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Impact of Distributed Generation and Battery Energy Storage Systems on an Interconnected Power System

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***Abstract*—This research describes the integration of Distributed Generation and Battery Energy Storage Systems into an IEEE 14-bus power system network, as well as the simulation of the effects of symmetrical and unsymmetrical faults and harmonics on the network during balanced, unbalanced, and no-load conditions. The paper will provide an elementary and detailed description of the network system used, power generation sources and the likely issues encountered, power stability concerns as they relate to power transmission and distribution to consumers, as well as consumer on-peak and off-peak usage situations on the network. It will also detail methods of improving the power quality and sustainability of our network system to withstand load demands, issues surrounding power transmission, and methods to integrate renewable energy. The Distributed Generation, which used only renewable energy, the Battery Energy Storage System, and the fault conditions were all simulated using the most efficient electrical engineering software, DIgSILENT Power Factory, and the results were used for the Load Flow (balanced and unbalanced) and harmonics analysis.**

Index Terms— Distributed Generation, Electric Grid, Energy Storage, faults, harmonic load flows, load flow analysis, Renewable Energy, Power systems.

I. INTRODUCTION AND LITERATURE REVIEW

Modern electrical systems are centralized, with high voltage transmission networks feeding interconnected large power plants and lower voltage distribution networks delivering power to customers. When connected in this manner, the overall goal is to deliver power to loads in an economical and reliable manner [1].

The introduction of distributed generation is having a significant impact on the central structure of the electrical system. Distributed generation systems are decentralized, modular, and adaptable technologies that are located close to the demand. They can include a variety of generation and storage components.

Distributed generation systems, which generally use renewable energy sources such as small hydro, biomass, biogas, solar, wind, and geothermal energy, are becoming increasingly important in the distribution of electric power. [2] Factors such as increased competition in the electricity market, environmental protection, issues of obsolete grid equipment generating harmonics, and capacity limitations are driving the adoption of distributed generation in line with renewable energy standards as part of the new power system with zero emission.

The amount of power fed into the electricity grid by distributed generating plants could pose problems for power system operators. These difficulties range from voltage fluctuations to reverse power flow and components overheating. Increased electrical energy inflow into the power network necessitates significant grid reinforcement, particularly in distribution networks where voltage stability is critical. [3] High penetration of distributed generation systems, particularly solar and wind, may cause significant problems due to their variable nature and bidirectional power flows. Some of the problems could be attributed to the inferiority of power converters, poor power quality around the network, excessive power loss from generation to distribution, and low power equipment utilization rates [4].

With the continued rapid deployment of renewable generation and low-carbon technologies in electrical networks, network operators have integrated smart solutions to actively manage their electricity networks while ensuring supply security, stability, and reliability. Battery energy storage systems (BESS) are one possible smart solution that network operators have recently adopted to provide a variety of ancillary services. [5] The battery energy storage system (BESS) is regarded as one of the most effective and efficient arrangements capable of increasing the operational flexibility of the power system [6] as well as a potential solution to the global warming problem [7]. When used in conjunction with distributed energy systems, BESS can provide an effective solution for peak load sharing or energy storage. It also improves the overall reliability of voltage regulation.

The increased reliability of the electrical power system network improves service quality and reduces power supply interruptions such as load-shedding and blackouts. A battery energy storing system (BESS) is made up of two parts: a storing part that can store and conserve energy through an electrochemical process and a rectifier/inverter that can convert the stored DC voltage to AC voltage required by the grid through a smart system. In most cases, the rectifier/inverter is based on a voltage-sourced converter (VSC) with pulse width modulation (PWM) [8].

The encompassing focus of this article is to design an interactive integrated system using grid-based distributed generation sources and to evaluate the stability of a power system using the Digital Simulator for Electrical Network (DIgSILENT) software in accordance with IEEE bus standards. The exercise entails simulating an Energy Storage System and a distributed generator in an IEEE 14-bus system to analyze load flow as it pertains to balanced and unbalanced load conditions, symmetrical and asymmetrical faults that can occur within the network, Harmonics voltage and current and the impact Total Harmonic Distortion have on buses in the network, as well as other power quality issues.

The IEEE 14-bus test system is made up of 5 synchronous machines with IEEE type-1 exciters, three of which are synchronous compensators that are only used for reactive power support. The total load demand was 259 MW with a capacity of 73.5 MVA [9]. After the Energy Storage System and Distributed Generation have been integrated into the bus, the first step is to run a load flow analysis. Then, on selected buses, symmetrical and unsymmetrical fault simulations are performed to analyze the responses of energy storage systems and distributed generation to these faults. The emphasis here focuses on analyzing the stability of the power system via dynamic simulation.

The impact of the energy storage system on the overall system is investigated using switching events when it is grid-connected and in isolated mode. It is critical for grid system sustainability to modify the load requirement for the system model and analyze system performance for network sustainability [10].

The final stage entails testing for Total Harmonic Distortion levels at various bus systems and performing Harmonic Load Flow Analysis. Based on those results, the overall results were analyzed and discussed giving reasons for the occurrences as observed during the simulation exercises. Finally, an assessment of the effects of distributed generation and BESS on the distribution grid will be made.

The power industry is in a period of rapid expansion as a result of rising power demand from end users and this has led to the integration of Distributed Networks into the power system [11]. In addition to ensuring network stability and availability, power-supplying companies also ensure high power quality to the end user [11]. The importance of power quality cannot be overemphasized.

Power quality entails the availability of steady voltage (and current) magnitude, stable frequency value, and acceptable waveform characteristics. Poor power quality, on the other hand, is the rate at which the three main power parameters, voltage, frequency, and current, vary from their nominal values and may lead to damage to the underlying power infrastructure, and operational equipment or cause harm to power users.

Poor power quality affects both the power-generating companies and the end users, though in different capacities. One of the effects of poor power quality is power losses along the transmission lines. Distribution system power loss mitigation is therefore very important. Higher voltage levels were required to deliver power over longer distances due to significant line losses caused by increased currents [11].

In order to reduce losses, distribution generators are ideally situated within the power network system. However, the costs of installing more generators may raise the overall cost, which may increase operational costs, resulting in higher service charges for consumers. As a result, when adding the new generator, a trade-off must be made to ensure that both costs and losses are reduced. In this study, an IEEE 14-bus System model was used to analyze power flow characteristics with PV and Wind Energy as the network's distributed power systems.

Furthermore, our power system may be vulnerable to instability as a result of a variety of frequently occurring events, such as line faults, generator trips, load-generation imbalance, and natural disasters. This will lead to the breakdown of commercial and industrial activities, poor delivery of health and medical services, and many residential homes not having electric energy because of widespread rolling blackouts caused by instability within the network [12]. To ensure there will always be a consistent supply of quality electric power, it is important to conduct research on power or load flow analysis.

Power system analysis is critical for power system planning, equipment selection, and reliability evaluations. This process entails evaluating the voltages, currents, and other parameters of the power system in various situations in order to prioritize safe modes of operations and ensure the electric network will be smart to identify and mitigate faults, ensuring operators are safe and the final consumers are given the best of service [13].

II. NETWORK MODELS

Our network system analysis was modelled on a 14-bus system for the sole purpose of performing load flow and harmonics analysis. DIgSILENT PowerFactory software, one of the most powerful and widely used power system analysis software in electrical engineering was used for the simulation exercises. A licensed version was provided by the institution to enable us to demonstrate several scenarios relating to power generation, transmission lines, and distribution links. The 14-bus system for simulation was made up of five (5) synchronous machines with IEEE type-1 exciters, 19 buses, 17 transmission lines, eight transformers, and eleven constant impedance loads. [14] iterates that power systems undergo complex metamorphosis due to the integration of distributed generation into networks and the highly variable levels of renewable energy penetration. According to this paradigm, load flow analyses are necessary not only to understand the electrical grid's operating point at any given moment but also to plan efficiently for network operations, do contingency analyses, and design future expansions. Additionally, load fluxes are a crucial prerequisite for the implementation of dynamic simulation assessments. Figure 1 shows the 14-bus system used in our analysis.

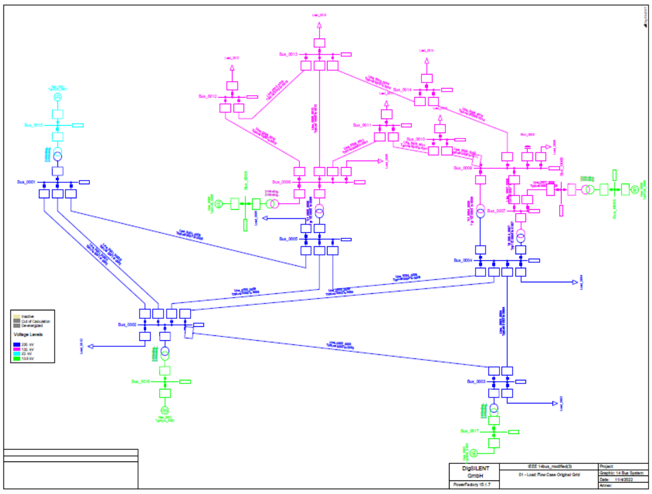

Figure 1: IEEE 14-bus System

According to [15], With a constant rise in power consumption, the complexity in the power transmission, and the increasing distribution sectors, Circuit breakers frequently trip because of the symmetrical, unsymmetrical fault and harmonic frequencies dramatically that constantly increase complexity. Since this puts the dependability and quality of the service provided to consumers in danger, it is imperative to create an intelligent mechanism that can quickly identify a power system fault, preventing transmission and distribution lines from failing more frequently as a result of symmetrical and unsymmetrical faults. As a result, the Power Sector's power reliability and service quality have been identified as being at risk.

To enable us to carry out efficient load flow and harmonic simulations, we added at least an external form of distributed generating system and electrical loads into the existing structure of the grid. The analysis will then be on several scenarios that will evaluate the impact of various types of three-phase faults and increasing load demands will have on the network and what can be done to ensure the network remains sustainable irrespective of any irregularities that may happen during transmission or distribution. To achieve this, our choice of a generating system consisted of a wind generator plant and a Photovoltaic (PV) system. Because the solar system cannot operate at night or in cloudy conditions, and wind speed fluctuates constantly, a hybrid PV-wind generation system is more efficient and reliable than renewable energy having just a single-source system. Also, [16] gave insights on how Renewable energy sources are being strongly considered for use more often as a result of the strict restrictions that are currently in place regarding emissions of greenhouse gases and other dangerous pollutants for both human health and the environment, and also owing to government and private sector fundings towards the rapid technology advancement into large scale production of wind and solar forms of energy as alternatives to fossil fuels as backed by the EU long-term climate change strategy of achieving net-zero greenhouse gas emissions By 2050. The hybrid generating system as discussed will get connected to busbar Bus 13 in our network as shown in figure 2 below.

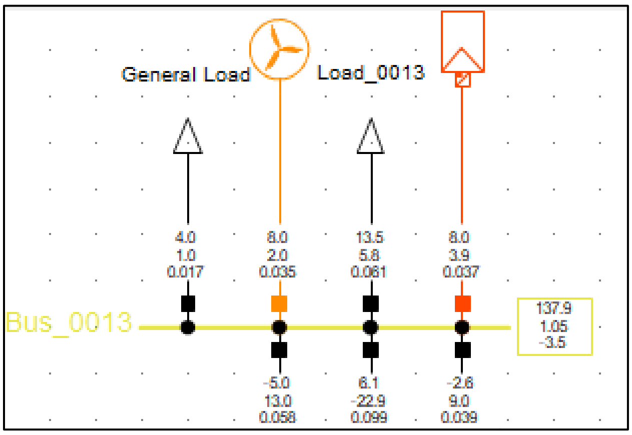

Figure 2: 8-MW Wind and 8-MW Solar PV generators added on bus 13.

For our load consideration as shown in figure 3 below, we integrated two (2) battery storage components which are BESS having a nominal voltage of 0.25kV at two (2) different locations within the grid. [17] further disclosed Battery Energy Storage Systems (BESS) are becoming a more appealing solution in electrical power systems because they properly address the operational flexibility of battery systems using real market data, utilization factors such as potentially profitable utilization time, and significantly outperform in terms of providing frequency support services. To enable effective charging of BESS connected and added to the network, two (2) two-winding step-down transformers with ratings of 230/0.4kV, two (2) PWM converters with ratings of 0.4/0.25kV for converting voltage from AC to DC, and two (2) DC Busbar with ratings of 0.25kV are the final components. [18] clarifies that integrating PWM converters with energy storage systems such as BESS can overcome the slow response issues associated with renewable energy sources. It can either provide the extra energy required by the load or absorb the extra energy provided by the power sources, greatly improving the overall system dynamics. The proposed converter can lower system costs and size while increasing efficiency and reliability.

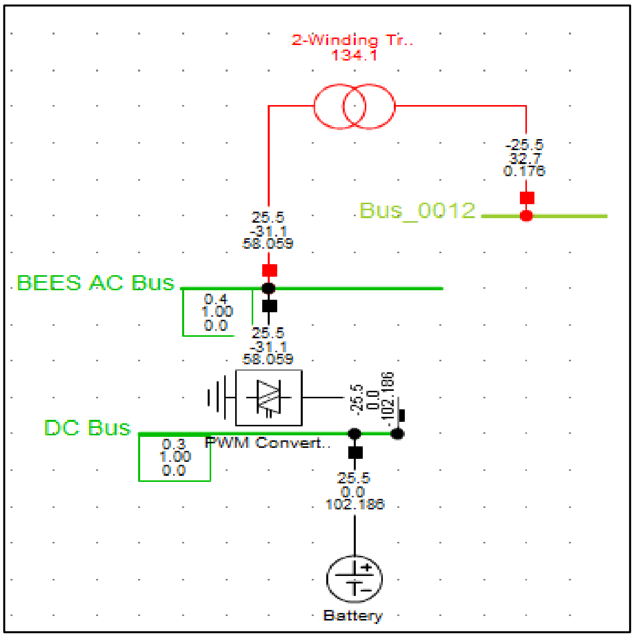

Figure 3: Structure of 25-MW Battery Energy Storage System added on bus-12 and bus-14.

III. Network Analysis with Results and Discussion

I. *System response to transient symmetrical fault with DG and BESS connected during a dynamic simulation.*

Figure 4 shows the response of the bus voltages when a symmetrical fault occurred on 14-bus. The pre-fault and after-fault conditions are shown; the fault started at 80 sec and was cleared at 82 seconds.

With a three-phase balanced fault occurring at the 80-sec mark, a sharp decrease in voltage coupled with some oscillations was witnessed on all the buses. When the fault was isolated on the 82-sec mark, all bus voltages increased more than the nominal value for a short period of time before stabilizing.

Table 1: Dynamic events on the network

Event Type	Time intant	Location
Switch Event (Turn on)	5	Wind Generator
Switch Event(Turn on)	20	PV System
Switch Event(Turn on)	35	BESS 1
Switch Event(Turn on)	60	BESS 2
Short-Circuit Event(3-phase short circuit)	80	on Bus 14
Short-Circuit Event(Clear short circuit)	82	on Bus 14
Short-Circuit Event (L-L or 2-phase short circuit)	100	on Bus 14
Short-Circuit Event(Clear short circuit)	102	on Bus 14

Figure 4: Variation in voltage (in per-unit) with respect to time

Figure 5 below shows how the line currents responded to a symmetrical fault on 14-bus. The pre-fault and after-fault conditions are shown; the fault occurred at 80 sec and was cleared at 82 seconds. With a three-phase balanced fault occurring at the 80 sec mark, an exponential increase in current was witnessed on all the lines with the one on the lines connected to 14-bus more pronounced. When the fault was isolated on the 82 sec mark, all line current stabilized within a short period of time.

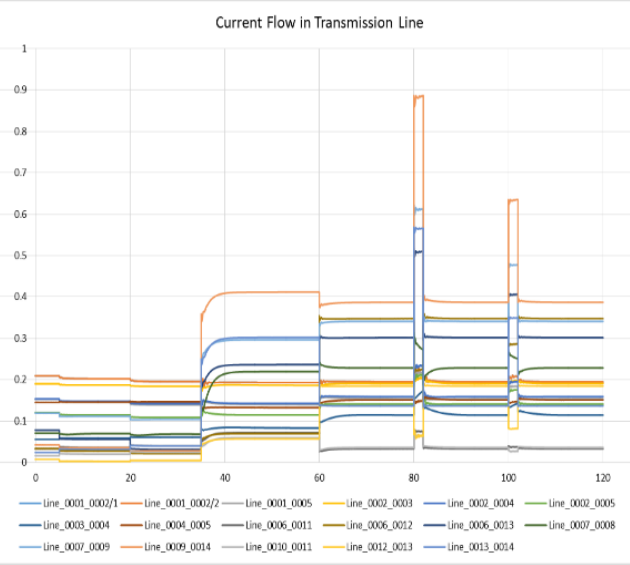

Figure 5: Current flow in transmission lines

Figure 6 below shows the active power flow in the transmission lines when a symmetrical fault occurred on 14-bus. The pre-fault and after-fault conditions are shown; the fault started at 80 seconds and was cleared at 82 seconds. With a three-phase balanced fault occurring at the 80 seconds mark, there was a drop in power which remained until the fault was cleared. When the fault isolated on the 82 seconds mark, all line power flow stabilized within a short period of time.

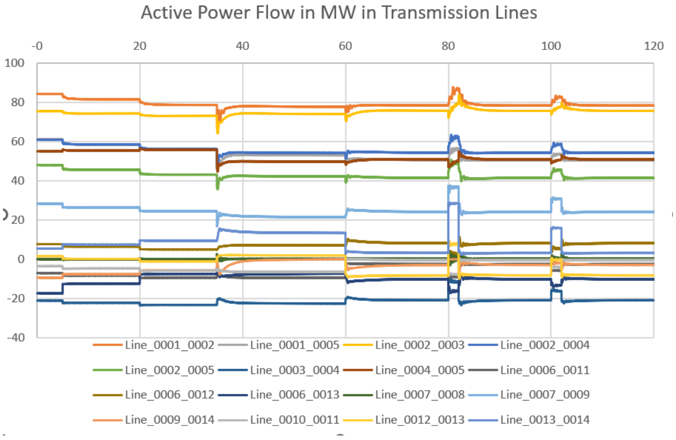

Figure 6: Active Power Flow in Transmission Lines

II. *Frequency*

The short circuit fault resulted in a drop in frequency, which was measured for each Bus. Figure 7 gives variations in frequency in response to various events. When the unsymmetrical short circuit event occurred, the frequency dropped to around 49.97Hz and then returned to around 50.03Hz when the fault was cleared.

Unsymmetrical faults, in general, have a negative impact on power quality. The following have an impact on power quality:

i. A sudden drop in voltage
ii. A sudden rise in current
iii. Damping of the overall power value
iv. Fluctuation in the frequency of the transmission line

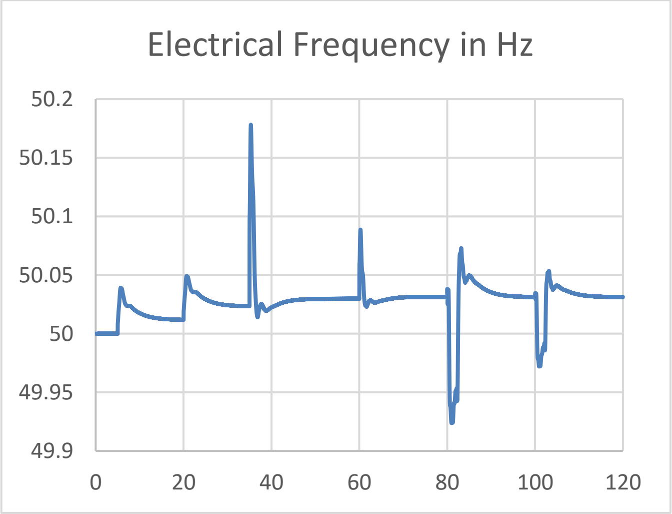

Figure 7: Change in System Frequency during dynamic events.

III. *Harmonics*

Harmonics are created when current and voltage waveforms within a power system deviate from a sinewave sinusoidal shape or pattern. They have a major impact on the electrical distribution network (including transmission lines), and the connected loads. Harmonics are mainly created by electronic equipment incorporated in a power system network either during the initial design implementation, during the modification of existing networks, or by industrial and domestic consumers. Most electronic devices are used for power generation, distribution, and as connected loads create non-linear currents in rapid short pulses during operation and this mainly occurs during voltage transformation from AC to DC voltage form.

Switch-Mode Power Supplies such as rectifiers, inverters, variable frequency drives (VFDs), fax machines, battery chargers, energy-efficient lighting, and computers are a few examples of equipment that can be classified as nonlinear loads which generate harmonics while connected to the electric network. Harmonic voltages or currents are of frequencies integer to the multiples of their basic power frequency. [19] discussed that at both low and high frequencies, harmonics and inter-harmonics result in undesirable outcomes such as flicker, equipment overheating, generator and motor failures, power bank capacitor failures, increased network losses, interference in communications systems, and mistakes in control systems and digital meters. [20] explains that High-frequency switching circuits used in power converter equipment and devices cause distortion above the typical 2 kHz harmonic frequency region, moving it to the 0-150 kHz range.

Low-frequency distortions also have the propensity to spread throughout the network. The distortion over an extended period tends to reduce the functionality and life expectancy of all electrical machines and equipment within the network such as transformers and generators, it causes overload conditions on transmission cables and persistent tripping on circuit breakers while they try to clear transient faults it had created and will also result in the damage and breakdown of major consumers' loads due to increase of the RMS current within the network. Figure 13 below shows the electrical frequency generated within a fundamental frequency of 50Hz on Bus 16. Given that our fundamental frequency was 50Hz as shown in the figure above, harmonic currents and voltages are known to be multiples of the fundamental frequency. The network's harmonic currents or voltages will be an integer multiple of our fundamental frequency. The second harmonic is thus 100 Hz (2 x 50 Hz), the third harmonic is 150 Hz (3 x 50 Hz), the fifth harmonic is 250 Hz, the seventh harmonic is 350 Hz, and so on. [21] explained that harmonic sequence refers to the phasor rotation of the harmonic voltages and currents with respect to the fundamental waveform in a balanced, three-phase, four-wire system. A positive sequence harmonic (4th, 7th, 10th, etc.) rotates in the same direction as the fundamental frequency (forward). A negative sequence harmonic (2nd, 5th, 8th, etc.), on the other hand, rotates in the opposite direction (reverse) of the fundamental frequency. Positive sequence harmonics are typically unwanted because the combining of their waveforms causes generators, transmission lines, and transformers to overheat. On the other hand, negative sequence harmonics move back and forth between the phases, which causes more issues for motors because the opposite phasor rotation reduces the strength of the rotating magnetic field needed by motors, which results in a reduction in mechanical torque.

D. System response to an Order of Harmonics on Load and no-Load conditions

To better illustrate the effects of harmonic voltage and current on the network, we ran a simulation based on a set of specified harmonic data to show an order of significant harmonics for 3rd, 5th, 7th,9th,11th,13th,15th, and 17th. The results are as shown in figures 15 and 16 below. Data for harmonics in the load was used for compact fluorescent lamps based lighting as given in [22]. Similarly, the data for harmonics in converters is used from [23].

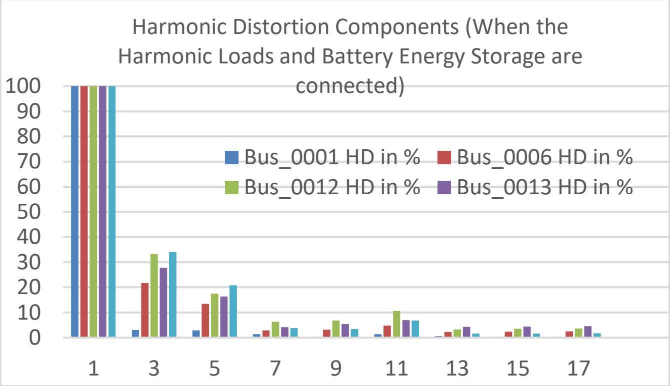

Figure 8: Harmonic Distortion Components (When the Harmonic Loads and Battery Energy Storage are connected)

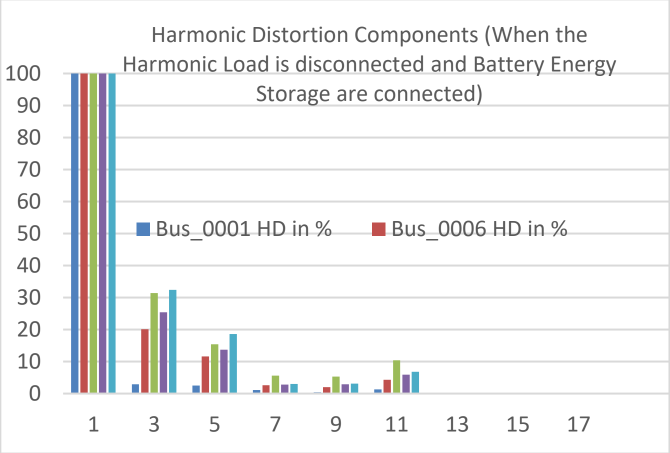

Figure 9: Harmonic Distortion Components (When the Harmonic Load is disconnected, and Battery Energy Storage are connected)

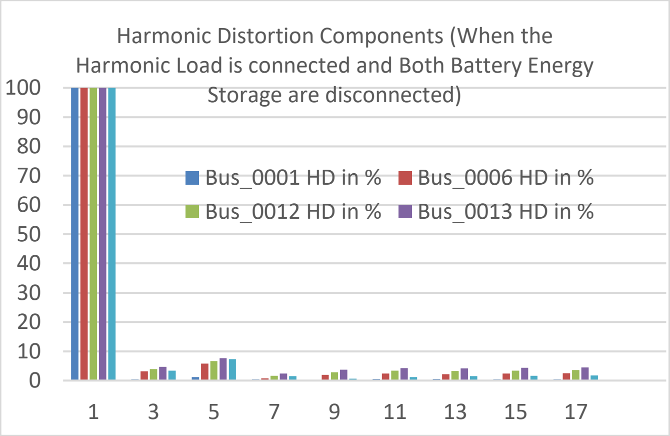

Figure 10: Harmonic Distortion Components (When the Harmonic Load is connected, and Both Battery Energy Storage are disconnected)

Figure 8 was the results obtained when a series of harmonics were applied to a network connection with a load Bus 13 had a higher Total Harmonic Distortion (THD) than the other buses due to its connection to the generating system and load fluctuations from the distribution network based on consumer needs. Figure 9 was to show the effect of harmonics on a no-load condition. After the 11th order, the harmonics faded away, and Bus 12 had a higher Total Harmonic Distortion (THD) over the period. This was caused by the distribution's

BESS and PWM converters attempting to synchronize power flow for storage. Figure 10 gives harmonic distortion in the case of only harmonic load connected while both BESS systems disconnected.

IV. CONCLUSION

This study assesses the efficiency of an IEEE Bus-14 power system network that includes added battery energy storage systems (BESS) and distributed generation sources. The emphasis was on the network's resilience to various fabricated fault conditions, its capacity to withstand fault conditions while also being proactive in the face of fault occurrences, maintaining power stability and quality during faults, and the most efficient production of clean renewable energy while taking into account greenhouse gas emissions by use of fossil fuels for power generation and its detrimental effects on the environment, and finally the stable transmission of power to various distribution hub within the network to meet consumer's increasing demands. DIgSILENT PowerFactory software was used to simulate these developments or events, and the outcomes of the simulation were then analyzed.

With the use of parameters, we were able to change the IEEE 14-Bus power system network in order to first include BESS and our distributed generation sources before creating fault circumstances. From our analysis, it is critical to consider the effects of symmetrical and unsymmetrical faults on the network when designing a new grid or modifying an existing one. Additionally, it is important to also consider the impact of harmonics generated by equipment within the network can have on the entirety of the network. Total Harmonic Distortion can be used to determine harmonic levels within a network, which will help identify the best methods to reduce harmonic effects and improve the span and efficiency of equipment within the network.

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