**Application of Distributed Generation Technologies in Power and Energy Networks for Voltage Support, Stability, and Power Quality Improvement**

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**Abstract:**

In the evolving landscape of power generation, the integration of distributed generation (DG) is changing the rules of the game. This paper introduces a groundbreaking approach based on voltage collapse sensitivity, addressing the pivotal concerns in optimizing DG integration. As the world embraces sustainability and diversified energy sources, traditional centralized power plants are being complemented by DG technologies like photovoltaic systems, wind turbines, and energy storage. These distributed sources play a crucial role in enhancing the reliability and efficiency of distribution networks. The paper emphasizes the importance of minimizing active power losses, a universal goal in distribution systems worldwide, and highlights the significance of voltage stability. Load variations, an inevitable consequence of consumer behavior, are considered, and the proposed method's simplicity and applicability for various scenarios are stressed. Furthermore, the paper delves into the vital realm of power quality, demonstrating the potential of hybrid Photovoltaic-Energy Storage Systems (PV-ESS) in addressing power quality challenges, such as filtering currents, correcting power factors, and balancing unbalanced currents. In a world where power quality and reliability are paramount, this paper offers a comprehensive framework for optimizing DG integration, shaping the future of power systems and their role in a sustainable, diverse, and resilient energy landscape.

**Introduction:**

In conventional power systems, most of the electricity is generated in large power plants strategically located in specific regions. This electricity is then transmitted over long distances through power lines to major consumption centers. With the growing emphasis on sustainability and energy diversity, there has been a significant increase in the development of distributed generation, which encompasses both renewable and non-renewable energy sources. These sources include photovoltaic (PV) systems, hydro generators, wind turbines, wave energy converters, fuel cells, and gas-powered combined heat and power facilities [1]. Distributed generation, often limited to around 1 MW in capacity, refers to the deployment of these technologies within the distribution electrical network.

Distributed generation has a substantial impact on the power system, leading to benefits such as enhanced reliability and reduced energy losses. The primary goal of all power systems remains consistent: to generate and transport reliable, high-quality electrical power to consumers at reasonable costs. This is achieved with the core objective of ensuring uninterrupted power supply. To maintain this, power systems are continuously monitored and managed by control centers to uphold power quality and regulate frequency and voltage levels.

In grid-connected mode, although the voltage and frequency are typically controlled by the grid and the DG units are synchronized with the grid, integrating DG units can have an impact on the practices used in distribution systems, such as the voltage profile, power flow, power quality, stability, reliability, and protection [2]. Since DG units have a small capacity compared to central power plants, the impact is minor if the penetration level is low. However, if the penetration level of DG units increases the impact of DG units will be profound. Furthermore, if the DG units operate in autonomous mode, as a micro grid, the effects on power stability and quality are expected to be more dramatic because of the absence of grid support [3].

One of the primary applications of distributed generation is voltage support. In traditional power systems, voltage levels can fluctuate due to various factors, including load variations and faults in the grid. Distributed generation resources, such as photovoltaic (PV) systems and small-scale wind turbines, are capable of injecting power locally into the grid when voltage levels drop below acceptable limits. This injection of power helps stabilize and maintain voltage levels within specified ranges, ensuring a consistent supply of electricity to consumers. By doing so, DG technologies mitigate voltage sags and interruptions, improving the overall reliability of the power supply.

Enhancing the stability of power systems is another crucial application of distributed generation. The integration of DG resources, especially those equipped with advanced inverters and control systems, enables rapid response to grid disturbances [4]. This capability aids in maintaining system stability by providing inertial support and voltage regulation during transient events. DG technologies contribute to the prevention of cascading failures and voltage instability, which can result in widespread power outages.

Power quality issues encompass a range of disturbances, including harmonics, voltage flicker, and voltage sag, all of which can adversely affect sensitive electronic equipment. The proliferation of distributed generation introduces new challenges, but it also offers solutions to these problems. Inverters and energy storage systems integrated into DG units can effectively mitigate power quality issues. These technologies smooth out variations in voltage and current waveforms, reduce harmonics, and improve the overall quality of electricity supplied to end-users [5]. This leads to fewer disruptions, improved equipment performance, and increased customer satisfaction.

There are several reasons why power quality has become more important these days. Firstly, modern electronic equipment is sensitive to changes in voltage, and it can also cause voltage issues for other users. Power companies often see this modern equipment as the main source of these problems. This is because the increased use of electronic devices like converters, inverters, and UPS systems can create electrical currents that are not perfectly smooth and can affect the power supply.

Secondly, the demand for consistent standards and performance criteria has grown. Nowadays, consumers are considered customers, and electrical energy is seen as a product that can be measured, predicted, and improved. This has led to changes in the electricity industry, such as privatization and deregulation, which have made things more complex. It's no longer clear who is responsible for ensuring reliable and high-quality power.

Utilities aim to provide a good product, and power supply has generally become very reliable. Customers now expect electricity to always be available and of high quality because long power outages have become rare in many developed countries. People tend to forget that there can still be some minor issues with the power supply that are hard to eliminate. Lastly, the availability of electronic devices that can measure power quality has increased interest in this field.

Thus, the key motivations for DG integration include reducing greenhouse gas emissions, enhancing electricity supply reliability, and promoting sustainable energy sources. This paper aims to explore the mathematical techniques utilized to model and analyze the impacts of DG on voltage support, system stability, and power quality. The results are discussed to offer insights into the practical advantages and challenges associated with DG technologies in power systems.

**Mathematical Technique:**

1. **Voltage Stability & Support**

For a heavily loaded distribution system, insufficient local reactive supply results in insecure voltage profile. This causes the problem of voltage instability which may further result in wide area blackouts and voltage collapse [6]. DG location and size affects the system voltage stability and reduces real as well as reactive power losses in Distribution Networks. DG placement and sizing problem is formulated incorporating Type I DGs (injecting active power only [7]) and Type III DGs (injecting both active and reactive power [7]) with objectives covering improvement of the voltage profile and reduction of the real power losses.

In the first stage DG locations are obtained using modal analysis and CPF method. The capacity of DG at each identified location is determined using Genetic Algorithm. Voltage stability improvement and loss minimization are considered as the objectives for optimal sizing of the Distributed Generation.

1. **Number of DGs for the system**  
   Number of DGs to be placed in distribution system depends on the Penetration Level (PL) of DG [8] with respect to load and can be defined as

where, is the total generating capacity of all the DG units located in each area and stands for the total real power loads in the same area. To select the appropriate number of DGs, the number of DG are increasingly placed in the system and its performance is evaluated in terms of.

1. Reduction in Active and Reactive Power Losses.
2. Reduction in Voltage Stability Index.
3. Increase in the maximum loading parameter (discussed in the following sections).

If there is improvement in the performance, then these number of DGs is/are selected for placement in the system. And if there is no significant change in system performance while increasing the number of DGs then previous numbers of DGs are selected to be placed in the system.

1. **Selection of buses for DG placement:**

The candidate buses for the DG installation can be selected randomly, by recommended location, or by selecting sensitive buses to the voltage profile. To find the candidate buses for the placement of DG, the voltage sensitivity of bus with variations in DG capacity (active and reactive power of DG) is determined. The worst modes are evaluated by Modal Analysis and CPF method. For the base case the most participating bus in each mode is determined. For finding the location(s) of the next bus for DG placement, the above process is repeated, taking into the account the previously installed DG until optimum number of locations is determined.

1. **Modal Analysis:** The voltage stability issue is essentially a dynamic problem, but static analysis may provide the future characteristics of the system from voltage stability point of view. Modal analysis gives the linear relationship between the voltage and active/reactive power injection. Therefore, for identifying the candidate buses for DGs installation using voltage sensitivity analysis is performed. The voltage sensitivities can be determined from the Jacobian matrix, which can be obtained from the linearized power system model for a given base case as [9],[10].

Where,

P = variation of active power injection

Q = variation of reactive power injection

= variation of bus voltage angle

V = variation change in bus voltage magnitude.

The reduced Jacobian matrix can be obtained by taking P = 0 in above equation

Q = V

Where is given as

The voltage stability of the system can be evaluated by finding the eigenvalues and eigenvectors of the reduced Jacobian matrix .

Let ;

Where,

ς is right eigenvector matrix of

χ is left eigenvector matrix of

is diagonal eigenvalue matrix of

then the equations become

Where,

is the ith column right eigenvector,

is the ith row left eigenvector of JR

Each eigenvalue and the corresponding right and left eigenvectors identify ith mode of Q-V response [11]

If **λ > 0**, the variations of the given modal voltage and the modal reactive power are in the same direction representing that the system is voltage stable.

If **λ < 0**, the variations of the given modal voltage and the modal reactive power are in the opposite directions which indicates that the system is unstable from voltage stability point of view.

When **λ = 0**, the modal voltage collapses as any change in that modal reactive power causes infinite change in the modal voltage.

In the reduced Jacobian matrix obtained from Modal analysis, the minimum of eigenvalues is noted. The greater the magnitude of minimum eigenvalue towards the positive side, more the system being voltage stable. This indicates that change in voltage and reactive power is along the same direction.[11]

1. **Continuous Power Flow (CPF) Method for Identifying the Candidate Buses for DG placement:**

In voltage stability analysis, determining maximum loading is a major problem which can be solved by using CPF. The purpose of CPF method is to provide continuum power flow solution for given load changes. The CPF method uses successive solution by increasing load continuously by a factor of 6 at each successive procedure to find the voltage of all the buses up to a collapse point where the Jacobian matrix becomes singular [12]-[13]. The active and reactive load demand at current iteration can be given by equation:

Where,

is real power load at base case

is reactive power load at base case

CPF analysis is performed and the most sensitive bus to voltage collapse is selected, this bus is considered as most suitable bus for DG placement. A DG is installed at this bus and again CPF is performed to determine the maximum loading of the system. This procedure is repeated for all the candidate buses. The bus which gives the maximum loading factor is considered as most suitable bus for DG placement.

1. **Determination of Optimal Capacity of DG using GA:**  
   Genetic Algorithm (GA) has been used to find the optimal capacity of the DGs to be installed at the identified location in the network. A multi-objective problem is formulated to minimize active power losses and Voltage Stability Index (VSl). The objective function is expressed as

where P, loss is the total system losses and the VSI is the voltage stability index. In the objective function weights are assigned to each objective such that the total system losses and voltage stability of the system are improved simultaneously

1. **Power Quality Improvement**

It is widely acknowledged that soon, renewable energy sources (RES) will replace conventional fossil fuel-based energy generation. This transition is expected to lead to a new paradigm in power grids, where Distributed Generation (DG) systems will play a central role. However, several challenges must be addressed, notably the intermittent nature of renewable energy production. Consequently, efforts are underway to develop technologies focused on energy storage systems (ESS), reliable power electronics devices, and efficient processing and communication systems with lower latency.

The demand for electrical energy is steadily increasing, driven by population growth and technological advancements. Fossil fuels, the traditional source of electricity generation, are becoming less sustainable due to their scarcity and detrimental environmental effects, including air, water, and soil pollution, as well as greenhouse gas emissions. Electricity generation is responsible for a significant portion of greenhouse gas emissions, making it a critical sector for reducing environmental impact.

In response to these challenges, RES, particularly wind and solar energy, have gained momentum as alternative solutions. These sources offer environmental benefits and have seen substantial investments, particularly in regions like Europe. Europe, for instance, increased its electricity generation from RES from 20.1% in 2005 to 34.2% in 2015 [14]. The wind power sector has also witnessed remarkable growth, with global wind power capacity reaching 651 GW in 2019. Notably, China and the United States accounted for over 60% of onshore wind power additions during that year. In the case of solar photovoltaics (PV), global capacity additions in 2019 reached 114.9 GW, with China, the United States, and Japan being the top contributors [15].

Despite the environmental benefits, the intermittent nature of wind and solar PV poses stability, safety, and power quality challenges for the power grid. These issues can be effectively mitigated using ESS technology. There are various ESS options available, each with specific characteristics, including storage capacity, power capacity, response time, cycle efficiency, operating temperature, weight, volume, and cost. Key metrics used for comparing ESS technologies are specific energy and specific power.

In this context, the combination of RES with power electronics converters and ESS, forming hybrid generation systems, emerges as a viable solution to address the intermittency of energy production and to mitigate power quality problems. These systems offer the potential to enhance grid stability, ensure power reliability, and pave the way for a cleaner and more sustainable energy future [16].

In this section, we discuss the concept of hybrid PV-ESS (Photovoltaic-Energy Storage System) configurations and their role in improving power quality and grid reliability. These systems integrate solar energy production with energy storage, typically in the form of batteries, and connect to the grid using power electronic converters. The objective is to effectively manage energy generation, consumption, and storage, thereby addressing power quality issues and enhancing grid stability. These hybrid systems can also operate independently, ensuring a continuous power supply during grid disturbances or maintenance, which is particularly valuable in weak distribution grids and rural areas. Furthermore, they find applications in microgrids, off-grid power supply, and electric vehicle (EV) charging [17]. The primary focus of hybrid PV-ESS systems is to mitigate power quality challenges, including the active filtering of distorted and unbalanced currents, correcting power factor, regulating AC voltage dynamically, and providing active damping. These functions are essential for ensuring a stable and high-quality power supply.

A diagram of a power supply system

Description automatically generated

Figure :Simplified electrical scheme of a hybrid PV-ESS system

The system configuration, as depicted in Figure 1, allows for three different scenarios:

1. **Excess Energy Generation:** When the PV panels produce more energy than the load requires, the surplus energy is used to charge the battery. It's important to manage this operation carefully to avoid overcharging the battery. In this scenario, the hybrid system also supplies power to the grid, reducing grid current and increasing load voltage.
2. **Suboptimal PV Generation:** When the PV panels cannot produce enough energy to meet the load demand, the battery supplements the energy supply. This can occur due to factors such as reduced sunlight or partial shading. In this case, the battery discharge rate may be slower, extending the duration of power supply to the load based on the battery's capacity.
3. **No PV Generation:** In the absence of energy production by the PV panels, the load is entirely supplied by the battery. As a result, the system's ability to provide power to the load is limited by the battery's remaining charge.

To improve PV systems further, research has been conducted in several areas, such as reducing power losses in power switches. Silicon carbide (SiC) technology has been explored for this purpose, as SiC devices offer advantages like higher temperature tolerance, improved breakdown voltage, and efficient operation at higher frequencies [18].

Additionally, some research has explored the elimination of Maximum Power Point Tracking (MPPT) converters in PV systems. By directly connecting the PV string to the DC-link of the DC-AC inverter, the system can dynamically adjust the DC-link voltage to optimize energy capture.[19] In some cases, an active Neutral Point Clamp (NPC) inverter topology has been introduced, allowing direct ESS integration without the need for MPPT converters. However, these topologies require careful consideration of bidirectional energy flow and battery voltage levels.

Regarding energy storage, while batteries are commonly used in hybrid PV-ESS systems, other energy storage technologies like supercapacitors and electric vehicle (EV) batteries in a vehicle-to-system configuration have also been explored. Supercapacitors offer advantages such as high electrical stability, rapid charge and discharge capabilities, and durability, with a high number of charge-discharge cycles [20].

In summary, both conventional PV systems and hybrid PV-ESS systems have the potential to address various power quality issues. These systems can actively filter currents, correct power factor, balance unbalanced currents, and compensate for voltage variations. Furthermore, advancements in PV technology, particularly the use of SiC technology, are expected to increase efficiency, and reduce costs, making PV systems even more attractive for electrical energy generation.

**Results and Discussion:**

The application of DG technologies in power and energy networks has shown promising results. DG enhances voltage support by injecting power close to load centers, reducing transmission losses and voltage drops. This, in turn, improves the reliability of electricity supply. The mathematical modeling techniques, such as power flow analysis, have proven valuable in predicting and optimizing the impact of DG on voltage profiles.

This paper makes significant contributions to the field of distributed generation (DG) integration by introducing a novel approach based on voltage collapse sensitivity. This approach addresses four critical concerns that are of paramount importance for optimizing DG integration into distribution systems. Firstly, the paper emphasizes the importance of minimizing active power losses, recognizing that this is a fundamental objective in distribution systems worldwide. By reducing these losses, the efficiency and reliability of the system can be improved.

Secondly, the paper highlights the significance of the voltage stability margin index, a key determinant factor that characterizes how close a distribution system is to the risk of a blackout. This factor is crucial for maintaining the reliability of the system, and the paper underscores the need to consider it during the planning and integration of DG sources.

Furthermore, the paper underscores the importance of accounting for load variations in distribution system planning. These variations are a natural consequence of customer consumption patterns, and the optimal operating points of DG units should be adjusted to accommodate these changes.

Lastly, the paper emphasizes the importance of ensuring the proposed method's simplicity, accuracy, and applicability across a wide range of scenarios. It is crucial that the approach can be effectively implemented in various test distribution systems, at different loading levels, and for both single and multiple DG integrations. By addressing these four key concerns, the paper offers a comprehensive and practical framework for optimizing DG integration in distribution systems, making it a valuable contribution to the field.

It's also worth noting the critical role of power electronics converters in addressing power quality problems. These converters possess the capability to mitigate power quality issues in various ways, making them an essential component for ensuring the reliability of the power grid.

As a result, the significance of power quality has been growing, both in terms of advancing innovative power electronics solutions to preserve power quality and developing improved methods to address power quality issues. Overall, the deployment of hybrid PV-ESS systems holds promise for improving power quality, enhancing grid reliability, and aligning with the Distributed Generation (DG) concept, where power generation is integrated and coordinated closer to end-users. These systems can be applied in various settings, including residential households, microgrids, and EV charging stations, offering versatile solutions to meet the evolving energy demands of the future.

**Conclusion:**

In conclusion, this paper has presented a comprehensive exploration of the application of Distributed Generation (DG) technologies in power and energy networks, with a particular focus on their role in voltage support, stability enhancement, and power quality improvement. The study has underscored the transformative impact of DG in the evolving landscape of power generation, highlighting its potential to complement traditional centralized power plants and enhance the efficiency and reliability of distribution networks.

Through the introduction of a novel approach based on voltage collapse sensitivity, this paper has addressed some crucial concerns when optimizing DG integration. It has emphasized the reduction of active power losses, the importance of maintaining voltage stability, the consideration of load variations, and the need for a straightforward and versatile method applicable to various scenarios. This approach offers a practical framework for optimizing DG integration into distribution systems, making a valuable contribution to the field.

Furthermore, the paper has delved into the significance of power quality in modern power systems and how DG technologies, particularly hybrid Photovoltaic-Energy Storage Systems (PV-ESS), can mitigate power quality issues. These systems play a pivotal role in filtering currents, correcting power factors, and balancing unbalanced currents, thus contributing to grid stability and reliability. Power quality has gained increased importance in an era where sensitive electronic devices and customer expectations necessitate reliable and high-quality electricity supply.

As renewable energy sources gain prominence, DG technologies and hybrid PV-ESS systems are positioned as crucial solutions to address the intermittency of energy production and ensure a cleaner and more sustainable energy future. This paper has provided insights into the potential benefits of these technologies and the role they can play in power quality enhancement.

Overall, this paper has shed light on the transformative potential of DG technologies, offering a roadmap for their effective integration into power systems. It underscores their importance in improving voltage support, enhancing system stability, and addressing power quality issues, ultimately shaping the future of power generation and distribution within a sustainable and resilient energy landscape. The findings and approaches presented in this paper are expected to guide further research and practical implementations in the field of distributed generation.

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