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RESEARCH ARTICLE

Grid Impact of Battery Swapping Station for Electric Two-Wheelers in Indonesia

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Abstract

Indonesia's shift to electric transportation is advancing swiftly, with electric two-wheelers occupying a pivotal position owing to their ubiquity and cost-effectiveness. Battery Swapping Stations (BSS) offer a viable alternative to mitigate charging delays; yet, their intrinsic stochastic nature—resulting from unpredictable user swaps and variable battery state-of-charge (SoC)—presents operational difficulties, especially for low-voltage distribution feeders. This article provides a comprehensive grid effect assessment utilizing a modified IEEE 9-bus system, which exemplifies typical Indonesian urban feeders. A stochastic simulation produces per-minute BSS activity across a 24-hour timeframe, accurately reflecting load dynamics. Quasi-dynamic power flow analysis in DIgSILENT PowerFactory assesses voltage profiles, line loading, and transformer loading in the context of BSS integration. Findings indicate that even minimal BSS implementation can result in up to 1.1% voltage drop, a 30% increase in transformer loading, and line loading rising by 100%, especially during peak swapping intervals. These findings highlight the necessity for proactive infrastructure planning and grid preparedness techniques as Indonesia enhances its electric vehicle (EV) ecosystem.

Keywords: battery swapping station, 2-wheeler electric vehicle, quasi-dynamic power flow, stochastic simulation

1. INTRODUCTION

In 2022, the transportation industry became Indonesia's third most significant source of greenhouse gas emissions, accounting for around 20%, and it continues to expand annually [1]. Intending to reach Net-Zero Emissions (NZE) by the year 2060 or sooner, the Indonesian government is actively promoting the usage of battery electric vehicles (BEV) as a means of reducing the amount of environmental pollutants that are produced by the transportation sector [2], [3]. Starting at the issuance of Presidential Regulation No. 55/2019, which expedites the battery-based electric motor vehicle program for road transportation and its derivatives, to the provision of a variety of incentives and privileges to individuals who are willing to make the shift to BEVs [4], the Government of Indonesia has set an ambitious goal of utilizing 2 million units of four-wheeled and 13 million units of two-wheeled EVs by 2030 [5]. The significant aim of utilizing two-wheeled battery-powered vehicles results from Indonesia's predominant mode of transportation being two-wheeled vehicles, with over 110 million registered units [6].

Unfortunately, until January 2025, only about 200,000 units of two- and four-wheeled EVs have been granted licenses to drive on Indonesian roadways [7]. Compared to the goal set by the Indonesian government, this figure is extremely disappointing and unsatisfactory. The lack of public interest in using electric vehicles mainly stems from owners' anxiety that their vehicle might stop working in the middle of the road due to a battery shortage. Additionally, electric vehicles typically have lower mileage than those powered by internal combustion engines (ICE), primarily because of their batteries' limited capacity. Both of these issues arise from the scarcity of easily accessible charging stations [8]. The constrained power supply on the grid is believed to be the main reason for the insufficient installation of charging infrastructure in Indonesia. This problem is worsened by the prolonged charging times for each vehicle, leading to long lines and reducing convenience for BEV users [9]. Furthermore, the high cost of BEVs compared to conventional ICE, which are about 1.5 times cheaper, continues to concern the Indonesian public when considering a switch [10]. Even though electric vehicles have low operating costs, their high purchase price fails to attract potential buyers. The Indonesian government has offered several conveniences and incentives to encourage the public to transition to using BEVs; however, this is still regarded as insufficient.

The battery swapping approach is then implemented to address the issues associated with the charging infrastructure. The time it takes for electric vehicle drivers to switch their depleted batteries for fully charged batteries is less than five minutes when they use battery swapping stations [7], [8], [9], [10]. To a large extent, this is very similar to refueling at a petrol station. This is very different when using a conductive charging system at the charging station. When using an ultra-fast charger with a power of up to 400 kilowatts (kW), you still need to wait approximately 15 to 30 minutes. Additionally, the ultra-fast charger can only charge up to 80 percent of the battery capacity to preserve the lifespan of the vehicle's battery [11].

The restricted electricity supply on the grid can also be addressed with BSS, which does not require large amounts of electricity. This significantly impacts the state of health (SoH) of the battery, and BSS can also be utilized to help support the grid during peak load situations with the battery-to-grid (B2G) function [12]. Another benefit is that the cost of electric vehicles becomes more affordable with the implementation BSS. This is because EV owners are no longer required to purchase battery packs alongside their units, fostering a new business model for leasing batteries.

However, despite the many benefits of employing BSS, challenges still arise. One challenge is that Indonesia lacks a standard battery pack. This standard must be implemented during the early transition phases to attract investors' interest in green business, particularly in battery rental schemes [13], which could lead to more swap stations and alleviate users' concerns about mileage. Another issue concerning the operational pattern of BSS is that forecasting its demand is complex due to the absence of a standardized approach to address this problem. Therefore, modeling the utilization profile of a BSS is challenging because of the uncertainty surrounding the timing and quantity of the exchange pattern. This complexity creates difficulties for electricity providers, planners, and operators in assessing the implications of BSS on grid asset feeders, and currently, there are few options available to overcome this obstacle [14]. This motivates the author's research, which aims to investigate the effect of BSS on existing grid feeders. Several studies have analyzed the integration of BSS with power grids, particularly regarding electric two-wheelers [7], [15]. Some studies address challenges related to siting and sizing but often rely on simplified or deterministic demand models and overlook the behavioral process of the exchange, which is the root of the problem itself [9], [16]. Consequently, this paper distinguishes itself by implementing a stochastic BSS usage pattern based on Monte Carlo simulations and related battery parameters, providing a more accurate representation of user-driven BSS behavior in the Indonesian urban context. Unlike previous studies, this work conducts a per-minute quasi-dynamic load flow analysis using actual load profiles and examines the impacts on transformers and distribution lines, contributing new insights into the performance of distribution (low-voltage) feeders. The author utilized a real-world BSS load profile on a modified IEEE 9-Bus System to replicate an urban Indonesian feeder, incorporating residential and business loads typically found in Indonesia. The results of this study will be helpful to Indonesian operators and policymakers as they prepare for the expected rise in the number of BSS.

2. Research Methodology

This paper encompasses multiple stages, specifically modeling the daily operation of BSS to depict BSS usage in major Indonesian cities. It continues with modeling the electrical network of urban areas in Indonesia by utilizing a modified IEEE 9 bus system adapted to the typical electrical systems of Indonesian urban regions. This research aims solely to determine the impact of BSS on the urban distribution network in Indonesia as a whole. The daily load data is derived from field measurements in one of Indonesia's metropolitan areas. For the BSS usage data, it employs the specifications of battery packs commonly used in Indonesia. The final phase involves executing a power flow simulation on a minute-by-minute basis using DigSILENT PowerFactory to analyze the impact of BSS utilization on the current grid-feeder configuration.

2.1 Battery Swapping Station Profile

This research utilizes BSS with the specifications illustrated in Figure 1, indicating that the power consumption for each cabinet is 900 Watts. Although the government has not yet established a standard for batteries, the battery pack for this study has a capacity of 1440 watt-hour (Wh), which has become prevalent in Indonesia [12].

The BSS usage profile is generated randomly according to the criteria depicted in Figure 2, wherein the battery functions as a supply and load. The battery will supply when the State of Charge (SoC) exceeds 90%, the swapping procedure is permissible if SoC surpasses 70%, and the SoC limit for a battery in BSS is established between 10% and 99%, no battery pack will be put in the BSS when the SoC is below 10%.

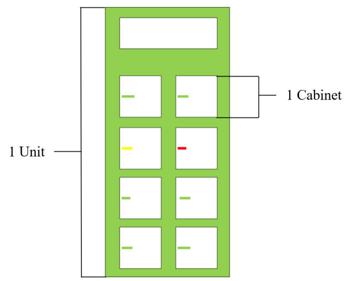

Figure 1. Battery Swapping Station Unit

One unit of BSS in this study comprises eight cabinets, with each cabinet housing one battery pack. The cabinet is also equipped with a charger that can both charge the battery when drained and discharge it when requirements are met. Nonetheless, one cabinet for each unit remains perpetually vacant during the battery changeover process. Each interconnection site in this study will be outfitted with five BSS devices.

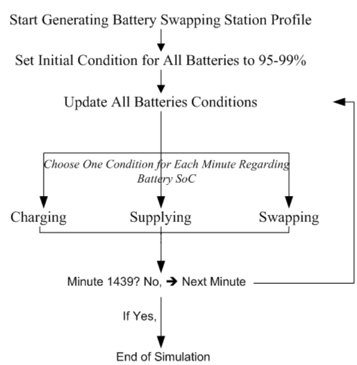

Figure 2. BSS Profile Generation Flowchart

As can be seen from the flowchart, all batteries will be preset to the initial state (minute-0) with a random SoC ranging from 95% to 99% using Monte Carlo Simulation, where the batteries will initially function to supply power to the network. Subsequently, the SoC of each battery will be assessed according to the previously outlined criteria above for one day (minute 0 – 1439). If the SoC falls outside that range, the battery will activate charging mode. To articulate it more succinctly, it is shown in Equation (1).

$$SoC_i(t) = \begin{cases} SoC_i(t-1) - \frac{P_{discharge}.\Delta t}{E_{cap}}\eta_d, \; if \; SoC_i(t-1) > 0.9 \\ SoC_i(t-1), \; if \; SoC_i(t-1) > 0.7 \; and \; U_i(t) < P_{swap}(swap \; event) \\ SoC_i(t-1) + \frac{P_{charge}\Delta t}{E_{cap}}\eta_c \end{cases} \quad (1)$$

Where,

$SoC_i(t)$: SoC of battery pack i at minute t

$P_{charge}/P_{discharge}$: charging/discharging power

E_{cap} : battery energy capacity

η : efficiency

P_{swap} : probability of swap event occurring

A Monte Carlo Simulation will randomly execute the swapping operation (SO) if the SoC conditions are met. The probability of random swapping is set at 10%. If a swap occurs, the cabinet will be empty for the next three minutes while electric vehicle drivers retrieve batteries from the BSS and exchange them for their depleted batteries. Later, the battery packs received after the swap will show a random SoC ranging from 10% to 40%.

After acquiring the BSS usage profile on a per-minute basis for a single day, it is assigned to the BSS connected to the Load Bus system. This case involved the installation of five BSS units at each BSS location.

2.2 Modified IEEE 9-Bus System

The IEEE 9-bus system has been modified to represent the typical low-voltage grid (LVG) feeder configuration of an urban setup in Indonesia. Its manageable size and complexity make the IEEE 9-bus system a benchmark test case in power system analysis, enabling detailed simulations and analyses without overwhelming computational resources. This standardized model allows for comparing various algorithms and methods across studies, including economic dispatch, stability analysis, and load flow analysis [x].

Another adjusted scheme involves replacing generator buses with external supply feeders, mirroring Jakarta's urban metropolitan area. Additionally, feeder assets, such as transformer ratings, are set at 630 kilovolts amperes (kVA), in line with the standard rates used by PLN (the state-owned electricity company) for 20 kV/380 V distribution feeder systems (DFS). The lines are also connected to the assets typically used by DFSs.

The load profile connected to the 380V LVG feeder has been developed using typical residential and office loads found in urban areas of Indonesia. These loads originate from direct field measurements that take over one minute. In this investigation, the BSS is connected to the load buses, specifically the 3rd, 4th, and 5th buses. Figure 4 illustrates the single-line diagram for the modified LVG feeder of the 9-Bus System.

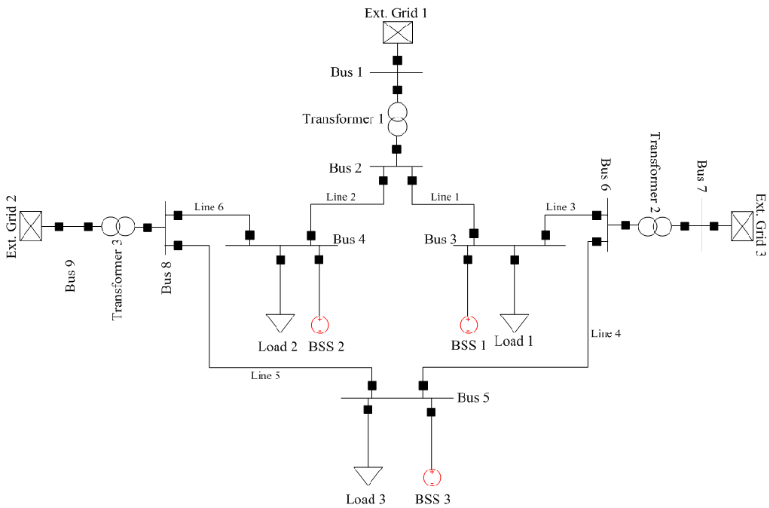

Figure 3. Modified IEEE 9-Bus System

2.3 Quasi-Dynamic Load Flow

A quasi-dynamic load flow simulation was carried out through the DigSILENT PowerFactory after generating the BSS and 9-Bus System profiles. The purpose of this simulation is to determine the effect that the BSS connection would have on the system. This simulation was carried out over the course of 1440 minutes in order to compare the conditions of the system immediately before the BSS was linked to the selected buses and after the BSS had been installed on those buses.

This quasi-dynamic analysis takes place before and after the installation of the BSS to evaluate the status of the bus voltage magnitude system, the load on the transformer, and the capacity of the lines' load system.

3. Results and Discussions

Figure 4 illustrates an examples of the day usage profile for one unit of BSS derived from the simulation. When the power is positive, the BSS is delivering energy to the grid; conversely, when the power is negative, the BSS is in charging mode. The generation profile results indicate that frequent swap actions, coupled with minimal charger power utilized in each cabinet, will likely cause the BSS unit to behave as a load rather than a supplier to the grid. The probability for urban regions will exhibit a profile akin to this, owing to the high density of vehicular usage.

As for the characteristics of the BSS that was utilized in this research, they are depicted in Figure 5, where the profile of each of the five BSS units is represented by a single line of BSS. The BSS 1 will be connected to Bus 3, the BSS 2 will be connected to Bus 4, and the BSS 3 will be installed on Bus 5 as illustrated in Figure 3.

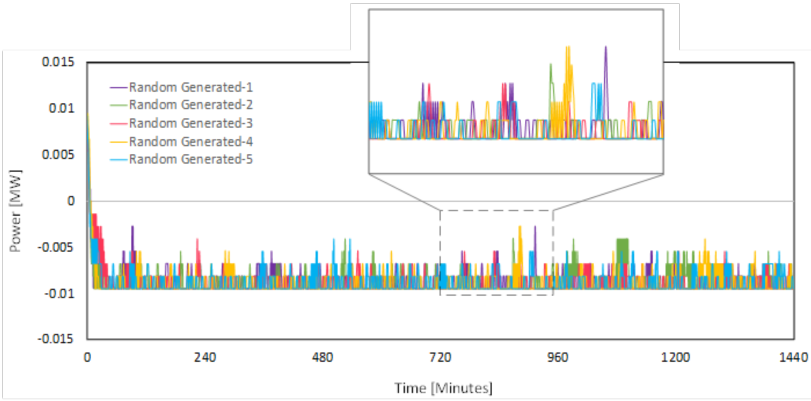

Figure 4. An Example Unit Profile Generation

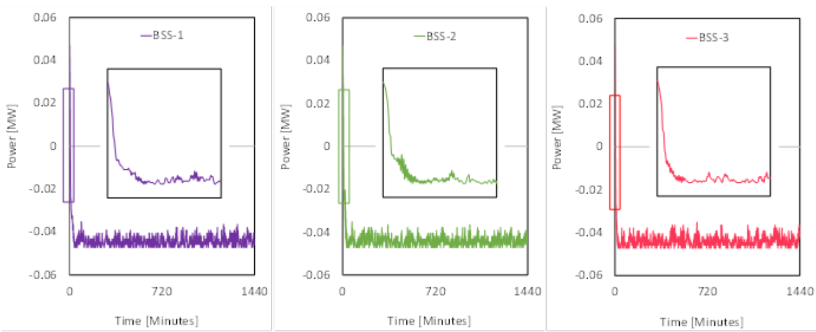

Figure 5. BSS Utilization Profiles Used

Following the acquisition of the three profiles from the BSS that will be linked to the system, a quasi-dynamic simulation was then executed. The results of this simulation included the voltage conditions, transformer loading, and system line loading both before and after the connections of the BSS. The voltages of each bus are shown below, both before and after the BSS has been linked to the three load buses that have been chosen.

All buses, with the exception of the grid buses, which are buses 1, 7, and 9, are subjected to analysis in order to determine the voltage condition. The results of the voltage simulation for the six buses that were chosen are displayed in Figure 6. It is noticeable that the voltage drops at Bus 3 and Bus 5 in general, with the exception of the first few minutes, during which the BSS is indeed designed to have an initial condition with SoC that is greater than 95%, which then satisfies the requirements for supplying the grid.

On the other hand, it has been noticed that the five BSS units that were installed on each of the three buses that were chosen did not result in a voltage drop that was lower than 0.9 p.u., which is the threshold for undervoltage situations. Likewise, the overvoltage limit when the BSS feeds the grid is not surpassed, which is 1.05 p.u.

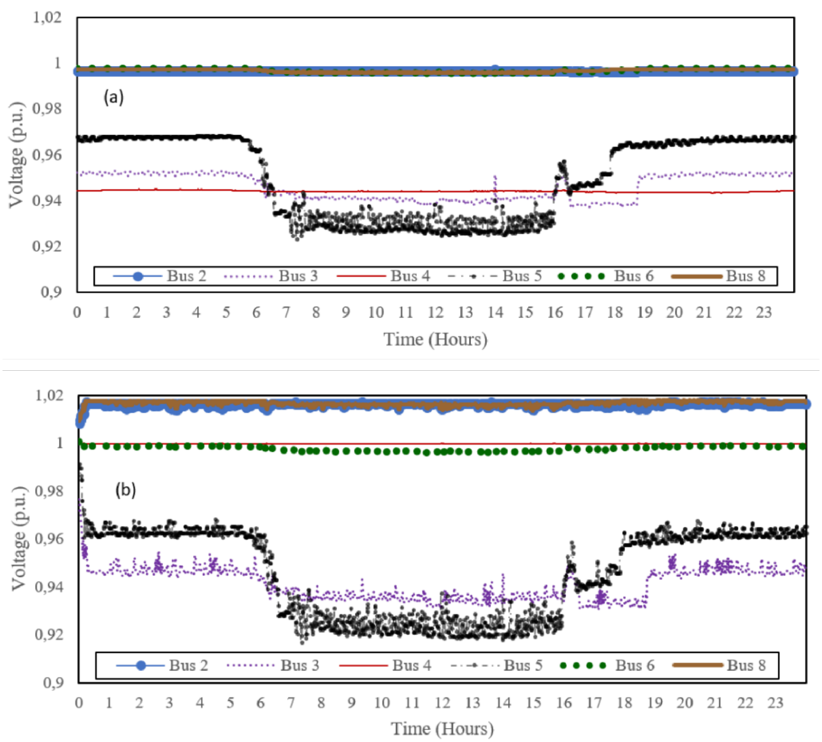

Figure 6. Buses Voltage Condition (a) Before BSS Connection, (b) After BSS Connection

Certain buses, including Bus 4, Bus 2, and Bus 8, observed an increase following the implementation of the BSS. The connection of the BSS leads to greater utilization of the supply from external grids 1 and 2, resulting in elevated voltage levels at the adjacent buses. The total amount of supply generated by the three external grids is illustrated in Figure 7. It is also noted that when the BSS is utilized to supply the grid, the output from the external grid diminishes.

The influence of integrating the BSS into the system is also seen from the transformer loading. Prior to being energized by the BSS, the loading of the three transformers reached up to 33% at peak demand, around 208 kVA for each. Nevertheless, when the BSS is integrated into the system, the load percentage of the three transformers typically escalates. A notable rise is noticed in transformers 1 and 3, where the presence of the BSS elevates their load to 60%, representing an increase of up to 30% from the baseline state which is around 189 kVA. The significant rise in transformers 1 and 3 is additionally affected by the considerable supply from external grids 1 and 2, as previously elucidated.

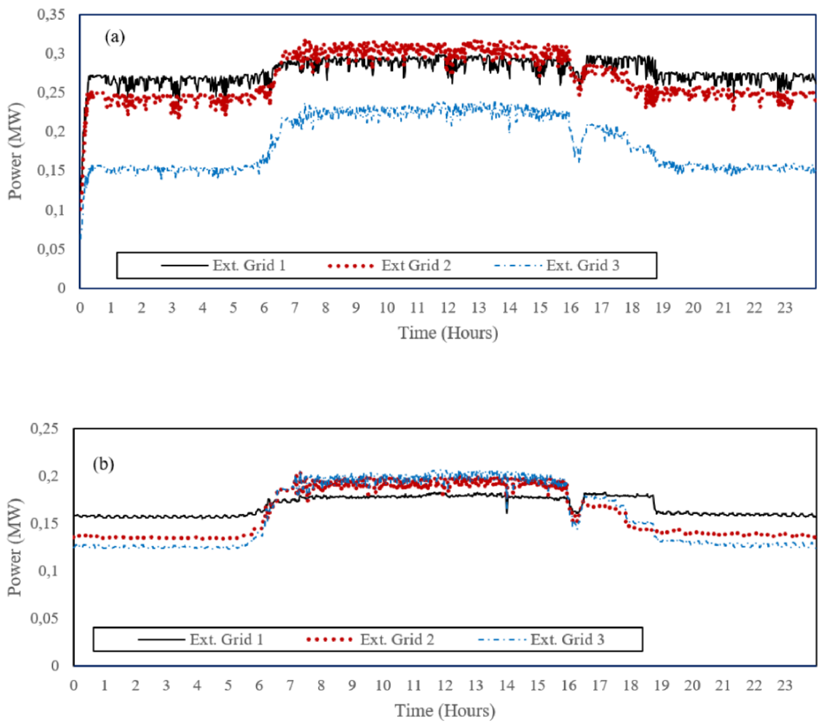

Figure 7. External Grid Supply (a) Before BSS Installation, (b) After BSS Installation

Despite two transformers registering an approximate 30% rise, the overload limit has not been surpassed, therefore maintaining the system's safety. In practical scenarios, it is probable that the operator, PLN, will necessitate further expenditure for transformer replacement if the BSS is incorporated into the system, given that a 30% load increase is considerable.

In addition to bus voltage and transformer loading, this simulation also analyzes the line conditions inside the system. It is crucial to assess the potential for heightened losses that may negatively impact the longevity of current assets.

The presence of BSS shows up in Figure 9, as the line burden also increases. Line 4 and Line 5 experienced the highest traffic prior to the installation of the BSS, with a peak load of approximately 60% in the afternoon. Nevertheless, the entire line encountered an increase in load when the BSS was installed on the three selected buses. A 20% increase was observed in line 5. Nevertheless, the load in Line 2 and Line 6 is actually the most considerable, with a maximum of ±160%. This is due to the fact that the majority of the load is supplied by external grids 1 and 2. Consequently, in order to transmit power from these two external grids, Lines 2 and 6 will be transmitted through, resulting in a substantial increase for both lines.

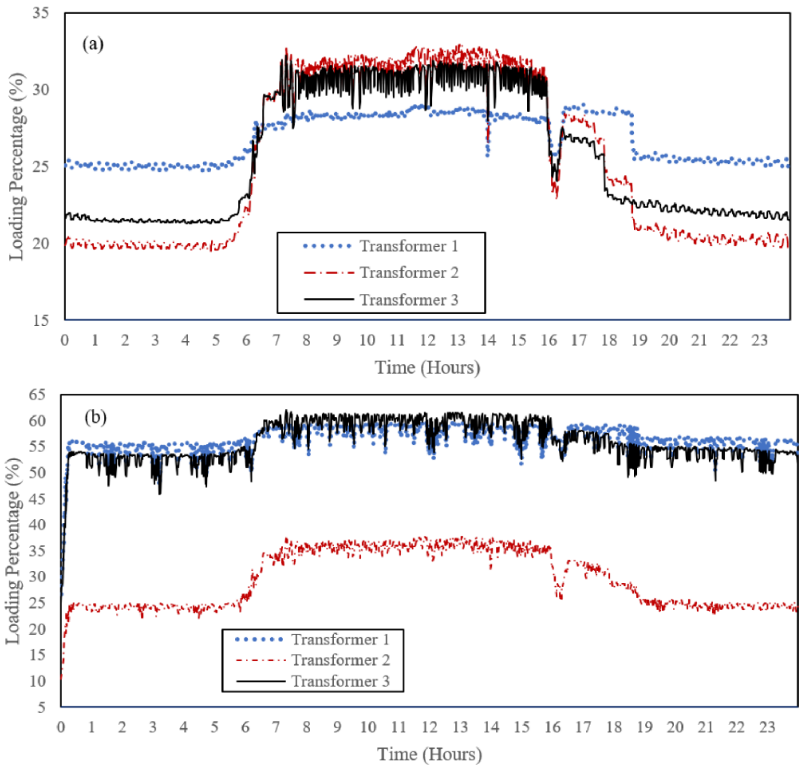

Figure 8. Transformer Loading (a) Before BSS Installation, (b) After BSS Installation

An increase of up to 160% is highly detrimental to the network, resulting in even greater heat losses. The power transfer utilized by the system must be monitored by operators to prevent the occurrence of incidents similar to those depicted in the simulation results.

The results suggest that, despite the operational convenience and acceleration of EV adoption that BSS provides, it also introduces significant stress to urban distribution networks. The necessity of anticipatory infrastructure enhancements is underscored by the observed increases in transformer and line loading. Utility providers such as PLN are required to evaluate the power quality metrics and feeder headroom before sanctioning BSS installations. in practical terms. Potential mitigation strategies include the optimization of BSS siting, the integration of local energy storage systems, and the implementation of scheduling algorithms that restrict simultaneous charge. The necessity of comprehensive system-level planning when deploying BSS in urban centers is further underscored by the impact of external grid locations on load transfer.

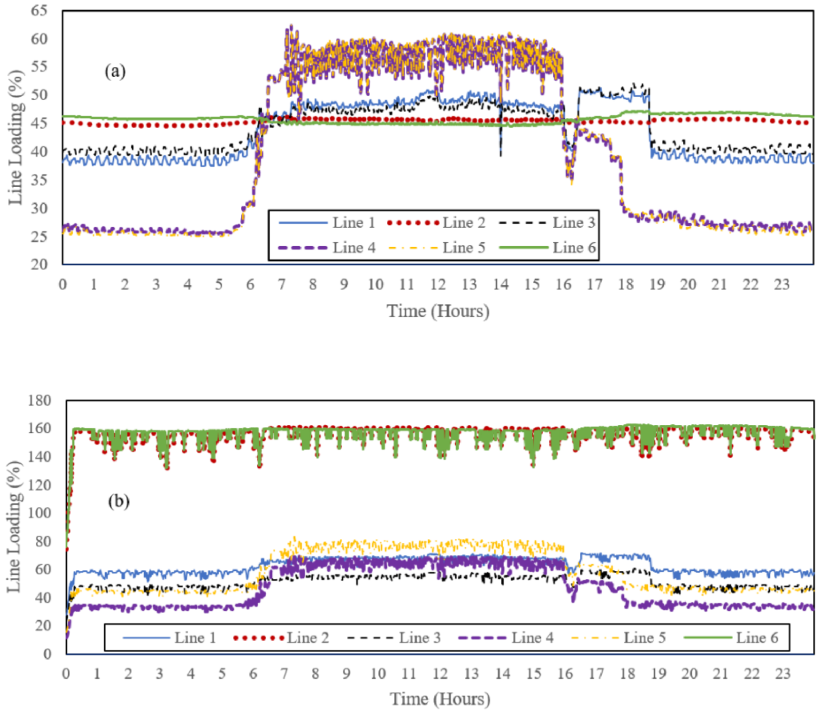

Figure 9. Line Loading (a) Before BSS Installation, (b) After BSS Installation

4. Conclusion

The impact of battery swapping for electric two-wheelers on the electrical infrastructure in Indonesia is the subject of this study, which provides a detailed analysis. We demonstrate that BSS integration, despite its advantages, results in substantial voltage fluctuations, increased line loading, and transformer loading by employing a modified IEEE 9-bus system and realistic random-based user behavior. The results underscore the significance of conducting a comprehensive time-series analysis when evaluating the deployment of electric vehicle infrastructure, particularly for low-voltage systems with restricted buffering capacity. When developing technical standards and support mechanisms for the deployment of BSS, policymakers and utility administrators should take these operational impacts into account. Future research should broaden the scope of this analysis to encompass larger networks, optimize placement and dimensions, and investigate mitigation strategies such as localized energy storage or demand response.

The complexity of full-scale distribution networks is not captured by the modified 9-bus system, which, while representative of Indonesian urban feeders, is a constraint on this study. This analysis should be expanded to encompass larger, meshed systems with medium-voltage integration in future research. Additionally, optimization studies could be implemented to ascertain the optimal placement and size of BSSs within the context of economic, spatial, and regulatory constraints. The planning of future electric mobility infrastructure would also be enhanced by the investigation of control schemes such as coordinated charging or demand response, which are based on grid conditions.

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