Analysis of Power Quality and Technical Challenges in Grid-Tied Renewable Energy

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Abstract: - The transition of power generation from fossil fuel to renewable energy is a cutting-edge phase in smart grid research. Renewable energy sources (RES), such as solar, photovoltaic, and wind are gradually overtaking other sources as the most attractive alternative within the power generation and distribution systems across many nations. Reduction in the carbon footprint is a major consideration in the choice of the RES. However, the technical challenges with RES pose a significant barrier to unified integration, even though the high penetration level appears plausible. The challenges are majorly caused by the variability and unpredictability of these sources. It is therefore a stimulating task to efficiently manage the electrical power distribution systems in the face of renewable energy integration. The purpose of this study is to examine the potential of renewable energy integration and the accompanying technical challenges that include power quality issues associated with grid-tied renewable energy (GtRE). The study also recommends techniques capable of mitigating prominent power quality challenges to guarantee seamless renewable energy integration in power systems.

Key-Words: - Power Grid, Renewable Energy, Power Quality, Technical Challenges, Integration, Distributed Generation

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1 Introduction

Fossil fuel-based power plants have major contributions to greenhouse effects which cause global climate change. The use of such plants has been declining globally over the past few decades, [1]. Emission of carbon dioxide and nitrogen oxides from fossil fuels have a great influence on climate, [2]. Apart from the effects of conventional power system generation on climate, the motivation to consider renewable energy sources (RES) is derived from other factors such as rising demand for electricity and energy poverty. Alternative power generation resources such as solar and wind are environmentally friendly and advanced technologically, with the capability to generate electrical power without contributing to carbon footprint or having any adverse effects on people or animals, [1], [2], [3], [4].

The integration of the RES into the utility grid has led to the development of various Distributed Generation (DG) technologies as one effective solution in line with the "Paris Agreement" to maintain global temperatures below 2^0C and 80% carbon footprint elimination by 2050, [3], [4], [5]. Grid-tied renewable energy (GtRE) has a positive impact on the stability of the power system, [6]. One of the most recent developments in the power distribution system is the DG, which offers a decentralized approach to power grid architecture, [7]. DG involves producing a considerable amount of power close to the distribution network with renewable generators as a typical example, [7], [8], [9]. DG has benefits that include: lower power loss, greater voltage support, peak shaving, and increased system efficiency, stability, and dependability, [8], [9]. Meanwhile, the technical challenges of GtRE from certain sources such as solar, photovoltaic, and wind turbines are critical power quality determinants, [10], [11], [12], [13]. According to, [11], power quality (PQ) is how closely the parameters of a power supply system such as voltage, frequency, and waveform adhere to the predetermined standards that operate end-user equipment appropriately.

This study focuses on reviewing the technical challenges and issues of power quality in GtRE to stimulate further research to address the challenges. The other part of this article is structured as follows: Section two presents an overview of global renewable energy growth and contributions. Section three presents the technical challenges and power quality challenges of GtRE. Section four gives the causes of power quality challenges, Section five gives the impact of power quality challenges. Section six presents possible mitigation techniques for prominent power quality challenges. Section seven concludes the study.

2 Global Renewable Energy Growth and Contributions

Renewables are presently considered the energy choice for new power generation, despite the terrible impact of the COVID-19 pandemic on society and public agenda priorities. According to the most recent edition of Renewable Capacity Statistics, at the end of 2021, 38% of the global power installed capacity was derived from renewable sources, [5]. The total global renewable energy generation from 2019 to 2021 is shown in Table 1. A sustainable energy future would result from energy being extracted from renewable natural resources with no or minimal ecological damage. Solar and wind power are two examples of renewable natural resources that have drawn global attention due to their popularity and investment growth, [14], [15]. These two technologies have recently grown in both scope and importance. They are both being deployed for use at medium and large-scale levels. Moreover, many individuals in African countries have either solar or wind energy systems installed to mitigate energy poverty.

Table 1. Global Renewable Energy Generation from 2019 to 2021

Continent	Generation Per Year in GW		
	The year 2019	The year 2020	Year 2021
Global	2542	2807	3064
Asia	1126	1300	1456
Europe	575	608	647
North America	389	420	458
South America	223	231	245
Other Continents	104	111	115
Africa	51	54	56
Oceania	36	43	45
Middle East	22	23	24
Central America	16	17	18

In recent years, the penetration of solar photovoltaic (PV) has surpassed that of wind given the developmental trend of solar PV, [5]. The years 2020 and 2021 were excellent ones for the energy transition; as presented in Figure 1, more than 250 Gigawatts (GW) of renewable energy were added globally each year. Power utilities' operators are now allowing higher levels of RE penetration. According to the reports presented in, [5], some countries, including Norway, Denmark, Portugal, Italy, Spain, Germany, the United States, and Australia, have recently achieved great success in integrating substantial volumes of renewable energy into their existing power infrastructures. With wind and solar only making up a tiny portion of renewable energy production in Norway, hydro dominates power generation. In Denmark, Spain, Germany, and Italy, the majority of renewable energy is generated by wind and solar PV, [5].

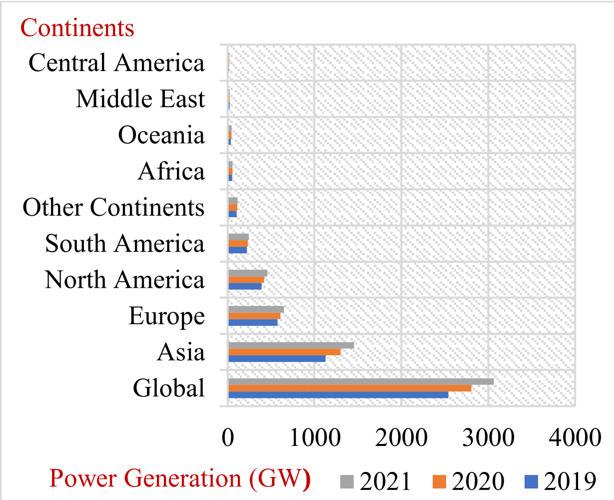

Fig. 1: Chart of Global Renewable Energy Generation

3 Technical Challenges of Grid-Tied Renewable Energy

Grid-tied renewable energy (GtRE) is affected by various technical challenges such as; power quality challenges, energy storage challenges, RES optimal placement challenges, islanding challenges, and power protection challenges.

3.1 Power Quality Challenges

The infrastructures for conventional power grids were designed to handle energy produced from conventional sources. Technologies behind these infrastructures can adjust their output to achieve an energy balance between supply and demand at all times to ensure the stability and reliability of the power grid. Due to the high penetration of RES like solar and wind, the operators in the power sector are worried about the stability of the grid, the quality of the power, and voltage regulation, [4], [6], [16].

Three power quality challenges are prominent in renewable energy systems such as; harmonics, voltage fluctuation, and frequency fluctuation, [17], [18]. Additionally, in the case of grid-tied RE, voltage and frequency changes may result from inherent power grid problems. Voltage and frequency, as specified by the IEEE Standard 519-2022 in, [19], are the two key factors to consider when evaluating the power quality of RES (PV and wind systems). Deviation from these parameters creates power quality problems. These problems can be discussed from two perspectives: The renewable energy perspective and the power grid perspective.

3.1.1 Power Quality Challenges in Grid-tied Renewable Energy

Harmonic

Harmonics are distortions in voltage and current, [10], [20], [21]. Harmonics are essentially the most prevalent issue in GtRE, [22], [23]. In RE generators, harmonic distortions are increased by the control circuit in conjunction with power electronics. According to IEEE standard 519-2022 reported in, [19], a low voltage system must undergo a harmonic analysis if the overall harmonic distortion at the point of common coupling is greater than 8%. Additionally, the term "harmonic" was used in, [24], to describe voltage or current that is multiplied by the system's fundamental frequency. Harmonics are created when the waveforms deviate from a sinusoidal shape. Such current harmonics change the voltage waveform and disrupt the power supply, which can cause several issues. The voltage swing of the applied sinusoid is confined by non-linear loads, such as an amplifier with smoothing distortion, and the pure tone is warped with a significant number of harmonics. Harmonic distortion prevents the power supply from functioning at its best.

In, [25], harmonics are said to be part of a periodic quantity that has a Fourier series of more than one order; for instance, the third harmonic order in a 50 Hz system is 150 Hz. Harmonics are capable of resulting in overheating and overcurrent, with impacts such as supply voltage distortion and rapid circuit breaker tripping. Authors in, [26], categorized harmonics into short time and very short time. For a 50Hz power supply, very short time harmonic values are evaluated over 3 seconds, based on the accumulation of 15 successive 10 cycles, using the rms estimate presented in equation 1, [19], [27], [28].

$$F_{n,vs} = \sqrt[2]{\frac{1}{15}\sum_{i=1}^{15} F_{n,i}^2} \quad (1)$$

where F stands for the voltage V or current I, n stands for the harmonic order, and i stands for a counter. The phrase "very short" is denoted by the subscript vs.

Short-time harmonic values for a given frequency component are evaluated over 10 minutes based on an accumulation of 200 consecutive extremely short values. According to equation 2, the 200 values are combined based on an rms calculation, [19], [27], [28].

$$F_{n,sh} = \sqrt[2]{\frac{1}{200}\sum_{i=1}^{200} F_{(n,vs),i}^2} \quad (2)$$

where the word "short" is denoted by the subscript sh.

Voltage Fluctuation

Voltage fluctuation is the variance in voltage amplitude from the nominal value. According to IEEE standards, it is a repeated voltage fluctuation with a magnitude of 0.9 to 1.1 pu, [24]. It is produced by sources whose output power varies over time. Voltage fluctuation is one of the key issues on power quality that emerges when RES are integrated with the grid. The significant prevalence of intermittent, uncontrollable RES is the main cause of voltage fluctuation.

Voltage flicker is the major effect of voltage fluctuations. According to, [24], voltage fluctuations can be described using two metrics, short-term flicker severity and long-term flicker severity. Although, there are other inherent grid factors capable of causing voltage fluctuations, but are particularly heightened by renewable energy, which has a negative impact on power quality. In other words, the voltage may increase or decrease more than usual when there is an excess of renewable energy in certain locations. A typical voltage fluctuation waveform is presented in Figure 2. All appliances connected to electrical power that has unstable voltage are susceptible to damage. Such power supply has a negative impact on the efficiency and proper operation of electrical and electronic appliances.

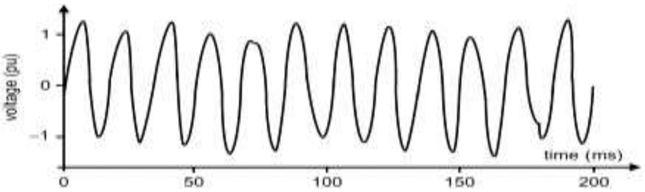

Fig. 2: Waveform of a typical voltage fluctuation, [24].

Frequency Fluctuations

Frequency fluctuation is a significant problem to power quality in the grid as a result of the large penetration of RES. Frequency fluctuation is the deviation from the nominal frequency, [29]. This is a result of the fluctuating output power of RES. Frequency deviation in the grid often happens when the demand is less than or more than the generation. And as more RES are used, this divergence gets worse, [24]. This may lead to equipment damage, load performance degradation, and power system instability. The deviation of the frequency from the reference value must never be too large, otherwise, it becomes a serious problem. The two nominal frequencies that are most frequently used in power systems are 50 Hz (Africa, Asia, and Europe) and 60 Hz (North America, South Korea, Virgin Islands). Normal conditions are often observed when a system works within a frequency deviation range of 0.1 Hz, while abnormal conditions occur when the frequency ranges from 47.5 to 51.5 Hz (for example, in a 50 Hz network), [30].

3.1.2 Power Quality Challenges in Conventional Grid

Apart from the identified power quality challenges in the RES power grid, existing disturbances also affect renewable energy integration. According to, [11], the quality of the electricity in the distribution grid is negatively impacted due to various sorts of disruptions at both the generator side and the load side, and this is capable of causing electrical supply failures. Continuous monitoring must be done on the power supply's parameters, including voltage and frequency. Poor power quality is caused by variations in voltage, frequency, and noise level. The various conditions leading to poor power quality are discussed below.

Voltage Sags

A power system phenomenon known as voltage sag causes the nominal RMS voltage to drop between 10% to 90% for small intervals of time, lasting from 0.5 cycles to 1 minute, [17], [31]. As shown visually in Figure 3, voltage sag is defined by the IEC 61000-4-30 standard as a transient drop in the RMS voltage of 10% or more just below the rated system voltage during a period of 1/2 cycle to 1 minute. An abrupt load change, such as the start-up of a motor or even a short circuit, may result in a voltage sag. Appliances that are connected are vulnerable to damage when there is voltage sag.

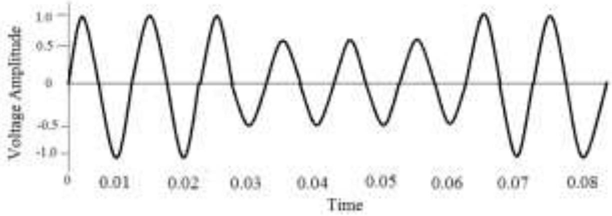

Fig. 3: Waveform of a typical voltage sag, [24].

Voltage Swells

The reverse of voltage sag is the voltage swell. In, [32], a voltage swell is defined as a brief rise in RMS voltage of 10% or more that lasts for up to one minute and occurs just over the rated system voltage. An example is observed when a large load in a power system shuts off, this will result in a brief rise in voltage. Some electric motors consume significantly more current during start-up than during rated speed operation. A voltage drop will result from a line-to-ground fault up until the protective switchgear trips, [31]. Swells may occur as a result of a single phase to the ground fault, temporarily raising the voltage of other phases. In the presence of voltage swell, appliances are susceptible to damage. Voltage swell is graphically presented in Figure 4.

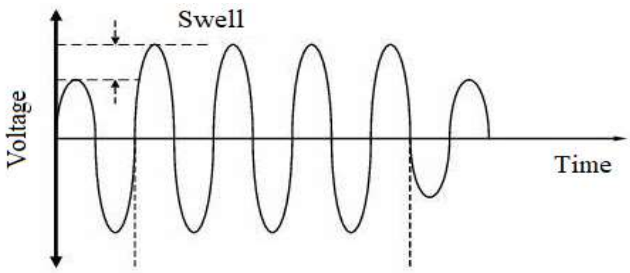

Fig. 4: Waveform of a typical voltage swell, [24].

Transients

According to, [33], [34], transients are disruptions that could damage the equipment in a power system and have an impact on the power quality. The electrical transients, which can be thought of as a brief spike, would last only a few milliseconds. The power system would receive a significant amount of electricity even if this condition would only last a few milliseconds. Despite having a much shorter running time than a steady state condition, transient conditions have a substantial impact on the power system. The presence of inductors and capacitors in the system is the main cause of a transient, [35]. Capacitor switching, dynamic load switching, circuit breaker activity, etc. are the main causes of transients. The study of transient periods is crucial because, during these times, high currents or voltages subject the circuit components to their maximum strains. These high voltages and currents damage sensitive loads as well as windings, and insulation, and cause inaccurate operation, [35].

It is therefore an important task to detect and eliminate transients in the power distribution networks. Researchers have used the Fourier transform, Hilbert transform, Wavelet transform, time-frequency resolution, and Stockwell transform to identify the usual transients' difficulties. However, it has been noted in the literature that whenever there is a sudden burst in the signal, these approaches are unable to accurately forecast the transient disturbance characteristics.

3.1 Energy Storage Challenge

Given the rising need for flexibility and mobility demanded by potential users of energy in the distribution grid, such as electric vehicles, the development of efficient storage solutions is necessary. RES like solar and wind present a significant problem when it comes to storage, [36], [37]. One of the major focus areas of research in renewable energy storage is batteries. The European Commission considers batteries as a critical value chain, batteries are the focus of a specific action plan called the European Battery Alliance, [38]. Lithium-ion technology has received widespread acceptance in recent years, due to its miniaturized features, and its high efficiency and robustness, which allow the storage of energy produced by solar PV and wind turbines, [39]. Although it is research in progress, this approach is still not ideal for long-term storage; Sodium Sulphur or redox-flow Batteries are two alternatives that are currently in full development.

3.2 RES Optimal Placement Challenges

Implementing DG is a practical means of taking the advantages provided by the dispersion of small and/or medium-sized power units, [32], [40]. Installation of such power units, typically at the distribution level, has shown to have a beneficial effect on several grid operational issues, including loss reduction, either independently or in conjunction with battery banks; reliability considerations, or even improvements; voltage stability; and other issues, such as improving DG or RES penetration, reducing the challenges associated with the integration of renewable energy in the distribution network, or applied to remote hybrid systems. The ideal positioning and sizing of the units is the main obstacle to effective renewable energy penetration.

To improve the grid, it is anticipated that the Distribution Network Operators will determine how renewable energy will be integrated. The number of units to be installed, the sites of installation, the capacity of each unit, and the overall amount of renewable energy capacity that needs to be integrated are the four variables that need to be optimized to get the best outcomes.

3.3 Islanding Challenges

A scenario known as islanding occurs when RES delivers power to the grid when there is no power from electrical utility, [24]. Islanding happens as a result of uncontrolled renewable energy connections. The detection of islanding is one of the difficulties that GtRE encounters, [10], [41], [42]. Islanding detection is crucial to the functioning of grid-tied renewable energy, and it should always be done in a timely manner regardless of the mode of operation. The enormous synchronous generators utilized in conventional power networks are generally known to have a significant amount of inertia, while the conventional synchronous generators with contemporary generating units coupled to inverters have low inertia because the network is decoupled from any significant kinetic energy. Voltage and frequency deviation from nominal values are expected to be quite large during severe transients in low-inertia networks. This affects the efficacy of islanding detection approaches as well as popular anti-islanding techniques like vector shift and frequency change rate, [24].

Real-time monitoring and forecast systems should specifically be deployed to grid-tied renewable energy so that the moment islanding is detected, necessary action can be taken. According to, [41], [42], [43], there are two types of islanding detection techniques: remote and local. The local technique is further grouped into passive, active, and hybrid techniques. Transfer trip and power line signaling techniques are two methods for detecting remote islands, [41], [43]. Communication between the main grid and the RES is necessary for the detection of islanding. The passive detection approach for local islanding detection involves detecting system parameters such as voltage, frequency, and harmonic distortion, [10]. Grid-tied mode and islanded mode have different set thresholds for these parameters. Other techniques for addressing islanding issues include; the utility grid's reactor insertion technique and the PV side's capacitor insertion technique, [24].

According to, [44], RES such as solar energy will operate as an island on its local connected load if the fault current level perceived by the embedded relay is high enough to trip it. The island network's operation could become unstable as a result of the power imbalance in the isolated system. This is represented in Figure 5.

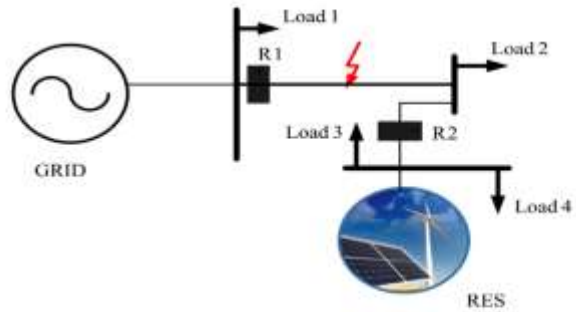

Fig. 5: Islanding problem in grid-tied RE, [44].

3.4 Power Protection Challenges

The design of power system protection faces various difficulties as more renewable energy units, particularly those with power electronics interfaces, are connected to the distribution network. It is well known that the majority of traditional distribution grid protection strategies in the primary radial system rely on unidirectional short-circuit current flow. The integration of renewable energy alters this order by producing a complicated system with several sources and bidirectional fault current flows. Additionally, the presence of renewable energy units can result in issues with reclosers, erroneous tripping, and/or blinding in traditional radial topologies, [1], [45], [46].

Power flows are not unidirectional in grid-tied renewable energy, and depending on where the fault is, fault currents might flow in either direction. In multi-loop systems, directional overcurrent relays are the best way to prevent incessant tripping. However, because of their intermittent nature, RES will have a greater impact on network failure levels when there is a significant penetration. The feeder won't be protected by the overcurrent relays with fixed time dial setting and plug multiplier setting with a significant RES penetration, [10], [44].

According to, [44], the source type, penetration level, and position of the RES integration in the network play a role in how the fault current changes. The fault is provided by both the grid and the RES, as seen in Figure 6. Depending on the RES rating and RES impedance, the fault current perceived by relay R2 for the fault close to relay R2 will grow and it will decrease for relay R1. The relays will operate below the reach due to the change in the fault level that they detect.

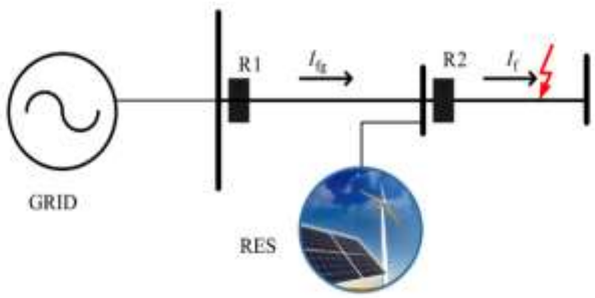

Fig. 6: Integration of RES into the existing grid, [44].

4 Causes Power Quality Challenges in Grid-Tied RE

In order to monitor and tackle power quality problems in the power grid, it is important to identify the causes. The following are the common causes of power quality challenges in GtRE.

4.1 Stochastic Nature of Renewable Energy Generators

Two features of conventional power generation are the ability to control where electricity generation can be carried out and when electricity can be generated. These features are lacking in solar and wind power generation. This factor increases the difficulty of the goal of instantaneously balancing supply and demand. Solar and wind power generation depend on natural resources. The places with the most sun and wind are typically not those with the most demand for electricity. For instance, it is difficult to manage the timing of power generation from solar and wind sources, because only when the sun is shining and the wind is blowing can solar panels and wind turbines provide electricity.

4.2 Reverse Power Flow

From medium voltage to low voltage networks, the distribution system's power flow has conventionally been unidirectional. However, when the overall amount of PV generation exceeds the total load demand, reverse power flow occurs on the feeders, moving from low-voltage to medium-voltage networks. Utilizing voltage control components, such as switching capacitors, automatic voltage regulators, and on-load tap changers may be challenging due to the reverse power flow. Because most distribution system components are not designed to handle the bidirectional power flow brought on by a sizable amount of PV generation, in some cases modifications to existing protection methods as well as additional equipment may be necessary.

4.3 Variation in Standard Load Patterns

The integration of the energy from solar PV panels in the distribution system can affect the typical load curve significantly. This is very prominent during the daytime when irradiance from the sun is at its peak, the resulting effect is noticeable load reduction. A sudden change in load can also occur when the equipment is powered on or off, this also has an impact on power quality.

4.4 Distribution System Stability

Small signal stability is another stability issue that has received a lot of attention recently in distribution systems, [30], [47], [48]. When a distribution system is completely passive, small signal stability might not be a problem. With the integration of renewable generation via power electronic interfaces and their supporting controllers, however, the stability of the system operating point when subjected to minor interruptions became a critical issue. State variable oscillation in close proximity to a growing number of dynamics has been documented. According to [30], small signal stability could cause oscillatory conditions in distribution systems and result in partial blackouts if there is insufficient damping applied to them. The distribution system's small signal stability may suffer significantly as the degree of imbalance rises.

5 Impacts of Power Quality Challenges in Grid-Tied RE

The identified power quality (PQ) challenges in grid-tied renewable energy (GtRE) are capable of resulting in anomaly conditions in the power network. Table 2 presents the prominent power quality issues in GtRE with their respective effects and severity levels.

Table 2. Severity Levels of Power Quality Conditions in Grid-Tied Renewable Energy

PQ Conditions	Effects	Severity
Voltage Fluctuations	Over-voltage, under-voltage	Very Severe
Harmonics	Electrical equipment losses, and overheating	Severe
Frequency Fluctuations	Disruption of the operations of motors and sensitive equipment	Severe
Voltage Sag	Overloading	Less severe
Voltage Swell	Data loss, Damage of equipment, Intermittent Lockup, Grabbled data	Less severe
Transient	Disturbance in electrical equipment	Less severe

6 Mitigation of Harmonic Distortion

The harmonics in GtRE emanate from background harmonics inherent in the RE sources. Other sources of harmonics are nonlinear loads and equipment such as inverters of the RE, [47], [49], [50]. To improve the power quality of GtRE, a harmonic filtering system is required. In an electrical power system, a filter is a circuit designed to scrutinize the frequencies of an electrical signal and pass only the desired signals.

Filters can be divided into noise filters and active and passive harmonic filters, [17], [51]. Noise filters are used to prevent unauthorized frequency, current, or voltage surges from damaging delicate equipment. A low-pass filter has capacitors and inductances and generates a low-impedance path to the fundamental frequency and a high-impedance passage to higher frequencies. The inductance of the coil is determined once the capacitor is selected. The consideration of the resonance frequency is presented in equation 3, [52].

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{3}$$

Hence, to eliminate the harmonic order h, the inductance is presented in equation 4, [52].

$$L = \frac{1}{(2\pi hf)^2 C} \tag{4}$$

6.1 Mitigation of Voltage Fluctuations

One of the extensively utilized methods for reducing voltage fluctuations in a power system is the “on the load” tap changer approach. The approach was used in [24], [53], to regulate voltage by shifting the location of its tap during voltage swings. According to [24], it is challenging for the tap changer devices to control the voltage if the voltage fluctuation happens at the end of the line. In such circumstances, the inverter functions as a capacitor or an inductor. In, [54], the authors proposed dynamic control systems to monitor certain reference values of voltage with the aid of iterative cycles to reduce voltage fluctuations.

By adding active and reactive power to the grid, voltage fluctuations can be reduced. In, [55], [56], the authors suggested a control structure that enables RES to extract the most power possible for network injection, supply the load to satisfy network requirements, and control the battery to balance the system's power flow and maximize the microgrid's performance. The suggested control technique uses linearization with feedback to provide transient stability within the microgrid's operational area. The system's operations can properly feed the system loads while improving the power quality metrics, particularly those related to the voltage profile, reactive regulation, and power factor correction, while also maximizing battery life and carrying out other tasks.

6.2 Mitigation of Frequency Fluctuations

Keeping the power supply frequency within set limits is crucial to maintaining the intended operating conditions and supplying energy to all connected users. This prevents unforeseen disturbances that could damage the connected loads or even bring the system to a halt. Adaptive deep dynamic programming was used in, [29], to eliminate the frequency variation in grid-tied renewable energy. This takes the place of generating command dispatch and load frequency control. In [29], the authors proposed dynamic control systems to maintain the frequency of a GtRE within a certain threshold.

7 Conclusion

The study examined the technical difficulties of grid-tied renewable energy, including problems with power quality. Solutions to the identified power quality challenges were analyzed. The cost-effectiveness of the techniques and features of the existing grids are important factors to put into cognizance in the selection of an approach to resolve the fluctuations and uncertainty of renewable energy generation. Seamless renewable energy integration in a power distribution network is possible if adequate measures are put in place to monitor power quality. The outcomes of this study are useful to power operators, especially in the determination of causes and solutions to power quality anomalies identified. An Edge-based neural network technique is currently being developed by the authors of this study to monitor power quality in GtRE. The technique is aimed at developing a robust solution to address the issues of system complexity, high bandwidth, and high latency involved in power quality data management.

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