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Research article

Load Flow Analysis of 132 kV Transmission Line with Optimally Terminated Service Potential Transformer Substations

Joel Mwithui Kitheka[1*], Peter Musau Moses[2], Abraham Mutunga Nyete[1], Nicodemus O. Abungu[3]

[1] Department of Electrical and Information Engineering, University of Nairobi, Nairobi, Kenya
[2] Department of Electrical and Electronic Engineering, South Eastern Kenya University, Nairobi, Kenya
[3] Department of Electrical and Electronic Engineering, Machakos University, Machakos, Kenya
*Correspondence: joel.kitheka@mksu.ac.ke

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Abstract: Most villages in Sub-Saharan Africa still lack electricity, despite numerous initiatives and commissions established to address power demands in developing countries. Renewable energy, rural electrification, and non-conventional substations are currently being employed to tackle the electricity issue. This research explored the penetration level of Service Potential Transformer (SPT) substations to solve the lack of electricity in villages near high-voltage transmission lines. The study analyzed the power flow in the 132 kV Juja-Rabai transmission line using PowerWorld Simulator software and determined the optimal termination points for SPT substations. Cost minimization was used as the objective function. At the same time, the voltage profile of the transmission line, the power demand of households, and the distance of villages from the transmission line served as the research constraints. The findings indicated that seven SPT substations could be installed along the 132 kV Juja-Rabai transmission line to supply electricity to nearby villages. These non-conventional substations would be integrated with the existing conventional substations on the transmission line. The power flow analysis for the line was also conducted.

Keywords: termination level, transmission line, pattern search algorithm, service potential transformer

1. Introduction

Developing countries in Africa have focused on building cities and large towns, often at the expense of rural areas, despite the fact that the majority of the population resides in these rural regions. This has led to a common trend of rural-to-urban migration across these countries. Long transmission lines pass through rural areas to supply power to cities and industrial zones near major towns, leaving rural areas without electricity. Power utility companies find it uneconomical to set up conventional substations to supply electricity to rural areas due to the lack of a sufficient return on investment [1].

Service Potential Transformer (SPT) is a new technology that utilizes the voltage transformer principle to step down the voltage from very high levels to lower levels suitable for distribution [2]. Non-conventional substations, such as SPTs, are an emerging technological solution that can help address the power shortages in villages located near high-voltage transmission lines [3].

This paper aims to determine the optimal number of SPT substations required to meet the power demand of villages along the Juja-Rabai transmission line, as well as to analyze the power flow of the line. Previous research has shown that non-conventional substations can step down high voltages to levels suitable for distribution purposes. Additionally, studies have indicated that SPT substations are three times cheaper than conventional substations [2], [4].

The study focuses on determining the optimal termination points for SPT substations along the 132 kV Juja-Rabai transmission line. The existing conventional substations along the line were considered, along with their capacities and the loads they are currently supplying. The study aimed to minimize the SPT substations' costs, including capital and maintenance expenses. The constraints included each region must be connected to at least two SPT substations, the total capacity of the SPT substations must meet or exceed the power demand of the region, only villages within a 500-meter radius of a substation will be supplied, and the voltage profile of the transmission line must remain within 132±5% kV [5], [6].

This paper is the first to present a live editor on the MATLAB platform for determining the optimal termination level of SPT substations on a transmission line with existing conventional substations without exceeding their loadability limits. Additionally, the paper provides a load flow analysis of the transmission line using PowerWorld Simulator software.

The rest of the paper is organized as follows. Section 2 presents the Literature Review. Section 3 outlines the Proposed Methodology. Section 4 discusses the Problem Formulation. Section 5 presents the Results and Analysis. Section 6 concludes the paper, followed by the list of references.

2. Literature Review

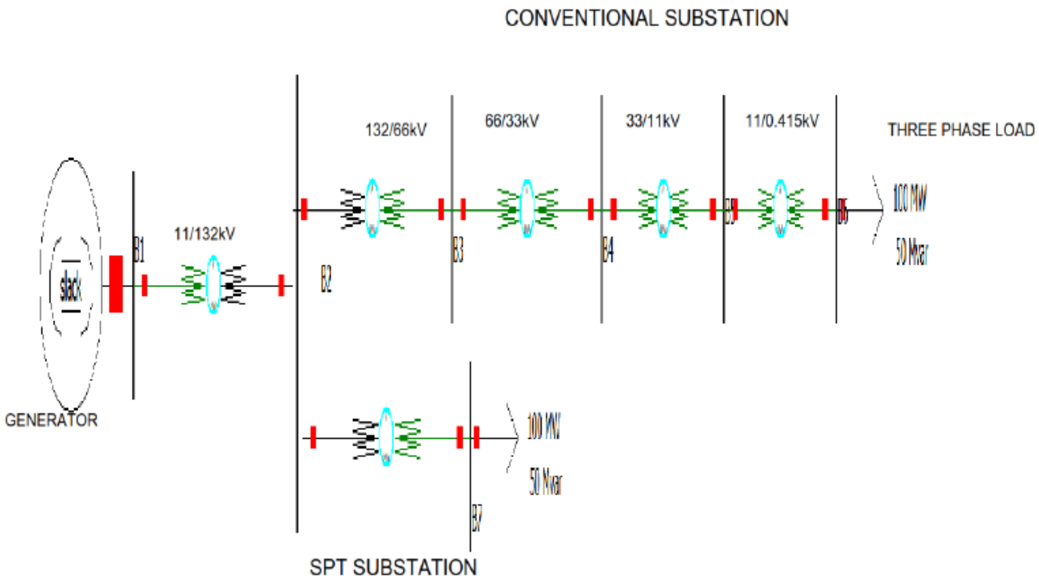
2.1. Service Potential Transformer Substation

Service Potential Transformer (SPT) substations are non-conventional substations that step down high voltage from transmission lines to lower voltages for supplying single-phase loads. SPT substations are instrument transformers with distribution capabilities [7]. Originally, SPTs were used in conventional substations to step down voltage from high voltage lines, primarily to provide power to the control room [8].

These technologies are important to developing countries with well-established transmission lines but lack distribution networks. SPT substations can tap power from high voltage lines that traverse rural areas to supply nearby households. These non-conventional technologies tap power using high voltage connectors without interrupting the power flow along the transmission line. Moreover, only a single disconnection switch and circuit breaker are required.

Figure 1 shows an SPT transformer that is used to step down the voltage from 132 kV to 240 V for supplying single-phase loads. In comparison, a conventional substation requires three transformers to step down the voltage from 132 kV to 66 kV; from 66 kV to 33 kV; and from 33 kV to 11 kV. Hitachi Energy's family of oil-filled Station Service Voltage Transformers [7] designed an instrument transformer that combines a voltage transformer's characteristics with a distribution transformer's power rating capability.

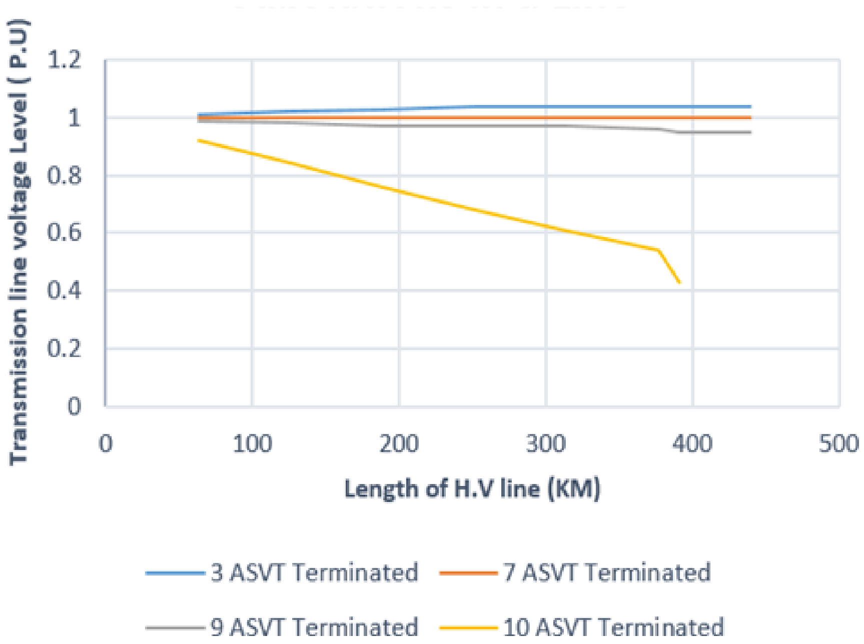
Figure 1. SPT compared to conventional substation.



2.2. Termination Level of Service Potential Transformer Substations

Research has shown that Service Potential Transformer (SPT) substations are secure, reliable, and three times cheaper than conventional substations [9]. Several studies have been conducted to establish the penetration level of these technologies. A study revealed that five Auxiliary Service Voltage Transformer (ASVT) substations can be terminated on a 220 kV transmission line without exceeding the line's power loadability limit [10]. Another study determined the penetration level of ASVT substations on a 220 kV transmission line [11]. The results are shown in Figure 2. The study used Simulink software to investigate the maximum number of ASVT substations that could be terminated on a 220 kV transmission line without violating the voltage profile. The research revealed that a maximum of nine non-conventional substations could be terminated on a 440 km transmission line. Voltage collapse occurred when the tenth ASVT substation was added, as shown in Figure 2.

Figure 2. Penetration level of ASVT substations in a line [11].



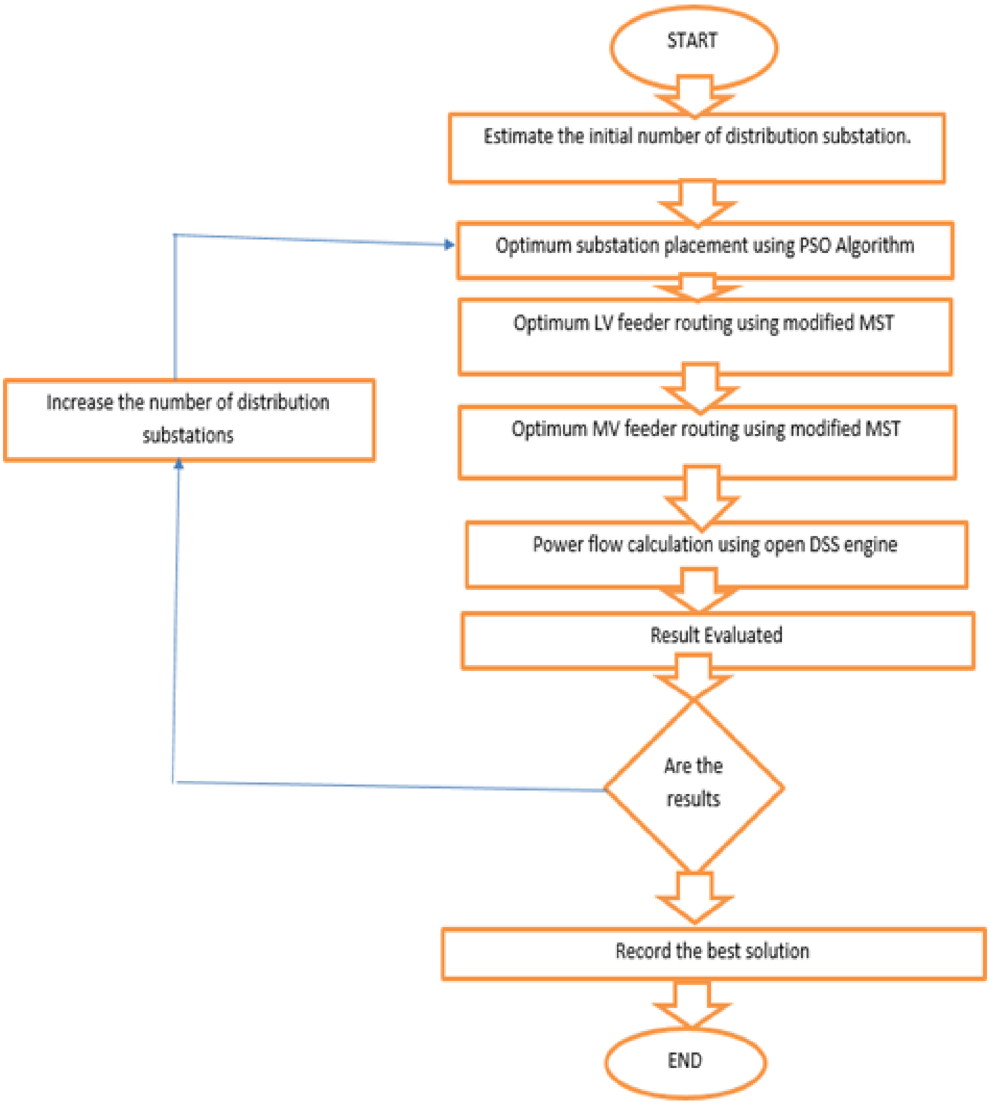
However, both previous studies failed to consider the impact of existing conventional substations on the transmission line. Furthermore, the optimal penetration level of ASVT substations was not determined, as the objective function and constraints of the system were not included in these studies.

2.3. Optimum Penetration Level of Substations

Optimal determination of the required rural electricity infrastructure has been carried out to provide connectivity to households for national development [12]. The main goal of these studies was to design a procedure for assessing the optimal location of secondary substations based on population data. A study used clustering algorithms to identify densely populated areas and determine the number of distribution substations required to meet power demand [6]. This approach for locating distribution substations was based on topology rather than economics. The idea was to place substations near the population to address power shortages in villages.

A similar project focused on the optimal location of distribution transformers using a modified prism algorithm. This study was based on minimizing the cost of the low-voltage network between transformers and households. The region was clustered, and the K-medoids algorithm was used to define the number of clusters, which could then be used as primary feeders [13]. Figure 3 displays the algorithm used in the research.

Figure 3. Optimum substation placement algorithm.



The results of the project indicate that when siting transformers, the voltage profile of the distribution network was maintained, and the maximum number of households served by each transformer was considered. Transformers spaced 30 to 40 meters apart served 45% to 65% of the population. When higher capacity transformers were used, spacing increased to 80 meters, improving power supply coverage to 95% [14]. The results of this study were not practical, as transformer spacing should be at least 1,000 meters. Consequently, the study provided theoretical results that cannot be implemented in real-world situations. A more practical approach should be developed to address the power shortage in rural or marginalized areas. Further research utilizing SPT substations should be explored.

Another study was conducted to evaluate the optimal deployment of the distribution transformer network, adapting to seasonal loads and neighborhood power demand [15]. The study focused on establishing low-voltage tie-lines between distribution transformer networks, changes in the operation mode through the switching state of the tie line, and scenarios where distribution transformers can be turned off during low load demand. A bi-level programming model of the distribution transformer network was used with the objective of minimizing cost. The optimization process combined a genetic algorithm and the Voronoi-prisma algorithm [14]. This research considered the total investment cost, line losses, and system reliability, with related constraints such as voltage drop and thermal issues [16].

The development of new methods for generating electricity has enabled the decentralization of energy sources. Distributed generation allows for efficient management of power networks, referred to as microgrids [17]. A new approach to the optimal planning of power devices in rural distribution networks was introduced. This model, based on a heuristic process, aims to minimize the resources required to route the grid over a defined time horizon [18]. The model takes into account factors such as population density, georeferenced zones, voltage drop, and the overload levels of transformers in order to deliver optimal power quality to consumers [19], [20].

Another study explored a method of predicting the power profile of substations using machine learning and GIS information. This prediction aimed to increase the network's observability and resilience, supporting the sustainable growth of substations [20]. The georeferenced scenario has improved the efficiency of identifying the most appropriate locations for SPT substations.

3. Methodology

3.1. Power Flow Analysis

Power flow analysis can be performed using various methods, such as the Gauss-Seidel method, the Newton-Raphson method, or the Fast-Decoupled method. In power flow analysis, software is typically used to assist in obtaining data for load flow analysis. MATLAB software has been widely used to analyze complex power system networks. A simulation environment in MATLAB allows for dynamic simulation of power system networks and provides the ability to model controllers using blocks [21], [22]. While this simulation software has been used for load flow analysis, no analysis of transmission lines with terminated non-conventional substations has yet been implemented.

MATLAB software offers several toolboxes, including those for fault analysis of a motor-generator set, demonstration of symmetrical components, fault analysis of unbalanced alternators, synchronous machine transient stability, fault analysis of interconnected buses, single-machine stability analysis, and load flow analysis. MATLAB's optimization tools include non-linear optimization, mixed integer programming, and global optimization.

PowerWorld Simulator is another tool that has been used for load flow analysis. This platform offers various techniques for building power system models. PowerWorld Simulator provides a wide range of analysis tools, such as contingency analysis, time-step simulation, sensitivity analysis, loss analysis, fault analysis, optimal power flow analysis, PV-QV curve analysis, availability transfer capability, security-constrained optimal power flow (OPF), transfer stability analysis, and distributed computing tools.

3.2. Optimal SPT Calculation

Optimization of Service Potential Transformers (SPTs) in a 132 kV transmission line involves several key components: identifying the nearest conventional substation, locating households in close proximity to high voltage lines to be supplied with electricity, determining where to place the SPTs for optimal power distribution, calculating the voltage drops along the distribution lines that supply the households, and estimating the required investment and maintenance costs to set up the non-conventional substations. Additionally, the power demand of the households in a village must be considered. The required number of SPTs to meet the power demand in villages located near high voltage lines is given by equation (1).

$$S_n = \frac{N}{m \times n} \tag{1}$$

where *N* is the total number of power consumers, *n* is the number of branches in the power network, and *m* is the number of consumers in each branch.

The objective function for the SPT substation aims to minimize the total cost of the substation, which includes both capital and maintenance costs. This is given by equation (2).

$$Z_{min} = \sum_{l}\sum_{r} C_r T_{lr} + \sum_{l}\sum_{r} m_r T_{lr} \tag{2}$$

where *l* is the set of potential locations for the SPTs, *r* is the set of regions where the SPTs can be located, *m* represents the maintenance cost of the SPT substations over 20 years, *C* is the capital cost of setting up an SPT substation, and *T* is the total number of SPT substations.

4. Problem Formulation

The minimization of capital and maintenance costs, as represented in equation (2) was used to determine the optimal number of SPT substations required to address the power demand of households living in close proximity to high voltage lines. This objective can be expressed as equation (3).

$$Z_{min} = \int_{l}\int_{r} C_r T_{lr} dT dy + \int_{l}\int_{r} m_r T_{lr} dT dy \tag{3}$$

The techno-economic life cycle costing of SPT substations [4] reveals the following costs: the capital cost is 434,600 US dollars, and the maintenance cost is 128,600 US dollars. The objective function is subject to the following constraints.

$$\sum_{l}\sum_{r} T_{lr}k_{lr} \geq 2 \tag{4}$$

$$\sum_{l}\sum_{r} Q_r T_{lr} \geq \sum_{l} n_l k_{lr} \tag{5}$$

$$\sum_{r} T_{lr} = 1 \tag{6}$$

where Q is the SPT substation power capacity, k is a constant number, n is the number of power consumers in a given region, n_l is the number of power consumers in a given location, T_{lr} is the number of SPT substations in given locations serving specific regions, and Q_r is the total power capacity of SPT substations in a given region.
The constraints are represented in integral form as follows.

$$\int_{l}\int_{r} k_{lr}T_{lr}dTdy \geq 2 \tag{7}$$

$$\int_{l}\int_{r} Q_r T_{lr}dTdy \geq \int_{r} n_l k_{lr}dT \tag{8}$$

$$\int_{r} T_{lr}dT = 1 \tag{9}$$

These constraints can be explained in the following way:

- Each village must be linked to at least two SPT substations.
- The total power capacity of the SPT substation must be greater than or equal to the total power demand in the village.
- Only one SPT substation will be required to supply power to households in a given village.
- The voltage profile of the transmission line must be maintained within 132 kV ±5%.

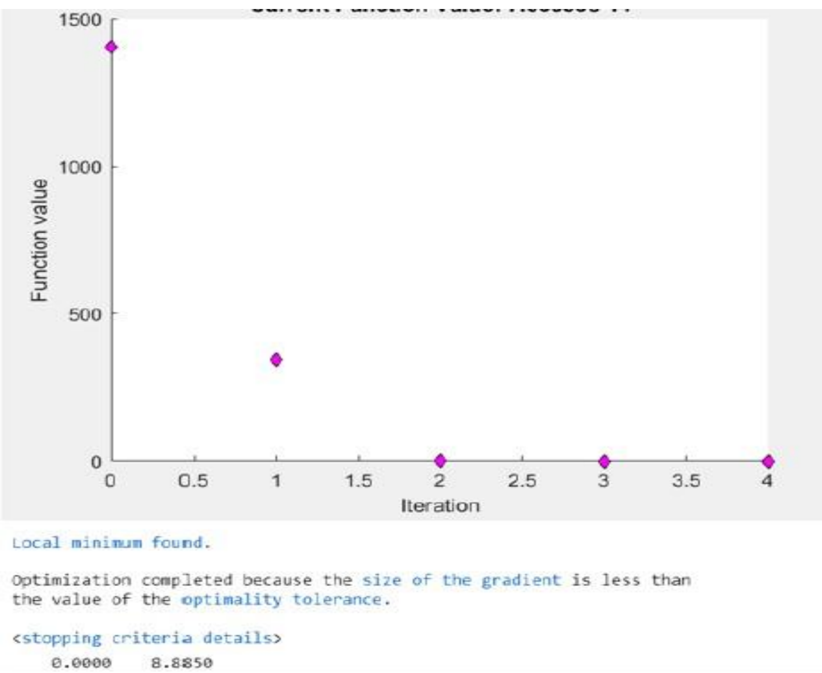
The load flow analysis for this study was carried out using PowerWorld simulator software, which employs the Newton-Raphson method for its power flow analysis.

5. Results and Discussion

5.1. Optimal Number of SPT

In this study, seven villages were supplied with electricity through Service Potential Transformer (SPT) substations. Each village contained approximately eight households, each with a daily load curve of 100 watts. The transmission line parameters used were R′=0.0090 p.u., X′=0.100 p.u., and B′=1.72 p.u. The objective function presented in equation (2) was applied in the Live Editor on the Matlab platform to determine the optimal number of SPT substations required to meet the power demand of households located close to the 132 kV Juja-Rabai transmission line. The iterative solution obtained is captured in Figure 4.

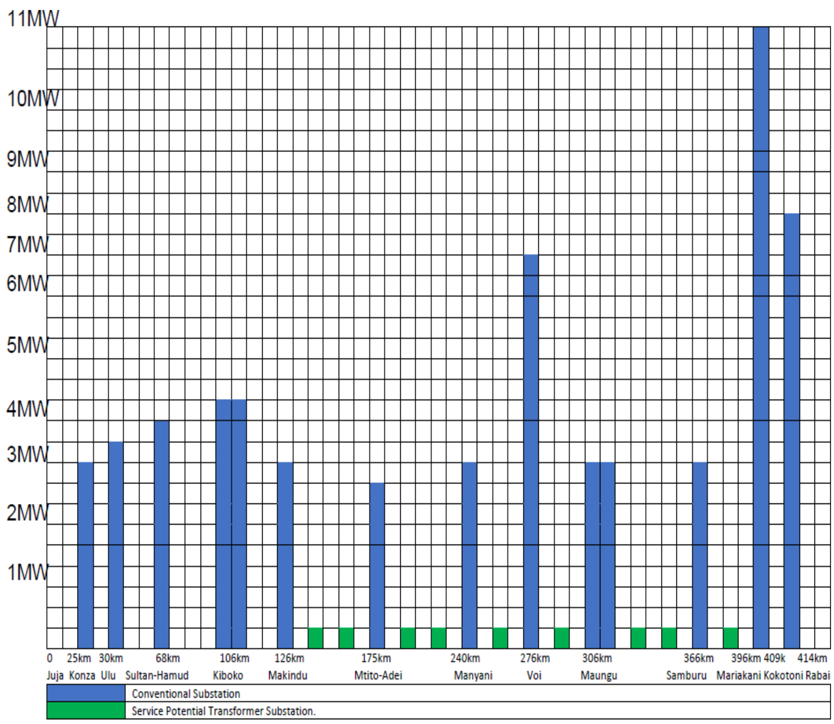
Figure 4. Unconstrained SPT substation optimal number.



The results of the study revealed that 8.850 SPT substations were required to meet the power demand of villages within a 500-meter radius from the 132 kV high-voltage line. This result aligns with previous studies carried out in Simulink, as shown in Figure 3, thereby validating the findings. The nine substations were distributed in regions located 15 km away from the conventional substations.

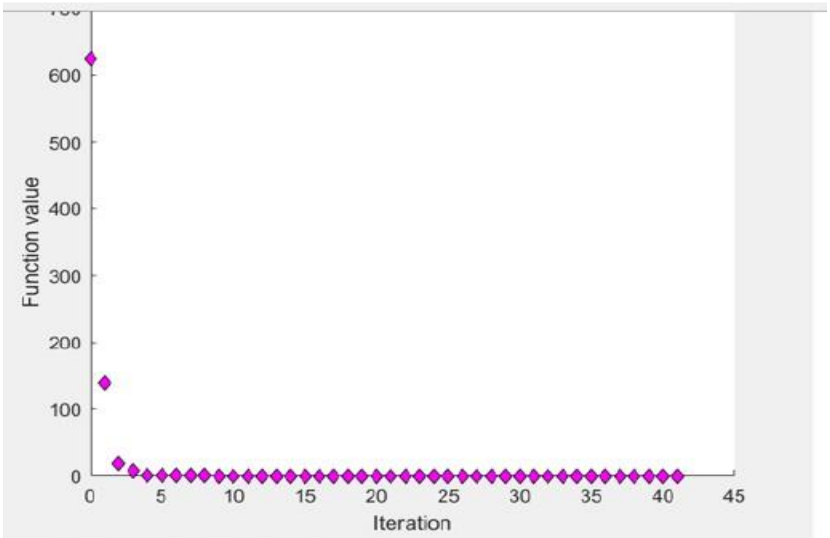
For the 69 km stretch between Makindu conventional substation and Mtito-Adei substation, two SPT substations were required. Similarly, a 69 km distance between Mtito-Adei and Manyani substation required two SPT substations. One SPT substation was installed between Manyani and Voi substations, and another was placed between Voi and Maungu substations. The remaining two SPT substations were installed between Maungu and Samburu substations, with the final SPT substation installed between Samburu and Mariakani substations. These results are shown in Figure 5.

Figure 5. Placement of unconstrained SPT substations.



The objective function of equation (2), combined with constraints captured in equations (7) to (9), was used in the Live Editor on Matlab to refine the optimization process, with results shown in Figure 6.

Figure 6. Constrained SPT substation optimal number.

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ocal minimum possible. Constraints satisfied.

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atisfied to within the value of the constraint tolerance.

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   0.0000     6.8598
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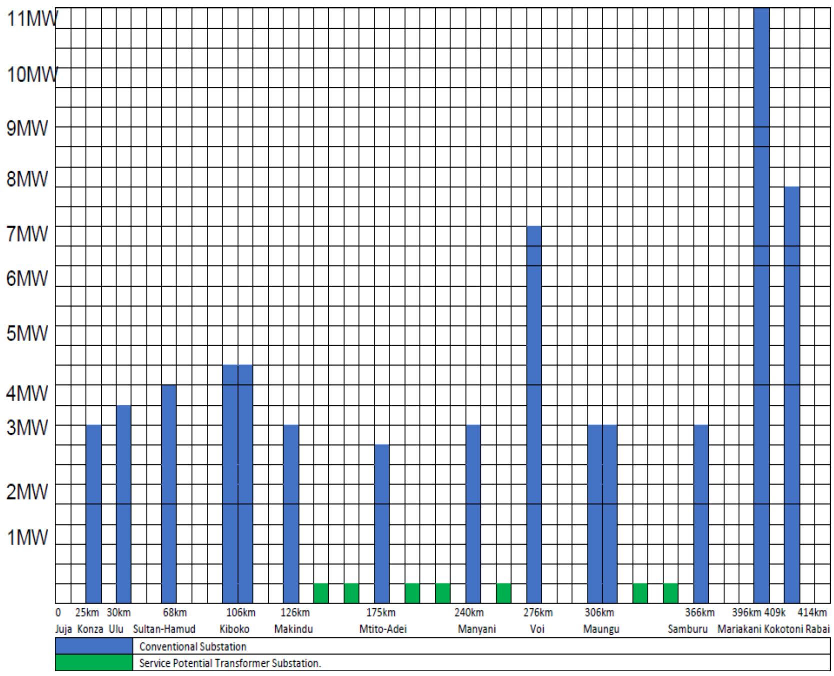
When the constraints were incorporated into the optimization process, the solution converged at 6.8598, meaning that the optimal number of SPT substations required to meet the power demand of households near the 132 kV Juja-Rabai transmission line was seven. This led to the installation of one SPT substation between Makindu and Mtito-Adei substations, and another between Mtito-Adei and Manyani substations. The remaining substations were maintained as part of the unconstrained solution, and the finalized SPT substation layout is presented in Figure 7.

Figure 7. Placement of constrained SPT substations.



5.2. Load Flow Results

The load flow analysis was conducted for the Juja-Rabai 132 kV transmission power network. Practical transmission line parameters and existing loads served by conventional substations were incorporated into the simulation. Initially, the network was simulated without any SPT substations. Then, the unconstrained nine SPT substations were terminated along the transmission line, followed by simulations with both unconstrained and constrained SPT substations. The results of these simulations were recorded in Tables 1 and 2, which were further analyzed and plotted.

The voltage profile of the network showed the presence of Ferranti effect. To mitigate this, a static Var compensation of -400 MVar was applied, resulting in a near-flat voltage profile. Table 1 presents the load flow results from the compensated network. With the installation of the nine unconstrained SPT substations, the study observed that the voltage profile of the network was violated. However, when the constraints of the system were incorporated, the optimum penetration level was reduced to seven, and the voltage profile of the transmission line became nearly flat. These results are captured in Table 2.

The load flow data from Tables 1 and 2 were plotted on a Cartesian plane and the results are shown in Figure 8. The study compared the power flow in the Juja-Rabai 132 kV transmission line both with and without the installation of the SPT substations. The results indicated that the voltage profile was violated when the highly inductive SPT substations were installed, causing an imbalance in reactance. This imbalance led to the Ferranti effect, as the supply of capacitive reactance was almost constant, and the inductive reactance increased. Reactance compensation was required to restore the voltage profile of the network.

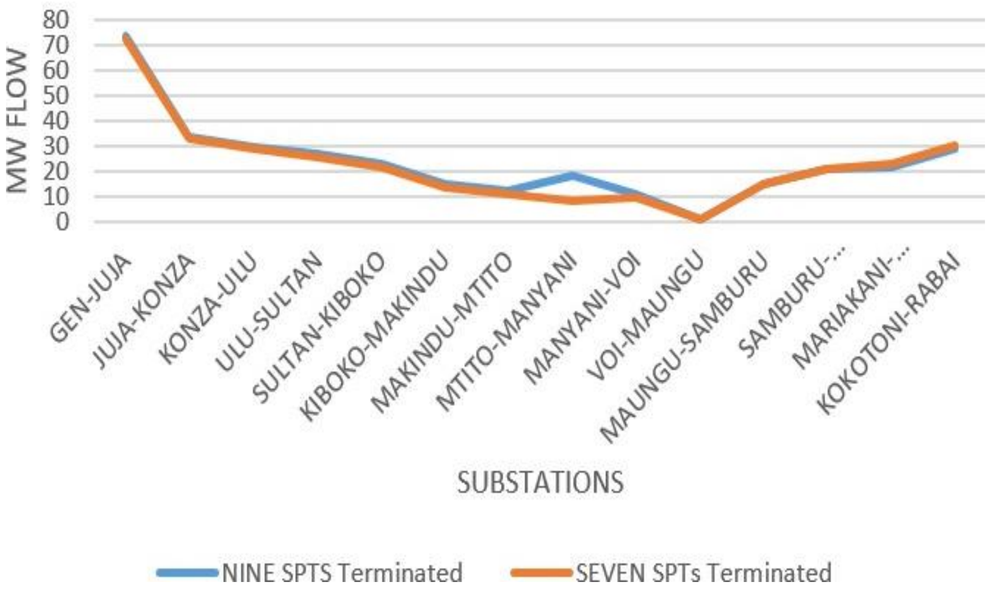


Figure 8. Juja-Rabai power flow simulation results.

Despite variations in the voltage profile, the overall load flow along the transmission line showed minimal changes, as seen in Figure 8. These findings are significant because they suggest that, while the installation of SPT substations might cause voltage fluctuations, the overall power distribution remains relatively stable.

Table 1. Load flow data when nine SPT terminated.

From	To	MW Flow	MVar Flow	MVA Flow	% MVA Limit	MW Loss	MVar Loss
Ken Gen	Juja	73.6	-175.7	190.5	19.4	0.27	3.60
Juja	Konza	34.0	-131.4	135.7	13.6	0.14	-16.44
Konza	Machakos	1.0	0.5	1.1	0.2	0.00	0.00
Konza	Ulu	29.8	-116.4	120.2	12.0	0.06	-8.52
Ulu	Sultan Hamud	26.5	-109.4	112.6	11.3	0.15	-34.17
Sultan Hamud	Kiboko	22.8	-76.7	80.1	8.0	0.06	-39.32
Kiboko	Makindu	15.4	-41.4	44.2	4.4	0.01	-20.91
Makindu	Mtito Adei	12.2	-21.5	24.8	2.5	0.00	-42.05
Mtito Adei	Manyani	18.5	167.6	158.7	9.8	0.10	-36.50
Manyani	Voi	11.3	252.2	252.5	64.3	0.25	-15.60
Mariakani	Kokotoni	22.7	22.9	32.2	4.2	0.01	-12.72
Kokotoni	Rabai	29.6	32.6	44.0	5.1	9.55	0.10

Table 2. Load flow data when seven SPT terminated.

From	To	MW Flow	MVar Flow	MVA Flow	% MVA Limit	MW Loss	MVar Loss
Ken Gen	Juja	72.9	-138.6	156.7	15.9	0.18	2.45
Juja	Konza	33.4	-113.8	118.6	11.9	0.11	-16.66
Konza	Machakos	1.0	0.5	1.1	0.2	0.00	0.00
Konza	Ulu	29.3	-98.6	102.9	10.3	0.04	-8.58
Ulu	Sultan Hamud	26.0	-91.5	95.1	9.5	0.10	-34.75
Sultan Hamud	Kiboko	22.4	-58.3	62.4	6.2	0.03	-38.66
Kiboko	Makindu	14.9	-23.6	28.0	2.8	0.00	-20.09
Makindu	Mtito Adei	11.7	35.3	37.2	7.4	0.05	-37.43
Mtito Adei	Manyani	8.7	104.6	105.6	13.8	0.27	-25.34
Manyani	Voi	21.0	17.0	32.1	77.0	0.00	0.00
Mariakani	Kokotoni	23.2	2.2	23.3	2.7	0.00	-12.15
Kokotoni	Rabai	30.1	11.3	32.1	4.1	9.11	0.06

This study contrasts with previous research which found that five SPT substations could be terminated on a 220 kV transmission line without violating the voltage profile [10]. Similarly, another study observed that nine ASVT substations could be terminated on a 132 kV transmission line without violating the voltage profile [11]. However, both studies failed to consider the existing conventional substations supplying power to various customers, which could affect the power flow on the transmission line. Additionally, prior research mainly focused on the termination of a single SPT substation to serve isolated villages near transmission lines. This paper fills the research gap by addressing the optimization of SPT substations on a line with existing conventional substations and performing a power flow analysis on the line.

5. Conclusions

This study demonstrates that seven optimally constrained Service Potential Transformer (SPT) substations are sufficient to meet the power demand of households located near the 132 kV Juja-Rabai transmission line without violating the voltage profile. The integration of these substations ensures that consumers previously served by conventional substations will experience no significant power variations or dips when the SPT substations are introduced to supply electricity to villages close to the high-voltage lines. Power system engineers should consider the use of SPT substations as an effective solution for addressing the power demands of rural communities near high-voltage transmission lines. Additionally, further research is recommended on the security-constrained power flow analysis of networks incorporating SPT substations to explore additional optimization and resilience in power systems.

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

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