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Enhancing line loadability in urban rail systems: evaluating the impact of distributed generation on voltage stability, power losses and generation costs

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Abstract: Alternative source of electrical energy for urban railway electrification system is Direct Current (DC). Traction Power Substations (TPS) were essentially connected to the electrical grid network managed by the electrical utility company for operating and powering purposes. Power unbalance frequently occurs in the high voltage railway network due to the load of the traction system. The aim of this project is to find the impact of distribution generation (DG) for line loadability in urban rail systems. The output that needs to be considered are the voltage profile, power losses and generation cost. The simulation was considered to prove the positive impact of distributed generation for line loadability in urban rail system. Electrical energy was crucial for Direct Current (DC) railway electrification systems, as it provided the traction power necessary for train operations via Traction Power Substations (TPS) that connected to the electrical grid network. However, power imbalances frequently arose due to the varying loads imposed by traction systems, resulting in inefficiencies, suboptimal voltage profiles, increased power losses and higher operational costs. With the expansion of urban rail networks and the growing need for efficient power management, it became vital to explore solutions that could enhance loadability and system performance. This project examined the impact of integrating Distributed Generation (DG) on the line loadability of urban rail systems, concentrating on improvements in voltage profiles, reductions in power losses and the evaluation of generation costs. The methodology involved developing a detailed simulation model of the urban rail system, incorporating DG scenarios, analyzing their effects on voltage stability, power losses and costs. The simulation results were anticipated to demonstrate that DG could improve voltage stability, reduce power losses, lower generation costs and increase line loadability. The implications of these findings encompassed enhanced operational efficiency, potential economic benefits despite high initial investments, increased sustainability through renewable energy and valuable guidance for future infrastructure development and investment decisions.

Keywords: *Direct current, Distributed generation, Traction power substation.*

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1. Introduction

A traditional traction power supply system that is widely used is by a step-down transformer in AC electrified railway system, studies by He (2019). However, nowadays the urban and sub-urban electrified transportation systems (ETS) are dominated by the DC power supply solutions, reported by Marcin (2023). Antonio (2014) presents that currently, one of two main categories of railway electrification systems coexist depending on the power needs which is DC systems, with voltages ranging from 600 V to 3 kV, which are adopted mainly for trams, suburb trains and medium distances. Light rail, metro and inter-urban services may use both aerial catenaries or third rail, with voltages ranging from 600 to 1500 V. These DC systems are adequate for rolling stocks with low power demand (less than 5 MW). Higher powers require catenary voltages to be increased up to 3 kV, which can be found in Italy, Belgium, Spain, Poland and other European countries. As a rule of thumb, 3-kV catenaries are limited to train speeds lower than 250 km/h. Recent paper by Ying (2021) stated that in recent years, with the development of power electronics technology, some studies propose using AC-DC-AC traction substation to replace traditional traction substation, eliminating neutral section, realizing co-phase power supply across the full line, and solving the problem of power quality in TPSS. This paper provides a study on the impact of DG in the urban railway distribution system by using power flow analysis method. In a literature by Chen (2024) stated that with the development of power electronics techniques, various power flow control-based RBE utilization solutions have been developed. These emerging solutions employ the power flow controller (PFC) to regulate the power flow of RBE, achieving flexible and efficient RBE utilization. The power flow analysis method has been proposed which aims to calculate the voltages for the given load generation and network condition. By using the power flow method, the losses in line can be minimized with maximizing the real power flow transfer to the system. For the cost of generating power and operating power due to line losses had been neglected because the power flow method does not consider the cost. The line distance plays a huge role ensuring the quality power transfer. In real situation, longer line distance between TPSs may contribute to power losses issues due to high resistance and reactance. This also can cause the excessively high investment cost for the railway operation and effect the voltage profile of urban rail distribution system. The implementation of DG in electrical distribution system gives a positive impact. Nowadays, the penetrating DG not just focusing on providing cheap electricity to the unaffordable community, but it's now also used in improving the electrical power quality. In conclusion, the impact of DG in urban railway distribution system shows the positive impact in reducing the power losses but also in minimizing the operational cost.

Hu (2024) presents that depletion of fossil fuels, increasing electricity demand, along with net zero emission targets, have driven the rapid prosperity of renewable power generations over the past decades. To facilitate the uptake of renewables, microgrids consisting of local loads, energy storage systems (ESSs), and distributed generations (DGs) such as diesel generators, wind turbines (WTs) and solar photovoltaic (PVs) are emerging as promising solutions. The integration of Distributed Generation (DG) has become increasingly relevant in modern urban railway distribution systems, where effective power management is crucial. DG, which involves generating electricity from decentralized sources, can be incorporated into existing grids to enhance performance. Perez (2020) states the intermittent characteristic of renewable energy and its application through distributed generation resulted in great impacts on power quality. He also acknowledged the fact that most renewable energy sources and storages use DC energy (as photovoltaics (PVs) and batteries for example) and allow the reduction in the number of power converters in the grid with simpler topology. By doing this, they increase energy efficiency and allow fast control of the grid. Zineb (2022) also presents that the production of clean energy from renewable sources have become the hot topics on social development where railway system integrates different renewable energy sources like photovoltaics (PV) and wind turbines. This paper examines the impact of DG on urban railway systems through a power flow analysis method designed to optimize voltage profiles and minimize power losses. Urban railway systems encounter significant challenges, such as power losses and deteriorating voltage

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profiles, due to varying load conditions and distances between Traction Power Substations (TPS). Longer line distances exacerbate these issues by increasing resistance and reactance, which results in higher power losses and greater investment costs. Traditional power flow analysis methods often overlook the costs associated with power generation and operational expenses, underscoring the need for a comprehensive evaluation of DG. This evaluation aims to assess DG's effectiveness in mitigating power losses, enhancing voltage stability, and reducing operational costs. Soukaina (2019) presents that reducing the subscribed power, eliminating the voltage drop in the line due to the acceleration and leading to the subscribed power exceeding and avoiding the voltage rise due to the deceleration by consuming the total of the regenerative energy not recovered by the other trains in the line, are the main issues related with electric train. Recent literature, including studies by Zhang et al. (2021) and Li and Wang (2022), has demonstrated that DG can improve voltage stability and reduce line losses, but has not fully addressed the impact of line distances or the comprehensive cost implications. This study introduces a novel power flow analysis method that incorporates DG's effects on power quality and costs, offering a more holistic assessment than traditional approaches. Key contribution of this study includes a refined analysis method, improved voltage profiles, insights into cost reductions, and practical guidance for integrating DG into urban railway systems, thus supporting better infrastructure planning and policy development.

2. Methodology

To identify the impact of DG in urban rail distribution system was simulated using Powerworld software. The simulation was divided into two cases whereby Figure 1 is the simulation of traditional urban rail distribution system and Figure 2 is the simulation of urban rail distribution system connected with DG. In both cases, the total number of load is nine which each load connected to TPS is about 2 MW and 1 MVAR. These cases then is analysed to obtain the impact of DG in urban rail distribution system. The voltage profile, power losses and generating cost are the parameters that need to obtain.

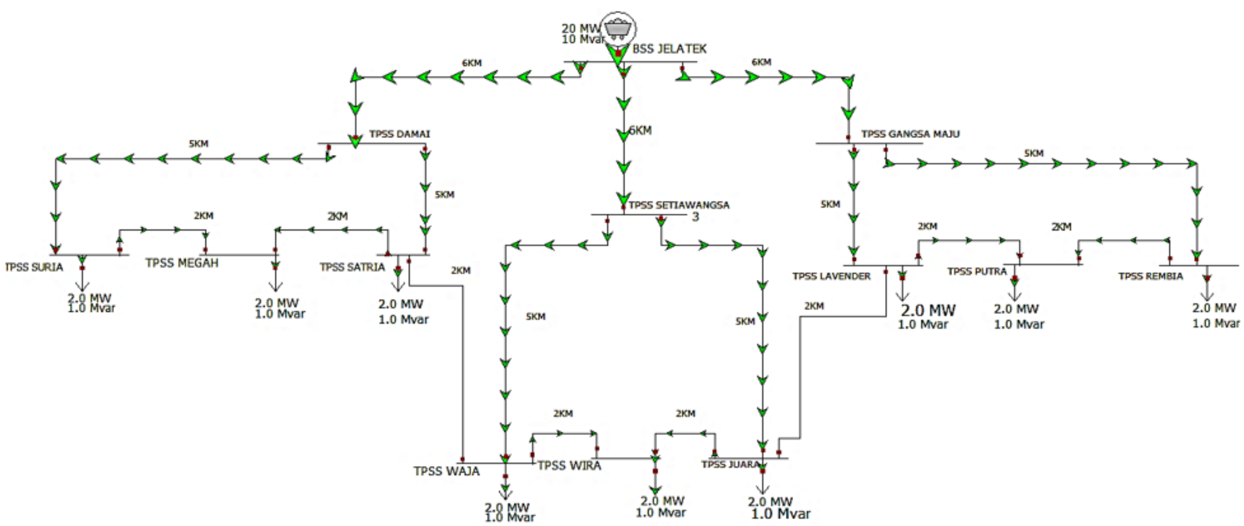

Figure 1.
Simulation of a conventional urban rail distribution system.

The 33 KV of nominal voltage was proposed to be set at each TPS and 132 KV was set at the bus of utility grid. After that the different condition of power management that had been considered, which is the condition of the line different distance going to be applied between DG and load between every area.. The type of generation used are coal-fired generation, wind generation and solar generation. For

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the renewable energy generation it was set at 1 MW and 2 MVAR. For the coal-fired generation it remain unknown due to it was set as a slack-bus.

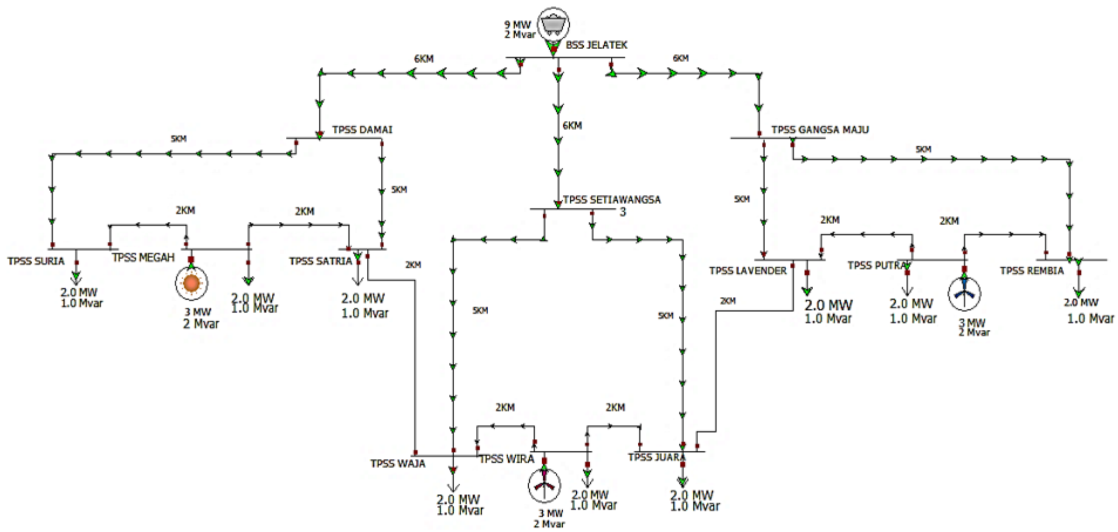

Figure 2.
Simulation of urban rail distribution system connected with DG.

Table 1.
The line distance with resistance and reactance between TPSs.

Line	Length (km)	R (Ω)	X (Ω)
BSS Jelatek to TPS Damai	6	1.158	0.659736
BSS Jelatek to TPS Setiawanga	6	1.158	0.659736
BSS Jelatek to TPS Ganga Maju	6	1.158	0.659736
TPS Damai to TPS Suria	5	0.965000	0.54978
TPS Damai to TPS Satria	5	0.965000	0.54978
TPS Setiawanga to TPS Waja	5	0.965000	0.54978
TPS Setiawangsa to TPS Juara	5	0.965000	0.54978
TPS Gangsa Maju to TPS Lavender	5	0.965000	0.54978
TPS Gangsa Maju to TPS Rembia	5	0.965000	0.54978
TPS Satria to TPS Waja	2	0.386000	0.219912
TPS Lavender to TPS Juara	2	0.386000	0.219912
TPS Suria to TPS Megah	2	0.386000	0.219912
TPS Megah to TPS Satria	2	0.386000	0.219912
TPS Waja to TPS Wira	2	0.386000	0.219912
TPS Wira to TPS Juara	2	0.386000	0.219912
TPS Lavender to TPS Putra	2	0.386000	0.219912
TPS Putra to TPS Rembia	2	0.386000	0.219912

3. Result and Discussion

By referring to Figure 3, the power losses for Case 1 are 2.71 MW and 1.55 MVAR. For Case 2, the power losses are 0.48 MW and 0.27 MVAR.

Meanwhile by referring to Figure 4, the total generation cost per hour for Case 1 is RM 732.97 meanwhile for Case 2 the generation cost per hour is RM 387.34.

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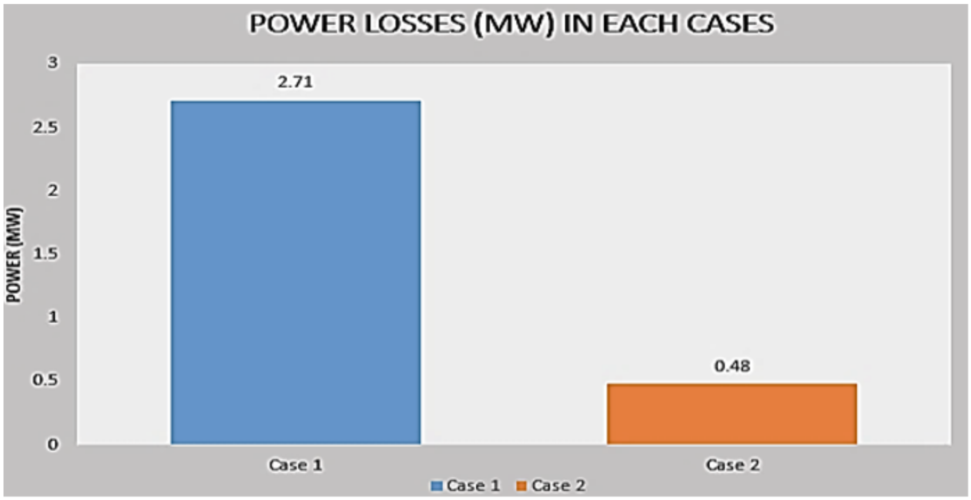

Figure 3.
Line losses in each case.

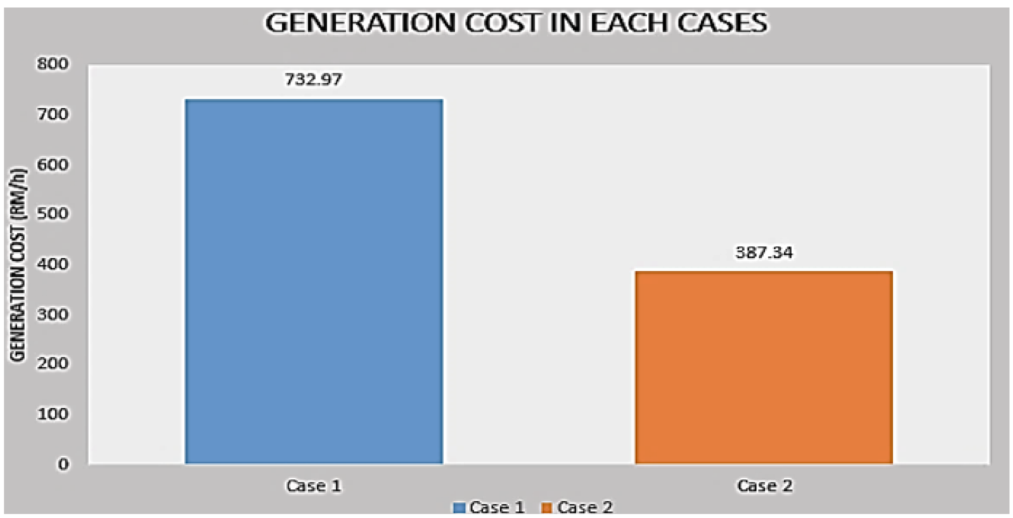

Figure 4.
Total generation cost.

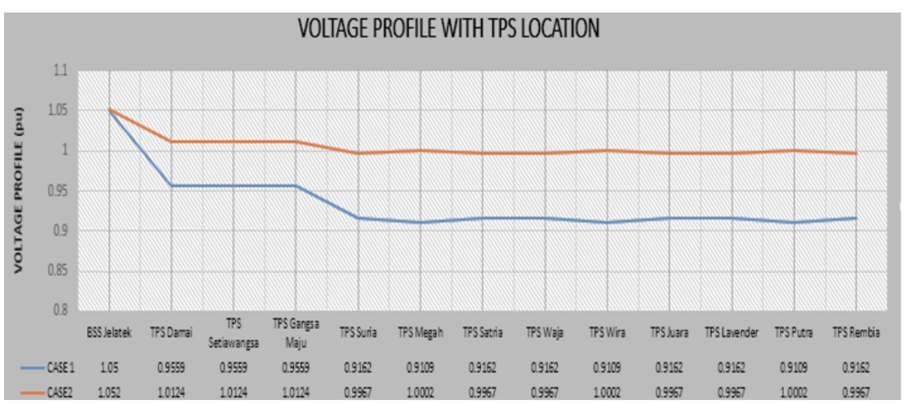

Figure 5.
Voltage profile of two different case.

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Based on Figure 5, for Case 1 the voltage profile drops significantly due to line distance. Longer distance from the central generation to TPS draws a large amount of resistance (R) and reactance (X) that affect the instability. The greater distance from central generation to the TPS resulting voltage profile will decrease. The impact of DG on voltage can be observed clearly in Case 2 where the voltage profile gets more balance and stable around 0.99 pu to 1.05 pu in comparison to Case 1 that drops until 0.92 pu. This is because the DG are near to the load which has reduced the reactive power loss.

4. Conclusion

As the conclusion, the penetration of distributed generation at urban rail system gives a very positive impact to a reliable and stable power system. It is also more cost-effective and economical.

The study's results confirm that integrating Distributed Generation (DG) significantly benefits urban railway distribution systems by enhancing voltage stability, reducing power losses, and lowering operational costs. Specifically, the power flow analysis revealed improved voltage profiles and reduced line losses with DG integration, while cost assessments demonstrated that DG implementation is more cost-effective and economically advantageous. These findings illustrate that DG not only improves system reliability and stability but also enhances economic efficiency. Future research should investigate the long-term effects of DG integration on urban railway systems, especially in the context of changing load conditions and technological advancements. Further exploration into the optimal placement and sizing of DG for various urban rail environments could further boost system performance. Additionally, integrating advanced technologies such as energy storage systems and smart grid solutions may provide additional benefits in power management. Future studies should also explore the effects of different DG technologies and their interactions with other grid components to develop more comprehensive strategies for urban railway distribution systems.

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