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Research article

Security Constrained Optimal Power Flow on A 132 kV Line with Service Potential Transformer Substations: A Case Study of Juja-Rabai Line

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Abstract: The frequent power outages in transmission lines have been associated with generation station expansion to meet growing power demand without corresponding transmission infrastructure development, leading to exceeded loadability limits and system outages. This paper utilized PowerWorld simulator and a modeled Juja-Rabai power network to analyze secure optimal power flow conditions of a 132 kV transmission line with installed Service Potential Transformer (SPT) substations that address power demand from scattered villages near high voltage lines. The study focused on economic load dispatch of three thermal power plants (Thika, Rabai, and Kipevu) supplying power via conventional and non-conventional substations. Security constrained economic load dispatch, optimal power flow, and security constrained optimal power flow were analyzed under both pre-contingency and post-contingency states, including forced contingency scenarios. The results revealed that generating stations successfully adjusted their economic dispatch to achieve secure and economical operation, eliminating line outage risks. The analysis demonstrated that up to nine SPT substations can be optimally terminated on a 132 kV line while maintaining voltage stability and system security. The SCOPF methodology effectively balanced economic optimization with security requirements, providing a robust framework for transmission system planning in developing countries and supporting the viability of SPT technology for rural electrification.

Keywords: security constrained, optimal power flow, transmission line, service potential transformer substation, Kenya

1. Introduction

Optimal power flow with security constraints has become central to power flow analysis due to its ability to maintain normal power flow states while considering contingent states of the power system [1], [2]. Power system operations have evolved with a key focus on minimizing operational costs while ensuring system security. These parameters involve the normal power flow, optimal power flow (OPF), economic load dispatch (ELD) of generating units, security constrained economic load dispatch (SCELD), and security constrained optimal power flow (SCOPF) [2]. OPF involves assessing the optimal settings of control variables like active power, generator voltages, transformer taps, and continuous variables such as shunt reactors and capacitors in order to minimize an objective function of capital and operational costs.

Fast-developing countries in Africa are facing a serious challenge of high-power demand [3]. This has led to rapid construction of thermal power plants to address the demand. Existing high voltage lines and distribution lines are being used to evacuate power to load centres. This phenomenon has resulted in recurrent power outages due to overstressed power lines. Kenya is one of the growing countries with rich power generation resources to address its power demand. These power generation sources range from hydropower plants, geothermal power plants, wind power plants, solar power plants, and thermal power plants [4], [5]. Despite the extensive sources of power generation, the transmission lines have remained unchanged for extended periods. This makes them inadequate to evacuate power to address the growing power demand, which has been the key source of national blackouts in Kenya.

Stability analysis methods, economic load dispatch, and optimal power flow have been employed in Kenyan power networks in attempts to address the issues of frequent power outages [3], [6]. However, these methods are insufficient. SCOPF analysis method should be employed to ascertain whether the optimal power flow is secure before and after a contingent state. Renewable energy has been used to address the power demand in rural areas and in towns. The use of Service Potential Transformer substations (SPT) is the current trend for addressing the lack of electricity in villages near high voltage (HV) lines [7], [8]. This paper aimed to determine whether security-constrained optimal power flow would address the optimal power flow and take care of contingent states in the system.

2. Literature Review

2.1. Service Potential Transformer (SPT) Substations

SPT refers to an instrument transformer, specifically a potential transformer capable of stepping down high voltages such as 132 kV, 220 kV, 440 kV to low voltages like 240 V in one step with distribution capabilities. These static machines have the capability of supplying single-phase loads [9]. Originally, SPTs were used in substations to step down voltage from transmission lines to low voltages to provide power in the control rooms [10].

Kenya has a widespread transmission network, transmitting power from generating stations to its main towns. SPT substations tap power using high voltage connectors without interrupting the power flow along the transmission line. In addition, only a single disconnection switch and circuit breaker are required. Figure 1 shows an SPT used to step down 220 kV to 240 V to supply single-phase loads in households, whereas a conventional substation used three transformers to step down voltages from 220 kV to 66 kV, from 66 kV to 33 kV, and from 33 kV to 11 kV [11]. An SPT substation was designed and installed to supply villages near the transmission line in Congo. This technology is secure and operational to date [9]. This technology was implemented in a rural village in Congo to supply electricity to households living near high voltage lines.

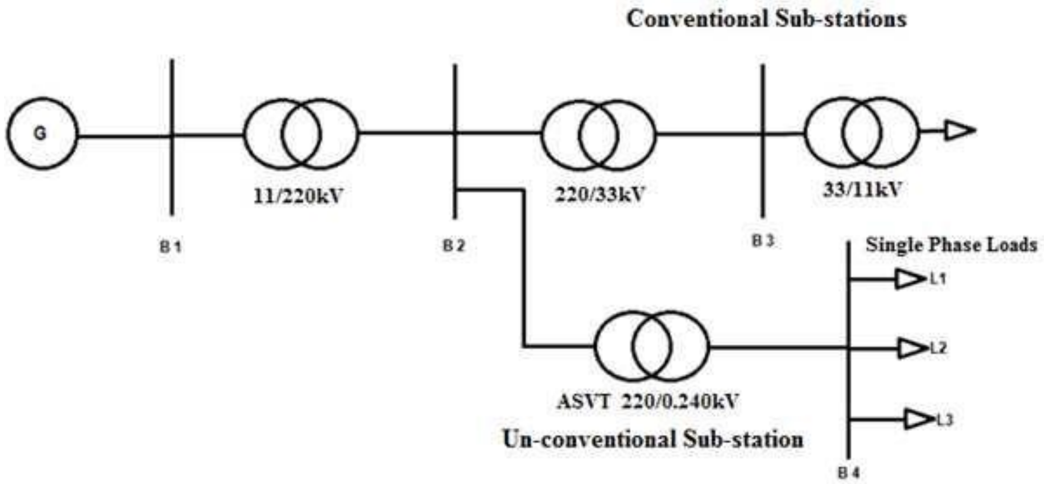

Figure 1. SPT versus conventional substation.

2.2. Voltage Profile of 132 kV Line with SPT Substations

The voltage profile of a power network is affected by the termination SPT substations, also known as Auxiliary Service Voltage Transformers (ASVT). A study revealed that a maximum of nine ASVT substations could be terminated on a 132 kV line without violation of the voltage profile of the power network [12]. The violation of the voltage profile also affected the OPF and SCOPF of the transmission line. Figure 2 demonstrates the behaviour of the transmission line when its loadability limit is exceeded.

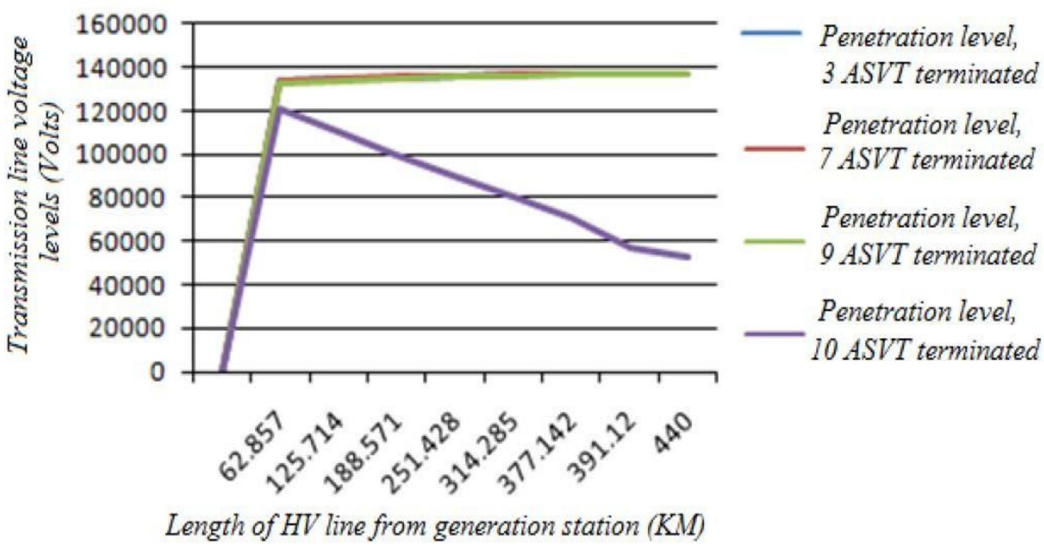

Figure 2. Penetration level of ASVT substations.

2.3. Security Constrained Optimal Power Flow

A power network with many generating units should be evaluated to determine if the power system operates under economic conditions [13], [14]. Economic load dispatch is usually evaluated using coordination equations, generator capacity limits, and transmission losses as constraints. Economic load dispatch enhances economy and security of systems while taking into account existing constraints. A system can attain economic load dispatch but still fail to meet security considerations. The security of a power network is only assured if, after a contingency state, the remaining power lines are capable of evacuating the generated power to final consumers without exceeding the loadability limits of the transmission lines. This calls for recalculation of a new state of economic load dispatch that will not lead to overstressed lines in case of a fault in one of the lines. This means the remaining lines will evacuate the power to meet load demand,

and the power flow along the lines will increase [15]. At any instance in time, a security power flow engineer monitors the load flow in a network with regard to induced contingencies to ensure the system remains in a stable state, despite the eventualities of system overload and voltage profile violations [16]. SCOPF studies assist in overcoming contingency states by adjusting the economic load dispatch of generating units to a secure state.

A study introduced a fast method of SCOPF analysis that was very useful in online analysis using a cyclic contingency screening model. The author used local perturbation effects, concentric relaxation methods, and double-stage pre-filters to separate non-critical cases when updating the database. This method was tested on the National French 225-400 kV grid containing 462 nodes and 855 branches, which produced stable results after a contingency state was simulated [17], [18]. Another study developed a new strategy using a decomposition approach to solve SCOPF problems. This algorithm had better capability to solve extremely large-scale power networks where other algorithms were unable to perform [19].

To ensure secure and economically viable operation of a power system, a plan for system restoration under various contingency scenarios must be evaluated. This is achieved through Security Constrained Optimal Power Flow (SCOPF) [20]. This involves evaluation of the best means of generating and transmitting power to meet forecasted power demands at various buses in the power network. The ability to solve SCOPF efficiently and effectively helps reduce power losses, which results in billions of US dollars being saved. The study used a two-level Benders Decomposition approach to solve large-scale networks using SCOPF with the following steps [20]:

- Step 1: Solved AC optimal power flow problems based on Benders decomposition as an inner loop.
- Step 2: Generated Benders optimality cuts to coordinate the solution of the base case using independent solutions of contingency cases in the outer loop.
- Step 3: Exploited the special block structures to improve the efficiency of the interior point method. Nonlinear and non-convex ACOPF problems of the inner loop are solved. Test cases ranging from small to very large power networks are used to demonstrate the efficiency and effectiveness of the proposed algorithms.

Security Constrained Optimal Power Flow aims at determining a minimum cost generation schedule to meet the demand for power at each bus in the power network while ensuring the integrity of the transmission network and all generating units, regardless of whether the operations are under normal or contingency conditions. The literature reviewed had not provided adequate answers on the prevailing low termination level of SPT substations in Sub-Saharan Africa. The study carried out on the termination level of SPT substations on power networks was also inconsistent. Moreover, the research carried out had not considered the existing conventional substations on the power networks. This paper explored the use of new technology in power system analysis on a 132 kV transmission line to determine the factors that led to low termination levels of SPT substations in Sub-Saharan Africa. The study addressed the research gaps of earlier research, which included optimal termination levels of SPT substations on high voltage lines, optimal power flow analysis, economic load dispatch of generating units, and Security Constrained Optimal Power Flow on a line with SPT substations.

3. Methodology

3.1. Simulation Platform Selection

Security constrained optimal power flow can be analyzed using a power network model in PowerWorld simulator. This study involves optimal power flow where contingent scenarios are simulated and analysis is carried out before and after contingent states. Previously, MATLAB software has been widely used to analyze complex power system networks. Load flow analysis, transient stability analysis, economic load dispatch, optimal power flow, and optimum penetration level of electric devices in distribution lines are some of the studies carried out using MATLAB software [21], [22]. A simulation software in MATLAB environment allows power system networks to be simulated dynamically and allows controllers to be modeled with the help of blocks [21], [23].

PowerWorld simulator, on the other hand, has also been used as a load flow analysis tool. This platform provides techniques for building power system models. This software has the following analysis tools: contingency analysis tool, time step simulation tool, sensitivity analysis tool, loss analysis tool, fault analysis tool, optimal power flow analysis tool, PVQV curve tool, availability transfer capability tool, security constrained OPF tool, transfer stability tool, and distributed computing tool [24]. For this study, PowerWorld simulator was selected due to its comprehensive SCOPF capabilities and user-friendly interface for modeling complex transmission networks with multiple substations.

3.2. Mathematical Formulation of SCOPF

3.2.1. System Stability and Security

System stability and security is developed through an objective function consisting of three components: i) real power generation cost, ii) violation penalty of power balance, and iii) violation limit of line thermal limit. Figure 3 shows a comparative mathematical model of OPF and SCOPF.

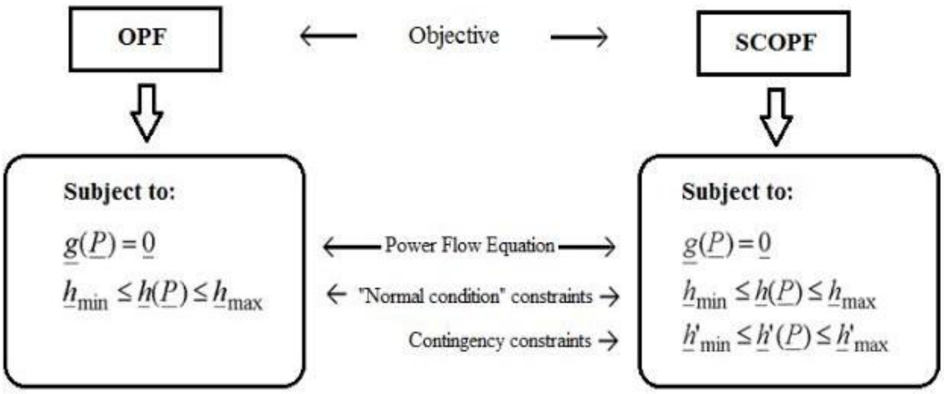

Figure 3. Comparison of OPF and SCOPF [25].

The objective fuction of SCOPF is given by equation (1).

$$C_T = C_p + C_{bv} + C_{lv} \tag{1}$$

where C_p is the cost of real power generation, C_{bv} represents the bus real and reactive power balance violations, C_{lv} is the cost of line power violation. The cost of real power is given by equation (2).

$$C_p = \sum_{k=1}^{N} C_{g,k} P_{g,k} \tag{2}$$

where $C_{g,k}$ represents the slope at the sample point cost k and $P_{g,k}$ represents the segment k in the real power output of generator g. The bus and reactive power balance violation is given by equation (3).

$$C_{bv} = \sum_{i=1,2,3} C_{s,k}S_{k,i}^{+} + \sum_{i=1,2,3} C_{s,k}S_{k,i}^{-} \tag{3}$$

where $S_{k,i}^{+}$ and $S_{k,i}^{-}$ are the segments representing minor violations, moderate violations, and severe violations. The line capacity limit violation is obtained using equation (4).

$$C_{lv} = \sum_{i=1,2,3} C_s k_{IJ} S_{ek} \tag{4}$$

where S_{ek} indicates the k^{th} segment in the apparent power violation.

3.2.2. Power Balance Constraints

The power balance constraint ensures that the total generated real and reactive power equals the total consumed and absorbed power by the electrical loads, respectively. Large penalties are usually attached to minimize power balance violations. The total generated real power is given by equation (5), while the total generated reactive power is given by equation (6).

$$\sum_{g=1}^{G_i} P_g = P_i^l + g_i^{fs} + \sum_{e=1}^{E_i^0} P_e^0 + \sum_{e=1}^{E_i^d} P_{eJ}^d + \sum_{f=1}^{F_i^0} P_f^0 + \sum_{f=1}^{F_i^d} P_f^d + S_i^{p+} + S_i^{p-} \tag{5}$$

$$\sum_{g=1}^{G_i} q_g = q_i^l - (y_i^{fs} + y_i^{cs})V_i^e + g_i^{fs} + \sum_{e=1}^{E_i^0} q_e^0 + \sum_{e=1}^{E_i^d} q_{eJ}^d + \sum_{f=1}^{F_i^d} q_f^0 + q_f^d + S_i^{Q+} + S_i^{Q-} \tag{6}$$

Subject to:

$$S_i^{P+}, S_i^{P-}, S_i^{Q+}, S_i^{Q-} \geq 0 \tag{7}$$

where P_g represents the real generated power and q_g represents the reactive generated power. P_{gl} and q_{gl} are the consumed and absorbed load powers, respectively. G_{fs}, y_{fs}, y_{cs} are the bus-connected fixed conductance, fixed susceptance, and controllable shunt susceptance, respectively.

3.2.3. Power Flow Constraints

The real power flow for the origin non-transformer branch is shown in equation (8), while The real power flow for the destination non-transformer branch is shown in equation (9).

$$P_e^0 = g_e V_{i_e^0}^2 + V_{i_e^0} V_{i_e^d} \left[-g_e \cos\left(\Theta_{i_e^0} - \Theta_{i_e^d}\right) - b_e \sin\left(\Theta_{i_e^0} - \Theta_{i_e^d}\right) \right] \tag{8}$$

$$P_e^d = g_e V_{i_e^d}^2 + V_{i_e^0} V_{i_e^d} \left[-g_e \cos\left(\Theta_{i_e^d} - \Theta_{i_e^0}\right) - b_e \sin\left(\Theta_{i_e^d} - \Theta_{i_e^0}\right) \right] \tag{9}$$

The reactive power flow for the origin non-transformer branch is shown in equation (10), while The reactive power flow for the destination non-transformer branch is shown in equation (11).

$$q_e^0 = -\left(b_e + b_e^{CH/2}\right) V_{i_e^0}^2 + V_{i_e^0} V_{i_e^d} \left[b_e \cos\left(\Theta_{i_e^0} - \Theta_{i_e^d}\right) - g_e \sin\left(\Theta_{i_e^0} - \Theta_{i_e^d}\right)\right] \tag{10}$$

$$q_e^d = -\left(b_e + b_e^{CH/2}\right) V_{i_e^d}^2 + V_{i_e^0} V_{i_e^d} \left[b_e \cos\left(\Theta_{i_e^d} - \Theta_{i_e^0}\right) - g_e \sin\left(\Theta_{i_e^d} - \Theta_{i_e^0}\right)\right] \tag{11}$$

3.2.4. Physical Limits and Security Constraints

These constraints consist of generator limits, voltage limits, and controllable shunt compensation devices. Physical generator real power limits and reactive power limits are shown in equations (12) and (13), respectively. The controllable shunt compensation devices constraint can be seen in equations (14), while voltage limits to maintain system security operation is shown in equation (15).

$$P_g^{\min} \le P_g \le P_g^{\max} \tag{12}$$

$$Q_g^{\min} \le Q_g \le Q_g^{\max} \tag{13}$$

$$y_{cs}^{\min} \le y_{cs} \le y_{cs}^{\max} \tag{14}$$

$$V_i^{\min} \le V_i \le V_i^{\max} \tag{15}$$

3.2.5. Post-Contingency Response

The post contingency generator constraints may be preventive or corrective. The real power is controlled by economic load dispatch command while the reactive power controls the regulated voltage on the buses. The real power post-contingency response follows equation (16).

$$P_g + \alpha_g \Delta_c \tag{16}$$

where P_g represents the real generated power and α_g is pre-defined participation factor. When the contingency response occurs, the actual real generation power the equation below unless it reaches its upper or lower limit.

- **Case 1:** $P_g^{\min} \le P_g + \alpha_g \Delta_c \le P_g^{\max}$

$$P_g^c = P_g^0 + \alpha_g \Delta_c \tag{17}$$

- **Case 2:** $P_g + \alpha_g \Delta_c \ge P_g^{\max}$

$$P_g^c = P_g^{\max} \tag{18}$$

- **Case 3:** $P_g + \alpha_g \Delta_c \le P_g^{\min}$

$$P_g^c = P_g^{\min} \tag{19}$$

In reactive power contingency response, a generator tries to maintain pre-contingency voltage magnitude at its terminal bus voltage. In case the bus voltage falls bellow the regulated voltage bus value, the generator reactive power increases until it attains its upper limit, similarly if the bus voltage exceeds the specified bus value, the reactive power value decreases till it reaches its minimum value.

- **Case 1:** $V_i^c = V_i^0$

$$Q_g^{\min} \le q_g^c \le Q_g^{\max} \tag{20}$$

- **Case 2:** $V_i^c < V_i^0$

$$q_g^c = Q_g^{\max} \tag{21}$$

- **Case 3:** $V_i^c > V_i^0$

$$q_g^c = Q_g^{\min} \tag{22}$$

3.2.6. Complete SCOPF Formulation

The SCOPF is formulated as equation (23).

$$\min C_T = \sum_{i=1}^{x} C_p + \sum_{e=1}^{E} C_{bv} + \sum_{f=1}^{F} C_{lv} \tag{23}$$

subject to:

$$g(x_e, x_g, x^0) = 0 \tag{24}$$

$$h(x_e, x_v, x^0) = 0 \tag{25}$$

$$l(x_e, x_{sc}) = 0 \tag{26}$$

$$V_i^{\min} \leq V_i \leq V_i^{\max} \tag{27}$$

where x_e denotes the individual line of real and reactive power flows, x_g includes the real and reactive power generation, x_v is the voltage-related constraints, and x^0 represents the base-case operating point. Additionally, x_{sc} includes variables relevant to system security, g represents the real and reactive balance constraints, h denotes the nonlinear power flow constraints, and l restricts line thermal capacity with small violation allowances.

3.3. PowerWorld Simulator Implementation

The implementation of Security Constrained Optimal Power Flow analysis in PowerWorld Simulator follows a systematic approach to ensure accurate modeling and analysis of the Juja-Rabai transmission line. The process begins by opening the Juja-Rabai line model and ensuring the simulator operates in Run mode to enable dynamic analysis capabilities.

The contingency analysis setup requires accessing the Contingency analysis tool from the Run mode ribbon group on the tools ribbon tab, which opens the Contingency analysis Dialog for configuration. To simulate realistic operating conditions, load variations are introduced by right-clicking on the grid and selecting Insert Special, followed by Quick Insert Single Element Dialog. Within this interface, the load element type is selected along with the specific 2(2) (132kV) element designation. The contingency scenario is configured by selecting "Change by" under Action type, entering 25 for the amount parameter, choosing "Constant" from the dropdown menu, and selecting "percent" under the field labeled input parameter.

The SCOPF analysis is initiated by accessing the SCOPF module from the Add-ons ribbon tab, which provides access to the comprehensive SCOPF dialog interface. This dialog serves dual purposes: specifying the base case solution process and providing access to SCOPF results upon completion of the analysis. The optimization parameters are configured within the OPF settings section, where the SCOPF objective function is defined through the OPF options and Results interface.

The SCOPF dialog provides comprehensive control over optimization options while simultaneously serving as the access point for reviewing optimization results once the analysis is complete. The actual SCOPF computation is executed using the "Run Full

SCOPF" button located at the top of the dialog form, which initiates the complete optimization process, including contingency analysis, economic dispatch calculations, and security constraint evaluations. This systematic approach ensures that all aspects of the power system operation are considered, from normal operating conditions through various contingency scenarios, providing comprehensive insights into the system's security and economic performance.

4. Results and Discussion

4.1. Economic Load Dispatch Analysis

The economic load dispatch analysis of the Kipevu, Rabai, and Thika thermal power plants during off-peak hours was performed using the coordination equation method. The analysis considered a total system demand of 70 MW distributed among the three generating units.

The initial economic load dispatch calculation yielded an incremental cost (λ) of 7.089 $/MWh. Under these conditions, the optimal generator loadings were determined as follows:

- Generator 1 (Thika): 5.56 MW
- Generator 2 (Rabai): 43.83 MW
- Generator 3 (Kipevu): 20.64 MW

The economic load dispatch convergence showed a minimal error of 0.0385 MW, indicating successful optimization without considering generator operational limits. When generator operational limits were considered, Generator 1 was found to be operating far below its lower limit of 20 MW. To address this constraint violation, Generator 1 was set to its minimum operational limit, and the loading of Generators 2 and 3 were recalculated. This adjustment resulted in a new incremental cost of 6.975 $/MWh. The revised generator loadings with operational limits were:

- Generator 1 (Thika): 20.00 MW (at minimum limit)
- Generator 2 (Rabai): 37.50 MW
- Generator 3 (Kipevu): 12.50 MW

The economic dispatch achieved perfect convergence with zero error, confirming optimal resource allocation under operational constraints.

4.2. Security Constrained Economic Load Dispatch

A forced contingency was implemented on the Juja-Rabai transmission line to evaluate the system's response under emergency conditions. During this contingency, the remaining lines were forced to operate above their normal capability limits to maintain power supply to the system loads.

Table 1 presents a comparative analysis between Economic Load Dispatch (ELD) and Security Constrained Economic Load Dispatch (SCELD). The results demonstrate that under SCELD conditions, the generating stations successfully adjusted their power dispatch to accommodate post-contingency scenarios. This adjustment ensures that in the event of another line outage, the remaining transmission lines can evacuate power from generating stations to consumers without exceeding their loadability limits.

Table 1. Security constrained economic load dispatch of three generators.

Units	Economic Dispatch using Gradient-Based (MW)	Economic Dispatch using PowerWorld Simulator considering losses (MW)	Security Constrained Economic Load Dispatch (MW)
1	20	20	20
2	37.5	38.90	40
3	12.5	14.72	10

The SCELD results show the following adjustments from the standard economic dispatch:

- Generator 1: Maintained at 20 MW (no change from ELD)
- Generator 2: Increased from 37.5 MW to 40 MW
- Generator 3: Decreased from 12.5 MW to 10 MW

These adjustments demonstrate the system's ability to maintain security while preserving economic operation as much as possible. The power flow distribution along the transmission line segments is detailed in Table 2, which shows how power flows vary at different substations along the Juja-Rabai corridor under different generator combination scenarios.

Table 2. Juja-Rabai optimal power flow considering losses.

Line Segment	$P_{g1} + P_{g2}$ (MW)	$P_{g2} + P_{g3}$
Juja – Konza	29.87	33.93
Konza – Ulu	19.40	23.38
Ulu – Sultan	11.92	15.70
Sultan – Kiboko	11.92	15.70
Kiboko – Makindu	4.23	7.88
Makindu – Mtito	1.05	4.63
Mtito – Manyani	4.12	4.64
Manyani – Voi	7.24	0.63
Voi – Maungu	13.88	3.73
Maungu – Samburu	20.37	10.28
Samburu – Mariakani	24.58	16.64
Mariakani – Kokoni	17.39	20.50
Kokoni – Rabai	24.29	32.92

4.3. Security Constrained Optimal Power Flow Analysis

Figure 4 illustrates the percentage MVA rating of the Juja-Rabai line under both OPF and SCOPF operating states. The analysis reveals significant differences in line loading between normal optimal power flow conditions and security-constrained conditions.

Figure 4. MVA percentage under OPF and SCOPF.

Under normal OPF conditions, the transmission line operated near its thermal limits, which created vulnerability during contingency events. The contingency simulation demonstrated that a line outage would force the loadability limit to be exceeded, potentially leading to cascading failures or system instability.

The implementation of SCOPF resulted in a proactive adjustment of the economic load dispatch, constraining the loadability of transmission lines within their stable operational limits. This preventive approach ensures system security by maintaining adequate reserve capacity in the transmission network.

The percentage MVA limits shifted from their OPF state to a new SCOPF operating point, which remained secure both before and after the forced contingency simulation. This shift represents a trade-off between maximum economic efficiency and system security, demonstrating that slight economic penalties can provide substantial security benefits.

4.4. Impact of SPT Substations on System Performance

The analysis of the 132 kV transmission line with optimally terminated SPT substations, as shown in Figure 5, reveals important insights into the integration of non-conventional substations with existing power infrastructure. The study confirmed that SPT substations can be successfully integrated into the transmission network without compromising system security or significantly affecting optimal power flow calculations.

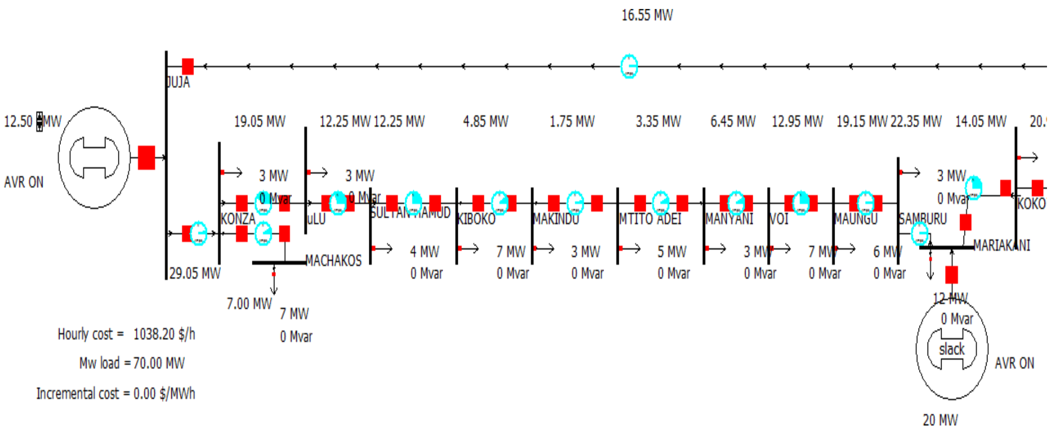

Figure 5. Juja-Rabai 132 kV transmission line with optimally terminated SPT substations.

The voltage profile analysis, referenced in Figure 2, demonstrates that the penetration level of SPT substations directly influences transmission line performance. The optimal termination of nine SPT substations on the 132 kV line maintains voltage stability while providing rural electrification benefits.

4.5. System Security and Economic Trade-offs

The comparative analysis between OPF and SCOPF reveals important trade-offs between economic optimization and system security. While pure economic dispatch minimizes generation costs, it may leave the system vulnerable to contingency events. The SCOPF approach sacrifices minimal economic efficiency to ensure robust system operation under various contingency scenarios.

The results demonstrate that the generating stations possess sufficient flexibility to adjust their economic dispatch to achieve both secure and economical operation, effectively eliminating line outage risks. This finding is particularly significant for developing power systems where transmission infrastructure expansion lags behind generation capacity growth.

4. Conclusions

This study successfully developed and validated a comprehensive approach for analyzing Security Constrained Economic Load Dispatch (SCELD) of transmission lines integrated with Service Potential Transformer (SPT) substations. The research demonstrates that SCOPF methodology can effectively ensure load dispatch security in power networks, even when contingency events such as forced line outages occur.

The analysis of the Juja-Rabai 132 kV transmission line revealed that SPT substations can be optimally integrated into existing power infrastructure without compromising system security or economic operation. The study confirmed that up to nine SPT substations can be terminated on a 132 kV line while maintaining voltage profile stability and ensuring secure power flow conditions. The comparative analysis between Economic Load Dispatch (ELD) and Security Constrained Economic Load Dispatch (SCELD) demonstrated the system's adaptive capabilities. When a forced outage was simulated on the Juja-Rabai line, the three thermal generating units (Thika, Rabai, and Kipevu) successfully adjusted their dispatch to maintain system security. This adjustment resulted in a new secure operating state for the transmission lines, ensuring continued power delivery to meet load demands without exceeding thermal limits.

The SCOPF analysis provided crucial insights into the trade-offs between economic optimization and system security. While pure economic dispatch minimizes generation costs, the security-constrained approach ensures robust system operation under contingency scenarios with minimal economic penalties. This finding is particularly significant for developing power systems where transmission infrastructure expansion often lags behind generation capacity growth. The PowerWorld simulator implementation validated the theoretical framework, demonstrating the practical applicability of SCOPF methods for real-world transmission system planning and operation. The results support the viability of SPT technology as an effective solution for rural electrification in transmission corridor development, particularly in Sub-Saharan Africa where scattered rural communities are located near high voltage transmission lines.

Future research should focus on extending this analysis to larger network topologies and investigating the integration of renewable energy sources with SPT substations under security-constrained optimal power flow conditions.

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Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

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