*Journal of Power, Energy, and Control*

*Research article*

# Economic Load Dispatch on a 132 kV Line with Service Potential Transformer Substations: A Case Study of Juja-Rabai Line

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https://doi.org/10.62777/pec.v1i2.26

Received: 19 August 2024
Revised: 15 September 2024
Accepted: 18 September 2024
Published: 28 September 2024

**Abstract**: Power outages have created significant challenges for power system networks, particularly in developing countries where the electricity demand continues to rise without a corresponding increase in power generation or the expansion of transmission and distribution networks. In Kenya, while there is a well-established transmission line network, the distribution infrastructure remains inadequate for supplying electricity to end consumers. This paper examines the economic load dispatch (ELD) of power system networks utilizing Service Potential Transformer (SPT) substations to provide electricity to villages located near high voltage (HV) lines. The ELD analysis was conducted to identify the optimal economic power output from the Kipevu, Rabai, and Thika thermal power plants, addressing the demand for both conventional and non-conventional substations. A gradient method was employed to calculate the ELD for these three generating units, and the results were validated using the PowerWorld simulator. Findings indicated that the three generators supplied 20 MW, 37.5 MW, and 12.5 MW, respectively. The results obtained from the gradient method are consistent with those obtained from PowerWorld software. Additionally, this study projected an annual fuel cost savings of USD 17,695.20 when ELD was implemented, compared to a scenario of equal load distribution among generating units. Over a ten-year period, these savings would be sufficient to establish a conventional distribution substation to meet the power demands of villages located further away from high voltage lines.

**Keywords**: economic load dispatch, transmission line, optimum load flow, conventional substation, service potential transformer, Kenya

## 1. Introduction

The increasing interconnection of power networks has led to recurrent power outages in many parts of the world, exacerbated by the constant rise in fuel prices. This situation necessitates a reevaluation of strategies to reduce the operational costs of power plants. One promising approach is to incorporate both conventional and service potential transformer substations, which offer a more cost-effective means of supplying electricity to consumers. Minimizing fuel consumption for a given load demand is a critical method for achieving this reduction in running costs [1].

Rapidly developing countries in South Sahara Africa face significant challenges in meeting power demand, prompting the swift construction of thermal generating units [2]. Existing high-voltage and distribution lines are being used to deliver power to load centers, but this has resulted in over-stressed power lines and recurring outages.

Kenya, rich in diverse energy resources, is among the countries striving to meet its growing power needs. These power plants include geothermal power plants in Olkaria, wind power in Turkana, hydroelectric plants such as Kiambere (168MW), Kindaruma (72MW), Gitaru (225MW), Sondu Miriu (61MW), and Masinga (40MW). Additionally, several thermal power plants contribute to the grid, including Rabai (90MW), Kipevu I (60Mw), Kipevu III (115MW), Iberafrica 1 (56MW), Iberafrica 2 (52.5MW), Athi River Gulf (80MW), Triump (83MW), Thika Power (87MW), Embakasi Gas Turbine 1 (27MW), and Embakasi Gas Turbine 2 (27MW), among others [3], [4]. Despite the extensive array of generation sources, the transmission lines infrastructure has not kept pace. This makes them inadequate to handle the increasing power demand and contributes to frequent national blackouts in Kenya.

Voltage stability analysis and transient stability analysis methods have been employed in Kenyan power networks to mitigate these frequent power outages [2], [5]. However, these methods are not sufficient. Economic load dispatch (ELD) could be employed to provide insights into the efficiency of power evacuation in relation to the growing demand. This would reduce the contingency states in transmission and distribution lines and eventually minimize the recurrent power outages.

The use of SPT substations represents a contemporary solution to address the lack of electricity access for households located near high voltage (HV) lines [6], [7]. This paper aims to investigate whether ELD could effectively address the power demands, minimize power outages, and generate annual savings. This study has the potential to contribute to the field of power distribution by exploring how sparsely populated areas could receive electricity through SPTs without compromising the financial stability of utility companies.

## 2. Literature Review

### 2.1. Service Potential Transformer Substation

Service Potential Transformers (SPT) are modified instrument transformers capable of stepping down high voltages, such as 132 kV, 220 kV, and 440 kV, to low voltages of 240 volts while providing distribution capabilities. These static machines are particularly effective in supplying single-phase loads [8]. Initially, SPTs were used in substations to step down voltage from transmission lines to levels that are suitable for control room operations [9].

Kenya has a widespread transmission network that traverses most of its rural areas, which currently lack electricity supply. The SPT substations play a crucial role by tapping power using high-voltage connectors, allowing them to draw energy without interfering with the load flow along the high-voltage lines. To ensure safety and reliability, the required protective devices include a disconnection switch and a circuit breaker.

Figure 1 illustrates an SPT that steps down voltage from 132 kV to 240 volts to supply single-phase loads in households. In contrast, a conventional substation utilizes three transformers to reduce the voltage sequentially from 132 kV to 66 kV, then from 66 kV to 33 kV, and finally from 33 kV to 11 kV [10]. An SPT substation was designed and installed to provide electricity to villages near the transmission line in Congo, demonstrating a secure and operational technology up to date [8]. This approach has proven effective in a rural village in Congo, as shown in Figure 2. However, the literature review reveals a lack of similar projects on the same transmission line aimed at supplying electricity to households near the high-voltage lines. This raises important questions about whether installing multiple SPTs along the line would impact system stability and potentially lead to outages. Therefore, further research on electrical load distribution (ELD) along the line is necessary to address these technical concerns.

**Figure 1.** SPT compared to conventional substation.

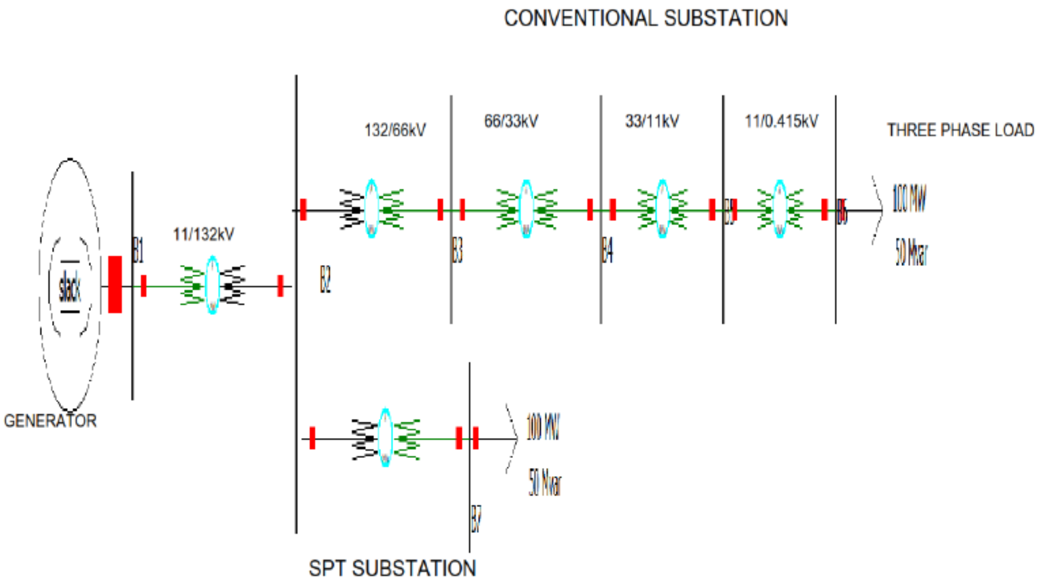

**Figure 2.** SPT compared to conventional substation.

## 2.2. Load Profile at the Grid System and Energy Mix

A power network with multiple generating units should be evaluated to determine if the power system operates under economically efficient conditions [11], [12], [13]. ELD is typically assessed using the coordination equation, generator capacity limits, and transmission losses as the constraints. Research by T. Pavani conducted a comparative economic load dispatch analysis of power flow from six generators using three different methods: the gradient calculation method, PowerWorld simulator, and TLBO software [14].

Table 1 presents the parameters used in the study, while table 2 displays the economic load dispatch results of six generators analyzed using the IEEE 30-bus system [14]. The results revealed some variations, highlighting the need for further research to investigate the inconsistencies among the economic load dispatch methods employed. Additionally, existing research has not addressed the economic load dispatch of generating units with SPT substations.

**Table 1.** Generator parameters.

| Generator ID | Cost coefficient | | | Min Power (MW) | Max Power (MW) |
|---|---|---|---|---|---|
| | a | b | c | | |
| 1 | 0.0 | 2.00 | 0.00375 | 50 | 200 |
| 2 | 0.0 | 1.75 | 0.01750 | 20 | 80 |
| 3 | 0.0 | 1.00 | 0.06250 | 10 | 50 |
| 4 | 0.0 | 3.25 | 0.00834 | 10 | 35 |
| 5 | 0.0 | 3.00 | 0.02500 | 10 | 30 |
| 6 | 0.0 | 3.00 | 0.02500 | 12 | 40 |

**Table 2.** Economic load dispatch of six generators.

| Units | Min Power (MW) | Max Power (MW) | TLBO | Gradient Based | PowerWorld Simulator |
|---|---|---|---|---|---|
| 1 | 50 | 200 | 185.40 | 187.219 | 197.99 |
| 2 | 20 | 80 | 46.87 | 53.781 | 44.00 |
| 3 | 10 | 50 | 10 | 16.955 | 22.00 |
| 4 | 10 | 35 | 10 | 11.288 | 10.00 |
| 5 | 15 | 30 | 19.12 | 11.287 | 10.00 |
| 6 | 12 | 40 | 12 | 13.353 | 12.00 |
| Fuel cost ($/hr) | | | 767.602 | 804.853 | 811.50 |

In the context of ELD, the objective function is to minimize the fuel cost. The constraints considered in ELD include system constraints, generator constraints, voltage constraints, running spare parts, transmission line constraints, and network security constraints [15]. This study focuses on the economic load dispatch of the Juja-Rabai 132 kV line, which is supported by three generating stations. The analysis showed that the line had a flat voltage profile before reaching SPT substations [16]. The study considered the fuel cost equations of generating units along with the generator limits, initially neglecting losses and subsequently accounted for line losses in the analysis.

# 3. Methodology

## 3.1. Software Tools and Optimization Techniques

Economic load dispatch involves unit commitment, which entails the optimal selection of available generating units to meet the demand. The subsequent step is to allocate the load among these generating units in such a way that minimizes the total operating cost [1]. In this context, MATLAB software is able to perform various analyses, including load flow analysis, transient stability analysis, economic load dispatch, optimal power flow, and optimum penetration level of electric devices in distribution lines [17], [18]. MATLAB environment allows dynamic simulation of power system networks and modeling of controllers using block diagrams [17], [19].

Additionally, the PowerWorld simulator can also be used for load flow analysis, economic load dispatch, security-constrained economic load dispatch, optimal power flow, security-constrained optimal power flow, transient stability, and voltage stability assessment [20]. The gradient method of economic dispatch was used in this study due to its straightforward application, ease of use, and high accuracy. PowerWorld simulator was chosen for its user-friendly interface and reliable results, making it an effective tool for this study.

### 3.2. Cost Calculation

The total cost of operation for generating units involves; fuel, labor and maintenance cost. For simplicity of analysis, the paper considered variable cost only i.e fuel cost. The economic load dispatch in this paper was carried out on a transmission with existing conventional substations and considering optimally terminated SPTs of 0.5 MW.

The fuel cost curve is given by equation (1) [21].

$$C_i\left(P_{gi}\right) = KF_i\left(P_{gi}\right) = KP_{gi} \cdot H_i\left(P_{gi}\right) \tag{1}$$

where $C_i$ is the cost of fuel used per hour, $P_{gi}$ denotes the three-phase power (MW), $K$ is the cost of the fuel, $F_i(P_{gi})$ is input energy rate (MKCal/hr), and $H_i(P_{gi})$ represents heat rate (MKCal/MWhr). The fuel cost considering heat rate curve is given by equation (2).

$$C_i\left(P_{gi}\right) = a_i + b_i P_{gi} + d_i P_{gi}^2 \tag{2}$$

where $a$, $b$, and $d$ are the cost coefficient.

The incremental cost $IC_i$ was obtained by differentiating equation (2) with respect to generated power, as described in equation (3).

$$\frac{dC_i}{dP_{gi}} = IC_i = b_i + 2d_i P_{gi} \tag{3}$$

The output of each generating unit was obtained using equation (4).

$$P_{gi} = \frac{\Lambda - b_i}{2d_i} \tag{4}$$

The iterative incremental cost of generating units was obtained using two-term Taylor's series as follows.

$$\Lambda^{(k+1)} = \Lambda^{(k)} + \Delta\Lambda^{(k)} \tag{5}$$

$$\Delta P = P_D - \sum P_{gi} \tag{6}$$

### 3.3. Problem Formulation

The economic load dispatch of Juja-Rabai 132 kV transmission line was carried out. In this study, three thermal power plants were used to address the load demand of 70 MW. The conventional substations were used to supply a load of 66.5 MW while seven SPTs addressed a load of 3.5 MW. These thermal power plants were Rabai Power with a generation capacity in the range 15 MW to 90 MW, Kipevu with a generation capacity of 20 MW to 115 MW and Thika power plant with a generation capacity in the range 10 MW to 75 MW [22], [23].

Taking Kipevu power plant the first thermal generator, Rabai power plant, as the second thermal generator and Thika Power plant as the third thermal generator, the fuel cost expression for the three plants were formulated as follows.

$$C_1 = 220 + 7.0P_{g1} + 0.008P_{g1}^2 \tag{7}$$

$$C_2 = 200 + 6.3P_{g2} + 0.009P_{g2}^2 \tag{8}$$

$$C_3 = 140 + 6.8P_{g3} + 0.007P_{g3}^2 \tag{9}$$

The load dispatch of the generators were under the following constraints: upper and lower generating limits of each generator, voltage profile of the network. The generator outputs were subject to the following limits.

$$20 \leq P_{g1} \leq 115\ MW \tag{10}$$

$$15 \leq P_{g2} \leq 90\ MW \tag{11}$$

$$10 \leq P_{g3} \leq 75\ MW \tag{12}$$

The total load demand which was addressed by conventional and SPT substations was 70 MW. The Fuel cost equations 4, 5 and 6 and their corresponding generator limits shown in equation 7, 8 and 9 were used to determine economic load dispatch using iterative gradient method followed by a PowerWorld simulator, neglecting transmission line losses and considering losses. The analysis of economic load dispatch only considers the active power. The load demand at each bus was captured in Table 3. Transmission line parameters of Table 4 where later considered and economic load dispatch considering line losses determined. The comparative results of the study were tabulated in Table 5.

**Table 3.** Juja-Rabai scheduled generation and loads.

| Bus Code *i* | Assumed bus voltage (p.u) | Generation (MW) | Generation (MVar) | Load (MW) | Load (MVar) |
|---|---|---|---|---|---|
| 1 (slack bus) | 1.05+j0.0 | - | - | 0 | 0 |
| 2 | 1+j0.0 | 40 | 20 | 3 | 1 |
| 3 | 1+j0.0 | 0.0 | 0.0 | 1 | 0.2 |
| 4 | 1+j0.0 | 0.0 | 0.0 | 3.3 | 1 |
| 5 | 1+j0.0 | 0.0 | 0.0 | 3.5 | 1.2 |
| 6 | 1+j0.1 | 0.0 | 0.0 | 3.7 | 1.0 |
| 7 | 1+j0.0 | 0.0 | 0.0 | 3.1 | 1.0 |
| 8 | 1+j0.0 | 0.0 | 0.0 | 2.5 | 0.5 |
| 9 | 1+j0.0 | 0.0 | 0.0 | 3.1 | 1.0 |
| 10 | 1+j0.0 | 0.0 | 0.0 | 6.5 | 2.0 |
| 11 | 1+j0.0 | 0.0 | 0.0 | 3.0 | 1.0 |
| 12 | 1+j0.0 | 0.0 | 0.0 | 3.2 | 1.0 |
| 13 | 1+j0.0 | 40 | 20 | 11.7 | 3.0 |
| 14 | 1+j0.0 | 0.0 | 0.0 | 6.9 | 2.0 |
| 15 | 1+j0.0 | 40 | 20 | 2.0 | 0.0 |

**Table 4.** Juja-Rabai transmission line input data.

| Bus to Bus | Distance (km) | R (p.u) | X (p.u) | B (p.u) | Maximum MVA (p.u) |
|---|---|---|---|---|---|
| Juja 1 – Konza 2 | 25 | 0.00090 | 0.0100 | 0.172 | 10.0 |
| Konza 2 – Machakos 3 | 20 | 0.00090 | 0.0100 | 0.172 | 10.0 |
| Konza 2 – Ulu 4 | 5 | 0.00045 | 0.0050 | 0.086 | 10.0 |
| Ulu 4 – Sultan 5 | 38 | 0.00180 | 0.0500 | 0.344 | 10.0 |
| Sultan 5 – Kiboko 6 | 38 | 0.00180 | 0.0500 | 0.344 | 10.0 |
| Kiboko 6 – Makindu 7 | 20 | 0.00090 | 0.0100 | 0.172 | 10.0 |
| Makindu 7 – Mtito Andei 8 | 69 | 0.00300 | 0.0330 | 0.573 | 10.0 |
| Mtito Andei 8 – Manyani 9 | 65 | 0.00300 | 0.0330 | 0.573 | 10.0 |
| Manyani 9 – Voi 10 | 36 | 0.00180 | 0.0500 | 0.344 | 10.0 |
| Voi 10 – Maungu 11 | 30 | 0.00180 | 0.0500 | 0.344 | 10.0 |
| Maungu 11 – Samburu 12 | 60 | 0.00300 | 0.0330 | 0.573 | 10.0 |
| Samburu 12 – Mariakani | 30 | 0.00180 | 0.0500 | 0.344 | 10.0 |
| Mariakani – Kokotoni | 13 | 0.00060 | 0.0066 | 0.115 | 10.0 |
| Kokotoni – Rabai | 5 | 0.00045 | 0.0050 | 0.086 | 10.0 |

The following steps describe the algorithm for solving the economic load dispatch problem:

1. Initialize the Lagrange Multiplier ($\lambda$)
   Set an initial value for the Lagrange multiplier $\lambda$, which will be used to balance the generation cost across all generators.
2. Solve for power output $P_{gi}$ (i = 1, 2, 3, …, k)
   Solve for the power output of each generator $P_{gi}$ by ensuring that the incremental cost of each generator is equal to $\lambda$, i.e.,

$$\frac{dC_1}{dP_{g1}} = \frac{dC_2}{dP_{g2}} = \cdots = \frac{dC_k}{dP_{gk}} = \lambda \tag{13}$$

3. Check the convergence condition
   If the absolute difference between the total generated power $\Sigma P_{gi}$ and the demand $P_D$ is less than or equal to a predefined tolerance ε, the optimal solution is reached.

$$\left|\Sigma P_{gi} - P_D\right| \leq \epsilon \tag{14}$$

   Otherwise, proceed to the next step.
4. Update incremental cost
   If the sum of the generated power is less than the demand ($\Sigma P_{gi} < P_D$), increment the incremental cost as follows.

$$IC = IC_0 + \delta IC \tag{15}$$

   If the generated power exceeds the demand ($\Sigma P_{gi} > P_D$), decrement the incremental cost as follows.

$$IC = IC_0 - \delta IC \tag{16}$$

   Return to step 2 and iterate until convergence is achieved.

The economic load dispatch was modeled and solved using PowerWorld Simulator. The software was utilized for load flow analysis and economic dispatch optimization, leveraging the built-in tools for Automatic Voltage Regulation (AVR) and Economic Dispatch (ED) configuration. The simulation was performed under real-world constraints, and the software's interactive tools were used to model generator behaviors and run the optimization. The results, including total generation cost and system stability, were then analyzed based on the outputs provided by the simulator.

## 4. Results and Discussion

The economic load dispatch of Kipevu, Rabai, and Thika thermal power plants during off-peak hours was evaluated using equations (7)-(12), hence obtaining the value of Λ = 7.089. This value was substituted to equation (4), and the economic load dispatch of each generator was evaluated without considering generator limits, as shown in equation (16)-(18). The generated power of each generator from the calculations is 5.5625 MW, 43.833 MW, and 20.643 MW, respectively.

The economic dispatch was analyzed, and equation (6) was used to verify convergence. The result obtained, 0.0385 MW, indicated a minimal deviation, confirming that the optimal generator loading had been achieved without violating the generator limits, as demonstrated by previous calculations. However, when the generator limits were considered, Generator 1 was found to be operating below its minimum capacity. This issue was corrected by setting its output to 20 MW. The loadings of Generators 2 and 3 were subsequently adjusted to balance the system demand, hence obtaining the value of -14.476 MW.

After updating the incremental cost and re-evaluating the generator outputs, the system successfully converged. The final loadings for Generators 1, 2, and 3 were 20 MW, 37.5 MW, and 12.5 MW, respectively. The total fuel cost for the system was calculated to be 1,038.2 USD per hour, indicating an optimal economic dispatch for the given power demand.

PowerWorld Simulator was also used to simulate the economic load dispatch for the Juja-Rabai line, as depicted in Figure 3, neglecting transmission line losses. The results closely matched the calculations from the gradient method, with a total cost of 1,038.51 USD per hour and an incremental cost of 6.98 USD/MWh, closely resembling the analytical results. These results were tabulated in Table 5.

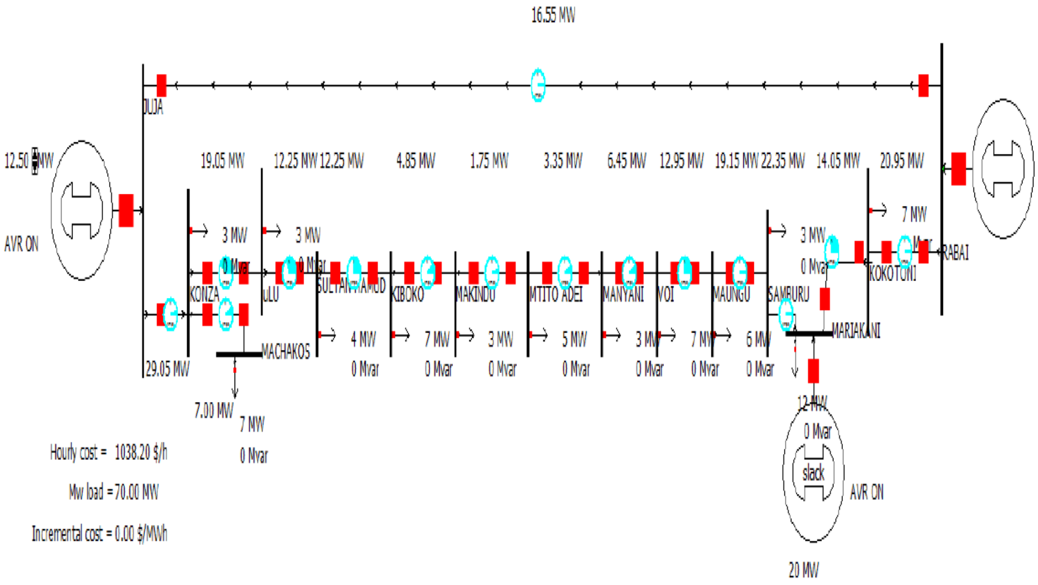

**Figure 3.** Juja-Rabai 132 kV transmission line with optimally terminated SPT substations.

**Table 5.** Economic load dispatch of three generators.

| Units | Gradient Based | PowerWorld Simulator Neglect Losses (MW) | PowerWorld Simulator Consider Losses (MW) |
|---|---|---|---|
| 1 | 20 | 20 | 20 |
| 2 | 37.5 | 37.57 | 38.90 |
| 3 | 12.5 | 12.48 | 14.72 |

When the transmission line parameters were considered, the loading of Generators 2 and 3 increased slightly to compensate for line losses. A total line loss of 3.62 MW was observed, as indicated by the updated dispatch results. Although the system could theoretically meet the demand of 70 MW using any of the three generators, relying on a single generator, such as Generator 3 (with its lowest upper limit of 75 MW), would create an insecure system configuration. Table 6 shows that while Generator 3 is the most economical option, using it alone would jeopardize the overall system security.

**Table 6.** Loading results of each generator.

| Generator | Incremental Cost (USD/MW·hr) | Load (MW) | Hourly Cost (USD/hr) |
|---|---|---|---|
| 1 | 8.12 | 70 | 749.20 |
| 2 | 7.56 | 70 | 685.10 |
| 3 | 7.78 | 70 | 650.30 |

To achieve an optimal and secure system for economic load dispatch, two generating units from Figure 3 were turned on to supply the loads, neglecting line losses, and the results were tabulated in Table 7. From Table 6, it was observed that Generator Three was the most economical unit to meet the load demand, but it did not provide system security. To enhance system security, Generator Two, the second in merit order for economic dispatch, was also activated. Thus, Generators Two and Three were utilized to supply power in the most cost-effective manner.

**Table 7.** Loading results of each generator.

| Operational Generators | Pg1 | Pg2 | Pg3 | Incremental Cost (USD/MW·hr) | Load (MW) | Hourly Cost (USD/hr) |
|---|---|---|---|---|---|---|
| 2 & 3 | - | 46.25 | 23.75 | 7.13 | 70 | 816.08 |
| 1 & 3 | 26.0 | - | 44 | 7.42 | 70 | 860.16 |

A further analysis was conducted to evaluate the savings from economic dispatch compared to equal load distribution. Economic load dispatch of Generators 2 and 3 resulted in a total hourly cost that led to annual savings on fuel costs, compared to operating generators under equal load distribution. The calculated savings are 2.02 USD/hr or 17,695.2 USD in a year. These savings are significant, especially considering the rising cost of fuel.

Further research was carried out to evaluate the impact of transmission line losses. Generators One and Two were turned on, and taking into account the line parameters from Table 4, it was found that Generator One supplied 20 MW, and Generator Two supplied 56.35 MW. In this case, the hourly cost increased slightly due to line losses. The procedure was then repeated with Generators Two and Three, where Generator Two supplied 48.07 MW and Generator Three supplied 26.22 MW. This combination resulted in a lower hourly cost. Optimal and secure results were achieved when Generators Two and Three were used to meet the load demand, even after accounting for transmission line losses. The results demonstrated the economic load dispatch of a network with SPTs that can reliably meet consumer power demands without power outages.

The findings were validated by comparing them as shown in Table 8. In that study, the load dispatch results from six generating units using the TLBO, gradient method, and PowerWorld simulator were consistent. Similarly, the economic load dispatch results from this study, using both the gradient method and PowerWorld simulator, showed strong alignment, further confirming their reliability.

**Table 7.** Loading results of each generator.

| Method | Merit | Demerit | Used in This Study |
|---|---|---|---|
| Lambda Iteration | Takes less time to converge solutions | Cannot be used in complicated cost equations | Not used |
| Gradient | Accurate and reliable for large power networks | Sensitive to initial point | To determine economic dispatch |
| Linear Programming | Accurate and reliable for large power networks | Uses complex codes | Not used |
| Newton | Accurate and reliable for large power networks | Sensitive to initial point | Used in PowerWorld software to determine economic dispatch |

## 5. Conclusions

This study demonstrated that the Rabai, Kipevu, and Thika power plants are capable of supplying the loads along the Juja-Rabai transmission line. For optimal economic load dispatch, Generator 1 was deactivated, and the remaining two generators were sufficient to meet the load demand at the lowest cost. The research also confirmed that the existing transmission line infrastructure is capable of evacuating power from these thermal plants to supply both current loads and additional loads via SPT substations.

Further analysis revealed that adopting economic load dispatch could result in significant cost savings for the country, compared to operating the generators with equal load distribution. Over a ten-year period, the fuel cost savings would be substantial enough to fund the construction of a new conventional substation, further addressing the power needs of households in remote areas. This would contribute to regional development by extending the reach of electricity to areas far from high-voltage lines.

In both cases—whether transmission line losses were neglected or considered—the results consistently showed that Generators 2 and 3 were the most economical options for meeting the current electrical load demand. Additionally, it was found to be safe and efficient to connect SPT substations to the 132 kV Juja-Rabai transmission line to supply nearby villages with electricity, without risking voltage collapse or negatively impacting the voltage profile of the line.

**Funding:** This research received no external funding.

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

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