Voltage Instability and Voltage Regulating Distribution Transformer Assessment Under Renewable Energy Penetration For Low Voltage Distribution System

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Article Info

Article history:

Received Jun 11, 2023
Revised Jul 13, 2023
Accepted Aug 26, 2023

Keywords:

Voltage-Regulated Distribution Transformer (VRDT)
Low Voltage (LV)
Voltage stability
Voltage Drop Model

ABSTRACT

The Voltage Regulating Distribution Transformer (VRDT) is a tap-changing transformer that regulates the voltage across all three phases. However, its application in the context of renewable energy penetration into low-voltage grids remains understudied. This paper addresses this research gap by presenting a refined voltage drop model tailored for the International Islamic University Malaysia (IIUM) distribution network. Based on a derived mathematical equation, the model is validated and analyzed using Simulink's modeling platform. Simulations are performed without and with the VRDT, revealing that renewable energy penetration can cause instability, leading to voltage deviations proportional to the injected renewable energy. Incorporating the VRDT in the low-voltage grid allows for voltage adjustment under loaded conditions, ensuring uninterrupted renewable energy injection. Voltage stability analysis is conducted using actual load consumption data from the IIUM network for 2020 and 2021, offering valuable insights despite assuming equal energy consumption across buildings. Most hostels exhibit stable distribution systems with solar energy, but instability arises when solar energy comprises 100% of the input for the Safiyyah and Zubair hostels' 11kV distribution transformers. Implementing the VRDT regulates this instability, restoring system stability. This study highlights the importance of VRDT integration in high renewable energy proportion low-voltage grids, enabling voltage regulation and stability under variable renewable energy injection scenarios. The findings demonstrate that VRDTs mitigate voltage instability caused by renewable energy, providing a reliable solution for incorporating renewables into low-voltage distribution networks. It contributes to understanding renewable energy's impact on distribution system stability and offers guidance for VRDT implementation in similar contexts.

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1. INTRODUCTION

The increase in mobile phone transactions in Malaysia, as demonstrated by a 2019 study, reflects a significant lifestyle shift in which gadgets have become indispensable [1]. As a result, the number of electrical consumers has increased steadily [2]. In accordance with the Malaysian government's commitment to the

Sustainable Development Goals (SDGs), solar energy adoption has increased dramatically [3-5]. Moreover, the increase in electric vehicles and the establishment of charging stations for electric vehicles demonstrate the nation's support for the SDGs and its desire for a greener environment [6, 7]. However, the passive nature of Low-Frequency Transformers, which fail to manage reactive power flow and grid voltage effectively, contributes to voltage instability issues [8]. Problems with distribution voltage control involve power quality, energy efficiency, and system stability [9, 10].

In order to address voltage instability and imbalance, the voltage drop model is used to detect such issues in the system. Several methods have been proposed to mitigate these issues, including installing poles and wires or Voltage Regulating Distribution Transformers (VRDTs) at substations [11]. Reducing grid impedance by poles and wires results in less severe voltage deviations and the maintenance of an acceptable voltage range. In contrast, VRDTs regulate voltage violations by imposing limits on voltage fluctuations. During grid expansion, another advantage of VRDTs is their ability to accommodate larger cable cross-sections and permit parallel cable installations [11, 12].

The number of feeders decreases as the length of the feeder increases, indicating that this method is only appropriate for feeders within a specific distance range, beyond which under-voltage issues may arise [11]. Moreover, the installation of poles and wires is more complicated than the installation of VRDTs. In contrast, distance does not affect VRDT operation. Moreover, VRDTs effectively resolve voltage instability issues caused by varying distances in secondary transformer distribution. By implementing VRDTs, the number of switching events can be limited, thereby reducing wear and enabling maintenance-free operation that exceeds the lifetime of Low-Frequency Transformers [13]. The strategic placement of VRDTs provides a significant technical buffer against increasing photovoltaic (PV) capacity, exceeding the benefits of conventional grid expansion (e.g., poles and cables) at low PV implementation levels, as stated in [14].

Therefore, this paper presents a novel, improved voltage drop model explicitly designed for International Islamic University Malaysia's distribution network (IIUM). The primary goal is identifying and resolving potential voltage instability issues within the system. The proposed model is exhaustively tested with and without the implementation of VRDTs, allowing for a thorough comparison with Matlab/Simulink simulations of IIUM's distribution line. The results of this study significantly contribute to the analysis and validation of the voltage drop model by utilizing MATLAB/Simulink simulations for a comprehensive comparison. In addition, it provides conclusive evidence that VRDTs effectively mitigate voltage instability caused by the high penetration of renewable energy in the Malaysian distribution system. The outcomes of this research will provide valuable insights for power system operators and policymakers, facilitating the making of well-informed decisions to ensure the reliable integration of renewable energy sources into low-voltage distribution networks.

2. VOLTAGE REGULATION MECHANISM AND EFFECTS OF VRDT

Voltage regulating distribution transformers (VRDTs) play a crucial role in maintaining a stable voltage band by dynamically adapting the voltage drop and rise in the transformer between medium and low-level voltage [11]. Consequently, VRDTs have emerged as a viable solution to counteract significant voltage fluctuations in power systems. Evidence from Germany demonstrates the positive impact of VRDT implementation on power distribution systems [15], optimizing the efficiency of electricity distribution [12]. While the initial cost of implementing VRDTs in a power system may be high, they are cost-effective in the long run, and they can generate savings of up to 80% when integrating renewable energy sources [16].

The technical mechanism of VRDTs revolves around integrating the On-Load Tap Changer (OLTC) in conventional transformers [17, 18]. OLTC serves as a critical component of VRDTs and enables the transformer to operate without isolation, either automatically or manually [15]. It works by adjusting the transformer's turns ratio, achieved by modifying the winding turns to adapt to the desired tap of a tap winding transformer under load conditions [15, 17].

The fundamental principle of all OLTC transformers involves two distinct parts: electrical and mechanical components. Figure 1 illustrates the electrical control of OLTC, featuring upper and lower control sections [19]. One part is the lower, which returns the value of tap position (m) from calculating the error by differentiating between the reference voltage ($v_{s,rif}$) and the actual value (v_s) based on fixed time pace (Ts), which depends on the types of OLTC regulators. Another part of the OLTC transformer is an upper control to generate a voltage reference signal ($v_{s,rif}$) that is dependent on the desired tap location (m_{rif}) to fulfill the required levels of quality in delivering power (bus voltage values) and a lifetime of OLTC. The input to the upper-level control is the OLTC's reference signal ($v_{s,rif}$). The difference in tap position values (m) between the reference and actual values is fixed by an adequately tuned integral regulator to alter the needed voltage (vs, rif) by slower dynamics than the previously established control.

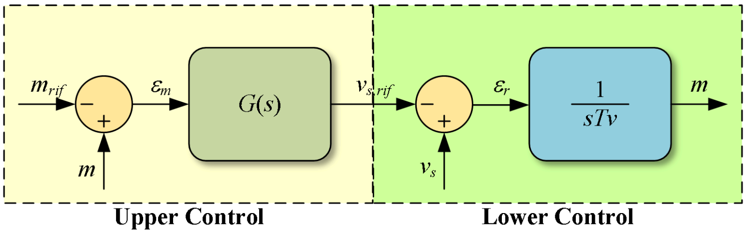


Figure 1. The control mechanism of OLTC transformer.

In the mechanical mechanism of OLTC, the transformer typically has 33 positions (16 lower and 16 higher), with the standard tap setting located between the lower and higher taps [20]. Each tap setting has incremental and decremental adjustments based on the OLTC's specifications. Eq. (1) highlights the inverse proportionality between V_2 and the winding ratio or the number of primary winding turns [21]. By adjusting the primary winding, the desired output voltage for the transformer can be obtained as follows:

$$\frac{N_1}{N_2} = \frac{V_1}{V_2} \tag{1}$$

where N_1 represents the number of turns on the primary side of the transformer, N_2 represents the number of turns on the secondary side, V_1 represents the primary voltage and V_2 represents the secondary voltage.

3. VOLTAGE DROP MODEL AND VOLTAGE STABILITY ANALYSIS

The voltage drop model is the primary detection method to ensure voltage stability in the IIUM's distribution grid. To improve the accuracy and efficacy of this model, however, integrating renewable energy (RE) sources into the IIUM low distribution grid must be considered. By incorporating the effect of RE penetration, the improved voltage drop model provides a complete understanding of the system's voltage stability dynamics. If the IIUM standard distribution grid experiences voltage instability, installing Voltage Regulating Distribution Transformers (VRDTs) becomes essential. These VRDTs are critical for maintaining voltage stability throughout the distribution network. VRDTs regulate and stabilize the voltage band by dynamically adjusting the voltage drop and rise in transformers between medium voltage (MV) and low voltage (LV) levels.

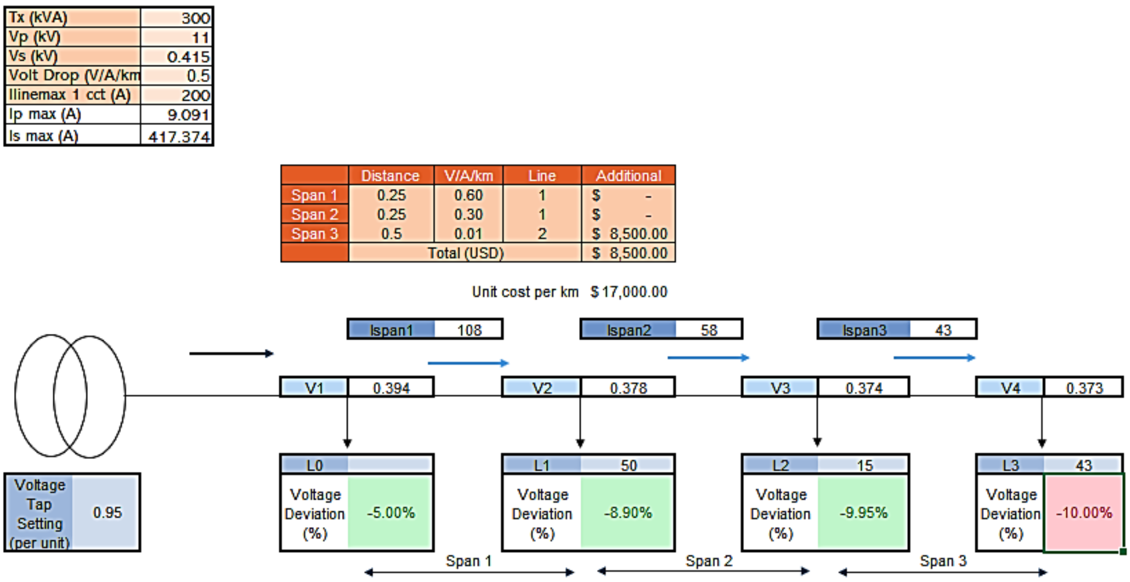


Figure 2. The voltage drops model simulation

The voltage drop model is illustrated in Figure 2, similar to our benchmark paper in [22]. The model demonstrates the voltage tap operation at the secondary substation, where the connection continues to the low-voltage users. The diagram's symbols provide vital insights into the system: "$Ispan$" represents the currents, "V" represents the voltage, and "L" represents the grid's loads. Ohm's law dictates that the current ($Ispan$) gradually decreases as one moves down the feeders. The voltage tap occurs between the MV and LV grids in the substation transformer. Assuming a radial configuration of feeder connections, the feeder begins at $V2$, and the downstream loads continue. Due to the parallel connection of the feeders, the voltage between them remains constant.

In the figure, the voltage deviation is denoted by color coding: green indicates that the load operates within the nominal voltage range without compromising voltage stability, whereas red indicates variations that show potential instability issues. This study seeks to ensure voltage stability and dependable power supply in the IIUM distribution system by analyzing the enhanced voltage drop model and implementing VRDTs. These measures support the transition to a greener, more sustainable energy infrastructure and align with the IIUM's commitment to sustainable development objectives.

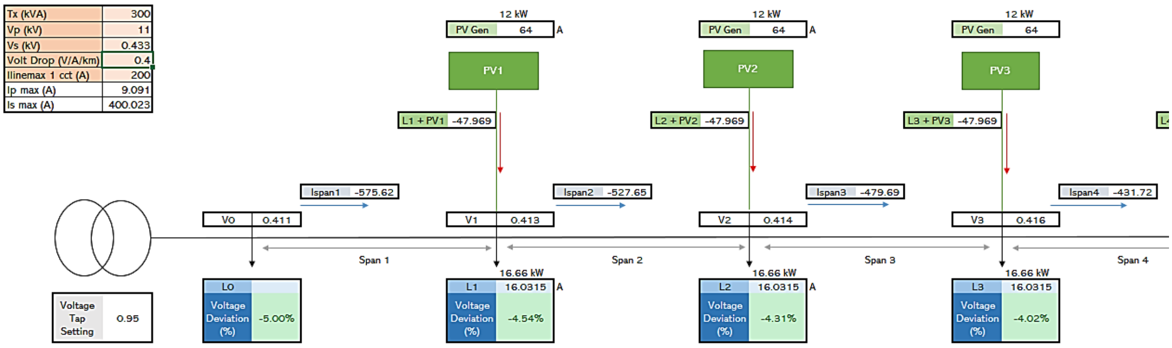


Figure 3. The voltage drops model simulation with RE in IIUM

Figure 2 depicts the original voltage drop model without injecting renewable energy. Figure 3 shows the new voltage drop model with the injection of renewable energy into the low distribution grid. Figure 4 illustrates the Zubair and Safiyyah hostels distribution grid chosen for this paper. The location of the transformers shared by these two hostels in the IIUM distribution system is indicated with an 'X' on the diagram. The simulation is based on a 25 percent increase every five years, as stated in [23]. Consequently, four percentages of RE injection are simulated, namely 25%, 50%, 75%, and 100%. The simulations considered a radial system in the low-voltage line, as shown in Figures 3 and 4. The equation of the new voltage drop model is derived by trial-and-error from Figure 3, referencing the industrial voltage drop equation and the voltage drop model without RE injection, as depicted in Figure 2. The new equation is displayed in Eq. (4) and Eq (5).

Figure 4. The distribution line of Zubair and Safiyyah hostel.

Eq. (2) shows the industry's widely used voltage drop calculation. The voltage after passing through the voltage tap is as in Eq. (3). The voltage drop formula in Eq. (4) is based on the voltage drop model simulation from Figure 2. Both Eq (3) and Eq (4) are based on [22]. This paper proposes an enhanced voltage drop formula where renewable energy penetration in the LV distribution line is considered based on Figure 3. This proposed equation is described in Eq. (5) and Eq. (6) using a three-phase voltage drop calculation.

$$v_{n+1,ll} = \sqrt{3}\left(\left(\frac{V_n, ll}{\sqrt{3}}\right) - I_{span,n} \times R_{span,n}\right) \tag{2}$$

where $V_{n+1,ll}$ is the line voltage at $n+1$, $V_{n,ll}$ is the line voltage at n, $I_{span,n}$ is the current along line n, and $R_{span,n}$ is the resistance along the line n.

$$Voltage(V) = voltage\ tap \times secondary\ voltage\ (V_s) \tag{3}$$

$$V_n(V) = V_{n-1} - \left(Resistivity\left(\frac{\Omega}{km}\right) \times L(km) \times I_{span}(A)\right) \tag{4}$$

$$V_n(V) = \sqrt{3}\left(\frac{V_{n-1}}{\sqrt{3}} - \left(Resistivity\left(\frac{\Omega}{km}\right) \times L(km) \times I_{span}(A)\right)\right) \tag{5}$$

where $Resistivity = R_{span}(\Omega)/length(km)$, V_n is the voltage at n, V_{n-1} is the voltage at $n-1$, and L is the distance between the substation and the load.

$$I_{span,n}(A) = I_{load} + I_{pv} - I_{n+1} \tag{6}$$

where $I_{span,n}$ is current along the n, I_{load} is current at load and I_{pv} is current of photovoltaic injection and I_{n+1} is the current at $n+1$.

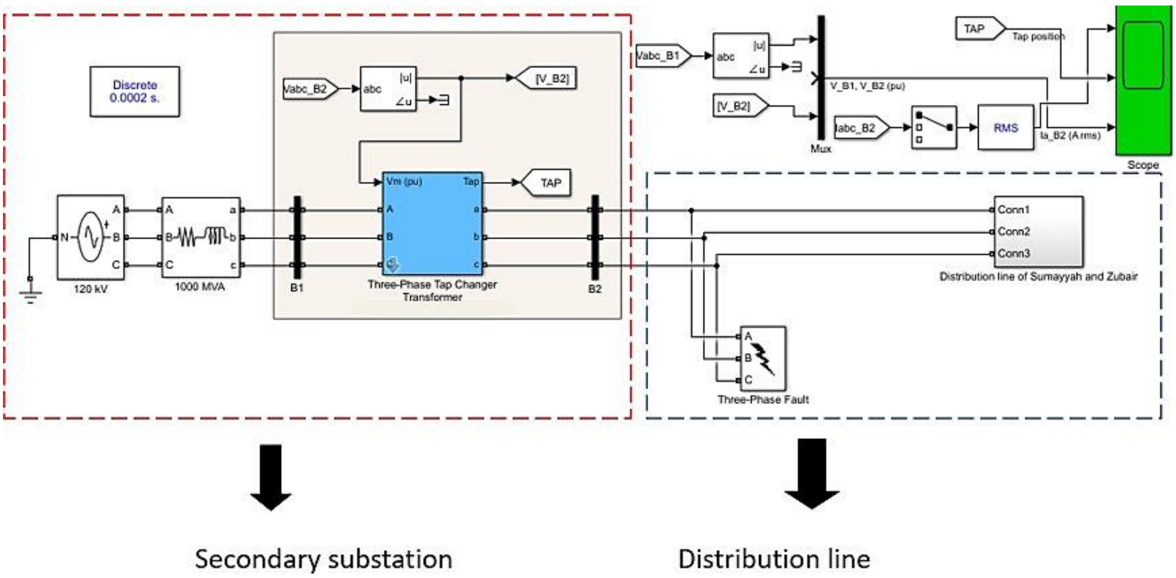


Figure 5. The VRDT in the secondary substation and the Zubair and Safiyyah hostel distribution line in Simulink.

A comprehensive MATLAB/Simulink simulation of the IIUM distribution line was created to compare and validate the performance of the voltage drop model and assess its efficacy. Together with the outcomes generated by the voltage drop model, the results of this simulation served as a benchmark for comparison and analysis. Figure 5 depicts the configuration of the VRDT and IIUM distribution system, which incorporates solar energy as the selected renewable energy source. The simulation considers the solar energy injection at each load along the IIUM distribution line. The voltage drop model and MATLAB/Simulink simulation use the same Zubair and Safiyyah hostel feeders.

This research aims to evaluate the performance of the voltage drop model in the context of the IIUM distribution system by simulating and analyzing the results. The comparison between the MATLAB/Simulink simulation and the voltage drop model provided valuable insights into the model's accuracy and dependability, particularly when considering the impact of renewable energy integration. Ultimately, this study aims to contribute to developing efficient strategies for managing voltage stability and optimizing electrical power distribution in the IIUM system.

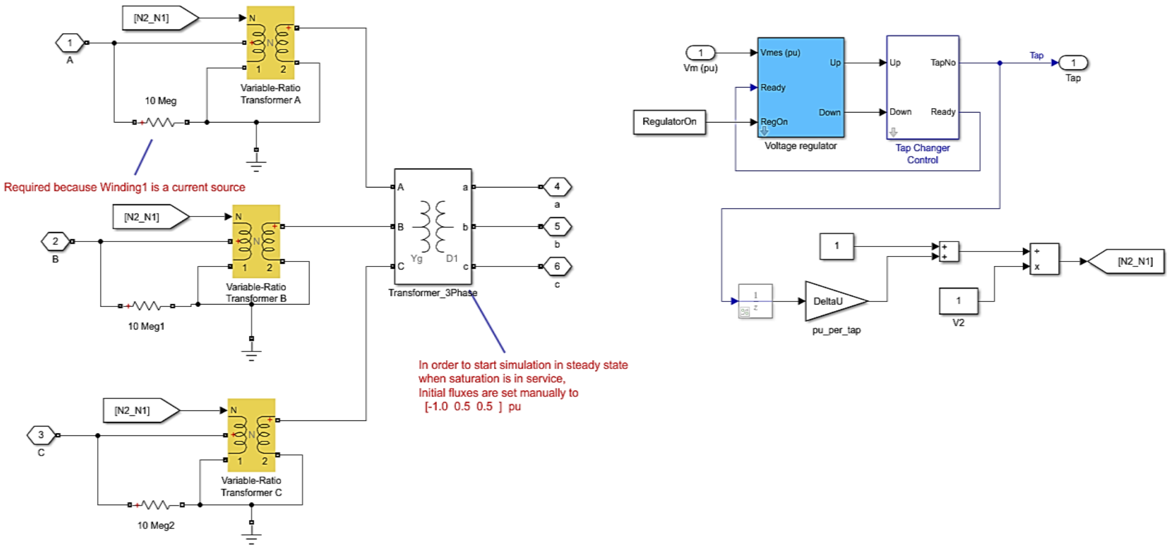


Figure 6. The VRDT configuration in Simulink

Figure 6 depicts the configuration of step-down transformers equipped with OLTC in the secondary substation VRDT. This configuration includes a three-phase transformer and OLTC. Variable-ratio transformers convert the continuous signal to a discrete signal to facilitate voltage injection into the transformer. The signal then enters the OLTC, which consists of a voltage regulator and tap changer control, after passing through the transformer.

The voltage regulator plays a vital role in maintaining a regulated output signal by adjusting the voltage level to achieve a fixed output. On the other hand, the tap changer control monitors the voltage signal. It determines whether to increase or decrease the tap changer, adjusting the voltage output to match the load requirements based on the reference voltage. By combining the functions of the voltage regulator and tap changer, the VRDT system can maintain the voltage on the low voltage side of the power transformer within a predetermined dead band.

This configuration of the VRDT system with OLTC demonstrates its ability to dynamically regulate and stabilize the output voltage, ensuring that it remains within the optimal operating range. The precise control provided by the voltage regulator and tap changer combination contributes to the overall voltage stability of the distribution system. This mechanism's effectiveness in preventing voltage fluctuations and maintaining constant voltage levels is essential for ensuring the reliable and efficient functioning of the power distribution network.

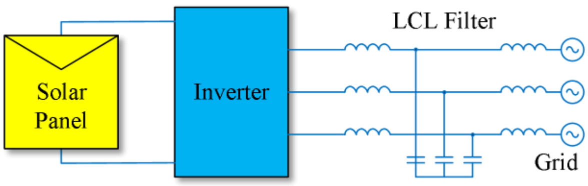


Figure 7. The solar panel system configuration

Figures 7 and 8 depict the configuration and schematic diagram of a single-stage, three-phase solar panel system. As shown in Figure 7, a single-stage solar system employs a single inverter to convert the DC power generated by solar panels into AC power fed into the grid. A single-stage solar system is preferred over a double-stage inverter configuration for several reasons, including its lower cost, higher power density, compact size, increased efficiency, and enhanced dependability.

An LCL resonance filter (inductor-capacitor-inductor) is incorporated into the system to minimize harmonics in the current absorbed by the power converters to ensure the quality of power injected into the grid. This filter is essential for reducing unwanted distortions and preserving the power quality of the solar system. In addition, the MATLAB/Simulink simulation requires the implementation of Maximum Power Point Tracking (MPPT). The schematic diagram of MPPT in a single-stage, three-phase solar system is depicted in Figure 9. MPPT is a technique used to continually track and maintain the operating point of solar panels at the maximum power level, regardless of environmental conditions. By dynamically adjusting the operating parameters, such as the voltage and current, the MPPT algorithm ensures that the solar system operates at its highest efficiency and generates the most energy.

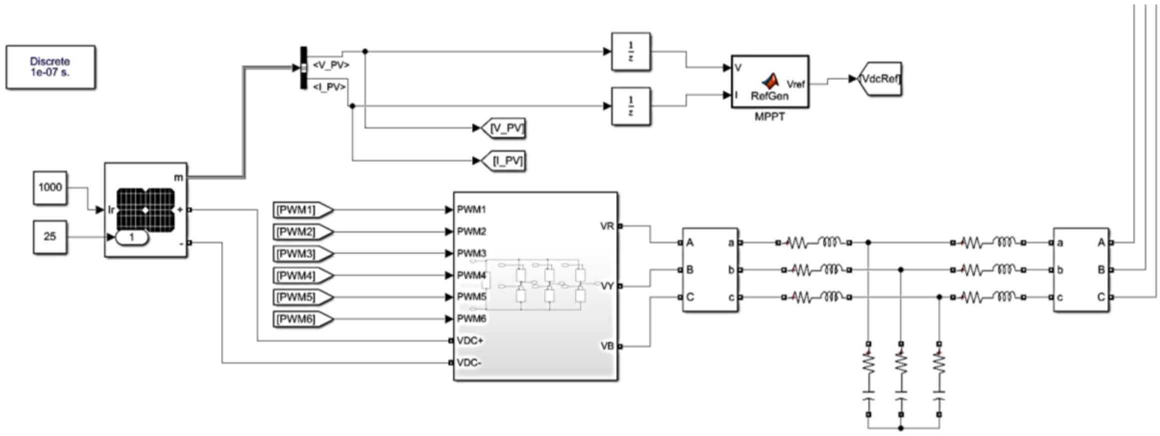


Figure 8. The solar panel system in Simulink

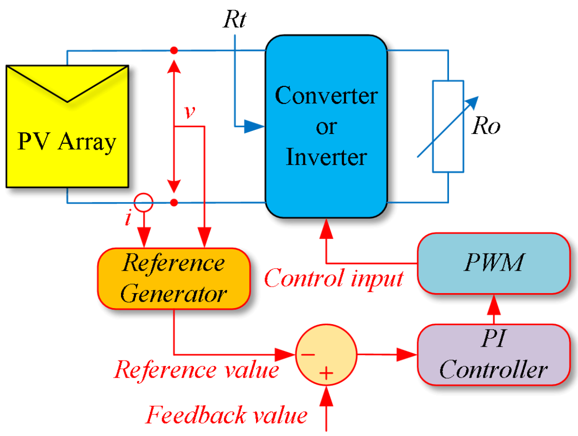


Figure 9. The schematic diagram of MPPT

Integrating a single-stage, three-phase solar system, in conjunction with an LCL filter and MPPT algorithm, improves the overall performance and efficiency of the solar energy conversion process. These components collaborate synergistically to optimize power generation, minimize losses, and enhance the solar system's dependability and stability.

Usually, the load pattern and RE production chart of a residential distribution line in Figure 10 demonstrate two separate high points, while the RE generation aligns with a typical curve. A forward current movement becomes apparent when the line carries a substantial load but has limited renewable energy generation. On the other hand, when the line showcases plentiful RE generation but minimal loads, a backward flow of current occurs, causing a reversal of power direction and potential instability within the line [24].

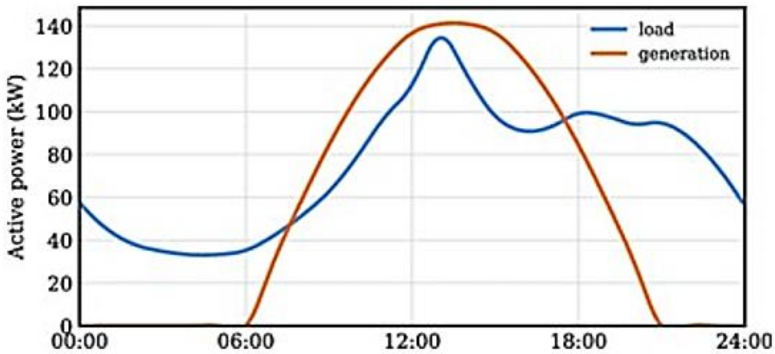


Figure 10. The load pattern and RE production chart of a residential distribution line, adopted from [24].

4. RESULTS AND DISCUSSION

With or without VRDT, the voltage drop model is a valuable tool for detecting voltage instability. MS-Excel was used to analyze 2020 and 2021 IIUM load consumption data to construct the voltage drop model. Due to the COVID-19 pandemic, it is essential to note that the load consumption during these years was not at its peak. In the analysis, it was assumed that each building consumes the same amount of energy.

Most hostels' distribution systems remain stable despite the addition of solar energy. However, the distribution transformer operating at 11kV for the Safiyyah and Zubair hostels exhibited instability when injected with 100 percent solar energy. By implementing VRDT, the instability caused by integrating renewable energy sources was effectively regulated, restoring distribution system stability.

The voltage deviation of the Zubair and Safiyyah hostels without VRDT and renewable energy injection is depicted in Figure 10. Figure 11 shows the voltage deviation data for the first four months of 2020 for the Safiyyah and Zubair hostels with RE injection but without VRDT. Any deviations exceeding or falling below 10% are considered unstable. After the injection of RE, the voltage deviation pattern is observed to change. When 100% of RE was injected, the voltage deviation exceeded 10%, indicating that the distribution systems could only accommodate up to 75% solar penetration. Figure 12 demonstrates that with the implementation of VRDT in the Safiyyah and Zubair distribution systems, the voltage became stable across all percentages of RE injection, and the voltage deviation remained within the range of ±10%.

The voltage drop model can detect voltage instability with and without VRDT. The voltage drop model has been constructed using IIUM load consumption data in 2020 and 2021 in MS-Excel and noted that in these years, the consumption is not at maximum because of the situation affected by COVID-19. The assumption that has been made in getting the results is that every building has the same amount of consumption. For most hostels, the distribution systems are stable even with the injection of solar energy. However, the distribution transformer of 11kV for Safiyyah and Zubair hostels shows instability only if 100% of solar energy is injected into the distribution system. With the implementation of VRDT, the instability created by renewable energy is regulated, making distribution systems stable again.

Figure 11 displays the voltage deviation of the Zubair and Safiyyah hostel without VRDT and RE injection. In contrast, Figure 12 shows the data of Safiyyah and Zubair hostel's voltage deviation with RE injection but without VRDT in the first four months of 2020. Percentages above or below 10% are considered unstable. After RE injection, the voltage deviation pattern changes. After 100% of RE injection, the voltage deviation exceeds +10%. It shows that the distribution systems can be catered to until 75% of solar penetration only. Then, the implementation of VRDT is executed in the Safiyyah and Zubair distribution system, and the voltage becomes stable again in all percentages of RE injection, where the voltage deviation was between ±10%, as seen in Figure 13.

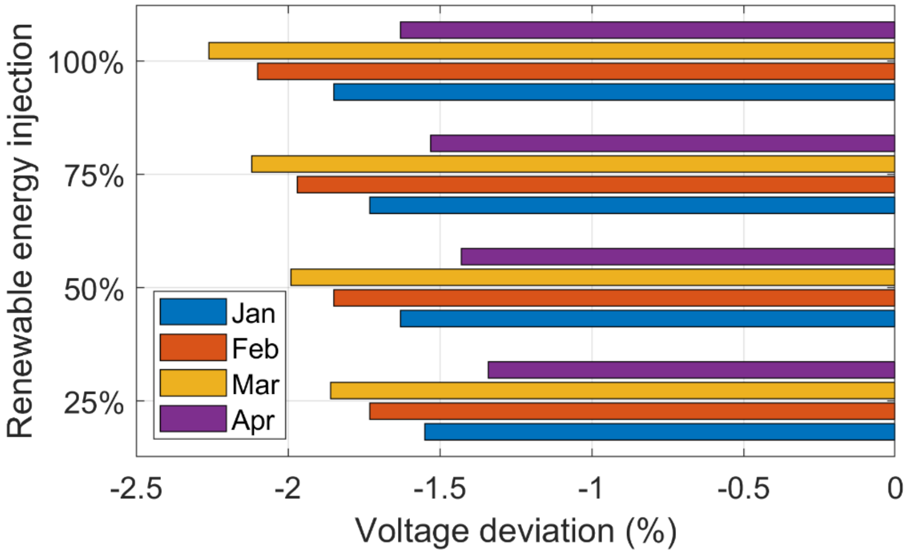


Figure 11. The voltage deviation of Safiyyah and Zubair hostel without VRDT and RE injection

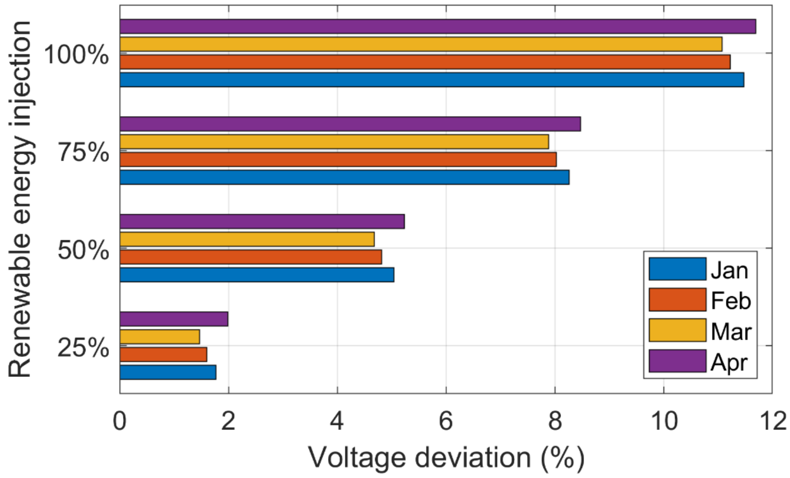


Figure 12. The voltage deviation of Safiyyah and Zubair hostel without VRDT with RE injection

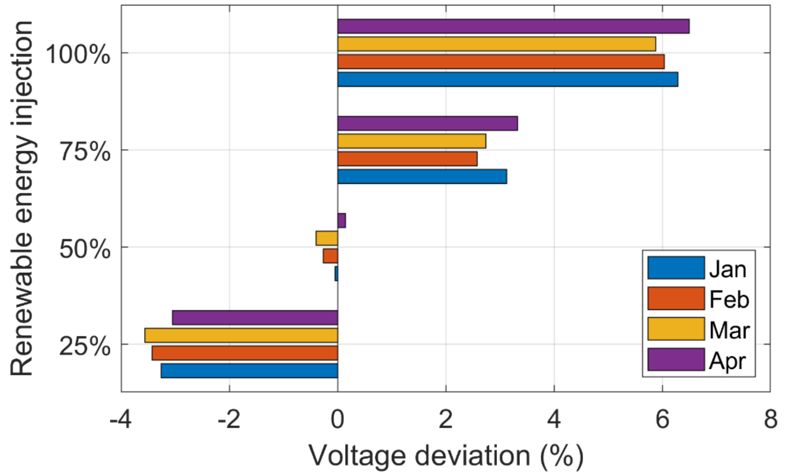


Figure 13. The voltage deviation of Safiyyah and Zubair hostel with VRDT and RE injection

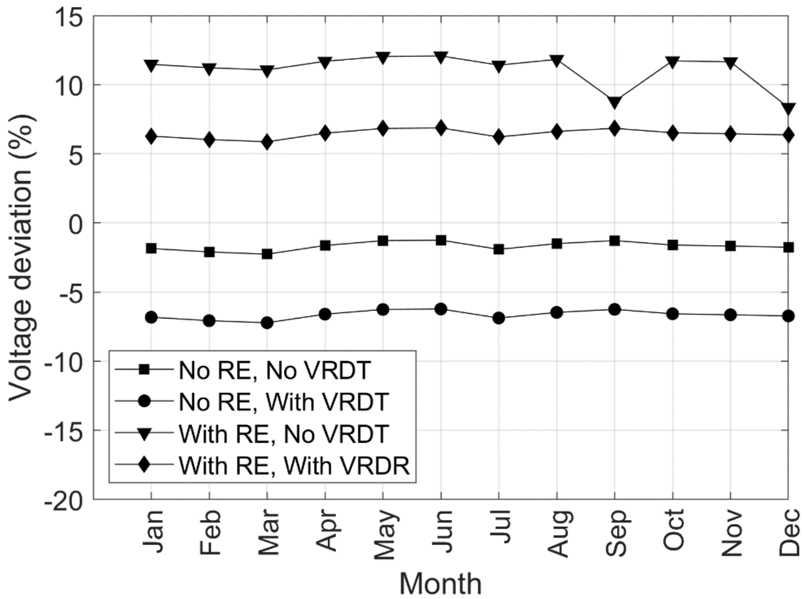


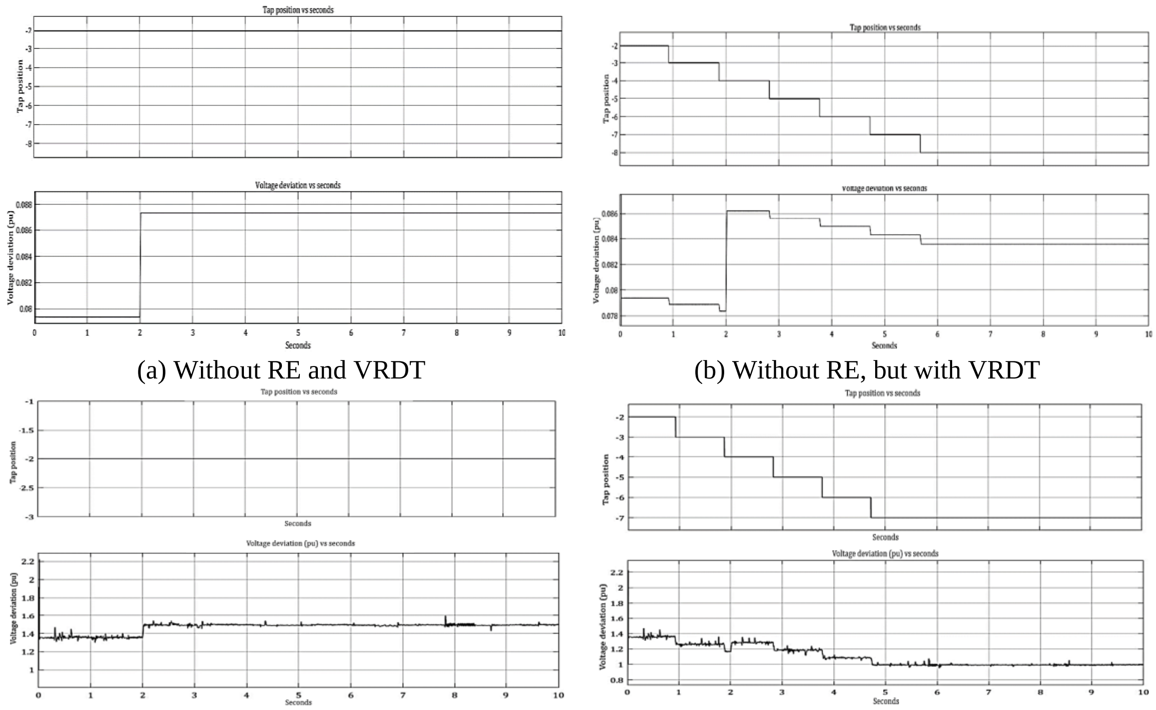
Figure 14. Comparison of Zubair and Safiyyah distribution line using voltage drop model

The graphs obtained from the enhanced voltage drop model and MATLAB/Simulink simulation are analyzed in detail in Figures 14 and 15. The information presented in Table 1 focuses on scenarios in which

100 % renewable energy (RE) is injected into the distribution systems of hostels Safiyyah and Zubair in 2021. The purpose of the table is to illustrate the presence or absence of voltage instability under various conditions.

When there is no RE injection, the voltage deviation in Figure 14 remains within the acceptable range of 10%, indicating no voltage instability. It suggests that the existing distribution systems can handle the load demand without experiencing any adverse effects. Except for September and December, most months exhibit voltage instability when solar power is introduced into the grid, with voltage deviations exceeding the permissible limits. This instability directly results from incorporating renewable energy into the distribution system and poses a significant challenge to maintaining a stable voltage profile.

Implementing VRDT in secondary substations effectively mitigates the voltage rise caused by integrating renewable energy sources. The VRDT regulates the output voltage, ensuring the voltage deviation remains below +10 % and preserving the distribution system's stability. This finding suggests that VRDT is crucial in addressing the difficulties of integrating renewable energy sources into the grid.



(a) Without RE and VRDT (b) Without RE, but with VRDT

(c) With RE, but without VRDT (d) With RE and VRDT

Figure 15. Comparison of Zubair and Safiyyah distribution lines in Simulink

Figure 15 illustrates the influence of solar power injection on voltage deviation, as simulated in MATLAB/Simulink. Solar power injection produces a modest increase in voltage deviation from 0.079 pu to 0.087 pu, which remains well below the acceptable threshold of +10 %. The modest increase in voltage indicates that the distribution system can accommodate the additional power produced by the solar panels without experiencing significant instability. However, voltage fluctuations become more pronounced when RE is integrated into the IIUM low distribution grid. In a short period, the voltage increases to 1.35 volts per unit in 0.1 seconds and 1.5 volts per unit in 2 seconds, representing significant increases of 35 % and 50 %, respectively. It highlights the potential for voltage instability in a system with a high proportion of RE.

Once more, the implementation of VRDT emerges as a critical factor in mitigating these voltage variations. With the implementation of VRDT, the voltage is reset to 1 pu, effectively resolving the instability caused by incorporating renewable energy. This finding highlights the importance of VRDT in maintaining a stable voltage profile, particularly when addressing the challenges of high levels of renewable energy integration.

Thus, when comparing the voltage drop model and Matlab/Simulink simulation, both consistently demonstrate stable voltage levels within the acceptable range of +10%/-10% when no renewable energy is injected into the distribution line. However, voltage instability becomes evident under 100% renewable energy injection, exceeding the +10% threshold. Nonetheless, VRDT successfully mitigates this instability, highlighting its significance in addressing the challenges associated with renewable energy integration. These findings provide valuable insights for designing and operating distribution systems with high penetrations of renewable energy, ensuring the grid's stability and dependability.

Table 1. Comparison of unstable load with and without VRDT.

Year (Percentage of RE injection)	Percentage of Unstable Feeders without VRDT			Percentage of Unstable Feeders with VRDT		
	Paper [22]	This Paper: Voltage drop model	This Paper: MATLAB/ Simulink	Paper [22]	This Paper: Voltage drop model	This Paper: MATLAB/ Simulink
2025 (25%)	0.00%	0.00%	-	0.00%	0.00%	-
2030 (50%)	0.00%	0.00%	-	0.00%	0.00%	-
2035 (75%)	0.00%	0.00%	-	0.00%	0.00%	-
2040 (100%)	100.00%	100.00%	100.00%	0.00%	0.00%	0.00%

Table 1 presents a side-by-side comparison of unstable loads in the distribution grids between this study and [22]. One noticeable difference is the number of loads assessed. Our study concentrated on the distribution of Mahallah Safiyyah and Zubair, comprising 21 loads spanning a distance of 1 km. Conversely, in [22], they evaluated 4 loads over a slightly longer distance of 1.2 km. For both studies, the feeders exhibited the highest instability when the renewable energy penetration reached 100% in the low-voltage distribution grid. Simulations conducted in MATLAB/Simulink for 2040, when the grid sees a full 100% renewable energy injection, echoed these findings. The voltage drop model in [22] and our results concur with the instability outcomes.

5. CONCLUSIONS AND FUTURE WORKS

The voltage drop model and Simulink simulations offer valuable insights into IIUM's distribution system voltage stability, demonstrating the effectiveness of VRDT in mitigating instability. In the absence of RE injection, the proximity of buildings and feeders ensures overall system stability, with voltage deviations within acceptable limits. However, voltage instability arises at 100% RE penetration in Safiyyah and Zubair Hostels. VRDT implementation successfully addresses this issue, maintaining voltage deviations below the permissible limit. These findings have significant implications for the practicality and management of RE integration in distribution systems. The voltage drop model accurately predicts voltage deviations as a valuable tool for assessing VRDT suitability. It can be applied to similar systems to evaluate the impact of RE integration and determine optimal VRDT deployment. Future endeavors should consider additional case studies, accounting for COVID-19 limitations and their impact on electricity consumption patterns, providing a comprehensive understanding of system behavior under normal conditions. Exploring the effect of different renewable energy sources, like wind and biomass, on voltage stability is recommended for assessing system response and identifying suitable energy sources for sustainable generation.

From a technological standpoint, integrating advanced monitoring and control systems such as SCADA and smart grid technologies enables real-time monitoring, data collection, and control, facilitating proactive measures to maintain voltage stability and optimize VRDT operation. Assessing scalability in more extensive distribution networks and interconnected grids with multiple substations is essential. Additionally, conducting an economic analysis is crucial to evaluate the cost-effectiveness of VRDT implementation, encompassing equipment, installation, and maintenance expenses. A comprehensive cost-benefit analysis will shed light on the financial viability and long-term benefits of VRDT deployment. This study enhances our understanding of distribution system voltage stability and RE integration. VRDT proves effective in mitigating voltage instability caused by high RE penetration levels. Future research should focus on conducting more case studies, exploring diverse renewable energy sources, integrating advanced monitoring systems, assessing scalability, and conducting economic analyses. These efforts will support decision-making and foster the development of resilient and sustainable distribution systems.

ACKNOWLEDGMENTS

We gratefully acknowledge the support provided by Petronas Research Sdn Bhd under grant number SPP22-124-0124, which has enabled us to conduct this research and make significant advancements in the field.

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