Modelling and Simulation of Energy Storage System and Distributed generation in DIgSILENT Power factory Software using Standard 9BUS IEEE network

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Abstract— **The power grid under huge development process over the past few years, thought it all began during ancient days. With the help of modern concepts and devices the conventional power grid is transformed in to smart grids with combination of several micro grids. These smart grids work with distribution system and battery energy storage system, which is not like the conventional but uses two-way communication for bringing in and out. The network modal is reference to IEEE standard 9-Bus and designed in the DIgSILENT Power Factory software to analyze the stability of the network, efficiency of the modal and monitor the power quality. Several tests are performed with symmetrical faults and unsymmetrical faults operating on Islanded mode, also in connected mode with main grid. The faults in the system were analyzed on the basis of multiple switch and short circuit events. In order to analyze the grid's harmonic distortion, the harmonic load flow is measured along several buses at several states. These analysis helps us to critically analyze the efficiency of the designed grid and the results shows a positive effect on the smart grid where the battery storage and distribution will lead the power system towards a definite future.**

Keywords—IEEE 9-Bus Modal, DIgSILENT Software, Battery Storage and Distribution system, Load Flow Analysis, Total Harmonic Distortion, and Simulation.

I. INTRODUCTION

In 17^{th} century, Benjamin Franklin's kite experiment led to the invention of electricity but the roots were traced back towards the ancient Greece where electricity is produced by rubbing the amber with fur by Thales of Miletus which is coined as static electricity to attract objects [1]. Later during the 19^{th} century, the discovery of generating electricity using magnets and coils by Faraday set a start to the development of electric concepts like, how volta invented electric storage battery.

Fig. 1. Evolution of electricity over period

Further, this developed into conventional power grids which holds connection between several components like generators, transformers, transmission lines, sub-stations, etc. This conventional method [3] is also referred as just one-way electricity communication from generation to customer directly without any retract.

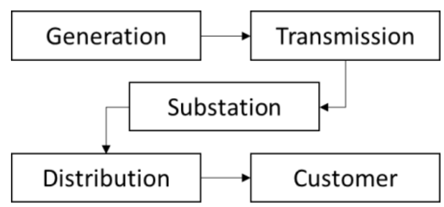


Fig. 2. Conventional Grid One-way Flow

The demands of the industrial revolution, it started to evolve in the late 1990's where organizations have started to explore a better way for generating and transmitted electricity across power resources [2] which later went to the development of smart grids, as the discovery of computers and smart technologies has paved a significant role in converting conventional local grids into modern smart grids. The main advantage of these smart grids is the two-way electricity communication from generation to customer. It is measured and monitored based on demand and supply needs of the customers. The smart grids [3] were enclosed with several micro grids diving it into multiple zones to avoid loss of electricity during power surge in any one micro grid is affected.

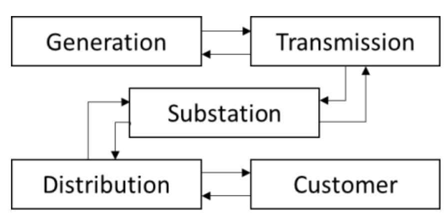


Fig. 3. Smart Grid Two-way Flow

Today we are prioritizing decarbonization and clean source of electricity [4] with the increase in demand for electricity across industrial and domestic needs. There are some important renewable sources as the solar, wind, hydro and thermal energy [5]. But solar power is generated on day time and not on night time. Also, the solar power generation has some of the factors to be considered like the direction on sun, surrounding disturbance, and cloud covering which will affect the electricity generation, as a result the energy will be wasted with loss in revenue when demand is higher than supply.

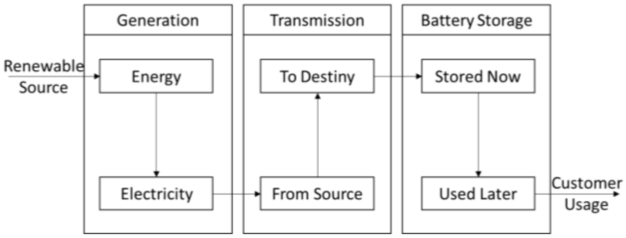


Fig. 4. Renewable - Transmission - Daily usage

II. Literature Review

The field of power systems engineering is dynamic, marked by an incessant evolution in modelling techniques and simulation tools. At its core, power system modelling involves the construction of mathematical representations that encapsulate the physical and operational intricacies inherent in electric power networks. This foundational process is indispensable for the comprehensive analysis, design, optimization, and control of power systems. A myriad of modelling approaches, ranging from steady state to dynamic, probabilistic, & stochastic model, collectively enrich understanding of the system behavior [8].

Integral to contemporary engineering, power system simulation software assumes a pivotal role across a spectrum of planning and operational scenarios. These critical decision-making tools are used in long-term generation and transmission expansion planning, short-term operational simulations, and market evaluations. They constitute an indispensable component in the arsenal of power systems professionals [7].

Within this expansive landscape, the IEEE 9-bus system emerges as a fundamental testbed for in-depth power system studies. Boasting 9-Buses, 3 generators, and 3 loads, it provides a realistic representation of power network scenarios. Widely embraced for load flow analysis, stability assessments, fault simulations, harmonic analysis, and dynamic modelling, the IEEE 9-bus system plays a pivotal role in advancing our comprehension of power system behavior. Its simplicity, effectiveness, and versatility render it the preferred choice for researchers and engineers dedicated to enhancing the reliability and efficiency of modern power grids [7][6].

Acknowledging the imperative for enhanced power system modelling techniques and simulation tools, the field has undergone thorough reviews, addressed current challenges and identified future gaps [9][10]. This dual focus on theoretical advancements and practical testing grounds underscores the commitment of the power systems community to ensure the resilience and adaptability of energy networks in the face of evolving demands and complexities.

III. Network Modelling

In modern world, the need of better transmission lines across the networks, is on high demand which led to the introduction of smart grids [11]. Resources like this forces the grid operators to make a consistent renewable resource to meet the customer demands, this is where the distribution generation system and battery energy storage system is introduced to improve the performance of managing the electricity.

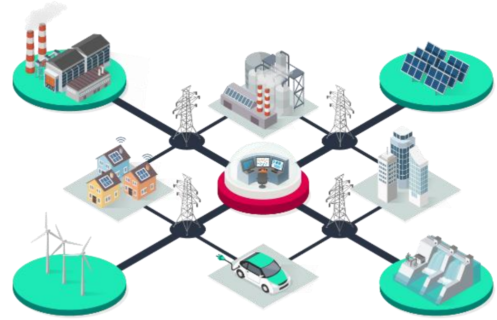


Fig. 5. Smart Grid

The modal for energy storage system & distributed generation system is designed [12] with reference to the standard IEEE 9buss network system and below is the schematic representation of how we will be designing the network modal in the software.

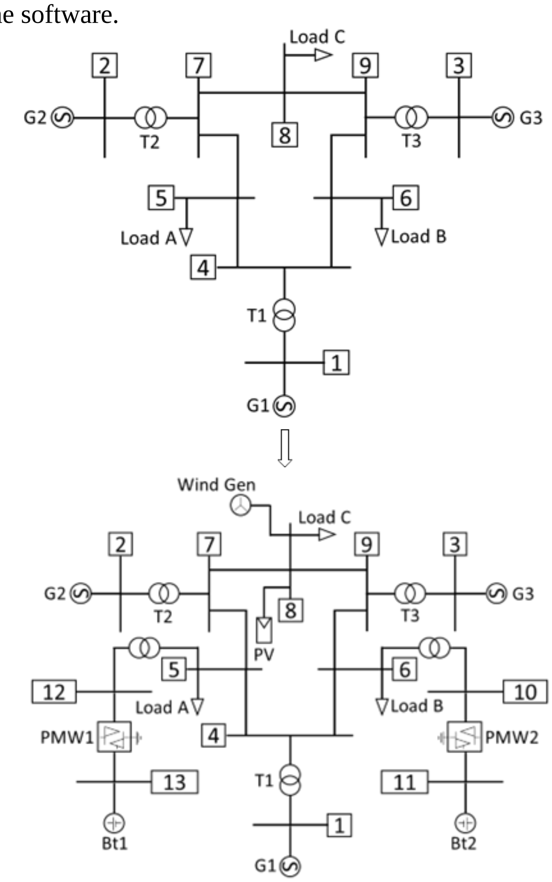


Fig. 6. Network Model Design

3.1 IEEE 9-bus network model

The IEEE standard 9-bus network model [13] is used in research and study purposes for testing and analysis, the network modal holds 9 transmission lines with synchronous generators G1 connected with bus 1, G2 with bus 2 and G3 with bus 3, along with this the three-phase winding transformer T1, T2 and T3 with each bus which is connected to the generators. The voltage across the generator 1 to transformer T1 is 16.5 kV, across generator 2 to transformer T2 is 18 kV, and across generator 3 to transformer T3 is 13.8 kV. Also, the network modal holds load A, B and C over bus 5, 6 and 8 with voltage levels across all other bus and transmission lines are 230 kV.

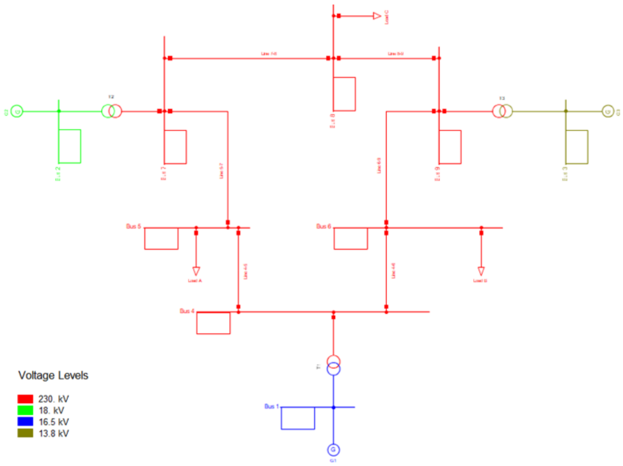


Fig. 7. 9-bus IEEE network model

3.2 Battery Storage System

The battery energy storage system is added to the power grid to balance and improve power generation from renewable sources like solar, wind, etc. The power generation transforms energy into electricity and transmitted from one place to other via transmission lines and stored in batteries for later usage, when demand is more later the stored electricity is transmitted for usage [14]. The use of battery storage system should always be planned properly, should be controllable and the budget should be affordable.

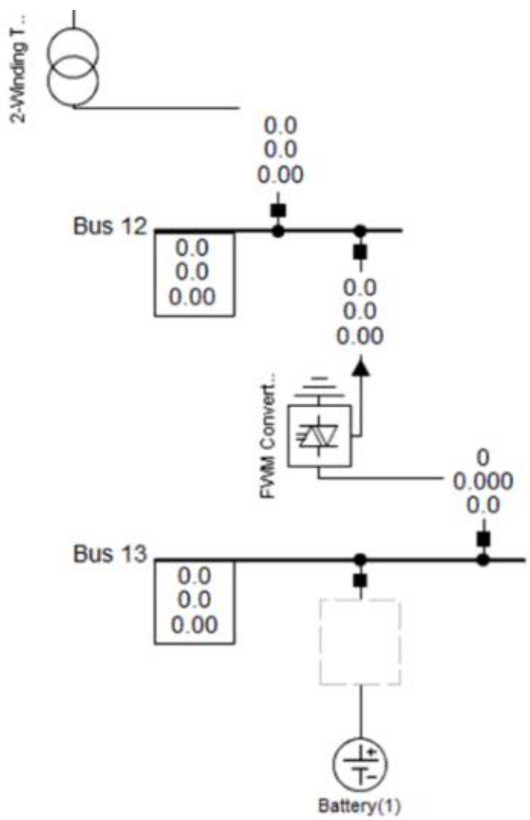


Fig. 8. Battery Energy Storage System

At Bus 5 and Bus 6 we are adding the battery storage system where each bus is connected to a transformer which is then connected to Bus 10 and Bus12. The three-phase winding transformer in highly needed in between the main bus and battery storage system as it connects the bus 6 & 5 which holds 230kV and bus 12 & 10 which holds 0.4 kV. The overall model is placed symmetrically on both the sides of 9-bus system.

Rated Power	30 MVA
Nominal Frequency	50 Hz
Rated Voltage HV-S	230 kV
Rated Voltage LV-S	0.4 kV
Short Circuit Voltage	3%

Transformer Configuration

The bus 12 and bus 10 is configured as AC bus which operates at a nominal voltage of 0.4kv line to line and 0.23kv line to ground. For the PWM converter which is a two-level type converter the AC and DC terminals were connected to their respective AC and DC bus as per the below configurations.

Rated Power	30 MVA
Rated AC-Voltage	0.4 kV
Rated DC-Voltage	0.25 kV

PWM Converter Configuration

The Bus 13 and bus 11 is nothing but the DC bus with nominal voltage of 0.25 kV included with positive DC polarity which is connected to the battery with the below configurations.

Nominal Voltage	0.25 kV
Voltage Setpoint	1 p.u.
Internal Resistance	0 Ohm
Internal Inductance	0 mH

Battery configuration

The battery storage system stores and release energy when needed, battery storage devices are essential to contemporary electric systems. Different battery technologies are used for different purposes. Various factors, including the intended use, energy density requirements, financial concerns, and environmental effect, influence the choice of battery storage system [15]. The subject is dynamic, and new developments and technologies are always being introduced to the market through continuing study. In contemporary electric systems, the following are some typical kinds of battery storage systems,

Lithium-ion	Long cycle life, high energy density, and comparatively low self-discharge rates. Examples are Panasonic's lithium-ion batteries and Tesla Powerwall.
Lead-Acid	Well-established, low-cost technology. Lead-acid batteries that have flooded and valve-regulated lead-acid (VRLA) batteries are two examples.
Flow	Long-term energy storage is possible, and for some use cases, it could be more affordable. Examples are zinc-bromine flow batteries and vanadium redox flow batteries.
Sodium-ion	Like lithium-ion batteries, but maybe less expensive because sodium is so plentiful. Examples include several pilot installations and research initiatives.
Nickel - Cadmium	dependable and robust. Examples: Found in some power backup systems.
Nickel-Metal Hydride	Greater density of energy in comparison to Ni-Cd batteries. A Toyota Prius, for instance, runs on NiMH batteries.
Solid-State	Extended cycle life, increased energy density, and enhanced safety. Examples include a range of R&D initiatives.
Advanced Lead-Acid	Enhanced longevity and efficiency in comparison to conventional lead-acid batteries. For instance, improved flooded batteries and absorbent.

3.3 Distribution System

The Distribution generation system is a mixture of wind and photovoltaic renewable energy sources to increase the efficiency of electricity production. This is also known as hybrid renewable energy system designed with wind turbine and PV system [16], Hybrid Renewable Energy system for on-grid applications". This system provides a number of advantages, such as lower transmission and distribution loss, the grid security is enhanced, along with stability of the system, and the effect over environment is less.

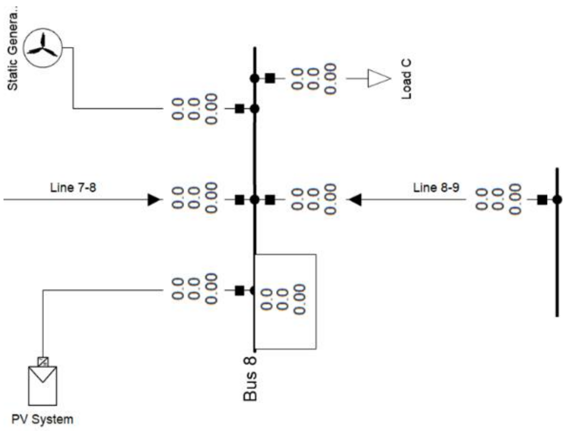


Fig. 9. Distribution Power System

The distribution generation system is connected to bus 8. The connected wind generator is a 3PH wind generator of 1 parallel unit with nominal apparent power of 10 MVA & power Factor of 0.8.

Active Power	8 MW
Reactive Power	2 Mvar
Apparent Power	8.25 MVA
Power Factor	0.97 ind
Scaling Factor	1

Load Flow Config on Wind Generator

Likewise, the PV system has active power input with 3PH technology with a parallel invertor, of nominal apparent power of 10000 kVA and power factor of 0.8.

Active Power	8 MW
Reactive Power	3.875 Mvar
Apparent Power	8.99 MVA
Power Factor	0.9 ind
Scaling Factor	1

Load Flow Config on PV Systems

Additionally, distribution networks are separated into two categories: network and radial. A radial system [17] contains one source of supply for each client, grouped like a tree. Multiple supply sources run concurrently in a network system. Concentrated loads are handled via spot networks. Rural and suburban regions frequently adopt radial networks.

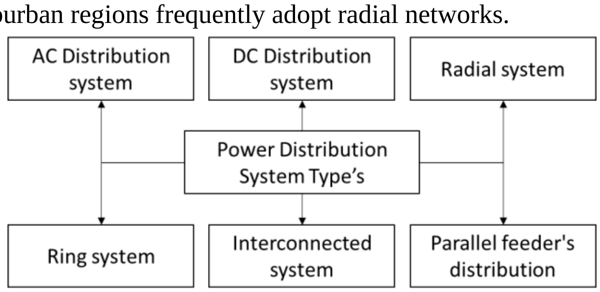


Fig. 10. Types of Distribution System

3.4 IEEE 9-Bus with Distribution and Battery Storage System

The smart grid is designed with distribution and energy storage system, connected to the standard IEEE 9-Bus network modal. Also, to calculate the harmonics, a load of AC type with 3PH-D technology is added to the bus 8 towards the same direction of wind and PV system [18]. This completes the modeling of smart grid in the DIgSILENT software.

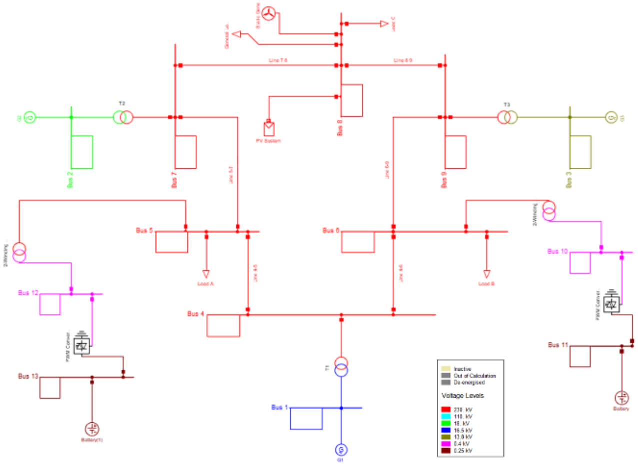


Fig. 11. Designed Network Modal

IV. Load flow analysis

Load flow analysis is also known as Power flow analysis-is used to study the steady-state operation of an electrical power system network. This analysis is essential for planning, designing, and operating power system efficiently and reliably.

It is a method used to determine the voltage, current, and power flows in a system during normal operating conditions. It considers factors like power demand, generator characteristics, transmission line parameters, and system topology. This study helps identify potential voltage violations, provides insight into power flow patterns, and aids in optimizing system performance.

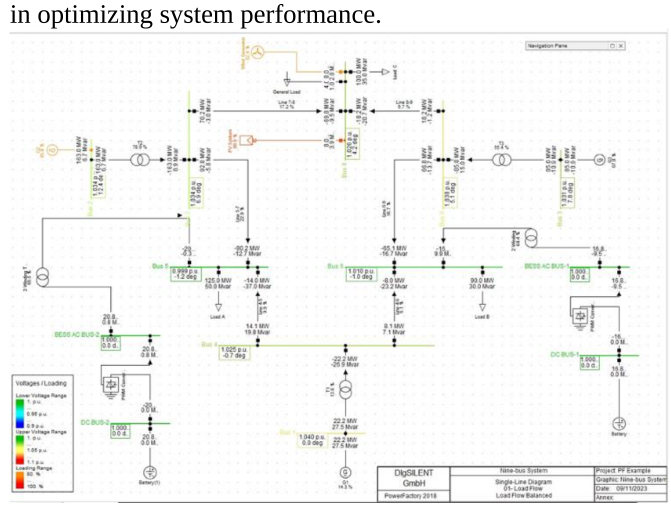


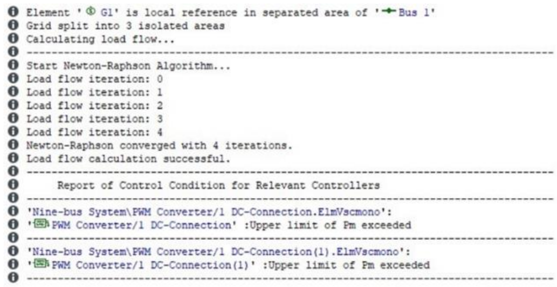
Fig. 12. IEEE 9-bus system Load Flow Simulation including energy storage and distributed generation sources.

Load flow studies are crucial in power systems to meet increasing demand for electrical energy, identify potential voltage stability issues, and assess the impact of adding new loads or generators to the system.

These tools use numerical methods and algorithms to solve the load flow analysis problems. The most common methods are

NR (Newton-Raphson Method), GS (Gauss-Seidel Method), FD (Fast-Decoupled Method) [19,20].

Figure.12 Present the outcome of a simulation run on the IEEE 9-bus system with an energy storage and distributed generation sources which shows the load flow analysis was completed successfully.



```
Element ' G1' is local reference in separated area of ' Bus 1'
Grid split into 3 isolated areas
Calculating load flow...
-------------------------------------------------------------------------------
Start Newton-Raphson Algorithm...
Load flow iteration: 0
Load flow iteration: 1
Load flow iteration: 2
Load flow iteration: 3
Load flow iteration: 4
Newton-Raphson converged with 4 iterations.
Load flow calculation successful.
-------------------------------------------------------------------------------
     Report of Control Condition for Relevant Controllers
-------------------------------------------------------------------------------
'Nine-bus System\PWM Converter/1 DC-Connection.ElmVscmono':
' PWM Converter/1 DC-Connection' :Upper limit of Pm exceeded
-------------------------------------------------------------------------------
'Nine-bus System\PWM Converter/1 DC-Connection(1).ElmVscmono':
' PWM Converter/1 DC-Connection(1)' :Upper limit of Pm exceeded
-------------------------------------------------------------------------------
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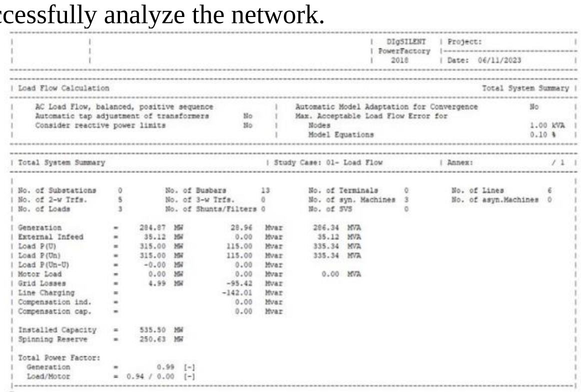
Fig. 13. Load Flow Analysis results on IEEE-9-Bus Network model energy storage and distributed generation sources.

From Figure.13; Displays the result of the output window after including the microgrid and electric vehicle showing Load Flow Calculation performed by the DIgSILENT Power Factory software which uses Newton-Raphson Algorithm to successfully analyze the network.



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|          |                                        |  DIgSILENT  | Project:             |
|          |                                        | PowerFactory |--------------------|
|          |                                        |    2018     | Date:  06/11/2023    |
| Load Flow Calculation                                              Total System Summary |
|    AC Load Flow, balanced, positive sequence        | Automatic Model Adaptation for Convergence     No       |
|    Automatic tap adjustment of transformers    No   | Max. Acceptable Load Flow Error for                      |
|    Consider reactive power limits              No   |    Nodes                                    1.00 kVA |
|                                                     |    Model Equations                          0.10 %   |
| Total System Summary                    | Study Case: 01- Load Flow        | Annex:            / 1 |
|
| No. of Substations    0      No. of Busbars        13     No. of Terminals     0     No. of Lines          6 |
| No. of 2-w Trfs.      5      No. of 3-w Trfs.       0     No. of syn. Machines 3     No. of asyn.Machines  0 |
| No. of Loads          3      No. of Shunts/Filters  0     No. of SVS           0                             |
|
| Generation          =    284.97  MW        28.96  Mvar     286.34  MVA
| External Infeed     =     35.12  MW         0.00  Mvar      35.12  MVA
| Load P(U)           =    315.00  MW       115.00  Mvar     335.34  MVA
| Load P(Un)          =    315.00  MW       115.00  Mvar     335.34  MVA
| Load P(Un-U)        =     -0.00  MW         0.00  Mvar
| Motor Load          =      0.00  MW         0.00  Mvar       0.00  MVA
| Grid Losses         =      4.99  MW       -95.42  Mvar
| Line Charging       =                   -142.01  Mvar
| Compensation ind.   =                      0.00  Mvar
| Compensation cap.   =                      0.00  Mvar
|
| Installed Capacity  =    535.50  MW
| Spinning Reserve    =    250.63  MW
|
| Total Power Factor:
|   Generation        =        0.99  [-]
|   Load/Motor        = 0.94 / 0.00  [-]
|-------------------------------------------------------------------------------------------|
```

Fig. 14: Load flow Calculation after Including Energy storage and distributed generation sources.

After incorporating energy storage and distributed generation sources, we have the behavior of the network from Figure.14. It generating 284.97MW of total power and external infeed of 35.12MW to supply the load which draws an 315MW of active power, the grid losses are approximately 4.99MW. The Load flow calculation result can be used to confirm that the network capacity of 535.50MW and a spinning reserve of 250.63MW, resulting in a total generation of 284.97MW.The apparent power results, which are 335.34 MVA for system load and 286.34 MVA for generation. Another metric shown on the result is reactive power, which provides 28.96 Mvar for generation, 115 Mvar for loads, -95.42 Mvar for grid losses, and -142.01 Mvar for line charging. These are some of the factors that the software takes into account before producing a grid summary.

The load flow analysis confirms that the 9-bus system, which integrates energy storage and distributed generation sources, is operating within acceptable parameters. The system has sufficient capacity to meet demand and a spinning reserve enhances its resilience to fluctuations. The analysis provides valuable insights for system planning, operation, and optimization, ensuring the reliability, efficiency, and stability of the power network.

V. Faults in Power System

Faults in the power system are mainly classified into two types they are 1. open circuit faults 2. Short circuit faults. The most common causes of all these faults are electrical equipment insulation failure, external factors such as wind, lightning strikes on towers or transmission lines, fallen trees on transmission lines and birds shorting transmission lines. These issues might lead to severe interruption in power [21].

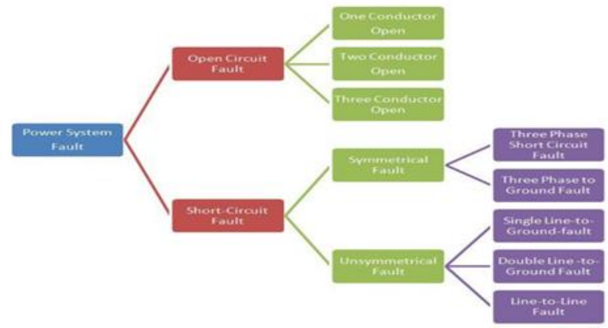

Fig. 15. different types of faults in power system

5.1 Short Circuit Faults

An unintended connection or low-resistance path generated between two points in an electrical circuit result in a short-circuit fault in a power system. This causes the current flow to significantly rise. The voltages are zero where the short circuit occurs in a three-phase short circuit [26]. In an electrical power system, short circuit faults are classified into two types

1. Symmetrical faults
2. Unsymmetrical faults

5.2 Symmetrical Faults

The most serious faults with high currents are symmetrical faults. The phases are shortened in this fault, along with ground. The load current in each of the three phases is constant when this fault occurs. this type of faults is also known as balanced faults [22]. Types of Symmetrical faults are L-L-L Fault (Triple line fault), L-L-L-G Fault (Triple line to ground). In this L-L-L fault all the three phases are short circuit with each other at same time. Thus, the phase voltages at the fault point are equal and zero. In this L-L-L-G fault all the three phases are short circuited with ground.

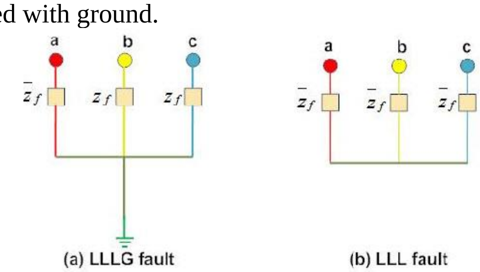

Fig. 16. Symmetrical Faults

5.3 Unsymmetrical Faults

Unsymmetrical faults are most common faults in the power system. This type of fault occurs when one or more phases of three phase system are involved in the fault, when the currents or voltages in the three phases of a power system are not equal, this results the system unbalance it is referred to as an unbalanced fault [23]. Types of Unsymmetrical faults are L-L Fault (Line to Line fault), L-L-G Fault (Double line to ground), L-G Fault (Line to ground).

1.L-L Fault (Line to Line fault): In this type of fault two phases are subjected to the short circuit in the system.

2.L-L-G Fault (Double line to ground fault): Any two phases are short circuited with the ground; this type of fault is called Double-line to ground fault.

3.L-G Fault (Line to ground fault): In this type of fault, any one of the phase will be short circuited with ground. This is the most common fault in the system [24].

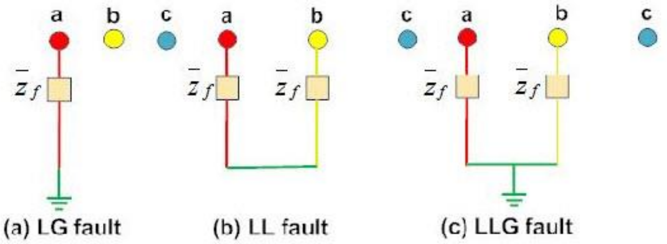

Fig. 17. Unsymmetrical Faults

Faults are highly undesirable, unexpected events that put the network at risk. The expenses incurred by enterprises owing to equipment damage might also have a significant impact on them [25].

5.4 Voltage response of 9-Bus system to symmetrical Fault

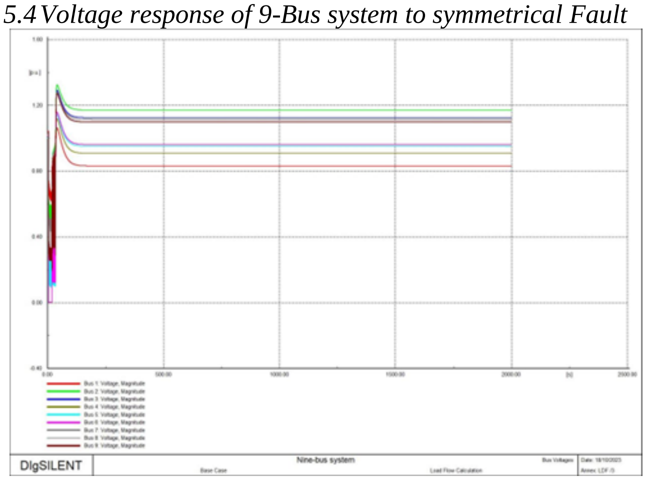

Fig. 18 Voltage Response of 9-Bus System (symmetrical)

We defined the short circuit event in bus 6 and chose the fault type as 3-phase short circuit (L-L-L Fault) and set the execution of short circuit event time-5seconds and then clear the fault at 10sec. Now after running the simulation, we will get the responses of voltage, current and power of the 9-bus system. In Fig. 18 shows entire nine bus system affected and voltage drop in all buses and at bus 6 voltage will drops to zero at the time of short circuit event. there is a large-fluctuations in the voltages during the 5 seconds when that fault occurs, then after 10 seconds clear the short circuit fault and the system reaches to stable state at 200 seconds.

5.5 Current response of 9-Bus system to symmetrical Fault

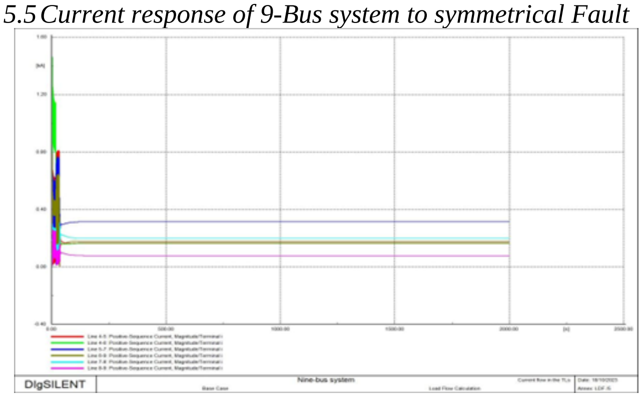

Fig. 19. Current Response of 9-Bus System (symmetrical)

During the last short circuit event, the system's current response increased suddenly at bus 6, causing a 3-phase fault that affected all buses. After 10 seconds, it gradually reduced and eventually stabilized after 180 seconds.

5.6 Power response of 9-Bus system to symmetrical Fault

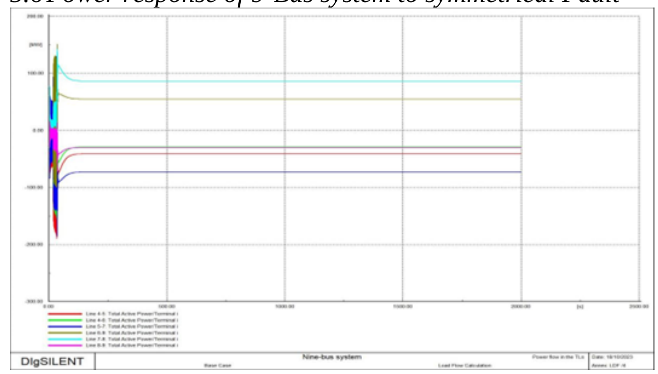

Fig. 20. Power Response of 9-Bus System (symmetrical)

Power fluctuations occur during 5 seconds of bus 6 faults, which are cleared in 10 seconds, and reduced in 60 seconds to reach a stable state.

5.7 Voltage response of Distributed Generation system to symmetrical Fault

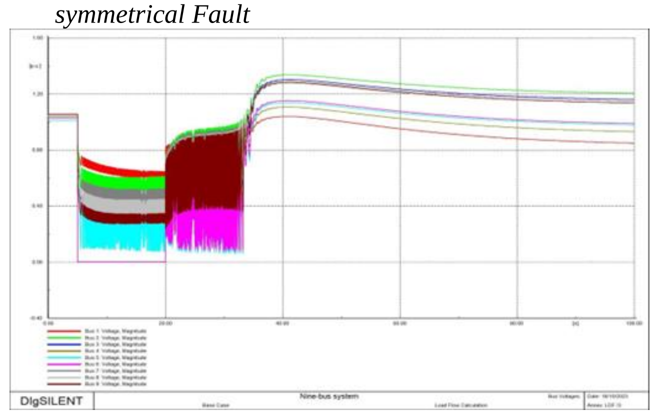

Fig. 21. Voltage response of Distributed Generation system (symmetrical)

For the same short circuit fault event, there is sudden drop in voltage at bus 6 and it affected the all buses in the system. After 20 seconds fault was cleared and after 40 seconds it reaches to stable state shown in Fig. 21

5.8 Current response of Distributed Generation system to symmetrical Fault

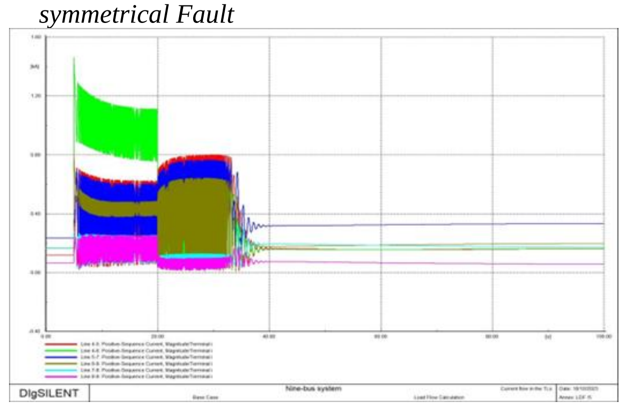

Fig. 22. Current response of Distributed Generation system (symmetrical)

During the fault, bus 6 experienced an exponential increase in current, affecting all buses. After 20 seconds, the fault was cleared, and the system stabilized after 50 seconds.

5.9 Power response of Distributed Generation system to symmetrical Fault

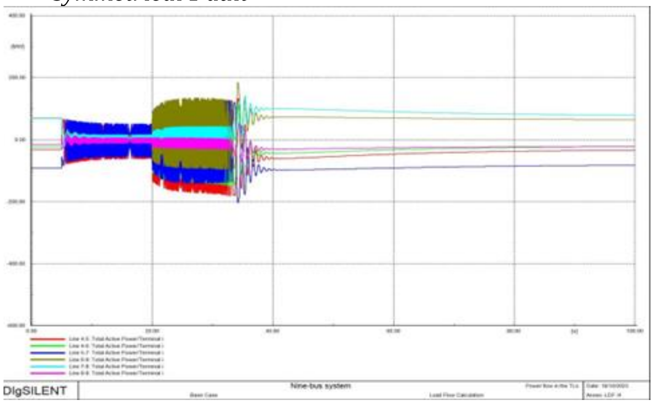

Fig. 23. Power Response o Distributed Generation System (symmetrical)

Figure.23 shows power fluctuations due to a 3-phase fault, affecting all buses. After 20 seconds, faults are cleared, and after 60 seconds, the system stabilizes.

5.10 Voltage response of Energy storage system to symmetrical Fault

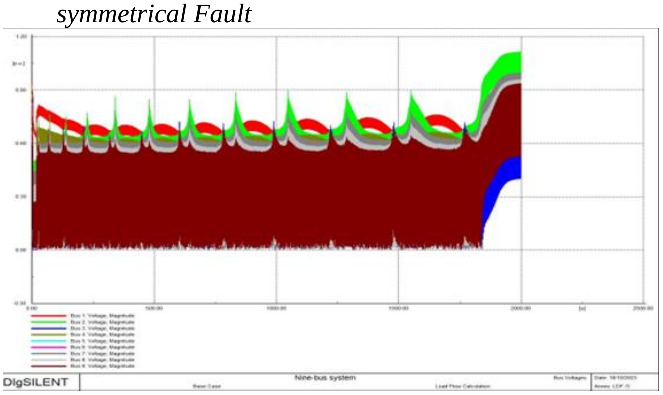

Fig. 24. Voltage response of Energy storage system (symmetrical)

The addition of an energy storage system to the 9-bus system caused system instability. A sudden voltage drops at bus 6 affected all buses, leading to high oscillations. After clearing the fault, the system took 2000 seconds to reach a stable state.

5.11 Current response of Energy storage system to symmetrical Fault

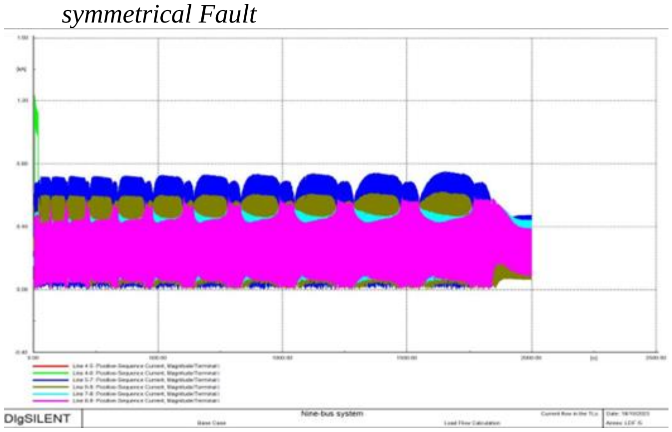

Fig. 25. Current response of Energy storage system (symmetrical)

The fault in the energy storage system causes exponential increase in current in all buses, leading to massive oscillation. After clearing the fault after 20 seconds, currents decrease exponentially. The network recovers and, after 2500 seconds, the system returns to a stable state.

5.12 Power response of Energy storage system to symmetrical Fault

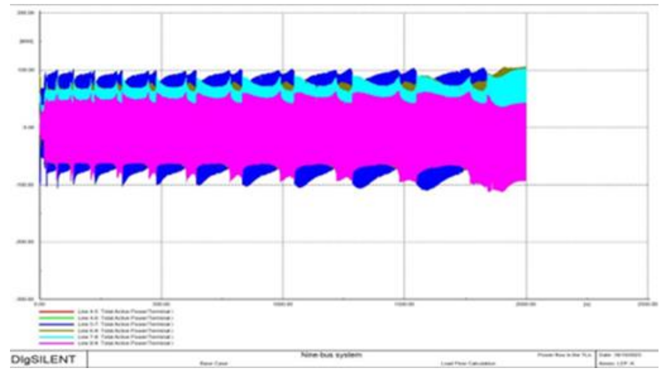

Fig. 26. Power response of Energy storage system (symmetrical)

The fault causes power fluctuations at bus 6, affecting all buses and causing high oscillation. After 20 seconds, faults are cleared, and the system gradually reduces and tries to stabilize. After 2500 seconds, it returns to a stable state.

5.13 Voltage response of ESS and DGS to symmetrical Fault

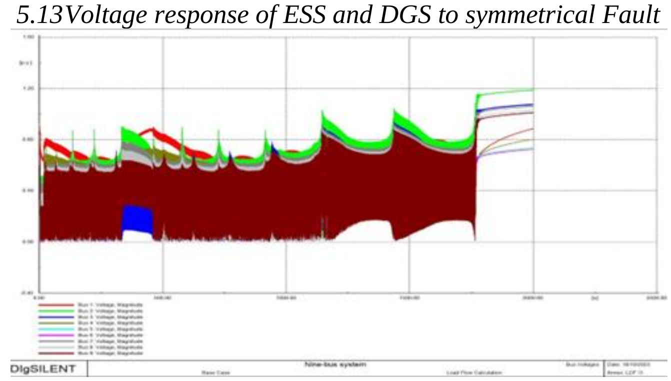

Fig. 27. Voltage response of ESS and DGS (symmetrical)

Now we added distribution generation system (DGS) while keeping the Energy storage system (ess) in the 9-bus system caused system instability. In similar way the 3-phase short circuit fault occurred for 5 seconds, followed by a 20-second fault clearing on bus 6. This caused a sudden voltage drop and high oscillation. After clearing the fault, the system took 2000 seconds to reach a stable state.

5.14 Current response of ESS and DGS to symmetrical Fault

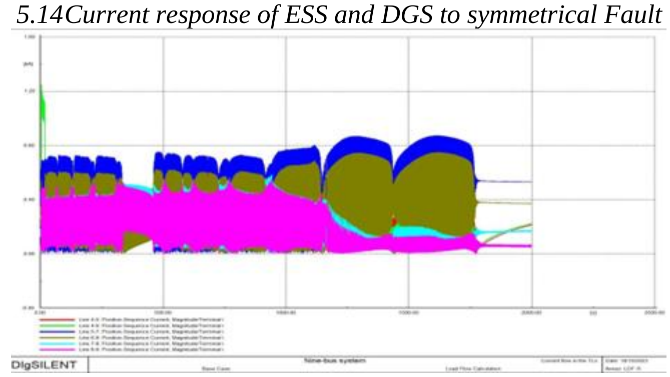

Fig. 28. Current response of ESS and DGS (symmetrical)

We also observed that the fault causes exponential increase in current in all buses and massive oscillation. After clearing the fault after 20 seconds, currents decrease exponentially, making the system unstable. The network recovers from the initial short circuit event, and the system returns to a stable state after 2500 seconds.

5.15 Power response of ESS and DGS to symmetrical Fault

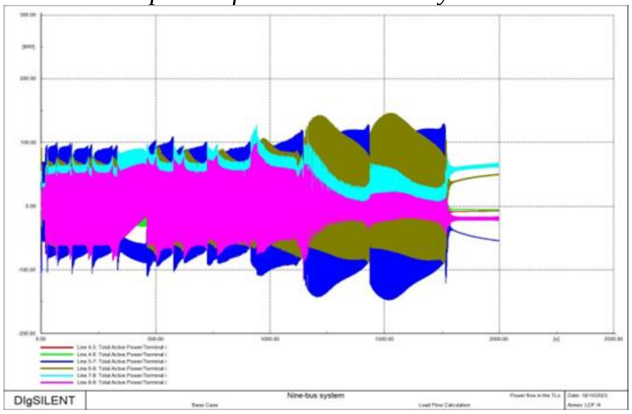

Fig. 29. Power response of ESS and DGS (symmetrical)

A 5-second fault causes power fluctuations at bus 6, affecting all buses and causing high oscillation. After 20 seconds, faults are cleared, and the system gradually tries to stabilize. After 2500 seconds, the system returns to a stable state, but still makes the overall system unstable.

5.16 Voltage response of 9-Bus system to Unsymmetrical Fault

Execute the load flow analysis for 9-Bus system then run initial conditions with unbalanced 3-phase (ABC) in network representation, go through the same short circuit events, change the type of the fault and set L-L Fault it refers the unsymmetrical fault, set the 5 seconds for creating fault and 20 seconds for clearing the fault.

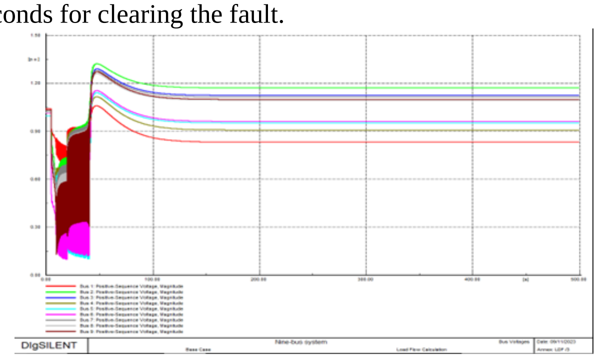

Fig. 30. Voltage response of 9-Bus system (unsymmetrical)

The faults start after running the simulation by 5 seconds and cleared the fault in 20 seconds on bus 6. When fault occurs, immediate voltage drops on the bus 6 and also drops in all buses. After 20 seconds fault is cleared the voltage gradually raises and reaches the stable state at 60seconds.

5.17 Current response of ESS and DGS to Unsymmetrical Fault

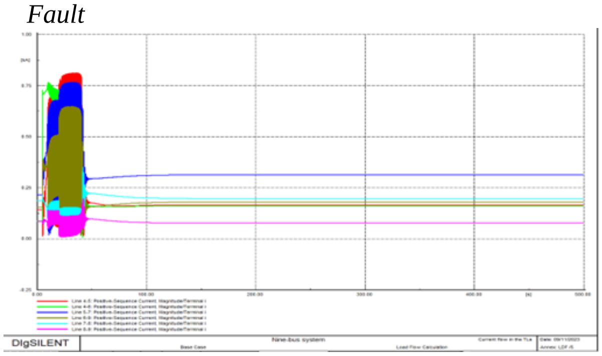

Fig. 31. Current response of 9-Bus system (unsymmetrical)

A simulation was conducted to analyze the current response to a 2-phase short circuit event. The simulation showed the fluctuations in current during the 5 seconds of fault, with a sudden increase at bus 6. After 20 seconds, faults were cleared, and the current gradually reduced, eventually reaching a stable state after 50 seconds.

5.18 Power response of 9-Bus system to Unsymmetrical Fault

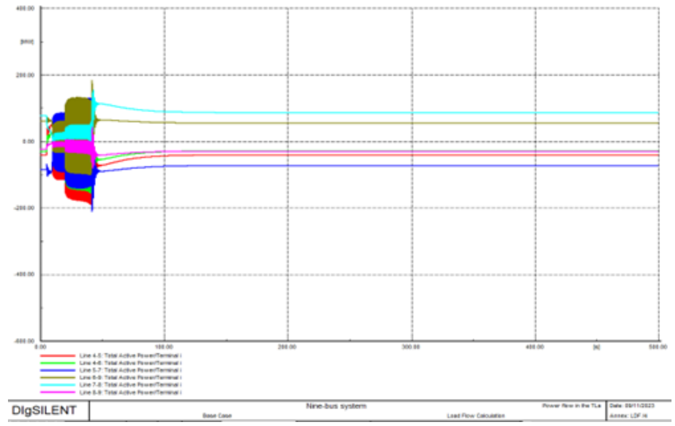

Fig. 32. Power response of 9-Bus system (unsymmetrical)

Figure.32 shows power fluctuations during the same fault affecting all buses. After 20 seconds, faults are cleared, and the system gradually reduces and tries to stabilize, reaching a stable state after 50 seconds.

5.19 Voltage response of 9-Bus system to Unsymmetrical Fault

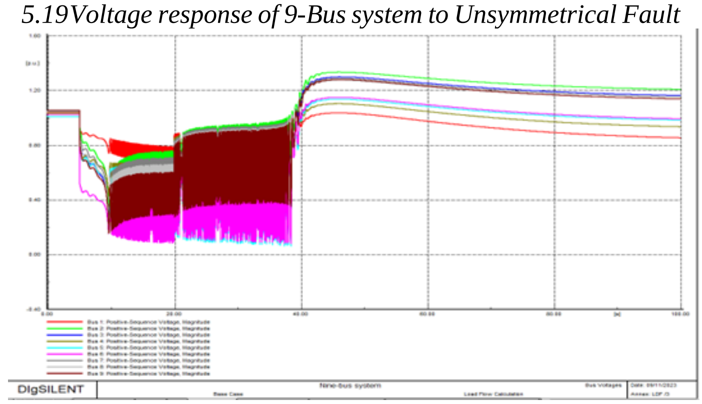

Fig. 33. Voltage response of Distributed Generation system (unsymmetrical)

Now after incorporating the distribution generation system (DGS) it causes a sudden voltage drop on bus 6, affecting all buses in the system. After 20 seconds of clearing the fault, the system tries to stabilize, and after 50 seconds, it reaches a stable state, as shown in Figure.33.

5.20 Current response of Distributed Generation system *to Unsymmetrical Fault*

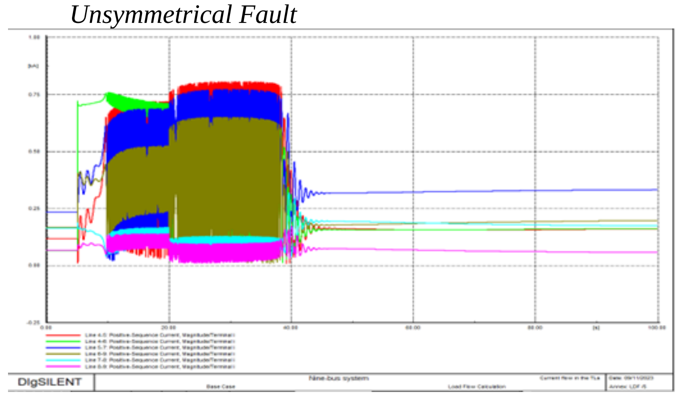

Fig. 34. Current response of Distributed Generation system (unsymmetrical)

The 2-phase short circuit fault occurred for 5 seconds, which was resolved after 20 seconds. The fault caused an exponential increase in current at bus 6, affecting all buses in the system.

After 20 seconds, the system tries to stabilize, and after 50 seconds, it reaches a stable state.

5.21Power response of Distributed Generation system *to Unsymmetrical Fault*

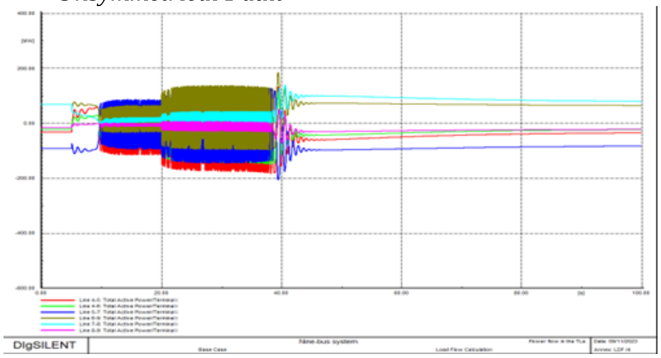

Fig. 35. Power response of Distributed Generation system (unsymmetrical)

Due to 2-phase fault (L-L Fault) power fluctuations occur, with power rising at bus 6, and affect all buses. After 20 seconds, faults are cleared, and the system gradually reduces and tries to stabilize after 50 seconds.

5.22Voltage response of Distributed Generation system *to Unsymmetrical Fault*

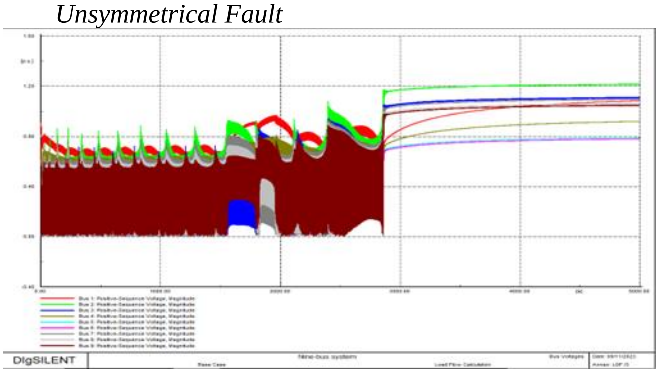

Fig. 36. Voltage response of Energy storage system (unsymmetrical)

After adding the energy storage system to the 9-bus system, this system makes unstable the entire system. then 2-phase short circuit fault happen for 5 seconds and after 20 seconds cleared the fault on bus 6, and it disturb the total system. During the fault there is sudden drop in voltage at bus 6 and it affected the all buses in the system and high oscillation occurs. After 20 seconds fault was cleared then system tries to get stable but it takes long time to settle after 3000 seconds it reaches to stable state shown in Fig. 36.

5.23Current response of Energy storage system to Unsymmetrical Fault

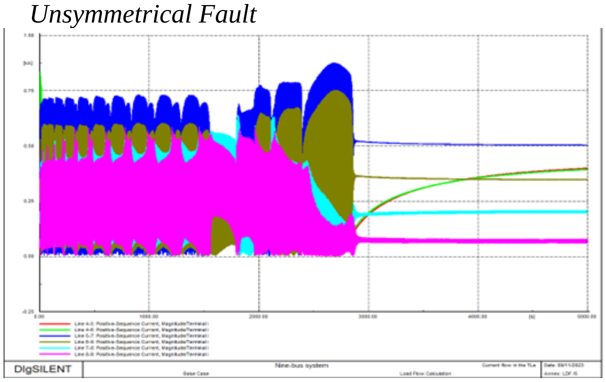

Fig. 37. Current response of Energy storage system (unsymmetrical)

A fault in the energy storage system causes exponential increase in current in all buses, leading to massive oscillation. After clearing the fault after 20 seconds, currents decrease exponentially. The network tries to recover, and after 3500 seconds, some bus voltages stabilize, but the system remains unstable.

5.24Power response of Energy storage system to Unsymmetrical Fault

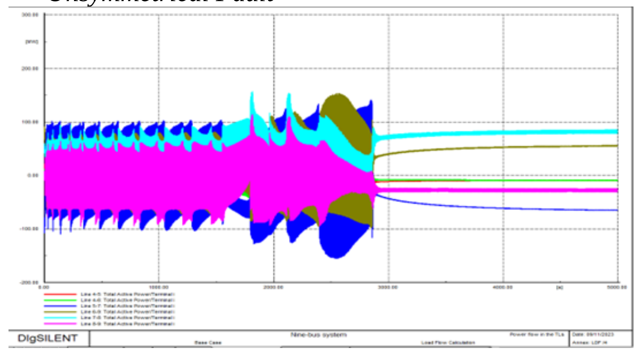

Fig. 38. Power response of Energy storage system (unsymmetrical)

We will see the power fluctuations during 5 seconds that fault occurs. At bus 6, the power rises due to L-L fault, affecting all buses and causing high oscillation. After 20 seconds, faults are cleared, and the system gradually reduces and stabilizes after 3000 seconds.

5.25Voltage response of ESS and DGS to Unsymmetrical Fault

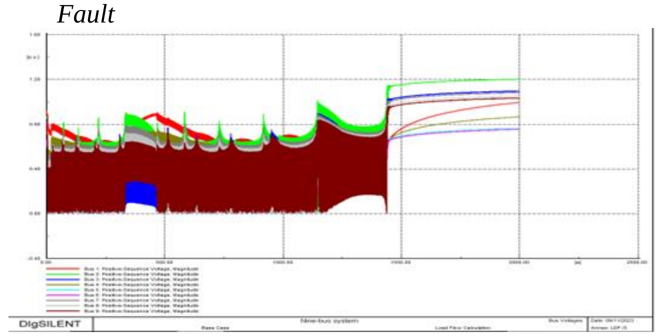

Fig. 39. Voltage response of ESS and DGS (unsymmetrical)

After incorporating both distribution generation system (DGS) and the Energy storage system (ess) to the 9-bus system, it destabilizes the entire system. then 2-phase short circuit fault happen for 5 seconds and after 20 seconds cleared the fault on bus 6, and it disturb the total system. During the fault there is sudden drop in voltage at bus 6 and it affected the all buses in the system and high oscillation occurs. After 20 seconds fault was cleared then system tries to get stable but it takes long time to settle after 1500 seconds it reaches to stable state.

5.26Current response of ESS and DGS to unsymmetrical Fault

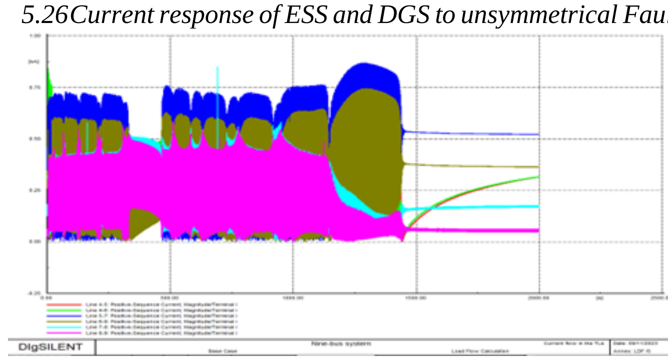

Fig. 40. Current response of ESS and DGS (unsymmetrical)

After the 5 seconds simulation begins, the fault occurs, and causes exponential increase in current in all buses and massive oscillation. After clearing the fault after 20 seconds, currents decrease exponentially, making the system unstable. The network recovers from the initial short circuit event, and the system returns to a stable state after 1500 seconds.

5.27 Power response of ESS and DGS to Unsymmetrical Fault

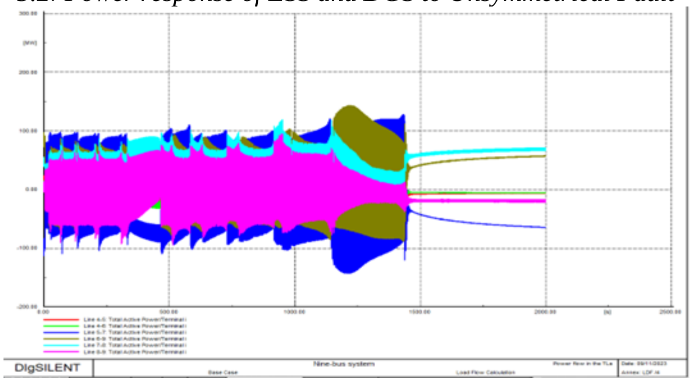

Fig. 41. Power response of ESS and DGS (unsymmetrical)

The fault also causes power fluctuations and high oscillations. At the bus 6 the power rises due to 2-phase short circuit fault. After 20 seconds, faults are cleared, and the system gradually reduces and tries to stabilize. After 20 seconds faults will be cleared then it gradually reduced and tries to stable, after 1500 seconds it comes to stable state.

VI. Simulation of Switch Events

6.1 Simulation of Switch events during Mode of Operation change

To fulfil power demands without solely relying on main power grids, distributed energy resources (DER) are implemented to maintain the required power supply for productive operations in the case of unexpected events such as power outages [28]. When implementing DERs, it is important to analyze a system's response to a grid connection to island mode transition, which involves activating key elements of the DER incrementally with time. In islanded mode, the system is a self-sustaining energy system that operates on the energy from its generators in the case of this paper. Grid connection mode here is defined as the system being connected to the primary power supply, which includes a wind generator, Photovoltaic system, and two battery energy storage systems (BESS1 and BESS2).

6.2 Factors to consider When Switching Modes of Operation

The aim of this simulation is to investigate which measures can be made on the system to achieve a smooth transition between modes of operation. There are several points to keep in mind:

i)Switch event timing: Switching on or off multiple power system components gradually is preferred as doing so separately reduces their combined effects on the network. The time between each switch event can impact its effect on the network. Simultaneously switching on multiple elements can lead to power disturbances.

ii)Load demand and system capacity: Overvoltage and undervoltage issues can arise from a mismatch in power demand and generation. Being aware of the system parameters is essential to execute the mode switch effectively.

iii)Frequency and voltage: There must be equipment present to monitor the behavior of parameters such as current, frequency and voltage during the transition to compare past data, log for future reference and monitor the event.

iv)Bi-directional power flow: Points of bidirectional flow must be noted and their relevant metrics must be observed and analysed.

v)Energy storage system (ESS) integration: Strategically timing ESS system activation as they tend to have a larger impact on a system than most elements.

vi)Grid Synchronisation: Ensure the islanded system is synchronised with the grid to maintain relatively good stability during the transition.

These factors are crucial because, if not carefully considered, even seemingly insignificant structural changes to a power system can have a significant impact on power quality and potentially pose safety hazards.

6.3 Simulation

When running the simulation, a load flow analysis was initiated with the 9-bus system operating in island mode, independent of the DER components, as shown in Fig. 42 schematic of the system.

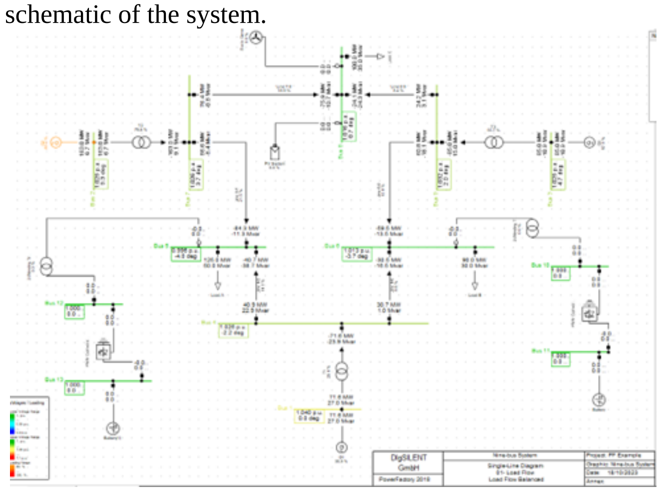

Fig. 42: 9-Bus system in Islanded connected Mode

In island connected mode, 3 main utility generators are operating at 163MW, 85MW and 71.6MW. Switch events are defined to be set as follows.

1)Wind power generation switched on after 5 seconds.

2)PV system was switched on at 20 seconds.

3)BESS1 was switched on at 35 seconds.

4)BESS2 was switched on at the 60 second mark.

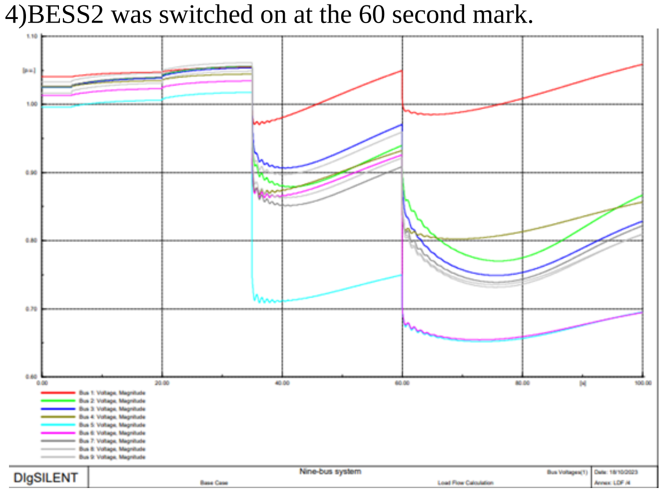

Fig. 43: Bus voltages during Switch events.

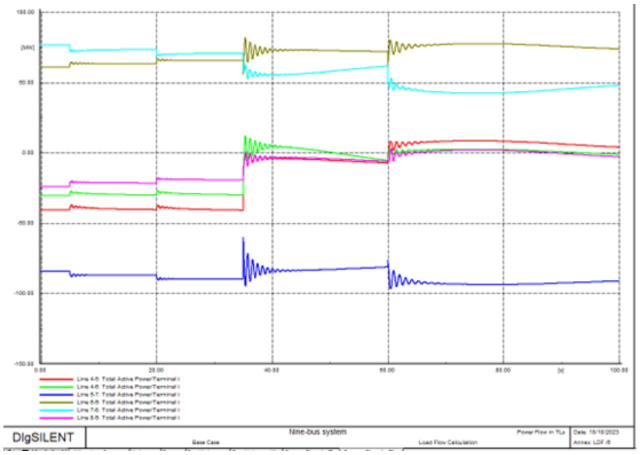

Fig. 44: Power flow during Switch events.

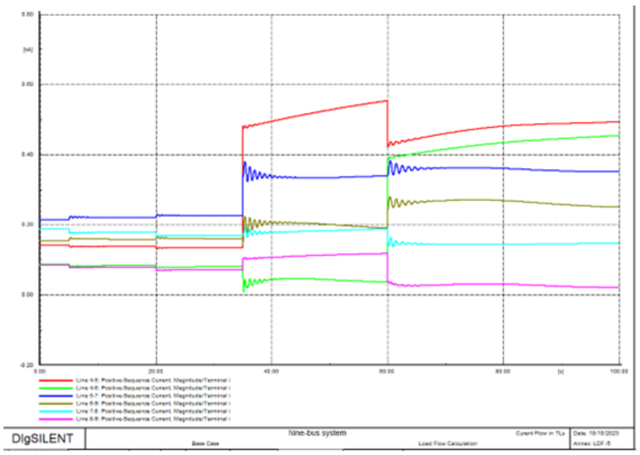

Fig. 45: Current flow during Switch events.

6.4 Impact of Wind and Photovoltaic Integration

Fig. 43 illustrates the impact of the Wind generator addition at 5 seconds, resulting in a slight voltage rise across all 9-Buses. This deviation from pre-switch event voltages is similarly observed with the addition of PV system, activated at the 20-second mark. It is also evident that the system is no longer stable after both switch events as there is a visible slope to the voltage plots in all buses which does not stabilize within the respective time frames. The corresponding power and current flow plots in Fig. 44 and Fig. 45 exhibit damped oscillations during the early stages, observed in each of the first two switch events, that gradually stabilize. These oscillations signify a decrease in power quality and can have a serious impact on the network.

6.5 Impact Of Battery Energy Storage Systems

At the 35-second mark in Fig. 43, the introduction of BESS1 causes significant transient events, namely voltage sag [29] and swell, in all 9-Buses. Bus 5 demonstrates the largest voltage sag of all buses signaling a high-risk potential. Such a voltage sag can lead to interruptions to communication systems, data loss or corruption and even equipment malfunction. All of these consequences appear as expenses for both demand and supply sides of the system. Visible damped oscillations on the power flow Fig. 44 and current flow Fig.4 plots in the early stages of switching on BESS1 indicate that adding the storage system at this point negatively impacts power quality, leading to further system destabilization. These plots for current and power flow during the switch events involving BESS1 and BESS2 reveal similar characteristics.
Observing the 35 second mark on Fig.4, line 4-5 experiences the largest current surge of all lines. Significant changes in current can lead to catastrophic circumstances. Since the magnitude of the current magnitude was measured in the order of Kiloamperes, this system has the conditions capable of causing damage to equipment that is able to sustain an arc and cause an arc blast event [30]. Arcing is a phenomenon where gas (usually air) acts as a conductor carrying the low fault current flow. Arc blasts result in shockwaves that lead to mass transport, these events can be violent and in the worst-case lead to the cost of lives. In less severe cases the health implications of exposure to arc blasting are potentially thermal burn, raspatory damage, vision impairment and eardrum raptures.

The results of the simulation imply that BESS's have a large impact on power quality and must be handled with caution during switch events. Switching on all of the components had a negative effect on the overall power quality of the system.

6.6 The Economics of Power Quality

A publication by the Electric Power Research Institute estimated that it costs the United States of America 15- 24 billion dollars as a result of power quality issues. Around 80% of these are caused by internal equipment in buildings and not the electric utility network [31]. This is important to understand as investigating the causes of power quality problems is usually a complicated process. The effects can be invisible and easily go undetected however, during switch events the power quality issues can be anticipated and minimized or mitigated by understanding the impact each physical component has on the network.

Unfortunately, not all switch events are premeditated or deliberate. For example, transient events triggered by lightning strikes, resulting in widespread malfunctions or fires, can lead to decreased productivity or a complete production halt in certain manufacturing plants. This can result in significant unexpected costs such as medical bills, legal fees and the costs associated with a halt in production.

Another example of an industry that pays a heavy price in the case of power quality issues is the health care industry. A well-known case of severe power disruption is the August 14 2003 blackout that affected regions in the United States of America and Ontario Canada. Lifesaving equipment were inoperable and even damaged during the event. Patients whose lives relied on life-support systems, ventilators and other such infrastructure faced severe stress and, in some cases, lost their lives. This demonstrates the significance of maintaining a reliable power supply and ensuring important facilities are prepared to operate in island mode when the situation requires.

6.7 Implications for Future Energy System Integrations

The results of this dynamic simulation highlight the intricate nature of the transition from grid-connected mode to island-connected mode. These findings are notably relevant today as the global community strives to increase the integration of renewable energy sources [32]. Manufacturers of electronic devices must be aware that poorly managed power systems can have a direct impact on the power quality, operation, and reliability of their products. Policymakers, engineers, and system operators must collaborate to ensure safe and effective transitions occur while maintaining power quality. Power quality evaluation procedures must be regularly researched and updated to consider the effect of increased load demand and the requirements of sensitive modern devices. Informing customers about factors to consider when operating these devices can prevent injury hazards and reduce the impact of power quality issues.

VII. HARMONIC DISTORTION

The final analysis that we performed was a harmonic load flow analysis to deduce Total Harmonic Distortion (THD) in the existing network. Harmonics are the additional frequencies that are integer multiples of the fundamental frequency, which is generally 50 Hz or 60 Hz, depending on the region. Harmonic distortion is a phenomenon that indicates the deviation of voltage and current waveforms from the actual sinusoidal waveforms. It is mostly generated by non-linear loads, such as switching-mode power supplies (SMPS) found in computers and televisions, rectifiers, DC converters, and other power electronics equipment, whose impedance varies with the alternating voltages. This type of load draws current in a way that is not directly proportional to the applied voltage, which results in distorted waveforms. Harmonics are high-frequency components that generate excess currents in an electrical system, which causes overheating in rotating machines and conductors, resulting in higher energy losses, overloading of transformers, and tripping of circuit breakers. It also contributes to poor power quality, which has an impact on overall stability and reliability. Furthermore, the most harmful to the electrical system are triplen harmonics, which are odd integer harmonics and the multiples of the 3rd harmonic (i.e., 3rd, 9th, 15th, etc.). In a three-phase system, triplen harmonics usually build up in the neutral conductor. While other harmonics and the fundamental frequencies tend to neutralise each other in the neutral conductor, the triplen harmonics do not. When these particular harmonics are present in a three-phase system, the neutral conductor experiences an increase in current, which eventually causes overheating and damages the associated equipment. Thus, it is crucial to assess the effects of harmonic voltages and currents, which is accomplished by harmonic load flow analysis. In contrast to the standard load flow analysis, which focuses on the fundamental frequency, this specialised load flow analysis demonstrates the effects of harmonics in the electrical network. Harmonic distortion is measured by total harmonic distortion (THD), and it is expressed as a percentage, as it provides a standardised measure of the level of distortion in a signal. THD is the ratio of the root mean square (RMS) value of the harmonic contents up to the 50th order.

The formula for calculating THD for current is [53]:

$$(\%)THD_i = \sqrt{\frac{I_2^2 + I_3^2 + \cdots + I_n^2}{I_1^2}} \times 100$$

Where:

- I_1 is the RMS current of the fundamental frequency component.
- $I_2, I_3, \ldots, I_n$ are the RMS currents of the individual harmonic components.

The IEEE network is an American system model that is intended to run at 60 Hz, so it is crucial to verify the nominal frequency and output frequency in the PowerFactory software before beginning the analysis. Those two frequencies need to be set to 60 Hz.

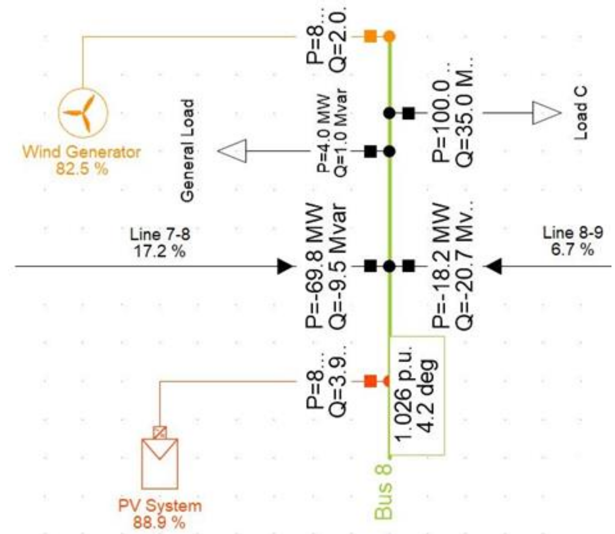

Fig. 46: A General load in the Bus 8

For our first analysis, we attached a general load to bus 8 (Fig. 46), where the wind generator and photovoltaic (PV) panel were added. We assumed this load as a large office building that utilises lots of computers and energy-efficient lights, which are non-linear loads, so that it could add some impact to the network. We chose the load model as a current source because we intended to inject current harmonics into the network. The load was then configured with proper power ratings and short-circuit levels. And in the last step, harmonic current data was given using the table below [54].

Order of the Significant Harmonics	Magnitude in percentage (%)
3rd	76.28
5th	56.29
7th	43.39
9th	34.95
11th	29.14
13th	24.93
15th	21.76
17th	19.29

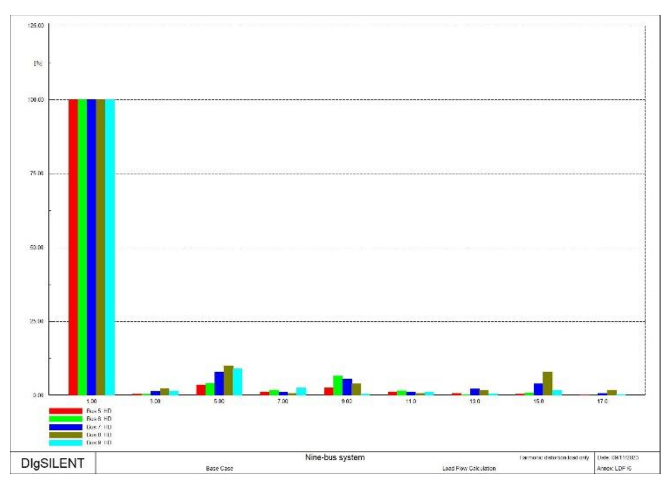

Fig. 47: Harmonic Distortion result in Bus 5,6,7,8 and 9

Based on the graph above, it is apparent that even if the load was added to bus 8, the harmonic distortion spreads across the other buses in the network. We also observed that the presence of the triplen harmonics (9th and 15th) is significant compared to others, except for the 5th harmonic.

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Harmonics Calculation Balanced, positive sequence | Busbars/Terminals

Nominal Frequency 60.00 Hz | Output Frequency 60.00 Hz | Calculate HD and THD Based on fundamental frequency values

Grid: Nine-bus System | System Stage: Nine-bus System | Study Case: 01- Load Flow | Annex: / 1

	Rated Voltage [kV]	Bus-voltage (60.00 Hz) [p.u.]	(60.00 Hz) [deg]	RMS [p.u.]	Sum [p.u.]	Distortion (60.00 Hz) [%]	Total [%]
BESS AC Bus	0.40	1.00	0.00	1.00	1.00	0.00	0.00
BESS AC Bus(1)	0.40	1.00	0.00	1.00	1.00	0.00	0.00
Bus 1	16.50	1.04	0.00	1.04	1.11	3.12	6.48
Bus 2	18.00	1.03	0.00	1.04	1.19	6.78	14.95
Bus 3	13.80	1.03	0.00	1.03	1.16	7.14	12.59
Bus 4	230.00	1.02	0.00	1.03	1.17	6.92	14.36
Bus 5	230.00	1.00	0.00	1.00	1.10	4.79	10.23
Bus 6	230.00	1.01	0.00	1.01	1.17	8.16	15.75
Bus 7	230.00	1.03	0.00	1.04	1.28	10.84	23.90
Bus 8	230.00	1.03	0.00	1.04	1.32	13.74	29.01
Bus 9	230.00	1.04	0.00	1.04	1.22	9.74	17.19
DC Bus	0.25	0.00	0.00	0.00	0.00	0.00	0.00
DC Bus(1)	0.25	0.00	0.00	0.00	0.00	0.00	0.00

Fig. 48: Harmonic Load Flow calculation result after adding harmonics in general load

The chart in Figure.48 demonstrates a detailed representation of the harmonic distortion calculation for the entire network. We saw that harmonic distortion is present in every bus in the network except battery energy storage system (BESS) AC buses, which clearly are not affected. Thus, we introduced harmonics into existing non-linear loads, which are PWM DC converters connected to BESS buses. We configured these DC converters with harmonic current data from the table below to further analyse the effect of harmonic distortion in the network [55].

Order of the Significant Harmonics	Magnitude in percentage (%)
3^{rd}	80
5^{th}	20
7^{th}	15
9^{th}	5
11^{th}	10
13^{th}	7.5
15^{th}	7.5
17^{th}	5

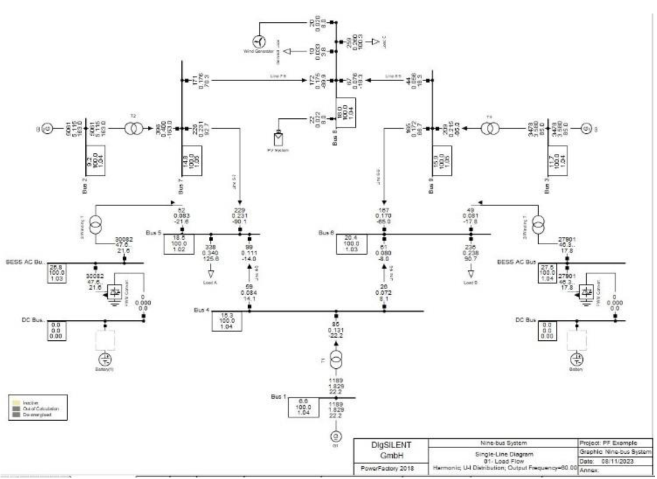

Fig. 49: IEEE 9-bus system network after harmonic load flow analysis

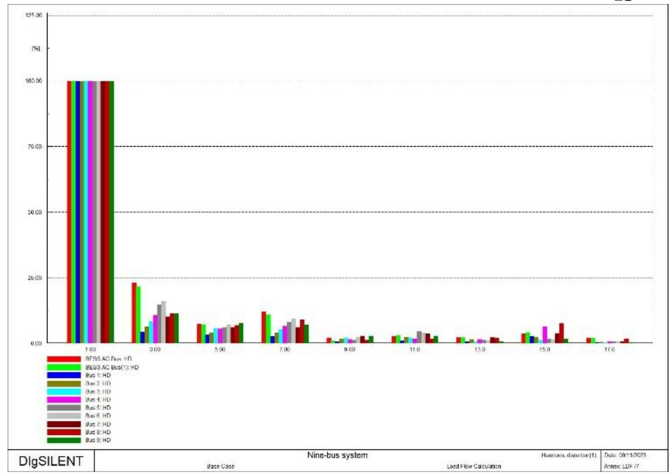

Fig. 50: Harmonic Distortion result in the entire network

Figure.50 shows the considerable amount of harmonic distortion in all of the network's buses, particularly in the battery energy storage system (BESS) AC buses. The 3rd harmonics of these two buses have a distortion of about 25%, and the subsequent two harmonics are similarly high in comparison to the others, with the exception of the 15th harmonic, a triplen harmonic, where we see higher distortion in a few buses.

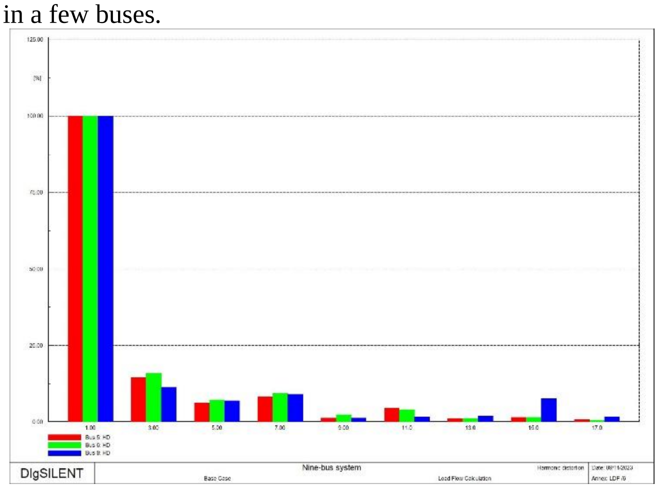

Fig. 51: Harmonic Distortion result at bus 5,6 and 8

DIgSILENT PowerFactory 2018 | Project: | Date: 09/11/2023

Harmonics Calculation Balanced, positive sequence | Busbars/Terminals

Nominal Frequency 60.00 Hz | Output Frequency 60.00 Hz | Calculate HD and THD Based on fundamental frequency values

Grid: Nine-bus System | System Stage: Nine-bus System | Study Case: 01- Load Flow | Annex: / 1

	Rated Voltage [kV]	Bus-voltage (60.00 Hz) [p.u.]	(60.00 Hz) [deg]	RMS [p.u.]	Sum [p.u.]	Distortion (60.00 Hz) [%]	Total [%]
BESS AC Bus	0.40	1.00	0.00	1.04	1.55	27.52	54.63
BESS AC Bus(1)	0.40	1.00	0.00	1.03	1.51	25.79	51.33
Bus 1	16.50	1.04	0.00	1.04	1.20	6.64	15.24
Bus 2	18.00	1.03	0.00	1.04	1.26	9.23	22.12
Bus 3	13.80	1.03	0.00	1.04	1.29	11.67	25.05
Bus 4	230.00	1.02	0.00	1.04	1.38	15.30	34.28
Bus 5	230.00	1.00	0.00	1.02	1.38	18.45	37.83
Bus 6	230.00	1.01	0.00	1.03	1.43	20.40	41.90
Bus 7	230.00	1.03	0.00	1.05	1.40	14.75	35.37
Bus 8	230.00	1.03	0.00	1.04	1.45	17.96	41.17
Bus 9	230.00	1.04	0.00	1.05	1.39	15.94	34.20
DC Bus	0.25	0.00	0.00	0.00	0.00	0.00	0.00
DC Bus(1)	0.25	0.00	0.00	0.00	0.00	0.00	0.00

Fig. 52: Harmonic Load Flow calculation result after adding harmonics in DC converters

A thorough illustration of the harmonic distortion computation for the whole network is shown in the chart in Figure.52. By comparing with the last calculation in Figure.48, it was noted that the total harmonic distortion increased significantly in

buses after putting harmonics in the DC converters.
Harmonic distortion is a major issue in real life, affecting not just industry but also other fields. Steel industries, for instance, manage large amounts of electricity and frequently use induction furnaces, which are excellent examples of non-linear loads [56]. The nonlinear characteristic originates from the fact that the induction heating process involves the use of power electronic components, specifically high-frequency inverters, or converters, to generate the alternating magnetic field. Due to the furnaces' high current consumption, the network experiences a considerable amount of harmonic distortion. To mitigate harmonic distortion, Y or delta transformers are employed in industrial and commercial distribution systems. Furthermore, standards and guidelines are in place to restrict the permissible harmonic levels in power systems to ensure equipment functionality and maintain power quality.

VIII. RESULT AND DISCUSSION

The dynamic simulation results highlight various power quality issues that arise when incorporating energy storage systems (ESS) and distributed generation (DG) sources into the 9-bus system. The integration of energy storage systems (ESS) and distributed generation (DG) sources into power systems has gained significant attention due to their potential benefits in enhancing grid resilience, reliability, and sustainability. However, the seamless integration of these technologies is not without challenges. Dynamic simulations play a pivotal role in thoroughly evaluating the impact of integrating energy storage systems (ESS) and distributed generation (DG) sources into power systems [33]. While these technologies offer numerous benefits, such as increased reliability and flexibility, their integration can introduce several power quality challenges. The subsequent paragraphs delve into an analysis of these potential issues and their consequences.

8.1 Voltage Fluctuations

Issue: Intermittent renewable energy sources and energy storage systems (ESS) charging and discharging cycles cause voltage fluctuations.

Analysis: Rapid variations in power output, common in renewable sources like solar and wind, or due to abrupt changes in load, lead to frequent fluctuations in voltage magnitude. These fluctuations can manifest as sudden increases or decreases in voltage, affecting the stability of the power supply.

Consequences: Voltage instability in electronic devices can cause disruptions, data loss, control system malfunctions, and equipment damage. In industrial processes, this can lead to inefficient operation and production losses. [33][34]

8.2 Voltage Sags and Swells

Issue: Rapid changes in power demand or intermittent renewable energy generation can cause voltage sags and swells.

Analysis: Voltage sags are short-term reductions, while swells are short-term increases in voltage. These can occur due to the intermittent nature of renewable energy sources and rapid changes in power demand, causing momentary imbalances.

Consequences: Sags have the potential to cause equipment malfunction, impact industrial processes, and swells may result overvoltage, shorten equipment lifespan, and deteriorate insulation, affecting sensitive electrical equipment. [35]

8.3 Frequency Instability

Issue: Inconsistent power output from distributed generation (DG) sources results in frequency deviations.

Analysis: Frequent frequency deviations can lead to generator instability, potential equipment damage, and cascading failures. The long-term consequences include reduced system reliability, increased maintenance costs, and the risk of blackouts.

Consequences: Frequent deviations from nominal frequency can disrupt generator synchronization, causing instability and potential cascading failures, compromising power system reliability and causing outages. [36]

8.4 Harmonic Distortion

Issue: Power electronics in energy storage systems (ESS) and distributed generation systems (DG) introduce harmonics.

Analysis & Consequences: The analysis and consequences of the Harmonic distortion [37] is elaborately discussed in the following section.

8.5 Voltage Unbalance

Issue: Uneven power generation or loading causes voltage unbalance.

Analysis: Voltage unbalance can lead to motor overheating, reduced equipment efficiency, and increased energy consumption. Persistent voltage unbalance may result in operational inefficiencies, higher maintenance costs, and potential damage to connected loads.

Consequences: reduced efficiency, increased maintenance costs, and potential damage to connected equipment. [40]

8.6 Islanding

Issue: Energy storage systems (ESS) may cause unintentional islanding during grid disturbances.

Analysis: Islanding poses safety risks for utility workers and may lead to uncontrolled reconnection issues. It can result in equipment damage, increased outage durations, and difficulties in restoring the system after an event.

Consequences: Islanding poses safety risks for maintenance personnel, potentially causing uncontrolled reconnection issues when the main grid is restored, potentially damaging equipment, and compromising the power system's stability.[41]

8.7 Voltage Flicker

Issue: Rapid power changes cause the voltage to flicker.

Analysis: Rapid changes in power output, especially from renewable sources, can cause fluctuations in voltage levels over short durations, leading to visible variations in light output.

Consequences: Voltage flicker may affect lighting systems, causing discomfort, visual fatigue, and potential disruptions in industrial processes that rely on consistent lighting conditions. In extreme cases, it can impact the performance of sensitive equipment that is sensitive to voltage variations. [42]

8.8 Ride-Through Capability

Issue: distributed generation (DG) systems cannot ride through disturbances.

Analysis: The inability to ride through faults may lead to frequent disconnections, impacting the reliability of distributed resources. Consequences include reduced system resilience, increased downtime, and potential revenue losses for distributed generation (DG) operators.

Consequences: reduced system resilience, increased downtime, and potential financial losses for distributed generation (DG) operators. [43]

8.9 Grid Synchronization Challenges

Issue: Coordinating distributed generation (DG) with the grid is challenging.

Analysis: Poor synchronisation can lead to synchronisation errors, potential equipment damage, and disturbances in the grid. Consequences include increased wear and tear on equipment, compromised power quality, and the risk of system-wide instability.

Consequences: increased wear on equipment, compromised power quality, and the risk of system-wide instability. [46]

8.10 Protection Coordination Challenges

Issue: Existing protection schemes may not be suitable.

Analysis: Inadequate protection coordination can lead to delayed fault clearing, equipment damage, and compromised system reliability. Consequences include increased outage durations, higher maintenance costs, and potential safety hazards.

Consequences: Failure to update protection schemes can result in miscoordination, leading to improper tripping or delayed response during fault conditions. This can exacerbate the impact of faults, prolong downtime, and compromise the reliability of the power system. [48]

8.11 Energy Storage System Control

Issue: Inefficient energy storage systems (ESS) control impacts system performance.

Analysis: ESS, or energy storage systems, are crucial for maintaining energy efficiency and reducing costs, but ineffective control can lead to suboptimal utilization, reduced responsiveness to grid events, and premature degradation.

Consequences: lower system efficiency, higher operating costs, and potential premature degradation of energy storage systems (ESS) assets. [49]

8.12 Transients and Surges

Issue: Switching operations, lightning strikes, or sudden disturbances can introduce both transient voltage deviations and high-voltage surges into the system.

Analysis: Switching events in energy storage systems (ESS) and distributed generation (DG) systems, such as rapid disconnection or connection, introduce transients and surges into the power system.

Consequences: Unmitigated transients and surges can damage equipment, especially sensitive electronics, and compromise the overall reliability of the power infrastructure if protective devices are not properly designed. This can lead to increased maintenance costs & operational disruptions. [51]

Addressing these power quality issues requires a comprehensive approach. This includes the implementation of advanced control strategies, meticulous grid planning, the integration of energy management systems, and the deployment of advanced power electronics and protective devices. Additionally, strict adherence to relevant standards and regulations is crucial to ensuring the seamless and reliable integration of energy storage and distributed generation into the existing power grid. This comprehensive strategy is essential for harnessing these technologies' benefits while maintaining the power system's stability and reliability.[52]

IX. Conclusion

The designed network modal is tested under Islanded mode as well as grid connected mode with multiple switch and short circuit events under symmetrical faults and unsymmetrical faults. The load flow analysis of the modified 13-bus IEEE system, incorporating energy storage and distributed generation, demonstrates its stable operation with sufficient capacity, providing crucial insights for effective system planning and optimization. When considering the integration of DER components, it was found that considering the impact of potential power quality issues is essential. Considering the order/timing of switch events and including power quality regulating technologies such as smart inverters and voltage regulators can greatly reduce the probability of power quality related damages. This allows for a smoother transition from island to grid mode of connection. In summary, power systems are significantly impacted by symmetrical and unsymmetrical faults. Which result in voltage decreases, current rises, and power variations. The complexity is increased by the combination of distributed generation and energy storage, which results in significant oscillations and extended recovery times. To keep the system stable, improving techniques like load shifting and fault isolation are essential. Since, the dc converters and the general domestic load are non-linear loads, integrating them into our simulated 9-bus system will undoubtedly induce harmonics. It is possible to lower harmonics in the system by using harmonic trap filters (such as passive L-C filters, or active power filters), specialised transformers, and proper load management & distribution. Based on the type of load which is going to be used, we can determine the type of transformer and the generator so that, the generators and transformers will meet load demands and it will avoid overloading the system completely, reducing the power quality and overheating issues, etc.

X. APPENDIX

Bus Number	Bus Type	Final Voltage (p.u)	Load (MW)	Load (MVAr)	Generation (MW)	Generation (MVAr)	Voltage Rated (kV)
1	3	1.04	0	0	0	0	16.5
2	2	1.025	0	0	163	0	18
3	2	1.025	0	0	85	0	13.8
4	0	1	0	0	0	0	230
5	0	1	125	50	0	0	230
6	0	1	90	30	0	0	230
7	0	1	0	0	0	0	230
8	0	1	100	35	0	0	230
9	0	1	0	0	0	0	230

Fig. 53. P.M Anderson Bus Data

From Bus	To Bus	Branch Resistance R	Branch Reactance X	Line Charging B
1	4	0.00000	0.05760	0.00000
2	7	0.00000	0.06250	0.00000
3	9	0.00000	0.05860	0.00000
4	5	0.01000	0.08500	0.17600
5	6	0.01700	0.09200	0.15800
6	7	0.03200	0.16100	0.30600
7	9	0.03900	0.17000	0.35800
8	8	0.00850	0.07200	0.14900
9	9	0.01190	0.10080	0.20900

Fig. 54. P.M Anderson Branch Data

From Bus	To Bus	Branch Resistance R (Ohm)	Branch Reactance X (Ohm)	Line Charging B (uS)
4	5	5.29	44.965	332.703214
4	6	8.993	48.668	298.676749
5	7	16.928	85.169	578.449905
6	9	20.631	89.93	676.748582
7	8	4.4965	38.088	281.663516
8	9	6.2951	53.3232	395.085066

Fig. 56. P.M Anderson Substituted Bus Data

XI. REFERENCES

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