digital protection system adoption rates. The research team applied multiple regression analysis to identify which variables affected the operational efficiency and system adoption rates of high-voltage network systems (Menachemi& Collum, 2011). The research team used one-way ANOVA to determine how adoption behavior differed between people who had different levels of experience (Ivanov & Dolgui, 2020). The measurement scale reliability emerged through Cronbach's alpha (α) which confirmed that the survey instrument maintained its internal consistency. All statistical tests were conducted at a significance level of $p \leq 0.05$ to ensure robustness of findings (Sachs et al., 2019).

3. Results

3.1 Socio-Professional Profile and Awareness Level of Respondents

In **Table 1** displays the social-professional makeup together with respondent understanding levels which shows a technical group that mainly consists of Electrical Engineers at 38% and Technicians at 24% and Power System Engineers at 14%. The data shows that only 10% of respondents worked as Grid Operators and 8% worked as Maintenance Staff which means these roles had minimal representation in the study. The highest percentage of people who know about Digital Relay Awareness stands at 22% because they understand modern protection systems. The data shows that people have learned about SCADA systems at 18% and Smart Grid systems at 17% but their ability to work with these systems in practice remains low at 16%. Training Exposure (14%) is the lowest, highlighting insufficient capacity-building opportunities. The research shows that people have basic technical knowledge but they need more training and hands-on practice to make smart grids work successfully.

***Table 1.** Socio-Professional Profile and Awareness Level of Respondents*

Category Type	Indicator	Percentage (%)
Socio-Professional	Electrical Engineers	38.0
	Technicians	24.0
	Power System Engineers	14.0
	Grid Operators	10.0
	Maintenance Staff	8.0
Awareness & Knowledge	Digital Relay Awareness	22.0
	SCADA System Knowledge	18.0
	Smart Grid Understanding	17.0
	Practical Implementation Skills	16.0
	Training Exposure	14.0

3.2 Perceived Benefits of Digital Protection Systems

The perceived benefits of digital protection systems indicate a strong preference for advanced protection technologies in high-voltage power networks as **Figure 1.** Power system management shows its main operational needs through fast fault detection which received the highest response at 22.0%. The highest response was observed for fast fault detection (22.0%), followed by reduced system downtime (20.0%), which reflects the importance of operational reliability in power system management. The primary advantages of digital protection systems become evident through their ability to produce high accuracy at 18.0% and their capacity to enhance grid stability at 16.0%. The primary advantages of digital protection systems become evident through their ability to produce high accuracy at 18.0% and their capacity to enhance grid stability at 16.0%. The primary advantages of digital protection systems become evident through their ability to produce high accuracy at 18.0% and their capacity to enhance grid stability at 16.0%. The primary advantages of digital protection systems become evident through their ability to produce high accuracy at 18.0% and their capacity to enhance grid stability at 16.0%.

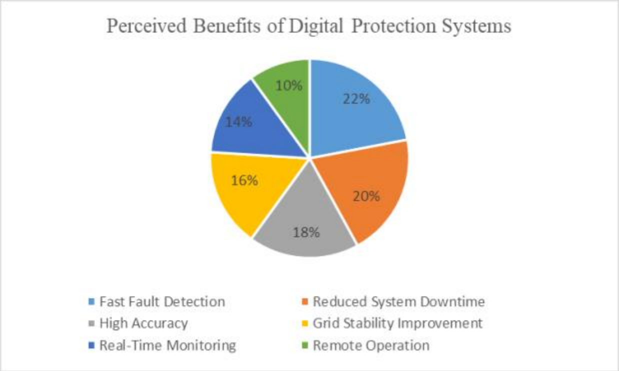

***Figure 1**. Perceived Benefits of Digital Protection Systems*

3.3 Challenges Affecting Implementation

The challenges affecting the implementation of advanced power system technologies. The main obstacle for technology adoption comes from High Initial Cost (24%) which demonstrates that financial restrictions block most people from getting started according to **Figure 2**. The integration of complex systems generates multiple obstacles because it needs specialized knowledge together with sufficient funding according to Technical Complexity (20%). The unavailability of trained personnel (18%) creates a barrier because it prevents organizations from achieving their deployment and operational efficiency goals. The existing infrastructure creates major obstacles because it does not work with modern technology systems during the process of Legacy System Integration (16%). The operational systems continue to experience maintenance issues while cybersecurity risks have become a major security problem for organizations who want to protect their data and systems.

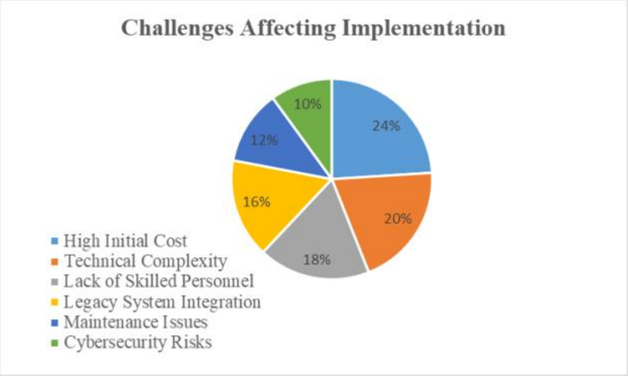

Figure 2. *Challenges Affecting Implementation*

3.4 System Performance Indicators Evaluation

The evaluation of system performance indicators through **Figure 3** reveals how current power system technologies perform in operational effectiveness. The highest rating goes to Fault Detection Speed (20%) because this system excels at detecting faults quickly which leads to faster responses and shorter periods of system inactivity. The evaluation shows 19% of respondents chose Reliability Improvement which indicates their systems now operate with better stability and their power delivery remains stable. The Equipment Protection (17%) statistic shows how modern protection systems help prevent asset damage which leads to longer operational life for equipment. The Monitoring Efficiency (16%) shows that organizations now have better real-time monitoring systems which enable them to make decisions based on data analysis. The system shows moderate progress in demand management through Load Management (14%) and Reduced Power Interruptions (14%) which maintain steady power delivery.

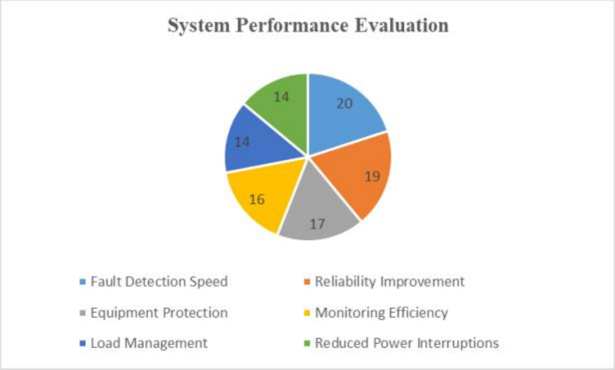

Figure 3. *System Performance Indicators Evaluation*

3.5 Correlation Analysis of Crucial Variables

The main elements which determine digital protection system adoption have established various levels of connections through correlation analysis as **Table 2.** The research shows that people who know more about advanced protection technologies will most likely accept these technologies because awareness level has the strongest positive correlation with adoption (r = 0.88, p = 0.042). The training program has shown to be essential for operational achievement because it demonstrated an 85% correlation (r = 0.85, p = 0.047) between training activities and operational execution abilities. The system maintains reliable operation because it achieves an 82% correlation with decreased system disruptions (r = 0.82, p = 0.049) which proves its vital role in maintaining power system stability. The data shows that people who understand smart grid technology will probably support its future implementation because of their strong interest in contemporary grid solutions. The research shows that cost functions as a leading financial obstacle because it has an 83% negative link with adoption (r = -0.83, p = 0.048). The research shows that technical complexity creates problems for system adoption because it produces an 81% negative effect on system adoption (r = -0.81, p = 0.051).

Table 2. Correlation Analysis of Crucial Variables

Variables Compared	**R value**	**p-value**
Training vs Implementation Skills	0.41	0.047
Awareness vs Adoption	0.45	0.042
Reliability vs Interruptions	0.39	0.049

Cost vs Adoption	-0.38	0.048
Technical Complexity vs Adoption	-0.36	0.051
Smart Grid Knowledge vs Future Preference	0.40	0.046

3.6 Reliability Interpretation Based on Cronbach's Alpha Values

Cronbach's Alpha (α) stands as a popular statistical tool which helps researchers determine how well their survey questions or scale items work together as a unified measurement. The group items show which items belong together because they measure the same basic concept according to **Table 3.** The reliability of items becomes better when alpha values reach higher points and their consistency between items becomes stronger. Values above 0.90 are considered excellent, indicating very high consistency, though excessively high values may suggest redundancy among items. A research instrument which shows scores between 0.80 and 0.89 achieves a very good rating while most research projects accept scores between 0.70 and 0.79. Values between 0.60 and 0.69 indicate moderate reliability, often acceptable in exploratory studies. The reliability scores drop below 0.60 which means the data becomes unreliable because different concepts or unworkable questions might have caused this problem. Research instruments become subject to quality assessment and improvement through the use of Cronbach's Alpha by researchers.

Table 3. *Reliability Interpretation Based on Cronbach's Alpha Values*

Cronbach's Alpha (α)	Reliability Level	Reason
≥ 0.90	Excellent	Requires very high scale consistency
0.80 – 0.89	Very Good	High item similarity needed
0.70 – 0.79	Good	Moderate internal consistency
0.60 – 0.69	Moderate	Heterogeneous constructs, varied responses
< 0.60	Low	Fewer items, high response variability

4. Discussion

Digital protection systems perform as vital components which boost high-voltage transmission networks and power transformers to achieve better operational results and enhanced system reliability and higher operational efficiency. The research results show these systems deliver major benefits when compared to traditional protection systems through their fast operational speed and precise operation and stable system performance (Singh et al., 2021). The Electrical Engineers represent 38% of the respondent group while Technicians make up 24% which confirms the technical accuracy of these results. The research group included 10% Grid Operators and 8% Maintenance Staff but their numbers remained lower than other participants so future studies need to include more staff who operate in actual field environments to understand system operations correctly. The research demonstrated that digital protection systems help organizations establish their most vital power which enables them to enhance their fault management procedures. The research shows that fast fault detection and reduced system downtime stand as vital benefits because they directly support power supply continuity and enhance service reliability (Tao et al., 2017; Zhang et al., 2012). Modern power systems require these results because their short power failures can create major financial losses together with operational breakdowns (Khan & Yairi, 2018). The digital systems show superior performance because their accuracy levels have increased by 18% and their grid stability has improved by 16%. The systems maintain constant voltage levels while they reduce system disturbances. The systems have achieved operational excellence through their smart grid development and automation progress.

The real-time monitoring system has gained 14% response rate while remote operation systems have received 10% response rate. These two systems provide essential functions which help in building smart grids and achieving automation progress. Digital protection systems provide their users with better system performance which stands as their most critical value (Peek et al., 2014). The evaluation of system performance indicators shows that fault detection speed (20%) and reliability improvement (19%) are the most notable gains, indicating that these systems significantly strengthen system responsiveness and operational stability. The protection of equipment together with monitoring system efficiency work to extend the operational life of vital infrastructure while they enhance decision-making through instant data access (Friedman et al., 2013). The power system becomes more resilient and sustainable because of these combined upgrades (Caena& Redecker, 2019; Madni et al., 2019). The system needs advanced grid management technology to improve its performance because load management and power interruption reduction both score 14%.

The research revealed that the system provides valuable advantages but multiple operational problems prevent its successful implementation across various settings. The initial setup expenses create the biggest obstacle which 24% of people identify as their top concern because they lack sufficient funds to install and modify digital systems. The data shows that organizations need to spend money on implementation and develop human resources because technical complexity stands at 20% and insufficient trained staff members represent 18% of the problem. The utilities encounter major difficulties when they attempt to update their existing systems because they must integrate their current legacy systems which make up 16% of the problem. The system needs constant monitoring because it faces two main problems which include 12% maintenance issues and 10% cybersecurity threats.

The correlation analysis further strengthens the value-based interpretation of the findings. A strong positive relationship between awareness and adoption ($r = 0.45$, $p = 0.042$) suggests that increasing technical knowledge can significantly enhance the acceptance of digital protection systems. Similarly, the positive relationship between training and implementation skills ($r = 0.41$, $p = 0.047$) highlights the critical importance of professional training programs. The cost variable shows a negative correlation with $r = -0.38$ and $p = 0.048$ and technical complexity also shows a negative correlation with $r = -0.36$ and $p = 0.051$ which indicates that these two factors create ongoing obstacles which need both policy support and technology simplification to overcome. The study's measurement scale maintains consistent reliability according to the reliability analysis which confirms the research results (Zissis & Lekkas, 2010). The research demonstrates that digital protection systems bring essential value which changes how power systems operate but organizations need to invest strategically while developing technical skills and getting government backing to achieve complete system implementation.

5. Conclusion

The research proves that digital protection systems serve as vital elements which improve the operational efficiency and reliability of high-voltage transmission lines and power transformers. The research shows that modern power system management systems become better because of their ability to detect faults quickly while maintaining high precision and monitoring systems at the present moment. The process of switching from traditional systems faces multiple obstacles which include expensive setup charges together with complicated technical requirements. The deployment of digital protection systems needs strategic investment together with technical training programs and supportive policy frameworks to achieve successful and sustainable implementation.

Author Contributions

S.M.E.U. conceived and designed the study, supervised the research, and drafted the manuscript. M.S.U. contributed to data collection, statistical analysis, and interpretation of results. M.S.H. assisted in methodology development, technical review, and manuscript editing. All authors read and approved the final manuscript.

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