Next Energy 8 (2025) 100327

Contents lists available at ScienceDirect

Next Energy

journal homepage: www.sciencedirect.com/journal/next-energy

Research article

Simulation of renewable energy source integration in a smart energy grid using MATLAB/Simulink

Edward Ofoegbu*, Harsh Nitin Raichura

School of Built Environment, Engineering and Computing, Leeds Beckett University, G01 Leighton Hall, Headingley Campus, Leeds LS6 3QR, UK

A R T I C L E I N F O

Keywords:
Renewable energy
Smart grids
System integration
Simulation
MATLAB
Simulink

A B S T R A C T

The transformation of the power grid from traditional methods into smart grids for the generation, transmission, distribution, and utilization of electric energy reduces the dependency on fossil fuels, thus taking a step towards environmental sustainability. This research paper simulates a smart grid's behavior when integrated with a renewable energy source. The grid network topology of a power system was modeled and simulated in MATLAB/SIMULINK, where the model consisted of renewable energy resources (RER's) having a series of solar panels, redundant power generating stations, a transmission infrastructure, and a power utilization section for 3-phase high voltage industrial load and low voltage domestic load, respectively. The results of the study showed that there is power loss and signal distortion in the output voltage when multiple generators are integrated. These harmonics can be easily filtered out when the integration is done between the generator and a renewable energy resource (RER) using properly designed Resistor-Inductor-capacitor filters and booster circuits. The results further demonstrated that when integration was accomplished between the generator and the RERs, a stable output voltage of 0.6e4 V was obtained, given a generator capacity of 6600 V. The industrial and domestic load also showed minimal instability by maintaining an output of 1100/440 V, respectively, before and after integration. The study also showed that RERs can be used to support the power supply to the grid to maintain its supply voltage and the overall stability of the system. However, RERs cannot withstand supplying a power grid on their own.

1. Introduction

Power plants transmit electricity in one direction at set rates to distribution substations [1]. The outdated electricity infrastructure of the Traditional Grid (TG) system cannot handle the growing needs for real-time pricing, congestion management, self-healing, Demand Response Programs (DRPs), reliability, and security [1]. Focusing on the latest technologies is crucial to meeting customer demand and providing a reliable, safe, and continuous electricity supply without power outages [1]. The traditional power grid system is focused on transmitting electricity over long distances and distributing it to users and faces numerous challenges, including limited real-time pricing, congestion management, and reliability [1]. To meet growing demands and ensure continuous supply, it is essential to embrace new technologies [1]. Incorporating variable renewable energy sources (VRES) into the grid poses a significant challenge, requiring updates and expansions to the transmission infrastructure. With the increasing penetration of VRES, the focus shifts to improving transmission capabilities to support remote locations and maintain system stability. Conventional power generation methods suffer from drawbacks like unidirectional power flow and limited internal regulation [7], necessitating the adoption of smart grid technologies. Smart grids, utilizing distributed generation, demand response programs, and advanced sensors, enable efficient energy monitoring, control, and fault rectification, ensuring a reliable and resilient power supply [8]. Some of the main factors driving the rise of renewable energy (RE) to the top of the energy portfolio are exponential growth in the demand for energy due to growing population and economic growth, growing concerns about energy security, climate change and global warming [14]. Since 2010, wind and solar photovoltaic (PV) systems have seen tremendous growth among other renewable energy sources. The combined global capacity of solar PV and wind power generation was 303 and 487 GW at the end of 2016, translating to penetration levels of 1.5 and 4.0%, respectively [14]. The percentage of renewable energy in the world until December 2016, excluding the 16.6% share of conventional hydropower, was only about 8.0% [14]. Also, energy consumption is projected to rise significantly from 663 to 736 quadrillion in the period of 2015–2040, leading to an estimated increase in carbon dioxide emissions from 31.2 to 45.5 billion

* Corresponding author.
E-mail address: e.ofoegbu@leedsbeckett.ac.uk (E. Ofoegbu).

https://doi.org/10.1016/j.nxener.2025.100327
Received 26 February 2025; Received in revised form 19 May 2025; Accepted 20 May 2025

metric tons per year [15]. Understanding the significance of integrated renewable energy sources, the European Union established a target to attain 27% of gross final energy consumption from renewable sources by the year 2030 [15]. Incorporating a significant proportion of VRES into the electricity grid is a critical obstacle in the global decarbonization and clean energy agenda. It is essential to encourage the economic deployment and usage of VRES generation while preserving or improving the stability and dependability of the power system as its installation grows. The infrastructure and services of the transmission grid must be updated and expanded due to the remote locations and intrinsic qualities of VRES.

An investigation into the integration of renewable energy into an electrical grid is driven not only by policy and regulatory drivers of world governments to be carbon-neutral post-2030, but also by a complex mix of factors ranging from environmental to economic, as well as technical reasons. Renewable energy sources (RERs) play a significant role in reducing greenhouse gases and have thus formed the foundation of the transition efforts to clean energy in line with the Paris Agreement. There is also the added benefit of improving the quality of air in cities and nearby towns, as the quality health outcomes observed in many regions of the world have been tied to the pollution levels observed therein. The cost of RERs has also been a motivating force, as falling costs to levels that are cheaper or competitive with fossil sources now place RERs as a viable alternative to replacing the energy transition efforts many countries are embarking on to have energy independence, as local renewable generation reduces dependence on imported energy. Economically, the benefits of RERs integration are immense as it has a direct impact on job creation, and cost savings accruing from a diversified energy portfolio, which technically also increases the resilience of the grid and its overall reliability.

This study aims to simulate the behavior of a smart grid when integrated with a renewable energy source. The next sections of this paper will be a literature review of the challenges of integration of renewable energy in smart grids, the Simulink model, and the simulation carried out, while the results and discussion will follow in subsequent sections.

2. Literature review

The conventional centralized power system, relying heavily on fossil fuels to nearly 81% [2], faces challenges due to increasing demand and environmental concerns. As a result, there's a global shift towards renewable energy sources. The smart grid (SG) concept emerged to facilitate this transition by providing a flexible and adaptable electrical grid capable of integrating renewable energy effectively. With renewable energy integration, the SG manages 2-way energy and information flows, allowing for decentralized energy production and real-time monitoring [11]. Renewable energy sources like solar, wind, and hydrogen are prioritized for integration into the grid, often through microgrids utilizing power electronics [14]. However, these sources lack inertia support, necessitating additional auxiliary systems and grid upgrades for stability [10]. Overall, grid modernization is crucial to accommodate renewable energy integration and ensure a sustainable and reliable energy future [10].

Integrating renewable energy into the smart grid offers numerous advantages for both the environment and consumers. By leveraging renewable resources such as solar PV energy, the grid can significantly reduce greenhouse gas emissions, contributing to a sustainable environment [10]. This integration shifts towards a more distributed energy production system, lessening reliance on centralized energy generation and reducing transmission power loss, ultimately leading to more efficient energy production and distribution.

Additionally, incorporating renewable energy stabilizes the grid, ensuring a consistent power supply even during peak demand periods [7]. The smart grid's flexibility allows for seamless power transfer to renewable sources for maintenance, ensuring uninterrupted service to consumers. With renewable energy integration, load shedding becomes less frequent, enabling consumers to utilize power without interruptions. Moreover, renewable energy tends to be more cost-effective, providing financial benefits to both consumers and the energy system. Overall, integrating renewable energy into the smart grid represents a crucial step towards a sustainable and resilient energy future.

The integration of renewable energy systems into the electric power system brings significant changes to traditional power network structures. In the traditional radial system, power flows from higher voltage levels to lower ones, with distribution systems serving as passive circuits [12]. However, with the introduction of renewable energy generators, distribution networks become more active, with multiple voltage sources in a single feeder. Most renewable energy systems are integrated at the low-voltage distribution level. This integration introduces abrupt fluctuations in generated power output, increasing the stochasticity of the power network [7]. To manage this complexity, upgrades are needed at both the generation and distribution levels. The current centralized power network needs improvements in monitoring, control, and regulation to accommodate fluctuating renewable energy sources effectively [7]. Coordinated upgrades are necessary to optimize power flow, ensure supply quality, and enhance system flexibility, especially at the distribution level. The goal is to achieve optimal power flow, supply quality, and reliability while reducing the complexity of stochasticity [14].

Some of the major integration challenges posed by renewable energies in smart grids are power balance issues, such as Inadequate Short-Term Ramping Capability; Conventional synchronous generation, crucial for grid stability, may lack the rapid ramping capabilities needed to accommodate the fluctuations in renewable energy output [7]. Without adequate ramping, the grid risks technical and economic losses due to frequency instability, Long-Term Generation Inadequacy; as RERs penetration increases, seasonal and annual energy balancing becomes more challenging, affecting the scheduling of synchronous generation [5]. Long-term instability can occur due to unpredictable fluctuations in renewable energy output, leading to financial challenges and a reliance on thermal unit maintenance [7], The inability to accurately forecast changes in renewable energy output on short, medium, and long timescales causes scheduling difficulties and localized grid congestion [8]. Inaccurate forecasts can result in unplanned grid operations, equipment damage, technical issues, and economic losses [7], Voltage Flickering; Harmonics may also lead to flickering in displays and lighting, spurious tripping of circuit breakers, malfunctioning of sensitive equipment etc [14] and locally integrated renewable energy through power electronics increases flicker leading to reduced equipment lifetime [7], Renewable Harmonic distortions are increased during integration via inverters. As a result, end users experience shorter equipment lifespans, more trips, or equipment damage [7]. The issue with oscillation is that it restricts power transfer capabilities, particularly in long transmission lines, and adds to the system's instability when anomalous events arise [3]. A detailed analysis of the electric field inside high-voltage (HV) substations using charge simulation methods was reported in [16].

Lower voltage levels of the grid may lack proper protection against the stochastic nature of renewable energy integration. Inadequate protection planning can result in overloading, unplanned trips, and negative impacts on equipment lifetime. Protection systems must also handle erratic fault currents and enable islanding for increased reliability [9], Reduced Capability Towards Fault Detection; RE generation systems have very low short-circuit power, which can make fault detection and voltage instability difficult to detect [4]. This complicates stable grid operations and may isolate RE microgrids, emphasizing the need for accurate statistical descriptions of forecast errors and adequate reserve requirements [9].

3. Materials and methods

This study uses MATLAB Simulink software R2022b to design and simulate a model considering all the electrical parameters. The virtual

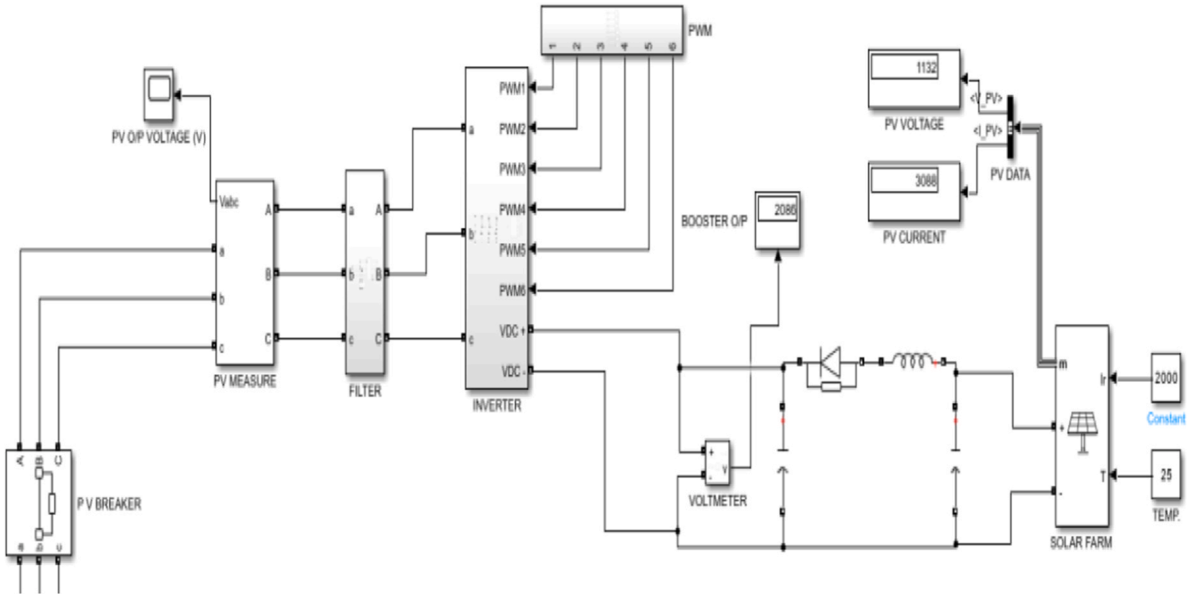

Fig. 1. A Simulink Model of renewable energy generation.

design is significant as it designs a model with all required parameters and analyzes the results before the actual implementation of the desired network into the present grid.

3.1. Renewable energy generation

The solar power is generated with the help of a PV array, followed by a booster circuit to boost the power generated by the PV array and supply it through an inverter circuit, to have a pulsating Direct current (DC) output converted into a pure AC sinusoidal waveform with R-L-C filters applied. The output voltage and waveform are measured by the scope attached to the measurement block and further connected to the circuit breaker used to integrate solar power output into the grid, as shown in Fig. 1 below.

3.1.1. Specifications of renewable energy generation (PV generation)

The solar farm has an input irradiance of 2000 W/m^2 and an input temperature of 25 °C, which allows it to generate an output voltage of 1132 V and an output current of 3088 A. Table 1 shows the input values of the PV array in the model.

The PV model consists of 200 Parallel Strings and 50 series-connected Strings. To evaluate the desired output of the renewable resources of energy and the module data specifications are shown in Table 2 below:

3.1.2. Output power calculation

Total output power is calculated as

Number of parallel strings*Number of series string*rated power of each module

i.e. Calculated Power (o/p) = 200*50*219watts

P(o/p) = 2190000 (2.19MW)

3.1.3. PV output

It measures the output voltage and current produced in the solar farm. The measured values, as expressed in Table 3 are as follows.

Table 1
PV array characteristic parameters

Parameters	Values	Reference of input values
Input Irradiance	2000 W/m^2	To obtain the desired output value
Input Temperature	25 °C	As the ambient room temperature is 25 °C.

PV = photovoltaic.

Table 2
Module parameters of A10 Green Technology, A10J-M60-220

Parameters	Values
Max Power	219 W
Cells per Module	60
Open Circuit Voltage (V_{oc})	36.06 V
Short Circuit Current (I_{sc})	7.95 A
Voltage at maximum Power Point V_{mp} (V)	30.12 V
Current at maximum Power Point I_{mp} (A)	7.3 A
Temperature coefficient of V_{oc} (%/deg.C)	−0.3624
Temperature coefficient of I_{sc} (%/deg.C)	0.05480
Light-generated Current IL (A)	7.9642 A
Diode saturation Current I0 (A)	2.8692e−10 A
Diode ideality factor	0.97455
Shunt Resistance R (sh) (ohms)	106.1817 Ohms
Series Resistance R (s) (ohms)	0.18964 Ohms

The values mentioned in the above table are the choice of specifications and in line with the best industrial practice.

Table 3
Output values of solar power generation

Parameters	Values
Output Voltage	1132 V
Output Current	3088 A
Output Power	2.198 W

Fig. 2 represents the following graphs, where the voltage-current output parameters of the PV array of type A10 Green Technology A10J-M60–220, having 50 series modules and 200 parallel strings, are shown.

i. Voltage-Current (V-I) graph
ii. Voltage-Power (V-W) graph

The maximum current drawn is 1460 A when the voltage across it is 1506 V. The maximum power generated at 1506 V is 2198760 W (approx. 2.198 MW), having an input irradiance of 1 kW/m^2. The output power value of 2198760 W matches the above-calculated output power value of 2.19 MW. It should be noted also that within the filter module is a phase-locked loop, which locks the phase of the output signal to the phase of a reference input.

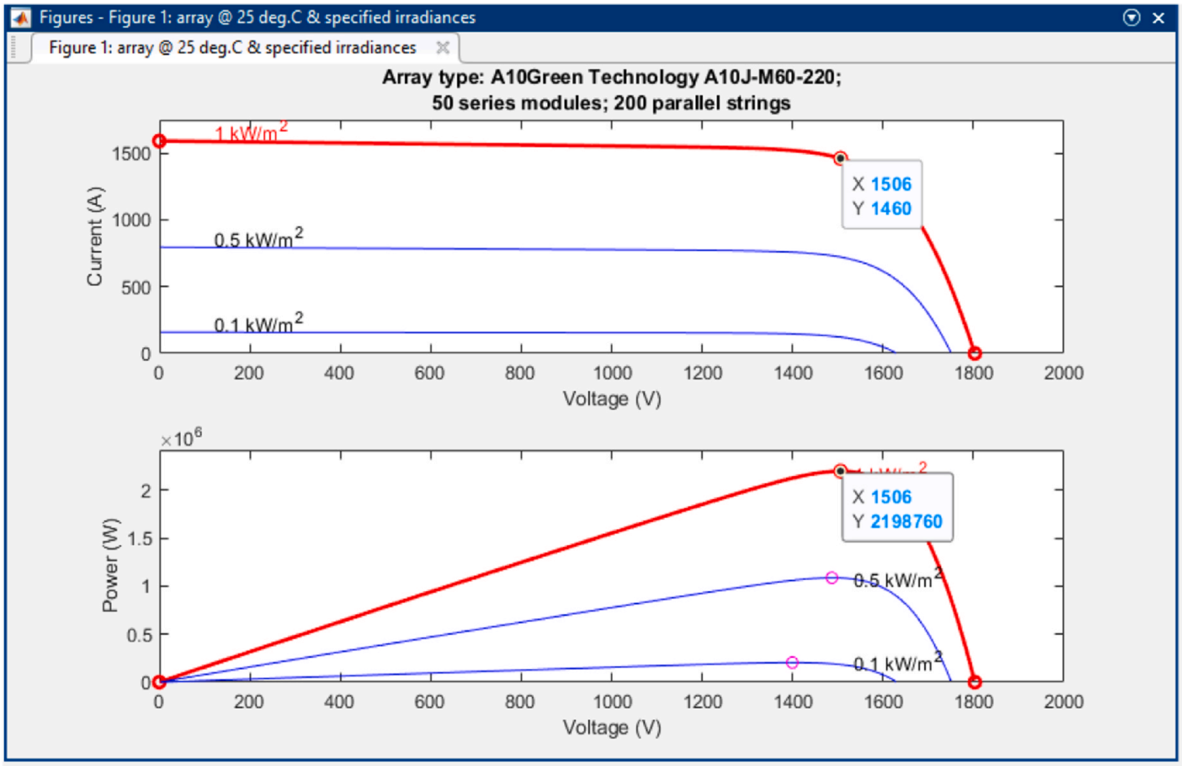

Fig. 2. Solar farm V-I graph and V-W graph. V-I = voltage-current; V-W = voltage-power.

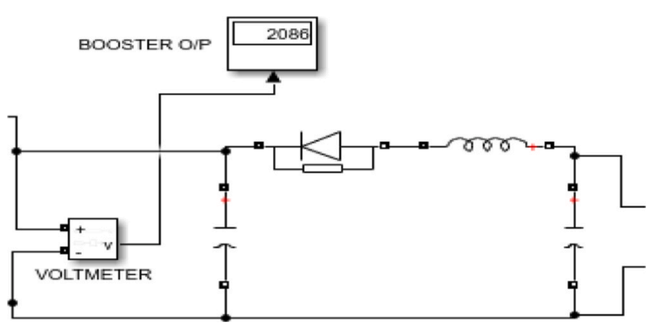

Fig. 3. Booster circuit [6].

Table 4
Booster circuit parameters

Parameters	Values	Reference of input values
Inductor (L)	1e − 3 H	
Capacitor (C)	6e − 3 F	[6]

The values mentioned in the above table are the choice of specifications and in line with the best industrial practice.

Table 5
Diode parameters

Parameters	Values
Internal Resistance (Ron)	1e − 3 Ohms
Inductance (Lon)	0 H
Forward Voltage (Vf)	0.8 V
Snubber resistance (Rs)	500 Ohms
Snubber Capacitance (Cs)	250e − 9 F

The values mentioned in the above table are the choice of specification and are in line with the best industrial practices.

Table 6
Inverter circuit parameters

Parameters	Values	Reference of input values
Internal Resistance (Ron)	1e − 3 Ohms	
Inductance (Lon)	0 H	
Forward Voltage (V_f)	1 V	
Snubber resistance (Rs)	1e5 Ohms	[13]
Snubber Capacitance (Cs)	inf. (infinite) F	

The values mentioned in the above table are the choice of specifications and are in line with the best industrial practice.

Table 7
R-C series circuit parameters of inverter circuit

Parameters	Values	Reference of input values
Resistor (R)	1e − 3 Ohms	[13]
Capacitor (C)	5600e − 6 F	[13]

Table 8
PWM parameters

Parameters	Values	Reference of input values
Time Values	[0 0.00005 0.0001]	[13]
Output values	[−1 1 −1]	[13]

PWM = pulse width modulation.

3.1.4. Booster circuit

The booster circuit is referred to from [6] and depicted in Fig. 3, consists of an inductor and a free-wheeling diode in series with 2 capacitors in parallel, with the values stated below in Table 4. Its function is to make the circuit ripple-free, stabilize, and boost the voltage from the PV array.

Table 9
R-L series filter parameter

Parameters	Values
Resistor (R)	1e − 3 Ohms
Inductor (L)	1e − 3 H

The values mentioned in the above table are the choice of specifications and in line with the best industrial practice.

Table 10
R-C shunt filter parameters

Parameters	Values	Reference of input values
Resistor (R)	1e5 Ohms	[13]
Capacitor (C)	1e − 9 F	[13]

3.1.5. Diode

The diode in the above booster circuit is forward biased with the following data specifications as in the Table 5 below:

3.1.6. Voltmeter

It is connected across the line to measure the voltage of the line to give a Booster Output Voltage (V_b) of 2086 V.

3.1.7. Inverter circuit

To convert the DC voltage generated in the PV array into pulsating AC Voltage. It consists of 6 insulated gate bipolar transistors (IGBTs) with pulse width modulation (PWM) as the gate signal for operation, with the R-C filters (values specified below) connected in parallel for the modulation. The Inverter circuit above has 6 IGBTs connected to give a pulsating DC output. The specifications are in Table 6 as follows:

The R-C series circuit is connected across the DC voltage line as a DC bus capacitor to reduce the switching loss and increase the life span of the semiconductors in the circuit. The values of the resistor and capacitor are in Table 7 as follows:

The PWM Circuit generates the pulse for the input of the gate in IGBTs, which consists of a reference pulse generator (V_{ref}), connected to a repetitive sequence for the carrier wave, and rational and logical operators to supply the gate pulse for the IGBTs.

3.1.8. Pulse-width-modulation (PWM) generator specifications

This sequence is used for repeating the signals and sampling the output waveform, with period values stated below in Table 8.

3.1.9. Filter

This filter is used to convert pulsating DC voltage from the inverter into a pure Alternating current waveform. It consists of R-L in series and R-C in shunt to compensate for the voltage. The measurements are as follows in the following Table 9 and Table 10 respectively.

3.2. The grid network topology

The power grid network has 3 generators, of which Generator A has an output of 6600 V, Generator B has an output of 3300 V, and Generator C (redundant) has an output voltage of 3300 V. The grid line voltage of 6600 V, a step-up voltage of 6600/11000 V, having a transmission line of 100 km, and a transmission line step-down transformer of voltage 11000/6600 V. Moreover, the utilization network has a distribution transformer of 6600/1100 V and is directly supplied to a 3-phase high-voltage consumer load (industrial load). Further, it also has a residential transformer of 1100/440 V and is supplied to a phase residential load of 440 V, as shown in Fig. 4.

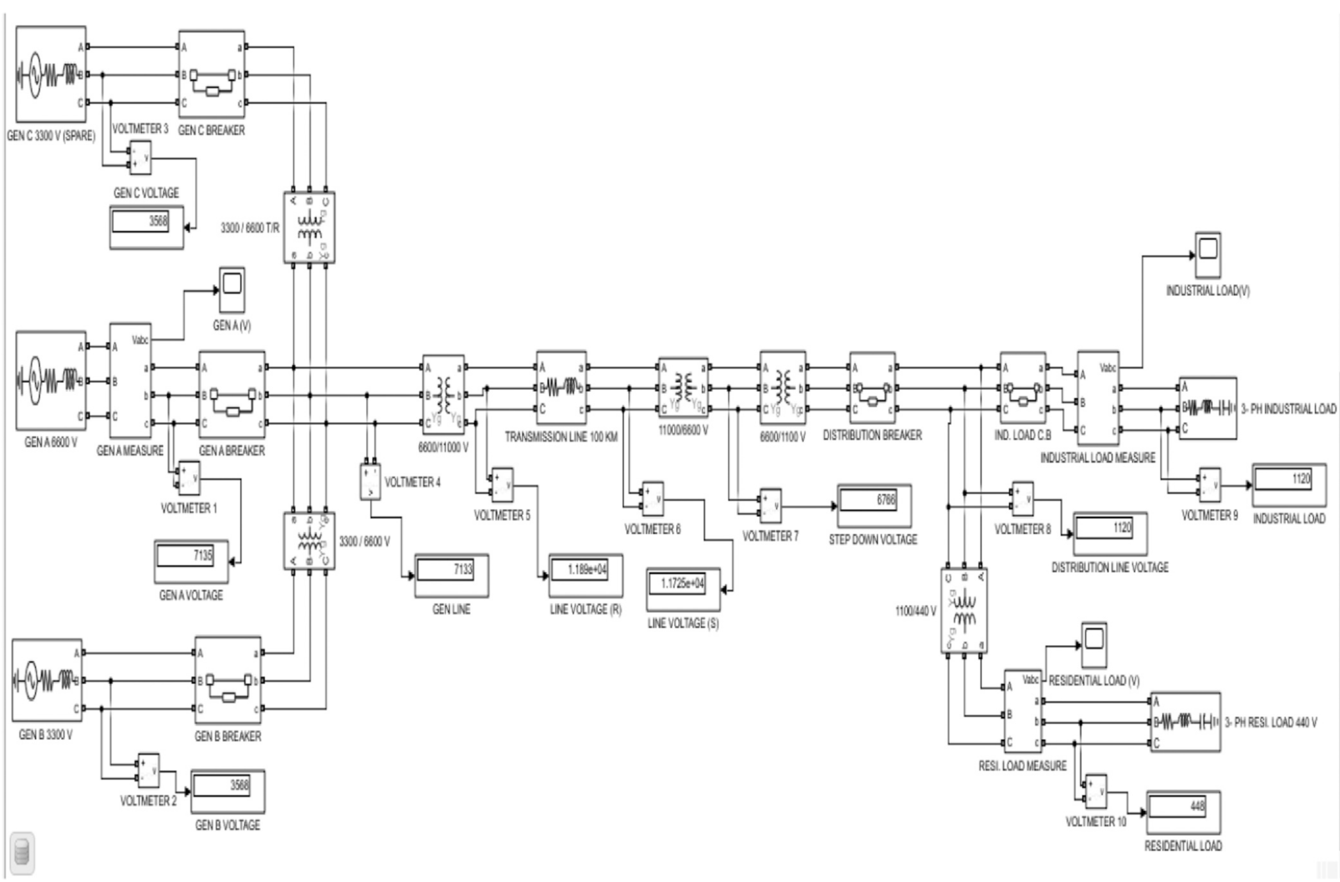

Fig. 4. A Simulink Model of grid network topology.

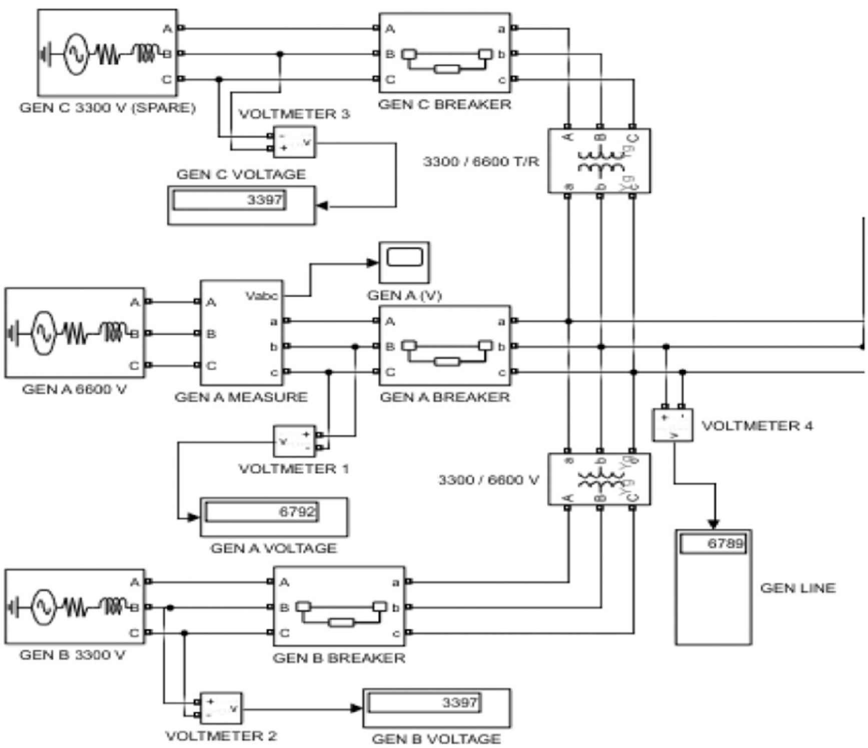

Fig. 5. Generation unit of the grid.

Table 11
Internal impedance parameters of Generators A, B, and C

Parameters	Values
Resistor (R)	1 Ohm(s)
Inductor (L)	16.58e − 3 H

The values mentioned in the above table are the choice of specifications and are in line with the best industrial practice.

3.2.1. Generation unit

As shown in Fig. 5, it consists of 2 main generators with a rated output voltage of 6600 and 3300 V, respectively, and a redundant generator with a rated output voltage of 3300 V. The voltage of the generators with a rating of 3300 V is stepped up to feed it into the grid line to meet the voltage level of the main Generator A, rated 6600 V.

Generator A: It is a 3-phase source connected in star with a grounded neutral connection (Yg), having swing characteristics of load flow.

Generator-A specifications: Phase-to-phase voltage (V_{rms}) = 6600 V, with frequency of 60 hertz. The internal impedance parameters of the Generator (A) are in Table 11, where it has an Output voltage of 6792 V.

The Circuit breaker installed in the line (Generator A-C/B) has the same default characteristics and specifications as of PV output circuit breaker.

Generator B: It shows a 3-phase source has a star connection with grounded neutral (Yg), with swing load flow characteristics. It has a 3-phase transformer of 3300/6600 V to meet the grid voltage.

Generator-B Specifications: Phase-to-phase voltage of 3300 V with frequency (f) = 60 hertz. The internal impedance parameters of Generator B are in the Table 11 as above:

Transformer Specifications: It is a 3 single-phase transformer type having winding 1 and winding 2 in star connection and neutral as grounded. The voltage values of winding 1 and winding 2 of the transformers are set as 3300 and 6600 V, respectively to maintain the grid line voltage. The values are described in Table 12.

Generator C: This 3-phase source (as shown in Fig. 4) is a redundant generator that has a star connection with grounded neutral (Yg), with swing load flow characteristics. Phase-to-phase phase-rated voltage of the Generator-C is rated as 3300 V with frequency (f) = 60 hertz. The internal impedance parameters of Generator C are shown in Table 11 above, with an output voltage of 3568 V.

3.2.2. Transmission unit

As shown in Fig. 6, the power generated by the generators is transferred by a 100 km transmission line to the consumers for utilization. It consists of a step-up transformer (6600/11000 V) and a step-down transformer (11000/6600 V).

Step-Up Transformer Specifications: It is a 3 single-phase transformer type having winding 1 and winding 2 in star connection and neutral as grounded. The voltage values of winding 1 and winding 2 of the transformer are 6600 and 11000 V, respectively. The values of the parameters are shown in Table 13:

The output of the step-up transformer (6600/11000 V) is 1.302e04 V; approx. 13020 V.

Table 12
Transformer specifications installed with Generator B

Parameters	Values
Nominal Power and frequency [Pn (VA), f (Hz)]	[250e6, 60]
Winding 1 parameters [V1 Ph-Ph (vrms), R1 {Ohms}, L1 (H)]	[3300 0.00034848 3.6975e − 05]
Winding 2 parameters [V2 Ph-Ph (Vrms), R2(Ohm), L2 (H)]	[6600 0.000968 0.00010271]
Magnetization resistance Rm (Ohm)	500 Ohms
Magnetization inductance Lm (H)	500 H

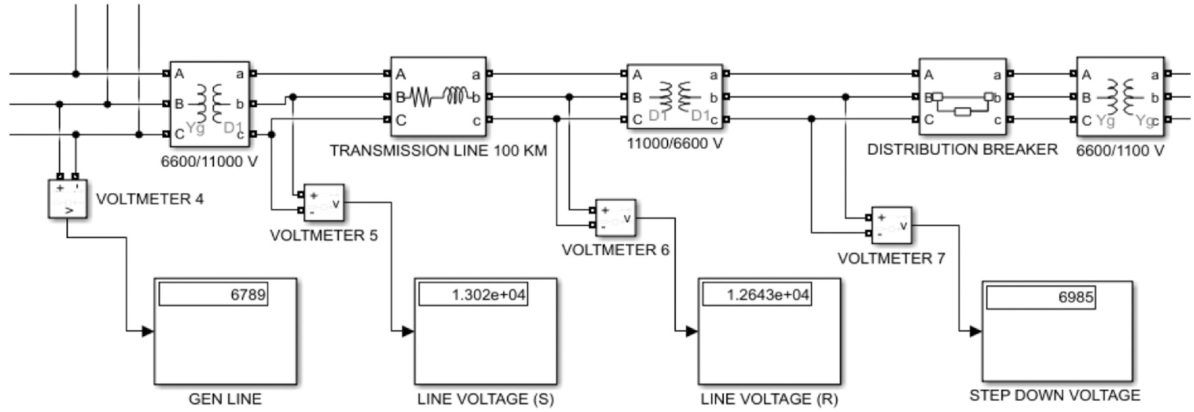

Fig. 6. Transmission unit of the grid.

Table 13
Step-up transformer parameters

Parameters	Values
Nominal Power and frequency [Pn (VA), f (Hz)]	[250e6, 60]
Winding 1 parameters [V1 Ph-Ph (Vrms), R1 {Ohms}, L1 (H)]	[6600 0.00034848 3.6975e − 05]
Winding 2 parameters [V2 Ph-Ph (Vrms), R2(Ohm), L2(H)]	[11000 0.000968 0.00010271]
Magnetization resistance Rm (Ohm)	500 Ohms
Magnetization inductance Lm (H)	500 H

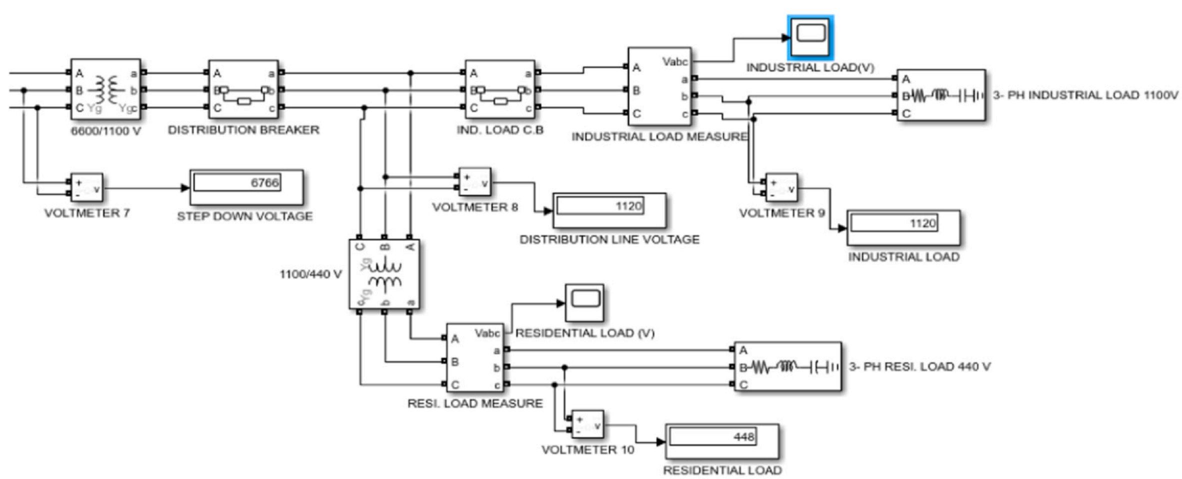

Fig. 7. Utilization unit of grid topology.

Table 14
Industrial load parameters

Parameters	Values	Reference of input values
Configuration	Star (Y) with neutral grounded	To have better efficiency
Phase to Phase voltage (Vrms)	1100 V	As the Industrial load is 1100 V
Nominal frequency	60 Hertz	The operating frequency is 60 Hz
Active power	10e3 W	
Inductive reactance power (QL)	100 var	
Capacitive reactance power (QC)	100 var	

3.2.3. Utilization unit

In this unit, the power generated and transmitted with various switch gear installed for protection is finally being supplied to the consumers; both high-voltage users (1100 V) and the residential connection have a 3-phase line of 440 V. It consists of distribution transformers that step down the voltage level from 6600 to 1100 V. This high voltage power is directly supplied to the industrial consumers, where the voltage is again stepped down to 440 V and supplied to the residential users as described in Fig. 7 below.

Distribution Transformer and Circuit Breaker: As the name suggests, the distribution transformer is a step-down transformer from a high voltage of 6600 to 1100 V and is supplied to consumers (both high

Table 15
Domestic load parameters

Parameters	Values	Reference of input values
Configuration	Star (Y) with neutral grounded	To have better efficiency
Phase to Phase voltage (Vrms)	440 V	As the domestic load is 440 V
Nominal frequency	60 Hertz	Operating frequency is 60 Hz
Active power	10e3 W	
Inductive reactance power (QL)	100 var	
Capacitive reactance power (QC)	100 var	

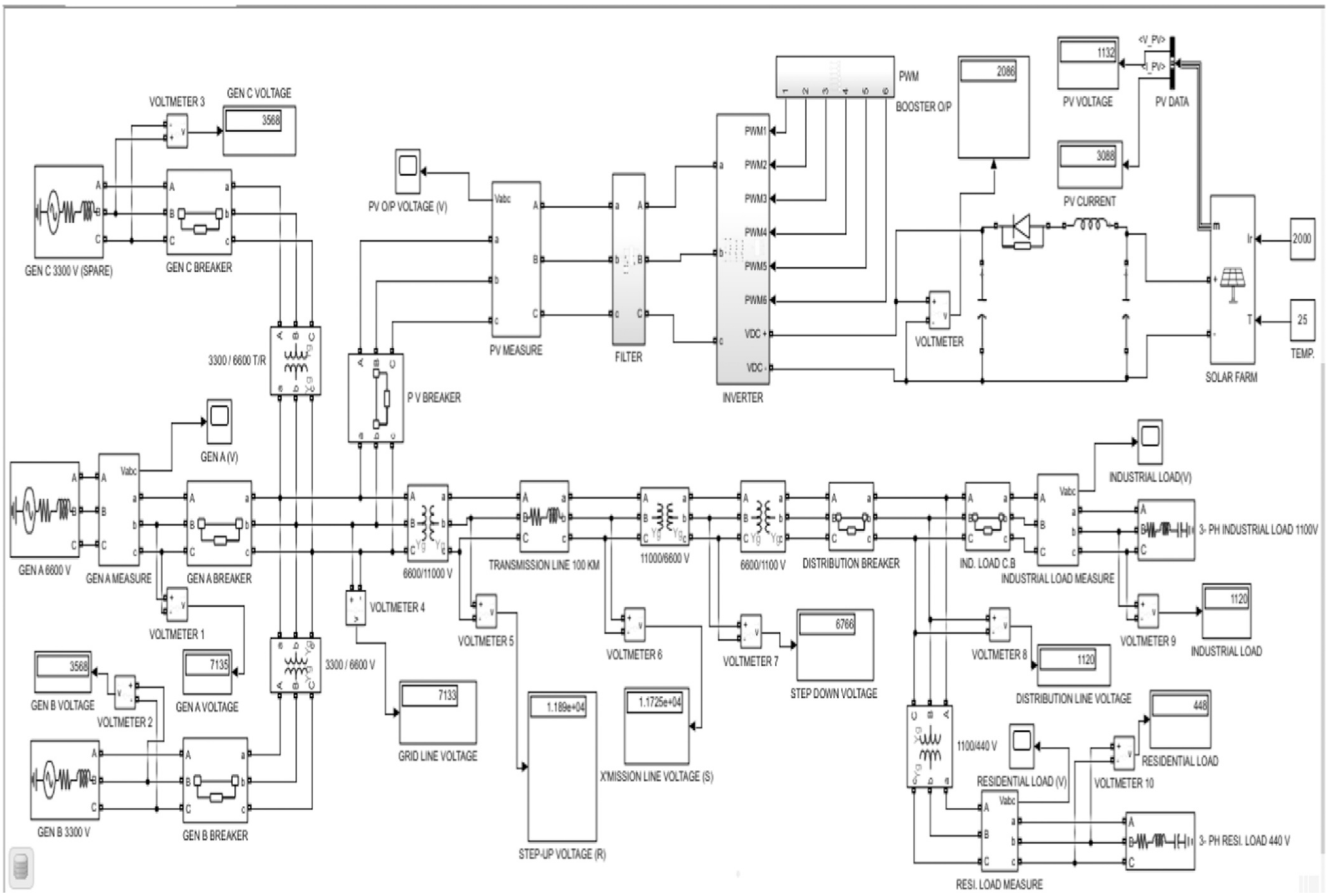

Fig. 8. A detailed Simulink Model of RERs integrated in the grid. RER's = renewable energy resources.

voltage and domestic consumers) for utilization. It also consists of a circuit breaker that automatically operates in case of any fault to isolate the faulty part. The output voltage of the distribution transformer used at this stage is measured as 1120 V.

Load specifications: This is a 3-phase load for the utilization of power and is divided into 2 sections:

Industrial load: It is a 3-phase high-voltage load of 1100 V directly supplied by the distribution transformer to industrial consumers. It is a star connected with a neutral grounded load to have a better efficiency with a better power factor. The specification of load in Table 14 is described below.

Residential load: The line voltage of 1100 V is stepped down to 440 V with a transformer, followed by a 3-phase residential load of 440 V. It is a star connected with a neutral grounded load to have a better efficiency with a better power factor. The domestic load specifications are stated in Table 15 as follows:

The output voltage of the residential load is 448 V. Fig. 8 shows the detailed representation of the model designed in MATLAB, where the values shown therein represent the system output/behavior after the integration of renewable energy resources (RERs) in the grid.

3.2.4. Generator output voltage waveform

Figs. 9 and 10 represents the sinusoidal waveform of Generator A (rated 6600 V) before and after the integration of RERs in the SG, respectively. As it does not show any change in the waveform, the integration has been accomplished and has a stable voltage value of 0.6e4 V.

3.2.5. Industrial load output voltage waveform

Figs. 11 and 12 represents the sinusoidal waveform of the industrial load (rated 1100 V) before and after the integration of RERs in SGs, respectively. As it does not show any change, the integration has been accomplished successfully, and it also has a stable voltage of 1100 V.

3.2.6. Domestic load output voltage waveform

Figs. 13 and 14 represent the sinusoidal waveform of the domestic load (rated 440 V) before and after the integration of RERs in SGs, respectively. As it does not show any change in the waveform, the integration has been accomplished, and also the voltage level is stable at the value of 440 V.

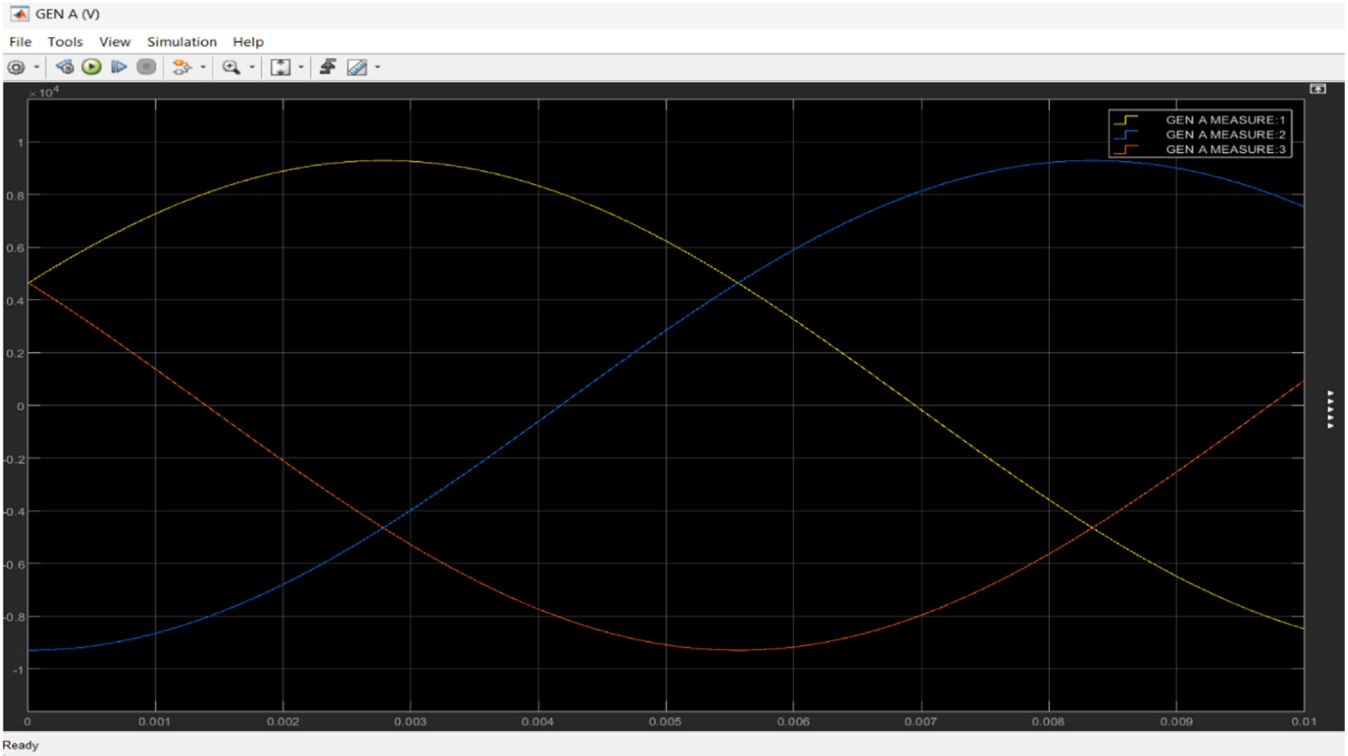

Fig. 9. Three-phase output waveform of Generator A before integration.

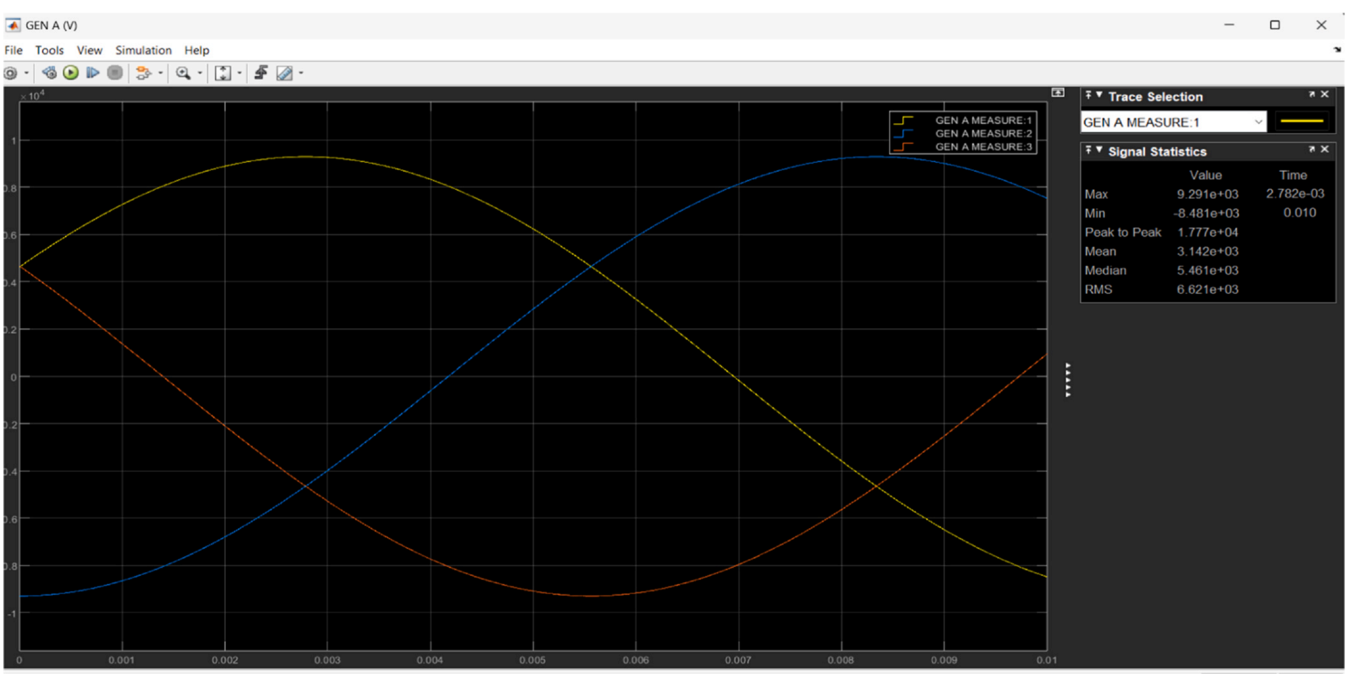

Fig. 10. Three-phase output waveform of Generator A after integration.

3.3. Comparison of output voltage before and after integration of RERs in SGs

Figs. 15 and 16 represents the bar graph for the output voltage values of generators and load voltages before and after the integration of RERs in SGs, respectively. In Fig. 15, the bar graph shows the output voltage is highest when all the Generators A, B, and C are running together to supply the power in the grid over 7200 V and degrading eventually when either Generator B or Generator C is off-loaded (i.e. either Generator A and B are operating or Generator A and C are operating) to 7000 V. But when Generator A is under maintenance or during non-peak hours, the grid voltage is supplied by Generators B and C operating together, and the output grid voltage drops to 6400 V.

When Generator B (rated output voltage of 3300 V) is operating individually and integrated with renewable resources, there is a dip in the output in line grid voltage and measures to 5200 V, in the output voltage of industrial load the measured value decreases to approximately 1000 V and the domestic load decreases to 432 V (as shown in

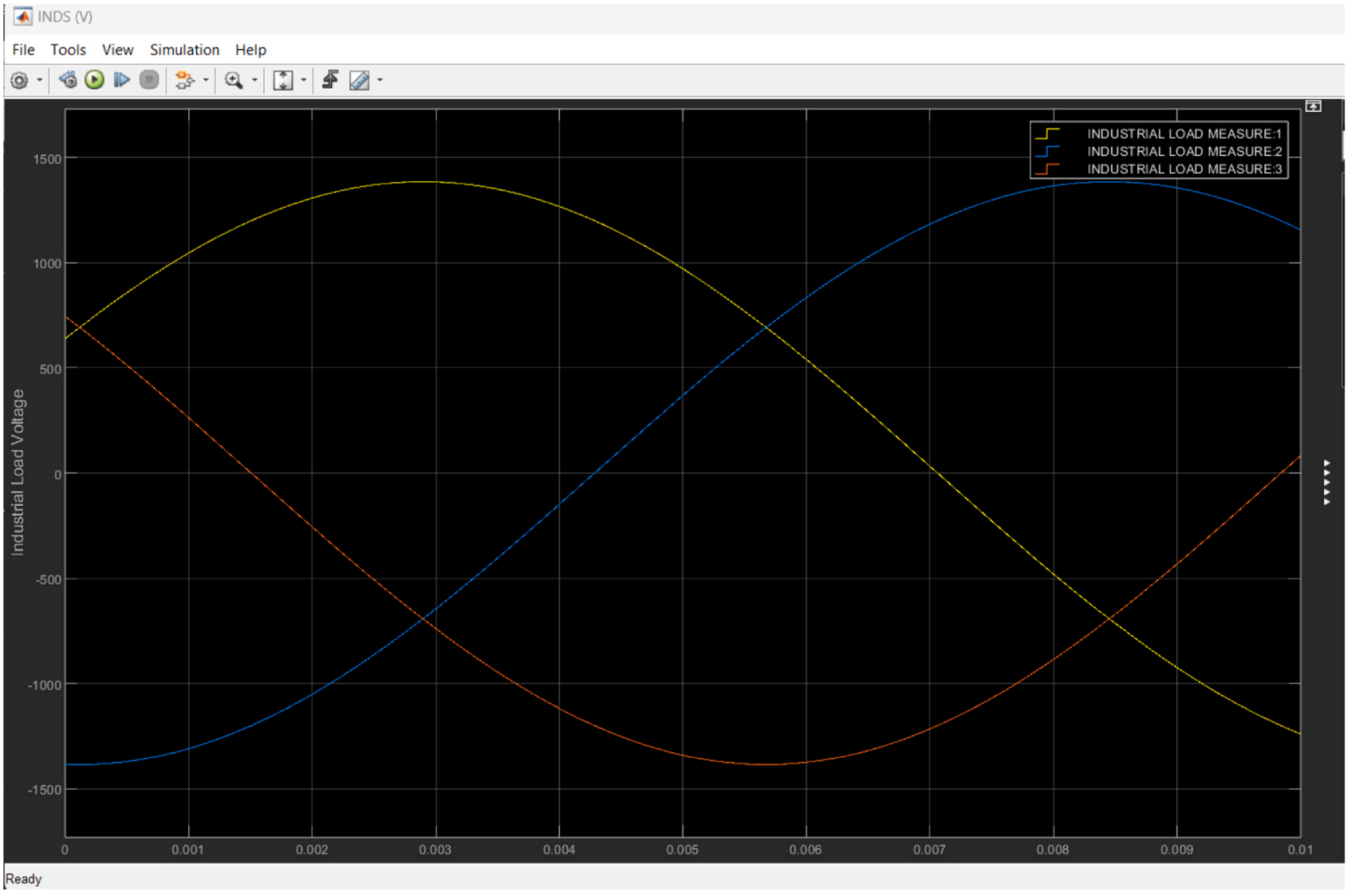

Fig. 11. Three-phase output waveform of industrial load before integration.

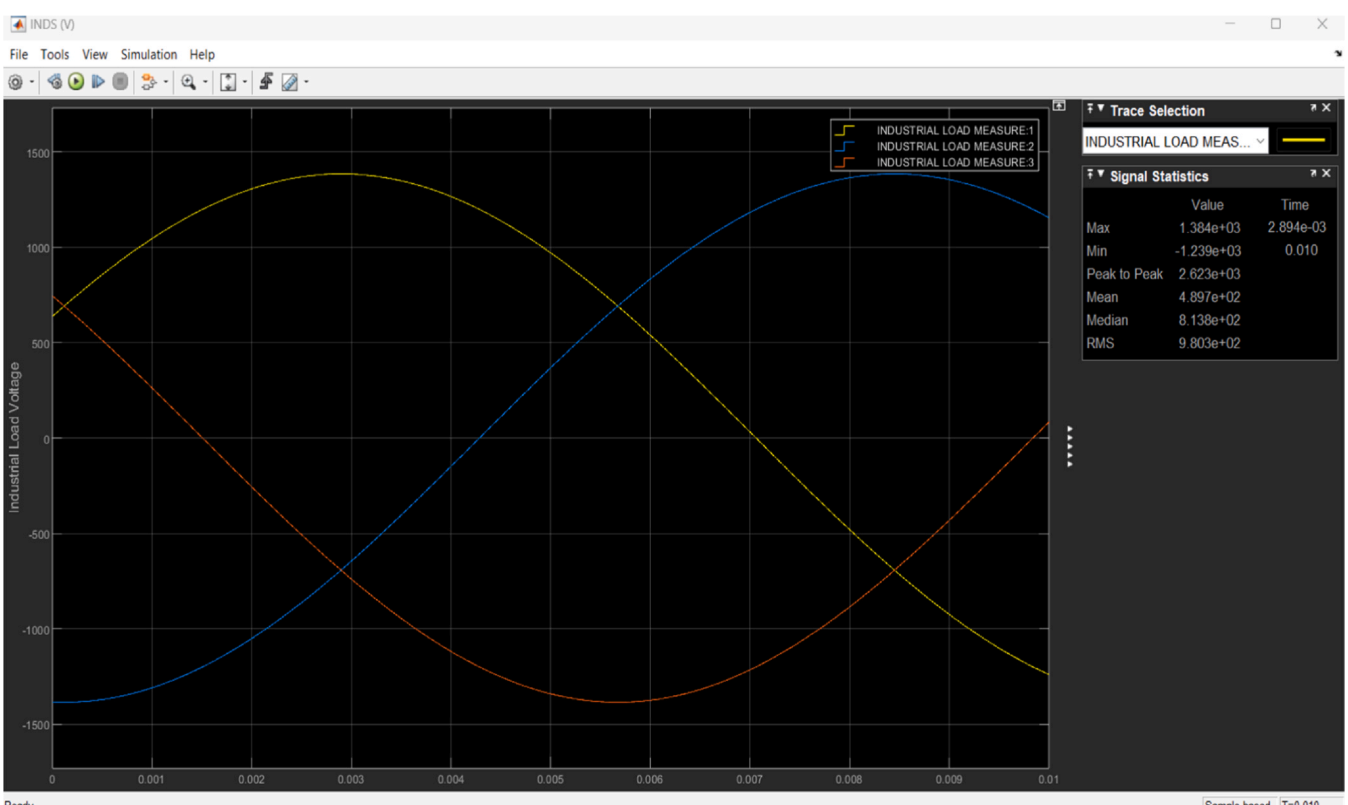

Fig. 12. Three-phase output waveform of industrial load after integration.

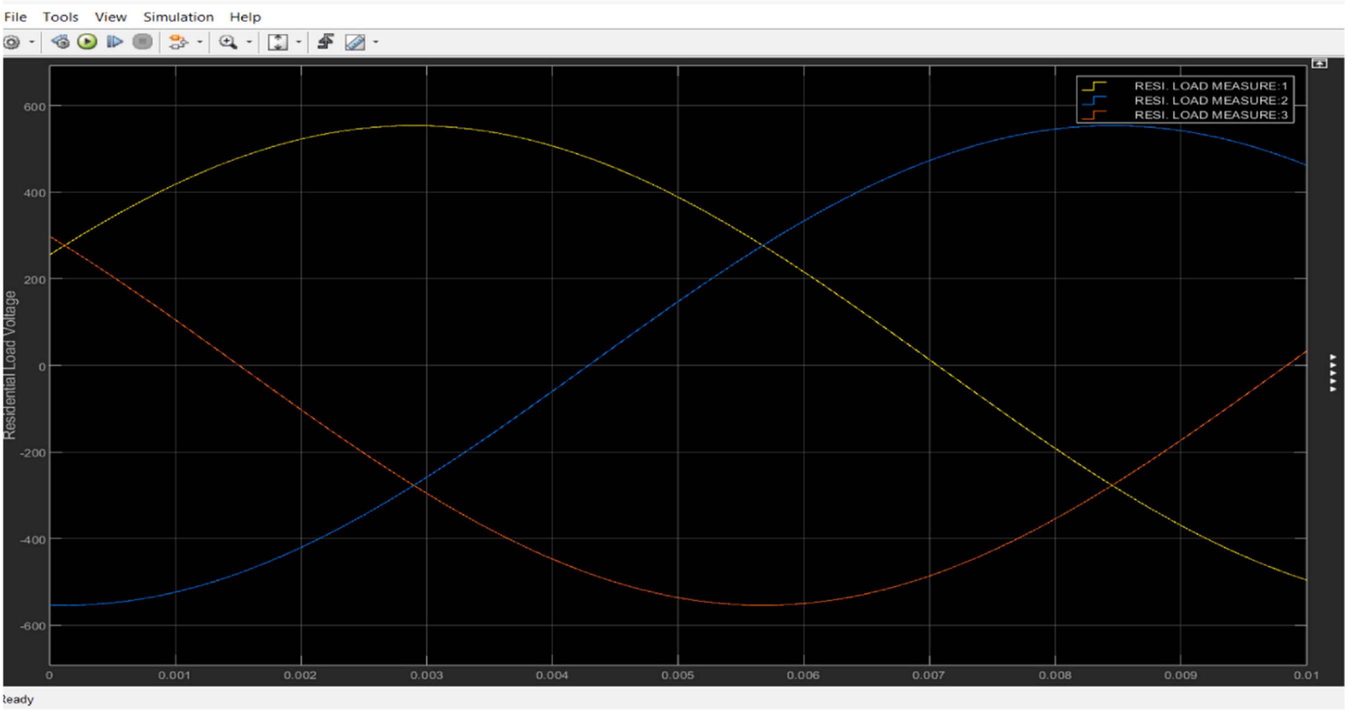

Fig. 13. Three-phase output waveform of domestic load before integration.

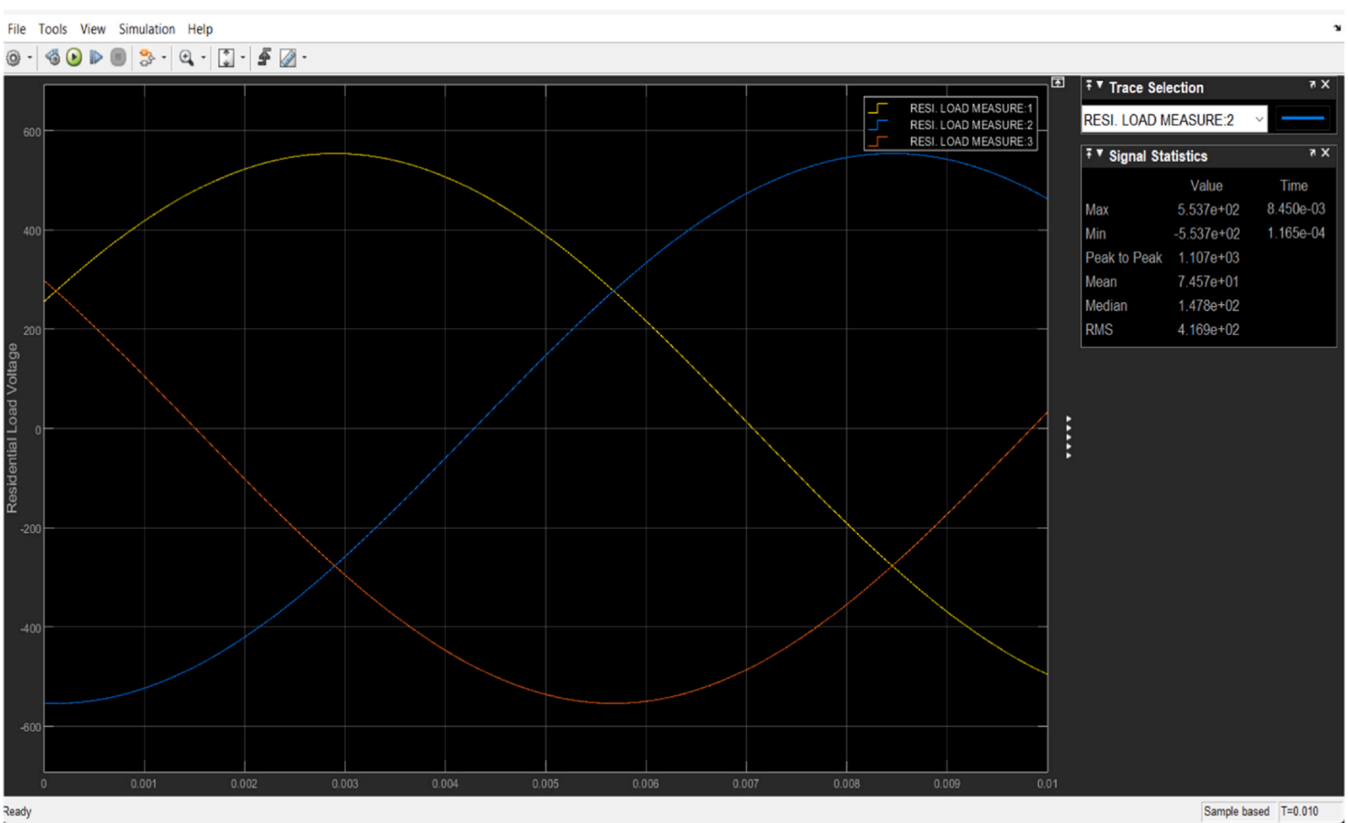

Fig. 14. Three-phase output waveform of domestic load after integration.

Fig. 16). Figs. 15 and 16 illustrate that the output voltage before integration and generators running independently is higher (6400 V) than the output voltage after the integration (5200 V) of the renewable resources into the smart grids.

Moreover, while integrating the RERs in the SGs in the MATLAB Simulink model, the values of electrical parameters (booster circuit, inverter circuit, PWM circuit, and the Resistor-Inductor-capacitor (RLC) filters) in the RERs generation circuit were the major challenge affecting the output of the PV generation. Also, the electrical parameters in the grid network (generators, step-up and step-down transformers, transmission line and its length, and the 3-phase loads) with the connection topology of the individual transformers affect the output values

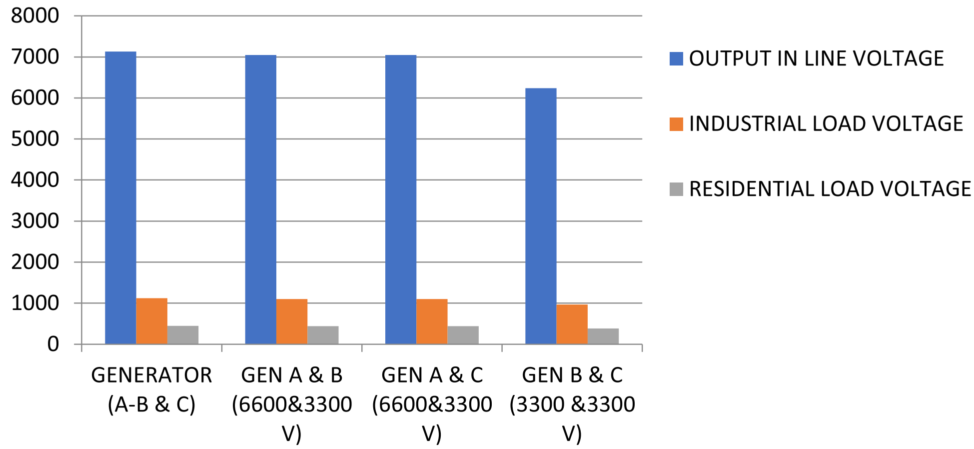

Fig. 15. Bar-chart of output voltage before integration.

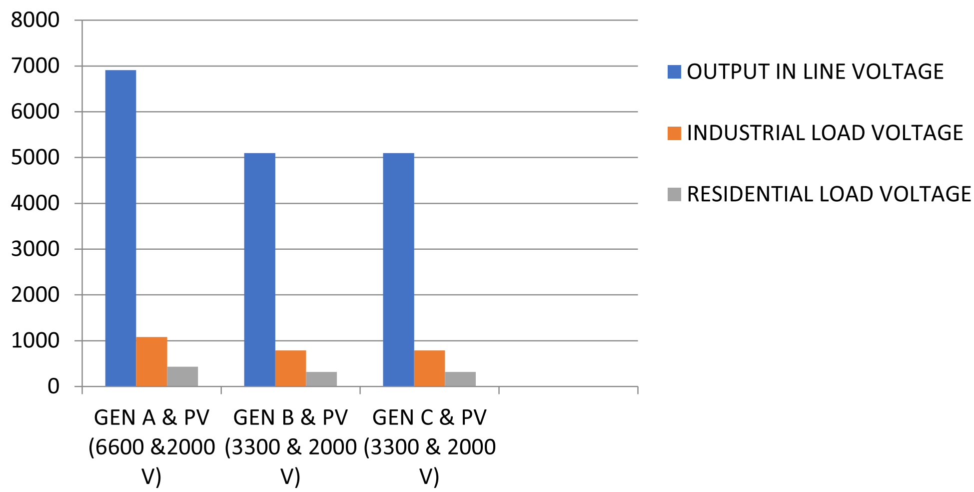

Fig. 16. Bar-chart of output voltage after integration.

and the voltage graphs of the generators, the industrial load, and domestic load values.

4. Conclusions

With the generation of the sinusoidal waveform of the Generator (A) (6600 V), the industrial load (1100 V), and the residential load (440 V), it can be concluded that there was successful integration of RERs into the SGs, with acceptable values of the electrical parameters of RERs, generation, and the grid system. Harmonics, being one of the greatest challenges amongst all mentioned above**,** can be mitigated by the installation of RLC filters as shown in the model and the modulation of it to reduce the harmonics. All smart grids use Internet-of-Things for stable and reliable communication**,** and this reduces the issues regarding the delay time of operation of switch gears to a great extent. Furthermore, by the usage of Internet-of-Things in SGs**,** the grid is safer by securing the communication system entirely or and its related data from digital intruders (i.e.**,** hacking).

According to the investigation of the model in Simulink, the RERs cannot supply power to consumers via the grid when acting on their own. However, with the output values after the integration, it can be concluded that RERs can only be used to support the power supply into the grid to maintain the supply voltage and the overall stability of the system. Also, it was observed that power generated by RERs can only be supplied effectively when one of the generators is in operation with the RERs.

Moreover, as the power generation from RERs is cost-effective with cheaper maintenance costs for energy producers, it is used in many different scenarios for isolating the main generator and operating the grid with a spare generator and RERs during off-peak hours. This is also beneficial to the consumers because of low tariff rates when the RERs are integrated and used as a power source for supplying power into the system.

This study did not consider, at this time in that intermittency issues are prevalent with renewable sources, thus, the results obtained do not explore the grid performance when intermittency in the renewable energy source is considered. Further work is currently underway to explore these effects, as well as exploring energy storage balancing issues and their resultant effect on grid integration. While the RLC filters discussed and demonstrated in this study support the integration of renewable energy systems through improvements in the power quality, as well as filtering the output of the inverter, further work could investigate how power flow is managed after integration using maximum power point tracking (MPPT) and grid-tie controllers.

Author contributions

Harsh Nitin Raichura: Resources, Simulink Model Design, Investigation, Validation, Formal Analysis, and Writing – original draft. **Edward Ofoegbu:** Draft review, Model and Result Validation, Supervision and Guidance. All authors have read and approved the final version of the manuscript for publication.

Use of AI tools declaration

The authors declare they have not used artificial intelligence (AI) tools in the creation of this article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] S. Kakran, S. Chanana(2018). Smart operations of smart grids integrated with distributed generation: a review. Renewable and Sustainable Energy Reviews [Online], 81 January, pp. 524–535. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1364032117311188.
[2] G.B. Bhavana, R. Anand, J. Ramprabhakar(2022). Designing microgrid energy markets using smart information system and blockchain technology [Online], in: 2022 International Interdisciplinary Humanitarian Conference for Sustainability (IIHC), November 18, 2022. Bengaluru, India: IEEE, pp. 12–15. Available from: https://ieeexplore.ieee.org/document/10060599/.
[3] D. Eltigani, S. Masri, Challenges of integrating renewable energy sources to smart grids: a review, Renew. Sustain. Energy Rev. [Online] 52 (2015) 770–780 ⟨https://linkinghub.elsevier.com/retrieve/pii/S136403211500787X⟩ (Available from).
[4] M. Hermans, K. Bruninx, E. Delarue(2020). Impact of generator start-up lead times on short-term scheduling with high shares of renewables. Applied Energy [Online], 268 June, p. 114935. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0306261920304475.
[5] H. Jiang, E. Du, N. Zhang, Z. Zhuo, P. Wang, Z. Wang, Y. Zhang(2023). Renewable electric energy system planning considering seasonal electricity imbalance risk. IEEE Transactions on Power Systems [Online], 38 (6) November, pp. 5432–5444. Available from: ⟨https://ieeexplore.ieee.org/document/9987654/⟩.
[6] All About EEE (2022). Solar power generation for home using MATLAB Simulink | Solar Power System for Home | Solar PV Grid [Online video], 18 October. Available from: https://www.youtube.com/watch?v=RQcMuLC8_DE.
[7] M. Khalid, Smart grids and renewable energy systems: perspectives and grid integration challenges, Energy Strategy Rev. [Online] 51 (2024) 101299Available from: ⟨https://linkinghub.elsevier.com/retrieve/pii/S2211467X24000063⟩.
[8] C. Medina, C.R.M. Ana, G. González, 2022. Transmission grids to foster high penetration of large-scale variable renewable energy sources–a review of challenges, problems, and solutions. International Journal of Renewable Energy Research (IJRER), [Online], (Vol12No1). Available from: ⟨https://www.ijrer.org/ijrer/index.php/ijrer/article/view/12738⟩.
[9] P.T. Manditereza, R. Bansal, Renewable distributed generation: the hidden challenges – a review from the protection perspective, Renew. Sustain. Energy Rev. [Online] 58 (2016) 1457–1465. Available from: ⟨https://linkinghub.elsevier.com/retrieve/pii/S1364032115016597⟩.
[10] C.P. Ohanu, S.A. Rufai, U.C. Oluchi, A comprehensive review of recent developments in smart grid through renewable energy resources integration, Heliyon [Online] 10 (3) (2024) e25705Available from: ⟨https://linkinghub.elsevier.com/retrieve/pii/S2405844024017365⟩.
[11] P.P. Parikh, M.G. Kanabar, T.S. Sidhu. Opportunities and challenges of wireless communication technologies for smart grid applications, in: IEEE PES General Meeting, Minneapolis, MN, USA, 2010, pp. 1-7, doi: http://dx.doi.org/10.1109/PES.2010.5589988. Available from: https://ieeexplore.ieee.org/document/5589988.
[12] M.H. Rehmani, M. Reisslein, A. Rachedi, M. Erol-Kantarci, M. Radenkovic, Integrating renewable energy resources into the smart grid: recent developments in information and communication technologies, IEEE Trans. Ind. Inform. [Online] 14 (7) (2018) 2814–2825, https://doi.org/10.1109/TII.2018.2819169.
[13] Tech Simulator (2020) 3 Level Neutral Point Clamped Grid Connected Inverter | MATLAB Simulation [Online video], 4 September. Available from: https://www.youtube.com/watch?v=jbXGXP1tfi8.
[14] K.V. Vidyanandan, B. Kamath, Grid integration of renewables: challenges and solutions, Indian J. Power River Val. Dev. [Online] (2022) 150–158 (Available from: Fourteen).
[15] I. Worighi, A. Maach, A. Hafid, O. Hegazy, J. Van Mierlo(2019). Integrating renewable energy in smart grid system: architecture, virtualization and analysis. Sustainable Energy, Grids and Networks [Online], 18 June, p. 100226. Available from: https://linkinghub.elsevier.com/retrieve/pii/S2352467718303187.
[16] E.M. Shaalan, S.M. Ghania, S.A. Ward. Analysis of electric field inside HV substations using charge simulation method in three dimensional, in: 2010 Annual Report Conference on Electrical Insulation and Dielectic Phenomena, West Lafayette, IN, USA, 2010, pp. 1-5, doi: http://dx.doi.org/10.1109/CEIDP.2010.5724041.