International Journal of Artificial Intelligence Trends (IJAIT)
Vol. 4, Issue X; No. 64, December, 2025, pp. 715-728

MODEL AND ANALYSIS OF THE IEEE 9-BUS SMART GRID INCORPORATING SOLID-STATE TRANSFORMERS (SSTS) UNDER VARYING LOAD CONDITIONS

[1*]Onyeaka Kenneth Chidiebere, [2]Mgbachi C.A, [3]Onuigbo C.M
[1,2,3]Department of Electrical and Electronics, Faculty of Engineering, Enugu State University of Science and Technology, Enugu State, Nigeria
Authors Email: [1*]chyken4546@gmail.com
Corresponding Author Email: chyken4546@gmail.com

Article Info
Received: 1/11/ 2025
Revised: 02/12/2025
Accepted 15/12/2025
Corresponding Authors [1*]Email:
chyken4546@gmail.com
Corresponding Author's Tel:
[1*]: +2348036904440

ABSTRACT
The traditional Low-Frequency Transformers (LFTs) have been used for a long time as fundamental units in electrical power systems, offering galvanic isolation and voltage transformation in both transmission and distribution power systems. Nevertheless, since they are constrained by their size, unidirectional operation, and inability to be flexible, they become less and less suitable to the contemporary smart grids that require bidirectional power flow, incorporation of renewable energy sources, and adaptable voltage regulation. The paper is a modelling and analysis of the behaviour of the IEEE 9-Bus smart grid with Solid-State Transformers (SSTs) under different load conditions to provide a baseline against which the smart grid could be compared. The system was improved with the renewable sources of energy, energy storage and monitoring systems using MATLAB/Simulink to provide a realistic setting of a smart grid. The study is an analysis of the performance parameters; namely energy efficiency and Voltage Stability Index (VSI) of simulated active and reactive power flows across buses. Results of the study shows that the system achieves an overall efficiency of 85.8%, with significant variation across transmission lines considering Line 4-6, therefore demonstrating the highest efficiency (95.31%) and stability, while Lines 4-5, 6-9, and 3-9 exhibit vulnerability to voltage collapse with VSI values approaching or exceeding unity. The results show that there is an apparent trade-off between efficiency and voltage stability with increase in load demand, and it indicates the operational constraint of traditional transformers in smart grid usage. The paper finds that the incorporation of Solid-State Transformers can greatly benefit grid functionality in converting energy more efficiently, more dependably and more controllably and hence meet the changing demands of intelligent, renewable-integrated power grids

Key words: Solid-State Transformer (SST); Conventional Transformer; Smart Grid; IEEE 9-Bus System; Voltage Stability Index (VSI)

1. INTRODUCTION

For over a century, conventional Low-Frequency Transformers (LFTs) have formed the bedrock of electrical power systems, serving as indispensable components in both transmission and distribution networks. These electromagnetic devices perform two fundamental functions: they provide crucial galvanic isolation between different segments of the grid for safety, and they step up or step down voltage levels to enable efficient long-distance transmission and safe local distribution, thereby achieving voltage matching at the input and output ends (Mehrotra, Ballard, and Hopkins, 2022). The widespread and prolonged use of LFTs is attributed to their relatively simple construction, proven high efficiency at rated load, operational safety, and exceptional longevity (Sun et al., 2020).

Their robustness and predictability have made them a trusted component in utility networks worldwide. However, the physical dimensions of the core and number of winding turns required are inversely proportional to the operating frequency, hence, transformers designed for low-frequency (50/60 Hz) operation become large and heavy. A primary drawback is their substantial size and weight. The physical dimensions of the core and the number of winding turns required are inversely proportional to the operating frequency. Consequently, for high-power applications, LFTs become exceptionally large and heavy, complicating their transportation, increasing installation costs, and occupying considerable real estate (She et al., 2013). This bulkiness is a critical disadvantage in space-constrained environments like urban substations or offshore wind farms.

Furthermore, the traditional grid, built around LFTs, is predominantly a passive, unidirectional system designed for centralized power generation. This architecture is increasingly incompatible with the emerging needs of the modern grid. The rapid proliferation of distributed energy resources (DERs)such as rooftop solar Photovoltaic (PV) systems, small-scale wind turbines, and residential energy storage units requires a grid that can accommodate bidirectional power flows, which LFTs are inherently incapable of managing (Bhawal, Chakraborty, and Hatua, 2022). Moreover, the growing interest in DC distribution systems, both for data centers and for efficient integration of solar PV and battery storage, exposes another limitation of LFTs: they are fundamentally AC devices and cannot interface natively with DC systems without additional power conversion stages. They also lack the ability to perform real-time power quality management, such as voltage regulation and harmonic filtering, often necessitating the use of external compensators like capacitor banks and static VAR compensators, which add to the system's complexity and cost (Huber and Kolar, 2014).

It is within this context of technological transition that Solid-State Transformers (SSTs) have emerged as a potent alternative and a subject of intense research. An SST, also referred to as a Power Electronic Transformer (PET), is not merely a magnetic device but an intelligent, multi-functional power conversion system. It is a potential competitive intelligent electronic device that enables bi-directional power flow, reactive power compensation, voltage sag and swell mitigation, harmonic reduction, and islanding detection, among many other advanced features (Costa et al., 2017). Physically, an SST is a combination of high-power semiconductor devices (such as IGBTs and SiC MOSFETs), advanced control circuitry, and a high-frequency transformer. The shift to high-frequency operation is a key differentiator; by operating at frequencies in the kilohertz range, the magnetic core of the high-frequency transformer can be dramatically reduced in size, leading to a compact, lightweight unit that is a fraction of the size and weight of an equivalent LFT (Kolar et al., 2011). This miniaturization is a critical enabler for applications in electric railway systems, offshore wind platforms, and next-generation traction systems.

The operational principle of a typical three-stage SST elucidates its multifunctional capabilities. The topology generally consists of an input stage, an isolation stage, and an output stage. The input stage is an AC-DC converter (rectifier) that converts the incoming AC grid voltage to a stable DC voltage. This stage can be controlled to draw sinusoidal current from the grid, thereby achieving a high-power factor and reducing input current harmonics (Wang et al., 2018). The isolation stage is a DC-DC converter featuring a high-frequency transformer. This stage provides the crucial galvanic isolation, similar to a traditional transformer, but does so at a much higher frequency, enabling the dramatic reduction in size. It also provides voltage conversion between the primary and secondary-side DC links. Finally, the output stage is a DC-AC converter (inverter) that converts the regulated DC voltage back to a high-quality AC voltage for the load (Bhawal, Chakraborty, and Hatua, 2022). This modular and controlled structure allows an SST to perform functions impossible for an LFT. For instance, unlike a traditional transformer, SSTs can seamlessly interconnect AC and DC grids, making them the ideal hub for hybrid AC/DC microgrids that integrate renewable sources and battery storage (Dutta et al., 2020).

The benefits of SSTs extend far beyond mere size reduction. The bidirectional power flow capability, inherent in its power electronics-based design, is essential for supporting vehicle-to-grid (V2G) technologies and for managing power from prosumers consumers who also produce energy. The fast-switching speed of solid-state devices, particularly with the advent of Wide Bandgap (WBG) semiconductors like Silicon Carbide (SiC) and Gallium Nitride (GaN), allows for millisecond-level control responses. This enables utilities and system operators to perform real-time fine-tuning of power quality, manage fault currents, and enhance the overall stability and resilience of the grid (Tarisciotti et al., 2017). Furthermore, the SST's ability to maintain a stable voltage output even with a highly distorted or variable input voltage makes it invaluable in areas with poor power quality. Hence, this study models, simulates, and evaluates the performance of the IEEE 9-bus smart grid under conventional transformer operation, establishing a performance baseline prior to SST integration.

2. RESEARCH METHOD

The process begins by transforming a standard power system model into a sophisticated smart grid environment, laying the groundwork for subsequent analysis and innovation. Initially, the IEEE 9-bus Simulink test system is meticulously modified to evolve into a smart grid. This transformation involves strategically integrating renewable energy sources like solar Photovoltaic (PV) systems and wind turbines at various buses, carefully modelling their intermittent output using historical or synthetic data. Concurrently, energy storage systems, such as lithium-ion batteries or flywheels, are incorporated at strategic locations to enhance grid stability during peak demand or generation shortfalls, with their detailed charge/discharge characteristics being accurately modelled. To ensure comprehensive grid visibility and control, advanced monitoring systems, including Phasor Measurement Units (PMUs) and smart meters, are conceptually deployed. Furthermore, the system is augmented with conceptual control strategies like demand response programs and distributed generation control, supported by modelled communication protocols to facilitate real-time data exchange. The integrity and functionality of this newly established smart grid baseline are then validated through extensive simulations under diverse operating conditions, including normal operation, fault scenarios, and high renewable energy penetration, to assess key performance indicators.

Following the establishment of the smart grid baseline, the research proceeds to characterize the energy efficiency and Voltage Stability Index (VSI) of this system when operating with conventional transformers under varying load conditions. This involves running simulations and meticulously analysing power losses across the grid, which are influenced by load demand and the operational characteristics of the conventional transformers. Energy efficiency (η) is quantified by comparing useful power output to total power input. Simultaneously, voltage stability is assessed through the VSI, which indicates the system's capacity to maintain acceptable voltage levels. This characterization provides vital insights into the inherent performance and limitations of the traditional grid setup.

A pivotal phase of the methodology involves the development of a detailed MATLAB/Simulink model of a SST. This comprehensive model begins by defining precise system requirements such as input/output voltage levels and power ratings. The SST is then meticulously constructed in a modular fashion, comprising an input AC-DC rectifier (modelled with semiconductor devices and passive components, and incorporating power factor correction), a DC-DC conversion stage (featuring a high-frequency transformer for galvanic isolation, often utilizing a dual-active bridge converter), and an output DC-AC inverter (employing full-bridge or half-bridge topologies with advanced control algorithms). Integral to the SST's functionality is the robust Proportional Integral (PI) controller design, which is meticulously developed with feedback loops, voltage/current sensors, and digital signal processing techniques to ensure efficient power conversion and system stability. The control law for the PI controller, u(t)=Kp e(t)+Ki∫e(t)dt, is fundamental to its operation.

3. MODELLING OF THE ENERGY EFFICIENCY AND VOLTAGE STABILITY INDEX OF THE IEEE 9-BUS SMART GRID WITH CONVENTIONAL TRANSFORMERS UNDER DIFFERENT LOAD CONDITIONS

The modelling of energy efficiency and voltage stability index in the IEEE 9-bus smart grid with conventional transformers under varying load conditions reveals critical insights into the system's performance. Energy efficiency is evaluated by analysing power losses across the grid, which are influenced by the load demand and the operational characteristics of conventional transformers. Under light load conditions, the system exhibits relatively low power losses, as the transformers operate closer to their optimal efficiency range. However, as the load increases, the transformers experience higher copper and core losses, leading to a decline in overall energy efficiency. This is particularly evident during peak load conditions, where the transformers may operate near or beyond their rated capacity, resulting in significant energy dissipation. The efficiency (η) of a smart grid can be calculated by comparing the useful power output to the total power input. The general formula is:

$$\eta = \left(\frac{P_{output}}{P_{input}}\right) \times 100\% \quad (1)$$

Where:

P_{output} = Useful electrical power delivered to consumers (MW)

P_{input} = Total electrical power generated or supplied (MW)

In a power system, efficiency can be determined using voltage and current measurements at a bus (a node where power is injected or extracted). The complex power (S) at a bus is given by:

$$S = V \times I^* \quad (2)$$

where:

V = Voltage at the bus (complex phasor form)

I^* = Conjugate of the current at the bus

The real power (P) input at the sending bus is:

$$P_{input} = Re(Sin) = V_{in} I_{in} * \cos(\theta_{in}) \quad (3)$$

Similarly, the power at the receiving bus is:

$$P_{output} = Re(S_{out}) = V_{out} I_{out} * \cos(\theta_{out}) \quad (4)$$

Voltage stability, on the other hand, is assessed through the voltage stability index (VSI), which indicates the system's ability to maintain acceptable voltage levels under varying load conditions. In the IEEE 9-bus system, conventional transformers play a crucial role in regulating voltage levels. Under normal load conditions, the voltage stability index remains within acceptable limits, ensuring reliable operation. However, as the load demand increases, the voltage profile across the buses begins to degrade, with some buses experiencing voltage drops below the permissible threshold. This is particularly pronounced in buses farther from the generation sources, where the impedance of transmission lines and transformers exacerbates voltage instability. Voltage stability refers to the ability of a power system to maintain acceptable voltage levels under normal and disturbed conditions. Instability often occurs due to insufficient reactive power support, leading to voltage collapse. To derive an expression for voltage stability, we consider a simple two-bus system with a sending-end voltage (V_s) and a receiving-end voltage (V_r), connected through an impedance (Z=R+jX). The complex power at the receiving end (Sr) is given by:

$$S_r = P_r + jQ_r = V_r I^* \quad (5)$$

where:

Pr = Real power at the receiving bus
Qr = Reactive power at the receiving bus
I = Line current

Using Ohm's Law, the current is:

$$I = \frac{V_s - V_r}{Z} = \frac{V_s - V_r}{(R + jX)} \quad (6)$$

Substituting into the power equation:

$$S_r = V_r \left(\frac{V_s - V_r}{R + jX}\right)^* \quad (7)$$

Expanding,

$$S_r = V_r \left(\frac{(V_s - V_r)^*}{R - jX}\right) \quad (8)$$

For small resistances (R ≈ 0), the impedance is mostly reactive, so Z ≈ jX, simplifying the equation:

$$S_r = V_r \left(\frac{(V_s - V_r)^*}{-jX}\right) \quad (9)$$

Separating real and reactive power:

$$P_r = \left(\frac{V_s V_r}{X}\right) \sin\delta \quad (10)$$

$$Q_r = \frac{V_r (V_s - V_r)}{X} \quad (11)$$

where δ is the voltage angle difference.

$$\frac{dQ_r}{dV_r} = 0 \quad (12)$$

Differentiating Qr with respect to Vr:

$$\frac{d}{dV_r}\left(\frac{V_r (V_s - V_r)}{X}\right) = 0 \quad (13)$$

Expanding,

$$\frac{V_s}{X} - \frac{2V_r}{X} = 0 \quad (14)$$

Solving for Vr:

$$\mathrm{V_r} = \frac{\mathrm{V_s}}{2} \quad (15)$$

This means voltage instability occurs when the receiving-end voltage falls to 50% of the sending-end voltage**.**
A common voltage stability index is defined as:

$$\mathrm{VSI} = 1 - \frac{4XQ_r}{V_s^2} \quad (16)$$

where:$\mathrm{VSI} < 1$ *indicates stable operation*; VSI → 1 indicates voltage collapse

Equation 16 provides a practical means of monitoring grid voltage stability. When VSI approaches unity, the system nears its voltage collapse point, indicating that reactive power compensation or load shedding may be required. From the above derivations, the voltage stability of a power grid is linked to reactive power support. When $\mathrm{V_r}$ drops below $0.5\mathrm{V_s}$, voltage instability begins. The voltage stability index (L) provides a mathematical way to assess how close the system is to collapse. Equation 12 shows the fundamental role of reactive power in maintaining voltage stability**,** crucial for preventing voltage collapse in modern power grids. The interplay between energy efficiency and voltage stability becomes more complex under heavy load conditions. While conventional transformers are designed to handle a range of loads, their inherent limitations in voltage regulation and efficiency become apparent under stress. The system's energy efficiency deteriorates due to increased losses, while the voltage stability index indicates a higher risk of voltage collapse in critical buses. This highlights the need for advanced control strategies or the integration of smart grid technologies, such as on-load tap changers or reactive power compensation devices, to enhance both energy efficiency and voltage stability under diverse load conditions.

The IEEE 9-bus smart grid with conventional transformers demonstrates a trade-off between energy efficiency and voltage stability as load conditions vary. Light loads favor higher efficiency and stable voltages, while heavy loads expose the limitations of conventional transformers, leading to increased losses and potential voltage instability. Addressing these challenges requires a holistic approach to grid management and the adoption of modern technologies to optimize performance across all load scenarios.

3.1 Development of a Simulink model of a SST, incorporating AC-DC, DC-DC, DC-AC, high frequency transformers, power electronic converters, and PI controller

Developing a detailed MATLAB/Simulink model of a SST involves a systematic approach to integrate its key components, including AC-DC, DC-DC, and DC-AC conversion stages, high-frequency transformers, power electronic converters, and advanced control algorithms.

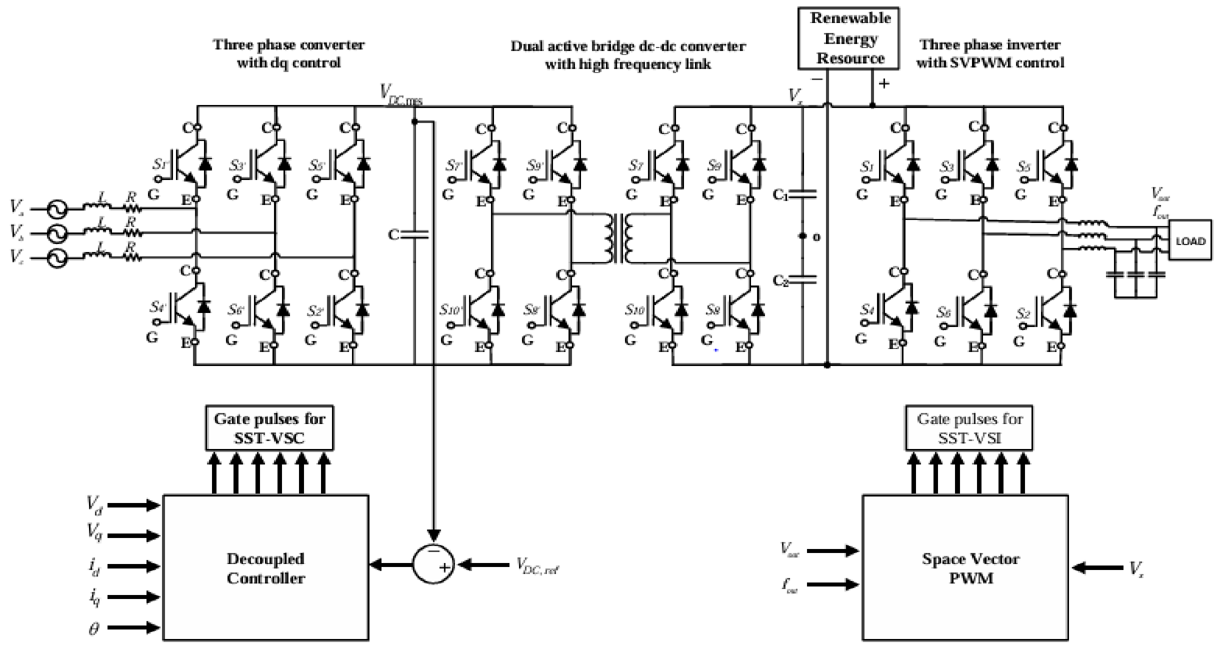


Figure 1. Proposed Circuit Diagram of the Solid-State Transformer (SST)

The process begins with defining the system requirements and specifications, such as input/output voltage levels, power ratings, and desired performance metrics. This is followed by breaking down the SST into its fundamental building blocks: the input AC-DC rectifier, the isolation stage with a high-frequency transformer, the DC-DC converter, and the output DC-AC inverter. The first step is to model the AC-DC rectifier, which converts the input AC voltage to a stable DC voltage. This stage typically employs a power factor correction (PFC) circuit to ensure high efficiency and compliance with power quality standards. The rectifier is modeled using semiconductor devices like IGBTs or MOSFETs, along with passive components such as inductors and capacitors. Control algorithms, such as pulse-width modulation (PWM), are implemented to regulate the output DC voltage and maintain unity power factor.

Next, the DC-DC conversion stage is modelled, which includes a high-frequency transformer for galvanic isolation and voltage adjustment. This stage often utilizes a dual-active bridge (DAB) converter topology, known for its high efficiency and bidirectional power flow capability. The high-frequency transformer is designed with appropriate turns ratio and core material to minimize losses. The DC-DC converter is controlled using phase-shift modulation or other advanced techniques to ensure efficient power transfer and voltage regulation.

The final stage involves modelling the DC-AC inverter, which converts the regulated DC voltage back to AC for the load. This stage employs a full-bridge or half-bridge inverter topology, with semiconductor switches and output filters to produce a clean sinusoidal waveform. Advanced control algorithms, such as Space Vector Modulation (SVM) or Proportional-Resonant (PR) controllers, are implemented to achieve precise voltage and frequency regulation.

Throughout the development process, the integration of advanced control algorithms is critical to ensure efficient power conversion and system stability. These algorithms include feedback loops, voltage and current sensors, and digital signal processing techniques to monitor and adjust the system in real-time. The control system is designed to handle transient conditions, load variations, and faults while maintaining optimal performance.

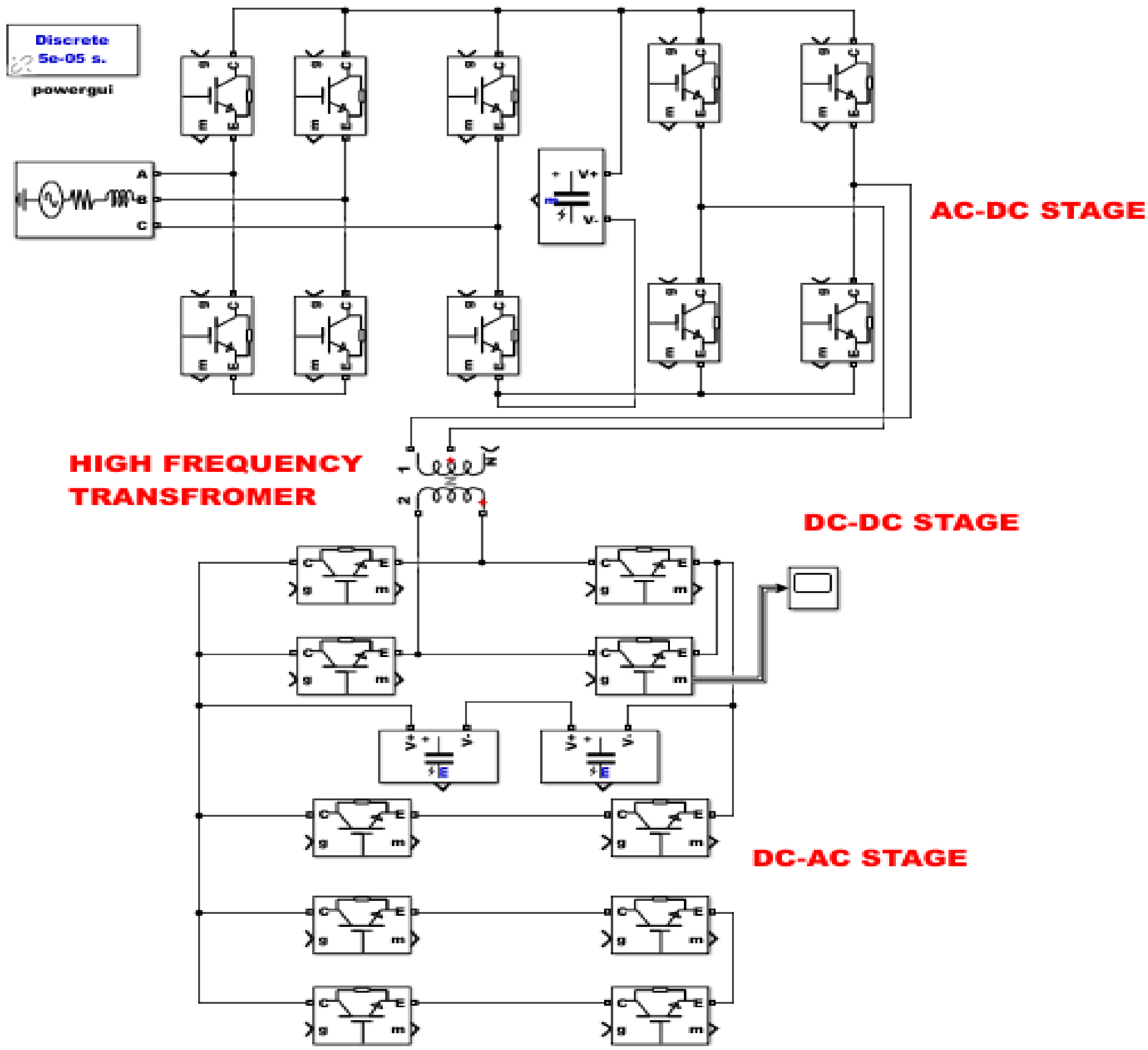


Figure 2: Simulink Model of a Solid State Transformer

The control system was designed using a PI controller. **A**PI Controller is a common feedback control mechanism used in voltage regulation to maintain a stable output voltage despite variations in input voltage or load conditions. The PI controller receives the voltage error signal. It computes an appropriate control signal u. The converter/regulator (plant) adjusts the output voltage accordingly. The feedback loop ensures that the actual voltage stays close to the reference. The control law of a PI controller is given by:

$$u(t) = K_p e(t) + K_i \int e(t)dt \quad (17)$$

$u(t)$ is the control signal

$e(t) = V_{ref} - V_{actual}$ is the voltage error

K_p is the proportional gain

K_i is the integral gain

Once the individual stages are modelled, they are interconnected to form the complete SST system in Simulink. The model is then simulated under various operating conditions to validate its performance, including efficiency, voltage regulation, and dynamic response. Parameter tuning and optimization are performed to enhance the system's performance and ensure it meets the design specifications.

Developing a detailed Simulink model of an SST involves designing and integrating its key components, implementing advanced control algorithms, and validating the system through simulation. This process ensures efficient power conversion, robust performance, and compliance with the desired operational requirements

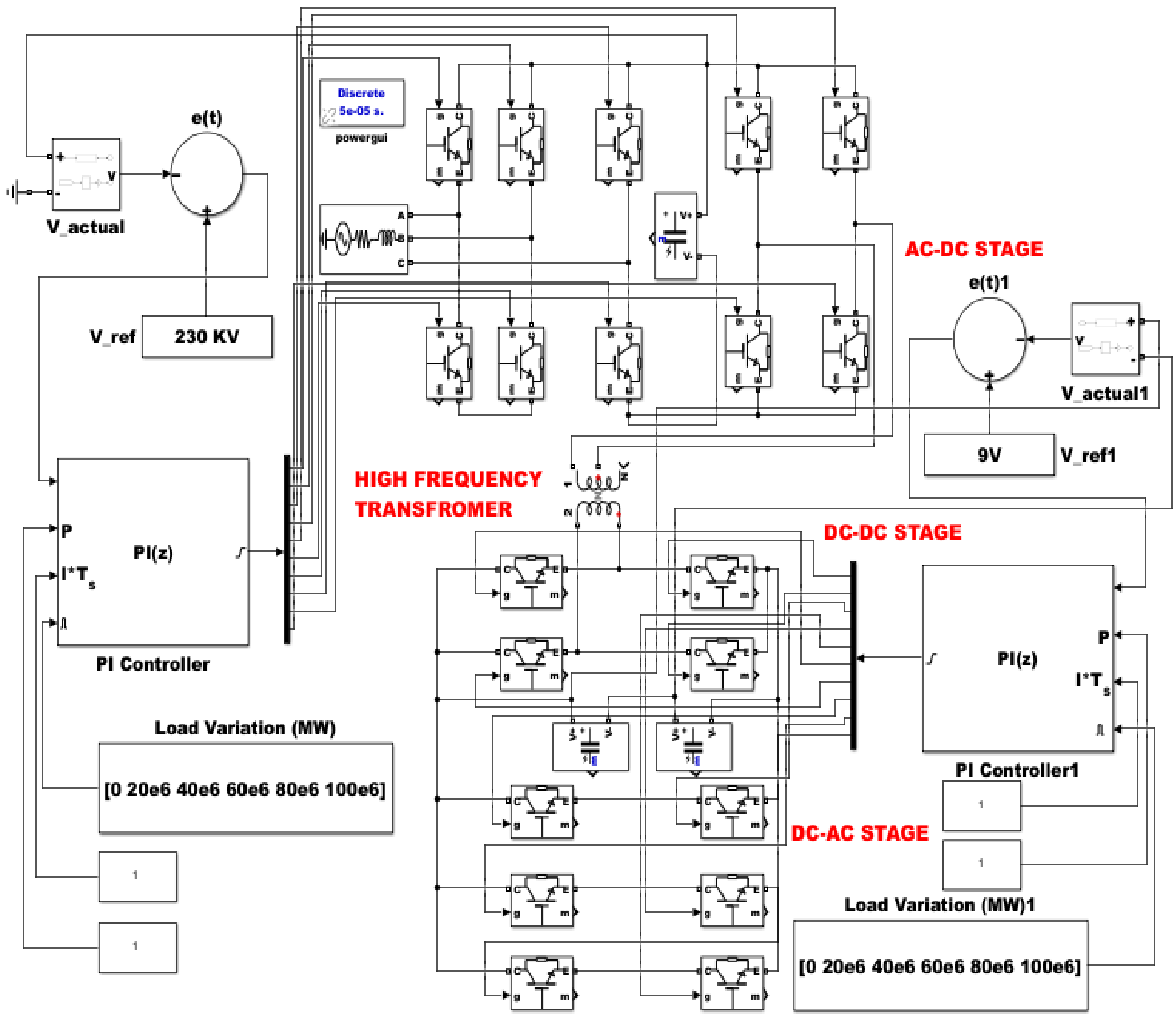


Figure 3: SST Simulink Model with PI Controller

.

4. RESULTS OF THE EFFICIENCY AND VOLTAGE STABILITY INDEX (VSI) OF THE IEEE 9-BUS SMART GRID

This section provides critical insights into the performance and stability of the IEEE 9-Bus smart grid under conventional transformer operation. The results are derived from the simulated active and reactive power values at each bus, as well as the calculated efficiency and VSI for each transmission line. These findings are essential for understanding the operational behaviour of the grid and identifying potential areas of improvement. Table 1 shows the simulated active and reactive power results of the model with conventional transformers.

Table 1: Simulated active and reactive power results of the model with transformers

Buses	Active Power (MW)	Reactive Power (MVAR)
Bus 1	0.3732	0.2778
Bus 2	0.5263	0.9120
Bus 3	0.4839	-0.4761
Bus 4	0.4396	0.2463
Bus 5	0.5662	-0.1708
Bus 6	0.4613	2.8452
Bus 7	0.6494	0.7413
Bus 8	0.6862	0.2915
Bus 9	0.5532	-0.4398

The active and reactive power profiles of the grid, as depicted in Figures 4 and 5, reveal the distribution of power across the buses. Bus 1, for instance, has an active power of 0.3732 MW and a reactive power of 0.2778 MVAR, indicating a relatively balanced load. In contrast, Bus 6 exhibits a significantly higher reactive power of 2.8452 MVAR, suggesting a potential reactive power surplus or a capacitive load. Bus 3 and Bus 5 show negative reactive power values of -0.4761 MVAR and -0.1708 MVAR, respectively, indicating inductive loads or reactive power absorption. These variations in active and reactive power across the buses highlight the diverse load conditions and the need for effective power management to maintain grid stability.

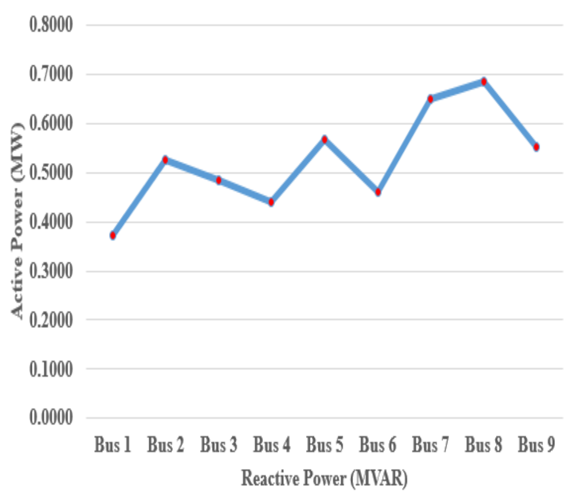


Figure 4: Active Power Profile of the Grid

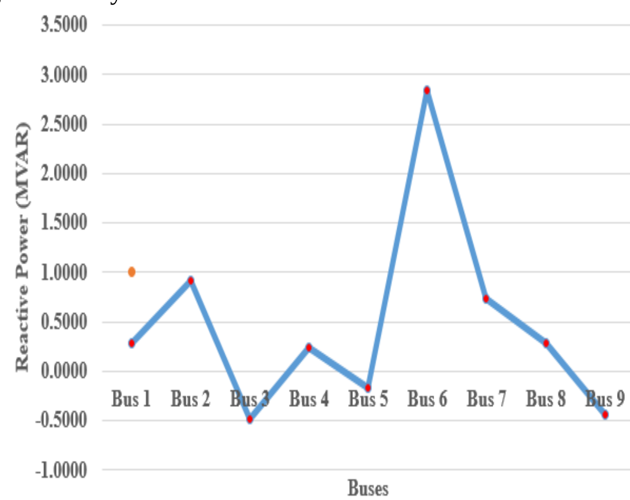


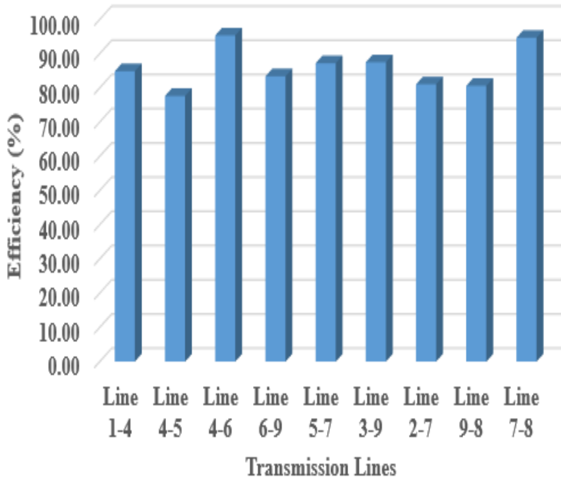
Figure 5: Reactive Power Profile of the Grid

The efficiency and VSI analysis, as presented in Table 2, provides a comprehensive assessment of the grid's performance. The overall efficiency of the grid is calculated to be 85.80%, indicating that the system operates with reasonable energy transfer effectiveness. However, the efficiency of individual transmission lines varies significantly. For example, Line 4-6 demonstrates the highest efficiency at 95.31%, suggesting minimal power losses and optimal energy transfer. In contrast, Line 4-5 has a lower efficiency of 77.64%, indicating higher losses and potential inefficiencies in this section of the grid.

Table 2: Efficiency and VSI of the Grid with conventional transformers

Transmission Lines	**Smart Grid Efficiency (%)**	**Voltage Stability Index (VSI)**	**Remarks**
Line 1-4	84.88	0.9888	Slightly Stable
Line 4-5	77.64	1.0115	Voltage Collapse
Line 4-6	95.31	0.7928	Stable
Line 6-9	83.39	1.0015	Voltage Collapse
Line 5-7	87.19	0.9876	Slightly Stable
Line 3-9	87.48	1.0091	Voltage Collapse
Line 2-7	81.04	0.9705	Slightly Stable
Line 9-8	80.62	0.9985	Slightly Stable
Line 7-8	94.65	0.9997	Slightly Stable
Overall	85.80		

The VSI is a critical metric for assessing the stability of the grid. A VSI close to 1 indicates a stable operating condition, while values significantly above or below 1 suggest potential instability or voltage collapse. Line 4-6, with a VSI of 0.7928, is classified as stable, reflecting a robust operating condition. However, several lines, including Line 4-5 (VSI = 1.0115), Line 6-9 (VSI = 1.0015), and Line 3-9 (VSI = 1.0091), are identified as being at risk of voltage collapse. These lines require immediate attention to prevent system instability and ensure reliable power delivery. Lines such as Line 1-4 (VSI = 0.9888), Line 5-7 (VSI = 0.9876), and Line 7-8 (VSI = 0.9997) are classified as slightly stable, indicating that they are operating near the threshold of instability and may require monitoring or corrective measures.



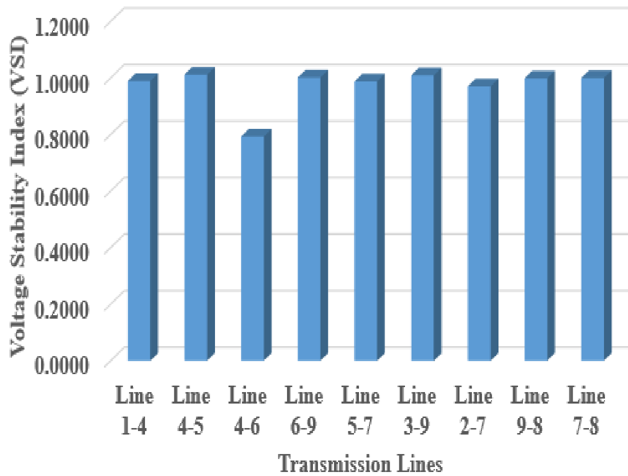


Figure 6: Power efficiency against lines Figure 7: VSI at different sections of the smart grid

Figures 6 and 7 provide graphical representations of the power efficiency and VSI across different sections of the smart grid. These figures visually reinforce the findings from Table 2, highlighting the variations in efficiency and stability across the grid. The power efficiency graph (Figure 6) underscores the disparities in energy transfer effectiveness, with some sections performing optimally while others exhibit significant losses. Similarly, the VSI graph (Figure 7) illustrates the stability conditions of the grid, with certain sections operating within safe limits and others approaching or exceeding critical thresholds.

The results analyzed in this section reveal a system with overall reasonable performance but notable areas of concern. The high efficiency of certain transmission lines, such as Line 4-6, demonstrates the potential for optimal energy transfer. However, the risk of voltage collapse in lines like Line 4-5, Line 6-9, and Line 3-9 highlights the need for targeted interventions to enhance grid stability. The slightly stable conditions of several other lines further emphasize the importance of continuous monitoring and proactive management to maintain system reliability. These findings provide a foundation for future improvements, including the integration of advanced technologies and optimization strategies to enhance the efficiency and stability of the smart grid.

The overall system efficiency of 85.8% highlights reasonable operational performance but exposes inefficiencies in specific transmission paths, particularly Lines 4–5 and 6–9, where elevated VSI values indicate potential voltage instability.

5. CONCLUSION

This paper has analysed the behaviour of IEEE 9-Bus model of smart grid against conventional LFTs utilisation to define a performance baseline before the addition of SSTs. The study was driven as a result of increasing constraints of LFTs, including their bulkiness, poor controllability, and incapability to accommodate two-way or DC-connected power flows, in the new context of the contemporary, distributed, and smart power systems. The system was improved with renewable energy sources, storage, and sophisticated monitoring elements through extensive modelling and simulation in MATLAB/Simulink to simulate the dynamics of the operational processes of a smart grid. The main performance indicators were determined to be energy efficiency and VSI that could be used to assess the system behaviour when various loading conditions were applied. Both parameters were obtained using analytical expressions and have an understanding of the impact of real and reactive power flows on grid efficiency and stability. Simulation results revealed that the overall energy efficiency of the IEEE 9-Bus smart grid with conventional transformers was approximately 85.8%, indicating moderate performance but with notable inefficiencies across specific transmission paths. The VSI analysis showed that some of the lines, especially Lines 4-5, 6-9, and 3-9 are vulnerable to voltage collapse, and this indicates the weakness of the traditional transformers that try to ensure voltage stability with high load and dynamic operating conditions. Conversely, lines such as 4-6 demonstrated high efficiency (95.31%) and strong voltage stability, showing that optimal operating points exist within the current network structure. The overall results emphasise a very obvious trade-off between energy efficiency and voltage stability in smart grids that are based on transformers. Although traditional transformers can be used satisfactorily at light to moderate loads, the efficiency deteriorates and stability increases with demand on the load. These findings reveal the importance of having adaptive and smart power conversion technologies that can help alleviate such constraints.

To sum up, the paper confirms that the IEEE 9-Bus smart grid including regular transformers performs well; however, it is still limited due to the nature of limitations on their physical and operational features of LFTs. The inefficiencies and risks of instability that are observed provide a strong argument to consider the implementation of SSTs, which, due to the high-frequency operation and the ability to regulate the dynamic voltage, or even provide a smooth integration of AC/DC networks with a hybrid, can be offered with better energy conversion efficiency, improved dynamic voltage regulation, and improved seamless integration of AC / DC networks. Future consists of the detailed modelling and simulation of the SST in the same IEEE 9-Bus environment to measure the benefits in performance of the SST in terms of energy efficiency, voltage stability as well as system-wide reliability as compared to the traditional transformer systems.

7. REFERENCES

Bhawal, S., Chakraborty, S. S., & Hatua, K. (2022). Dynamic modeling and closed loop control of a solid state transformer (SST) based on series resonant converter (SRC). *IEEE Journal of Emerging and Selected Topics in Power Electronics*, *10*(4), 3732–3744. https://doi.org/10.1109/JESTPE.2022.3169875

Costa, L., De Carne, G., Buticchi, G., & Liserre, M. (2017). The smart transformer: A solid-state transformer tailored to provide ancillary services to the distribution grid. *IEEE Power Electronics Magazine*, *4*(2), 56–67. https://doi.org/10.1109/MPEL.2017.2666049

Dutta, S., Roy, S., Debnath, S., & Bhattacharya, S. (2020). Integration of solid-state transformer with DC microgrid for seamless AC-DC interconnection. *IEEE Transactions on Power Electronics*, *35*(11), 11815–11828. https://doi.org/10.1109/TPEL.2020.2987654

Huber, J. E., & Kolar, J. W. (2014). Applicability of solid-state transformers in today's and future distribution grids. In *Proceedings of the 2014 International Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE ASIA)* (pp. 2101–2108). IEEE. https://doi.org/10.1109/IPEC.2014.6869876

Kolar, J. W., Krismer, F., Linner, Y., Ortiz, G., & Drofenik, U. (2011). Solid-state transformers: Key design challenges, applicability, and future concepts. In *Proceedings of the 2011 IEEE Energy Conversion Congress and Exposition (ECCE)* (pp. 745–752). IEEE. https://doi.org/10.1109/ECCE.2011.6063852

Mehrotra, U., Ballard, B., & Hopkins, D. C. (2022). Bidirectional solid-state circuit breaker using super cascode for MV SST and energy storage systems. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, *10*(4), 3651–3660. https://doi.org/10.1109/JESTPE.2022.3169876

She, X., Huang, A. Q., & Burgos, R. (2013). Review of solid-state transformer technologies and their application in power distribution systems. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, *1*(3), 186–198. https://doi.org/10.1109/JESTPE.2013.2277910

Sun, X., Wang, H., Qi, L., & Liu, F. (2020). Research on single-stage high-frequency-link SST topology and its optimization control. *IEEE Transactions on Power Electronics*, *35*(8), 8701–8711. https://doi.org/10.1109/TPEL.2020.2971645

Tarisciotti, L., Costabeber, A., Chen, L., & Zanchetta, P. (2017). Advanced control of power electronic transformers for electric vehicle charging applications. *IEEE Transactions on Industry Applications*, *53*(5), 4769–4778. https://doi.org/10.1109/TIA.2017.2709863

Wang, J., Burgos, R., & Boroyevich, D. (2018). Switching-cycle control of a high-frequency-link inverter for solid-state transformer applications. *IEEE Transactions on Power Electronics*, *33*(11), 9614–9626. https://doi.org/10.1109/TPEL.2018.2805321