

Analysis of Multi-energy Grid Power Supply Characteristics Based on Equivalent Circuit and Simulink Simulation

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Abstract. As renewable generation technologies develop, modern power grids must integrate diverse energy sources. In multi-energy interconnected systems, long-distance transmission introduces line impedance and losses that produce phase deviations between generation and load; these deviations reduce stability and power quality. To balance these effects, an idealized transmission model of a real power grid system will be simulated in Simulink to generate input–output simulation curves under various operating conditions. The results show that the phase delay between the transmission terminal and the power-source terminal grows as generation frequency increases, indicating that synchronization challenges intensify at higher operating frequencies. To mitigate these effects and improve grid stability, FACTS and VSG control methods are proposed to improve dynamic response, reduce phase deviations, and increase the reliability and flexibility of integrated power systems. By analyzing how FACTS and VSG control work, grid stability can be enhanced. This method helps people save on the cost of maintaining the power grid.

Keywords: Renewable generation, Grid stability, Phase deviations

1. Introduction

As renewable energy sources are becoming more and more developed and used, many traditional power utilities are switching to renewable generation technologies. On that basis, hybrid generation technologies combining renewable and conventional energy are becoming increasingly common. The increasing integration of wind, solar, and other renewable generators into power grids has introduced new stability challenges for multi-energy grid connection technologies. Wind and photovoltaic generation can change 20%–30% of their rated capacity on timescales from seconds to minutes, and photovoltaic output can drop by as much as 70% in 10 minutes under extreme weather. This can result in frequency deviations of more than 0.15Hz and voltage stability can drop by about 30%–40% more than conventional thermal generation. This means the traditional central single-source supply model has significant stability and efficiency issues at high renewable penetrations. This makes it one of the major challenges for future transmission technologies [1].

This paper studies the stability of a multi-energy power supply using equivalent circuit analysis of the grid. It compares input–output voltage transfer characteristics of idealized circuit models for multi-energy grid integration and standard power system Simulink circuit simulations. By comparing the simulation result, the characteristics of the input-output curve are shown, and the

factors that cause supply instability are evaluated. It then discusses FACTS and VSG technologies to improve reactive power compensation and dynamic stability. Overall, this paper constructs the basic circuit of a grid. It then simulates the circuit and compares the simulation result. To decrease the power loss and instability, FACTS and VSG technologies are introduced. The final section shows how FACTS and VSG contribute to maintaining the grid.

2. Basic method for power grid transmission efficiency analysis

This section presents circuit models for both the conventional power grid and the multi-energy grid. In each model, key components include resistors, inductors, capacitors, and AC voltages to accurately represent grid behavior. The circuit topology of each model and its connection with the other components are also presented. Moreover, the operational principles for the traditional power grid and multi-energy grid are explained, describing their function and characteristics. The transmission efficiency evaluation of both grid models provides insight into the efficiency of energy transfer of grids. With the grid performance measures, their efficiency and effectiveness can be understood. By studying circuit models and their performance evaluations, insights can be gained into optimizing and improving grid operations.

2.1. Definitions of traditional power grid and multi-energy grid

Before computing grid parameters, conventional and renewable power systems are introduced. Conventional grids depend on stable sources of electricity (hydropower, thermal power, nuclear power). In equivalent-circuit analysis, conventional generators are represented by one AC voltage-source model (this simplified model is not representative of actual grid topology) [2]. Multi-energy power systems are networks that supply electricity by combining different energy sources (e.g., wind and solar). Multi-energy grid interconnection is modeled as a parallel array of ideal AC voltage sources, each inverter strengthened for stability [3]. The configuration is described below.

2.2. Structure comparison between multi-energy power grid and traditional power grid

In the comparative analysis of multi-energy and single-energy power networks, the first section presents equivalent-circuit diagrams of the conventional grid and the multi-energy grid, as shown in Figure 1.

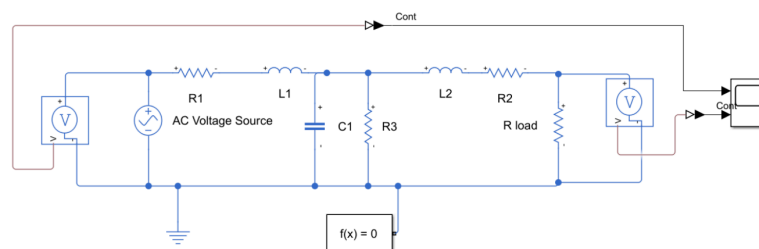


Figure 1. Equivalent circuit of traditional power grid

The voltage source on the left (an AC source) represents a single-phase generator model of the power grid, with the voltage as

$$V = A \sin \omega t \quad (1)$$

A represent the magnitude of voltage, and w represent the rotor angular speed of the generator. Since transmission lines are not ideal, an equivalent impedance is introduced for the nonideal behavior. Figure 1 shows the resistance of the line at the generator output and the equivalent circuit model for the multi-source power network. R_1 represents the resistance produced by the lines at the generator output, and L_1 represents the inductance coefficient generated by the power lines caused by electromagnetic induction. Since transmission lines are not perfectly isolated from ground, real circuits have distributed capacitance to earth (C_1) and leakage paths through the insulating media (R_3). Equipment connected to the supply also introduces losses. R_2 represents the resistance loss from line conduction and L_2 represents the line's electromagnetic energy storage at load end. The power supplied is consumed by the device as R_{load} . Voltage probes for simulation are located far left and far right of the circuit.

Building on the single-source network equivalent, the equivalent-circuit model for a multi-source power network is constructed (see below Figure 2).

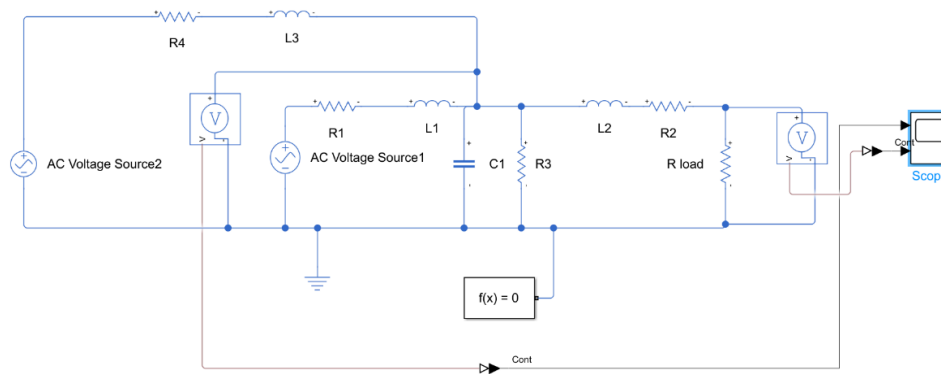


Figure 2. Equivalent circuit of multi-energy grid connection

Single-phase models in the equivalent-circuit scenario are used; other DC sources (wind turbines or photovoltaics) will connect to the device only after conversion by inverters. This simplified model is meant only to analyze the trend of parallel sources on line voltage; it does not take into account three-phase imbalance, harmonic content, switching dynamics, or protection action. Renewable interfaces are ideal, controlled AC voltage sources that stand for grid follower output after control [3]. The conclusions of this study are limited to qualitative analysis under simplified assumptions and do not directly represent a real power system. In the notation used, R_4 and L_3 are losses of the renewable transmission line; stability analysis methods are discussed in the next section.

2.3. Abbreviations and acronyms

In an RLC circuit, inductive reactance and capacitive reactance depend on frequency. As frequency increases, the same impedance and phase response change, which can reduce the voltage magnitude at load and increase phase shift. If the system lacks reactive power support and dynamic control, these effects can deteriorate voltage quality and compromise supply stability. Below are expressions for different impedances, illustrating the impedance formulations for multi-energy systems.

$$Z_1 = R_1 + j\omega L_1 \quad (2)$$

$$Z_2 = R_4 + j\omega L_3 \quad (3)$$

$$Z_3 = \frac{1}{j\omega C_1} + R_3 \quad (4)$$

$$Z_L = R_2 + j\omega L_2 \quad (5)$$

The equation shows that varying the rotational speed changes the impedance magnitude. Different impedance magnitudes produce different impedance angles. It can be expressed as follows:

$$Z = a + jb = \sqrt{a^2 + b^2} \angle \theta \quad (6)$$

$$\theta = \tan^{-1} \frac{b}{a} \quad (7)$$

The output voltage exhibits different delay responses depending on the impedance angle; specifically, it can be expressed as follows:

$$V = A \sin(\omega t + \theta) \quad (8)$$

Asynchronous input and output decrease power delivery. The supply is highly unstable. Altering generator rotor speed can reduce delay caused by impedance angle, and integrating multiple sources (wind power via power-electronic interface) can coordinate supply from multiple generators, reducing the impact of one source on the grid.

3. Circuit simulation of power grid

This section presents voltage simulation results for the traditional power grid and the multi-energy power grid. In each simulation, the input and output voltages exhibit a phase delay relative to one another. Based on these results, FACTS and VSG technologies are introduced and their roles in improving grid stability are illustrated. The final simulation result shows that at different frequencies, the phase delay is different between the input and output.

3.1. Simulation analysis of traditional power grid

This section examines how the generator and supply end source synchronize as the rotor frequency changes. Synchronization is evaluated by using two measures: phase difference between input and

output voltages and the ratio of input to output voltages. Simulink simulation results analyze the delayed response of the generator and explain how it changes as the rotor frequency changes.

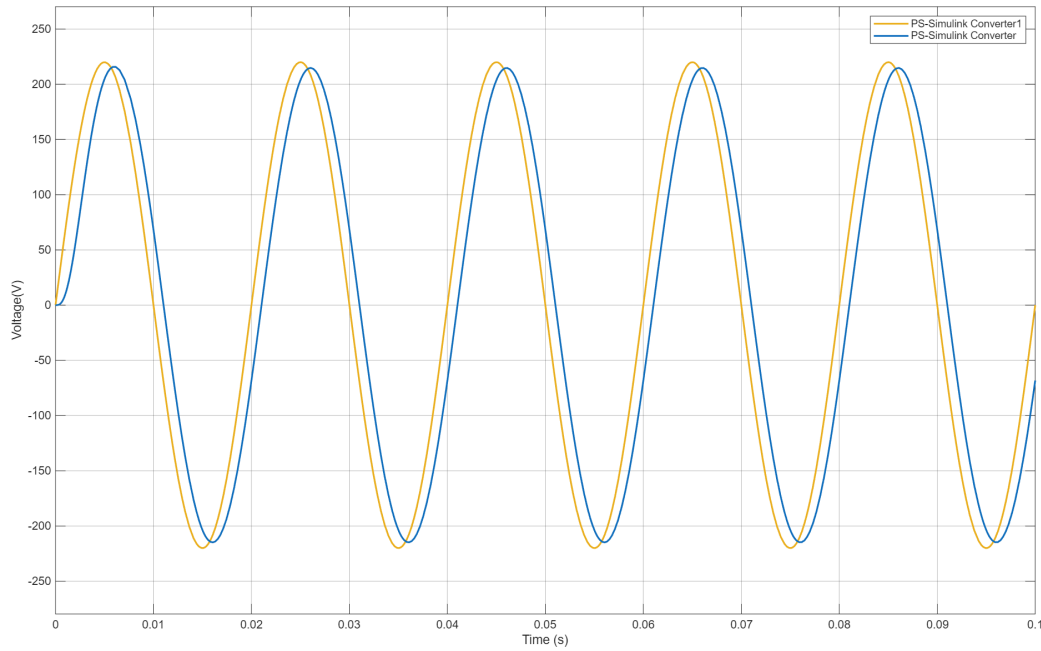


Figure 3. Traditional power grid impedance characteristic simulation diagram(50Hz)

Figure 3 shows that a measurable delay occurs during single-source power-grid transmission. The yellow trace represents the source-side waveform, and the blue trace represents the load-side waveform. The specific parameters are summarized in Table 1:

Table 1. Circuit parameters at 50Hz for traditional power grid

Circuit parameters	Values
R_1	0.3Ohm
L_1	8mH
C_1	90uF
R_3	100Ohm
L_2	2mH
R_2	0.5Ohm
R_{load}	50Ohm
f	50Hz
V_{max}	220V

As the frequency increases, oscillations and delays occur (Fig. 4). Changing frequency from 50Hz to 500Hz increases the impedance (this simulation is intended to illustrate how AC frequency changes affect the transmission characteristics of the equivalent circuit, but not the actual power grid operation), changes the voltage division, and supply delays. These delays reduce grid stability and introduce phase lag increasing the power factor. Increased reactive power leads to transmission energy losses [3, 4].

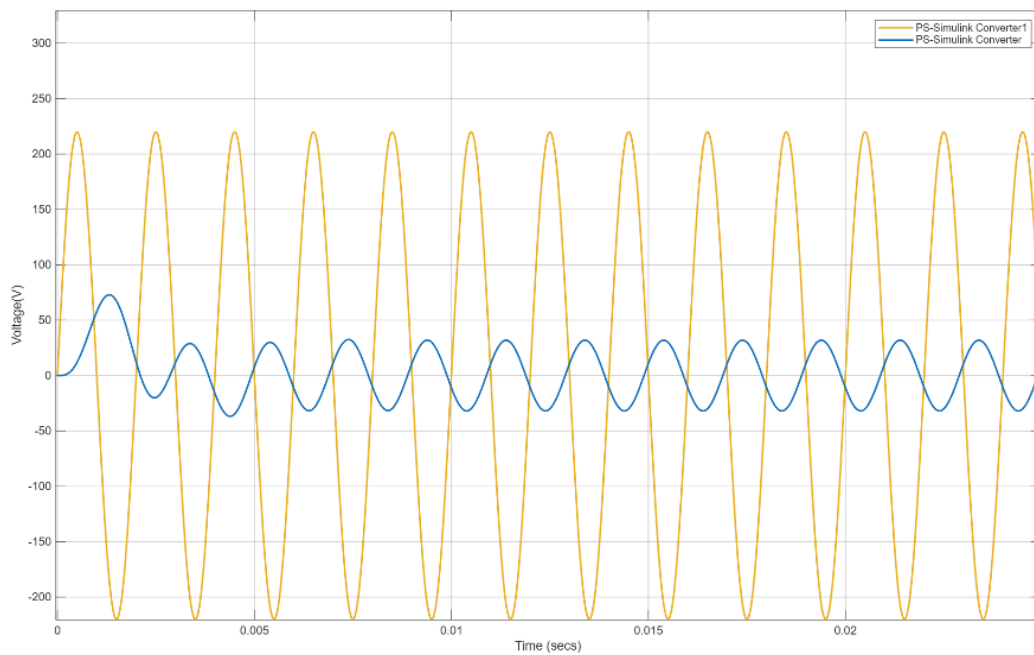


Figure 4. Traditional power grid impedance characteristic simulation diagram(500Hz)

3.2. Technological advantages of a multi-energy power grid

As multi-energy grid integration has developed, it can be used to mitigate power supply instability. Therefore, a new AC renewable generator was connected in parallel with the original source to compensate for voltage losses during high-frequency operation with the original frequency at 500Hz. The parameters are summarized in Table 2:

Table 2. Additional circuit parameters at 500Hz for multi-energy power grid

Circuit parameters	Values
R_4	10Ohm
L_3	2mH
V_{max}	1000V
f	500Hz

To simplify the analysis, this study models joint supply capability under multi-energy grid-connected conditions by paralleling two synchronized, controlled AC sources [4]. The simulation results are shown in Figure 5.

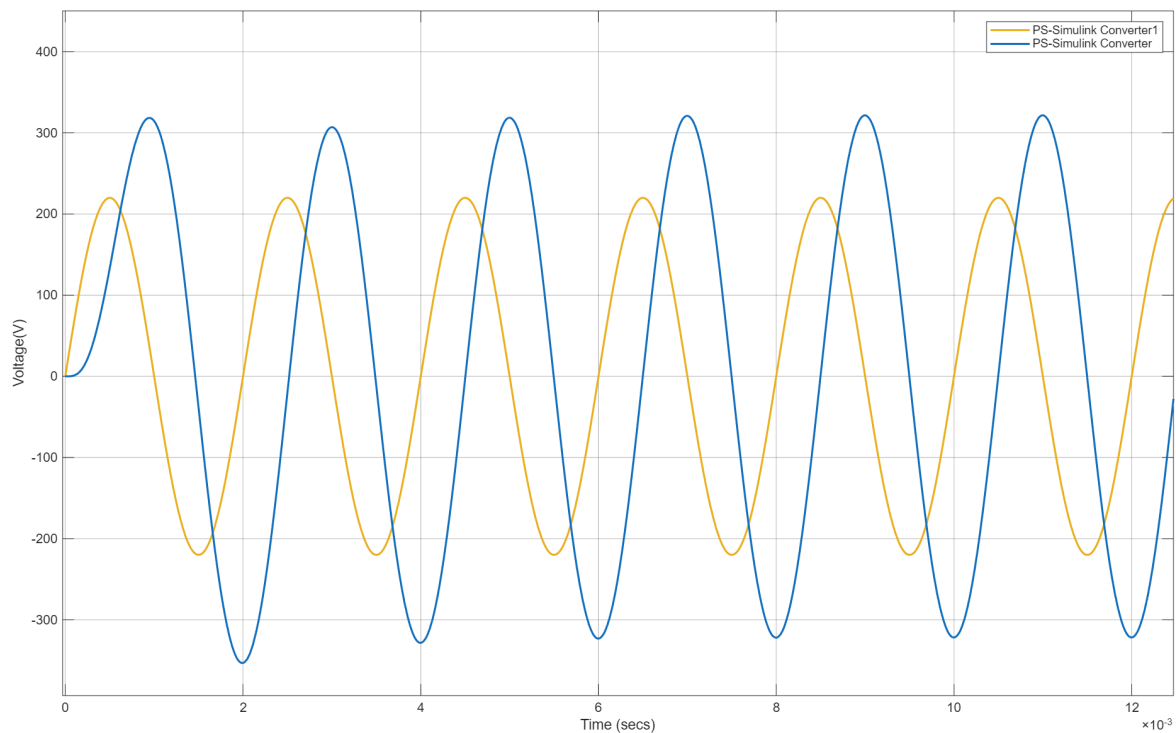


Figure 5. Multi-power grid impedance characteristic simulation diagram(500Hz)

The results show that adding a new energy motor for high voltage compensatory generation of the load side of high frequency transmission stabilizes load side voltage, but voltage delay due to impedance is not resolved, which is not real-world simulation. In next section, new international methods to deal with reactive power losses due to phase delay in conventional grids will be introduced.

3.3. Improvement directions for reactive power loss based on FACTS (Flexible AC Transmission System)

Since this is a simplified model, a STATCOM control model was not developed. Engineeringly, FACTS devices are important for improving voltage quality and reactive power compensation. FACTS devices are power electronics with single or integrated functions that actively control transmission systems to ensure power transfer stability and efficiency. Globally, FACTS devices are classified into three types: Static Var Compensator (SVC), Static Synchronous Compensator (STATCOM) and Unified power flow controller (UPFC). In this paper, how STATCOM can deal with reactive power loss is discussed [5].

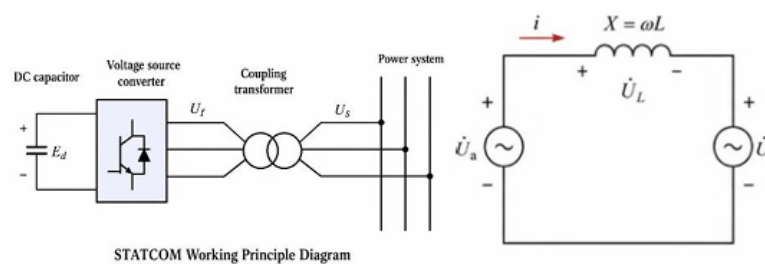


Figure 6. STATCOM working principle diagram

As shown in Figure 6, the three-phase AC bus connects to the inverter using a transformer. STATCOM can be modeled as a controllable AC voltage source, and by changing the voltage difference between the grid and the STATCOM terminals, it can compensate for reactive power.

When $U_I > U_a$, the current leads the voltage by 90° , and the grid terminal absorbs the reactive power generated by the capacitance. Conversely, when $U_I < U_a$, the current lags the voltage by 90° , and the grid absorbs the reactive power generated by the inductance. Therefore, by controlling the UI terminal, selectable reactive power compensation can be provided to the grid at U_a , and operators can choose the appropriate compensation mode according to the specific circumstances [5, 6].

In multi-energy systems, STATCOMs outperform single-energy grid solutions in terms of wind, photovoltaic and storage resource cyclicity. By providing millisecond dynamic reactive power compensation and voltage regulation, renewable integration capacity increases, weak grid stability is improved and voltages are less likely to be sped up and oscillated. Together with energy storage, STATCOMs can also provide frequency regulation, voltage support, and virtual inertia. Together, these functions help transform the grid from passive operation to a flexible, stable, and intelligent active control system.

3.4. Application of VSG Technology (Virtual Synchronous Generator) in multi energy grid connection

The equivalent-circuit model above is designed to characterize how the grid connection topology affects voltage transfer properties. In practice, multi-energy grid-connected systems, power-electronic inverters (power-electronic inverters) are power-electronic inverters without mechanical inertia and damping as conventional synchronous generators. Control schemes like virtual synchronous generator (VSG) methods are needed to improve dynamic stability. The VSG concept uses control algorithms to make the inverter rotor of a conventional synchronous machine and provide the inverter with mechanical inertia and damping [7, 8]. The standard mathematical form is the following:

$$Jw_0 \frac{dw}{dt} = P_m - P_e - D_p (w - w_0) \quad (9)$$

J is the virtual moment of inertia (the resistance of the system to frequency changes), w is the virtual angular frequency, and w_0 is the grid reference frequency. P_m is the input power of the virtual machine, P_e is the actual output power of the inverter, D_p is the virtual damping coefficient. If the grid power or angular frequency changes suddenly, the inertia term J prevents large frequency variations over short periods of time. This inertia-like behavior gives the inverter a motor-like damping characteristic and reduces supply instability caused by multi-source grid integration [9, 10].

4. Conclusion

Simulation results show that higher transmission frequency increases the phase difference between input and output voltages and reduces the output voltage amplitude. This shows a decline in power transmission performance and voltage control capabilities. As frequency deviates from its nominal value, reactive power losses increase and system stability may suffer, especially in high renewable

energy transmission networks. To mitigate these effects, Flexible AC Transmission System (FACTS) devices can be used. FACTS devices provide dynamic reactive power compensation and voltage control to maintain acceptable operating conditions under different frequencies. Two dynamically controlled reactive power compensators located at the source and load sides are proposed to reduce reactive power losses and improve voltage stability. Fast response capability allows the transmission network to adapt more to changing operating conditions and changing power demand.

Furthermore, in case of a major power outage or sudden power loss, VSG technology is used to supply system operation. Power electronic inverters can be controlled in order to emulate the power electronic generators of conventional synchronous generators. Thus, VSG technology can provide virtual inertia and frequency support, thereby improving power system stability and reliability. These technologies are useful for modern grids with a high proportion of renewable energy sources, where low inertia may also be a problem. The conclusions of this paper are based on idealized simulation conditions and thus may not fully represent real-world operating conditions. Equipment limitations, communication delays, measurement errors, and disturbances were not considered. Simulations and quantitative analysis of proposed FACTS and VSG technologies were not part of this work and should be investigated in future studies. Future work should also include experimental validation and performance tests under practical grids.

References

- [1] Shi, W. H., Shu, Y. B., Zhang, L. Y., et al. (2022). Research on grid integration and operation development of high-proportion renewable energy. *Strategic Study of CAE*, 24(3), 121-132.
- [2] Glover, J. D., Sarma, M. S., & Overbye, T. (2012). *Power system analysis and design*. Cengage Learning.
- [3] Zhou, X. X., Chen, S. Y., Lu, Z. X., et al. (2018). Technical characteristics of China's new-generation power system in the energy transition. *Proceedings of the CSEE*, 38(7), 1893-1904, 2205.
- [4] Lasseter, R. H. (2011). Smart distribution: Coupled microgrids. *Proceedings of the IEEE*, 99(6), 1074-1082.
- [5] Hingorani, N. G., & Gyugyi, L. (2000). *Understanding FACTS: Concepts and technology of flexible AC transmission systems*. New York: IEEE Press.
- [6] Shang, H. L. G. (2021). Review of FACTS devices and applications in power systems. *Renewable and Sustainable Energy Reviews*, 146, 111-123.
- [7] Zhong, Q. C., & Weiss, G. (2011). Synchronverters: Inverters that mimic synchronous generators. *IEEE Transactions on Industrial Electronics*, 58(4), 1259-1267.
- [8] Li, M., H, W., Tai, N., et al. (2022). Virtual inertia control of the virtual synchronous generator: A review. *Journal of Energy Storage*, 50, 104599.
- [9] Kundur, P. S., & Malik, O. P. (2022). *Power system stability and control* (2nd ed.). McGraw-Hill Education.
- [10] Li, M., Zhang, Y., Wen, B., et al. (2022). Phase feedforward damping control method for virtual synchronous generators. *IEEE Transactions on Power Electronics*, 37(9), 10433-10446.