

Network Comparative Analysis Of Distributed Generation In A Developing Power System Using D-Statcom And UPFC

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Abstract

The increasing penetration of Distributed Generation (DG) in medium-voltage (MV) distribution networks presents significant technical challenges, including voltage rise, increased power losses, and reduced network stability. This study presents a network comparative analysis of distributed generation in a developing power system using D-STATCOM and UPFC. A 33-bus, 11-kV radial distribution network of the Port Harcourt Electricity Distribution Company (PHED) was modelled and simulated in MATLAB/Simulink. The Distribution Static Synchronous Compensator (DSTATCOM) and Unified Power Flow Controller (UPFC) were modelled as alternative FACTS compensation strategies, and their performances were comparatively evaluated. Comparative analysis showed that DSTATCOM - DG configuration exhibited slightly better efficiency in power loss reduction, whereas UPFC-DG combination provided improved voltage control and system robustness, increasing the bus voltage to 0.9547 p.u as compared to 1.014 p.u for DSTATCOM-DG. The results further demonstrated that excessive compensation could result in overvoltage, emphasizing the importance of optimal device sizing and placement. Overall, the coordinated deployment of DG and FACTS devices significantly improved voltage stability, reduced network losses, and enhanced the technical and economic performance of the MV distribution network.

1. INTRODUCTION

1.1. Background

In many developing nations, power systems are facing challenges because of the growing demand for power, aging infrastructure and lack of expansion possibilities for the centralized power generation system. Some of these problems often manifest themselves as poor voltage profile, high technical and non-technical losses, frequent power outages, low system reliability, and poor power quality (Ackermann, Andersson, & Söder, 2001; Kundur et al., 2004; Emmanuel, 2024). Rapid urbanization, industrialization and population growth have overwhelmed the traditional electric grids, which are no longer enough, for present and future energy demands. Many emerging economies also face constraints to large-scale expansion of transmission and generation capacity, such as budgetary constraints, long projects timelines, and regulatory constraints (World Bank, 2020).

Distributed generation (DG) offer a handy and an appealing approach to some of the issues encountered in developing power systems such as that of Nigeria. By introducing small to medium sized power generation, located in the proximity of the load centers using gas fired generators, wind turbines, photovoltaic (PV) plants or biomass plants, one is introducing distributed generation (DG) (Pepermans, et al., 2005). Distributed generation (DG) for a developing power systems have a number of benefits, such as lower transmission and distribution system losses, better voltage support, greater energy supply stability and easier access to energy in under-served and rural communities. Further, the use of DG helps incorporate renewable energy resources, lessen the Green House Gases (GHGs) emission and dependence on fossil fuels (Emmanuel et al., 2025).

Although all these advantages can be offered, high penetration levels of DG can cause technical problems such as voltage rise, reverse power flow, increased fault current levels, protection coordination problems, and system instability, especially in weak and poorly-regulated networks (Bollen & Hassan, 2011). Disparities of these technical issues may increase the losses, stress on equipment and maintenance costs in the system and offset some of the economic benefits expected from distributed generation.

The use of advanced power electronic based control devices has been developed, to overcome these problems. Flexible AC Transmission System (FACTS) devices are highly useful because they provide a dynamic control on power flow and on reactive power which increases the controllability, stability and improves the power quality of power systems (Hingorani & Gyugyi, 2000). Of these devices the Unified Power Flow Controller (UPFC) exhibits outstanding performance on controlling

power flow and the Distribution Static Synchronous Compensator (DSTATCOM) exhibits outstanding performance on reactive power compensation. DSTATCOM has the ability of dynamic injection or absorption of Reactive power hence it is very useful in rapid and efficient voltage control especially when enhanced by DG integration causing voltage swings (Schauder & Mehta, 1993). The UPFC is a combination of series and shunt compensation, and gives the full control of voltage magnitude, line impedance, active and reactive power flow of the network, resulting in an overall improvement of the flexibility and stability of the network (Gyugyi et al., 1995).

1.2 Statement of the Problem

In recent years, Flexible AC Transmission Systems (FACTS) devices such as Distribution Static Synchronous Compensators (DSTATCOM) and Unified Power Flow Controller (UPFC) have been proposed as advanced solutions for mitigating voltage rise problems. These devices are capable of supplying reactive power support quickly and dynamically to provide stable operation of distributed systems (Hingorani & Gyugyi, 2000 and Singh, 2018) high DG penetration. But, finding the optimum deployment of FACTS devices in MV distribution network with regard to location, capacity, topology and cost of the network still remains a challenge (Rashid, 2015).

The problem addressed therefore in this study is the continuing increase in the values of voltage, resulting from the high penetration of DG, in medium voltage distribution networks and the fact that the conventional technique for voltage control is not able to control such problems. In this study, the effectiveness of FACTS devices as compensation apparatus to stabilize the voltage, increase the degree of DG hosting and increase the reliability of the system overall will be evaluated.

2. LITERATURE REVIEW

2.1 Conceptual Review

2.1.1 Distributed Generation

Distributed Generation is the term used for the small to medium size electricity generation source(s) that are directly connected to the distribution network or to the customer's side of the metering device (Ackermann, Andersson, & Söder, 2001). The generators come in renewable (solar PV and wind generation) or non-renewable (microturbines, diesel generators). DG systems have been gaining in popularity, because of their advantages such as serving the local demand, minimization of transmission losses, and improvement of reliability of power supply (Bayod-Rújula, 2009). Unfortunately, the non controlled or imbalanced penetration of DGs in distribution networks can lead to a number of technical issues like voltage fluctuations, reverse power flow, power losses and protection coordination (Pepermans et al., 2005). Hence, the installation, sizing and management of DG is important to achieve desired network performance.

In this work FACTS devices, which are power electronic-based systems used to improve the flow and power transfer capability of AC systems (Hingorani and Gyugyi, 2000) has been incorporated. At the distribution level these are called Distribution FACTS (D-FACTS) devices and these are used in the following ways to combat voltage instability, reactive power imbalance and harmonics. Some of the commonly used D-FACTS devices are Static Var Generation (SVC), Distribution Static Synchronous Compensator (DSTATCOM), Dynamic Voltage Restorer (DVR) and Unified Power Flow Controller (UPFC). These devices offer better voltage profile, reduce line losses and improve the quality of power, by intelligent way of controlling the reactive power flow (Singh, Al-Haddad, & Chandra, 1999).

2.1.2 Flexible AC Transmission Systems (FACTS) Devices

Flexible AC Transmission Systems (FACTS) are the most sophisticated technologies based on power electronics technology which improve the control, stability and power transfer capacity of power transmission and distribution system. They do this by controlling, dynamically, other important electrical parameters like voltage magnitude, phase angle and line impedance (Hingorani & Gyugyi, 2000). Inclusion of these FACTS devices allows for addressing the operational constraints of the conventional power systems that they are deployed to and make them more flexible and responsive to fluctuations in load and generation.

With the growing penetration of renewable energy and distributed generation (DG) sources in modern power system, which are often intermittent and may supply power to the grid and/or may demand power from the grid, there is an urgent need to improve the stability of the power system and manage the power quality. By incorporating FACTS devices, these challenges can be addressed as it can provide fast reactive power compensation, voltage regulation and loss reduction for both the transmission and distribution networks (Kumar & Ghosh, 2009; Song & Johns, 1999).

FACTS devices can drastically manage active and reactive power flows and therefore enhance transient stability, voltage control, power oscillation damping with fast response. It should be noted that unlike traditional mechanical devices like tap changers and capacitors banks, the FACTS devices provide continuous and dynamic control which is an important requirement for modern power grid with fluctuating renewable power generation and dynamic load behaviour (Schauder & Mehta, 1993).

2.1.3 Classification of FACTS Devices

FACTS devices can be categorized into four groups (as shown in figure 1): Series FACTS devices, Shunt FACTS devices, Series-Series FACTS devices, and Series-Shunt FACTS devices. The series FACTS devices consist of the Thyristor Controlled Series Capacitor (TCSC), the Thyristor Controlled Series Reactor (TCSR), the Thyristor Switched Series Capacitor (TSSC), and the Static Synchronous Series Compensator (SSSC). The shunt FACTS devices include the Static VAR Compensator (SVC), Thyristor Controller Reactor (TCR), Thyristor Switched Capacitor (TSC), Thyristor Switched Reactor (TSR), and Static Synchronous Compensator (STATCOM). The Interline Power Flow Controller (IPFC) belongs to the Series-Series FACTS devices category. The Unified Power Flow Controller (UPFC) is classified as a series shunt FACTS device. The UPFC is called a Generalized Unified Power Flow Controller (GUPFC) if it has more than one series branch (Subramanian et al., 2018; and Sharma et al., 2024).

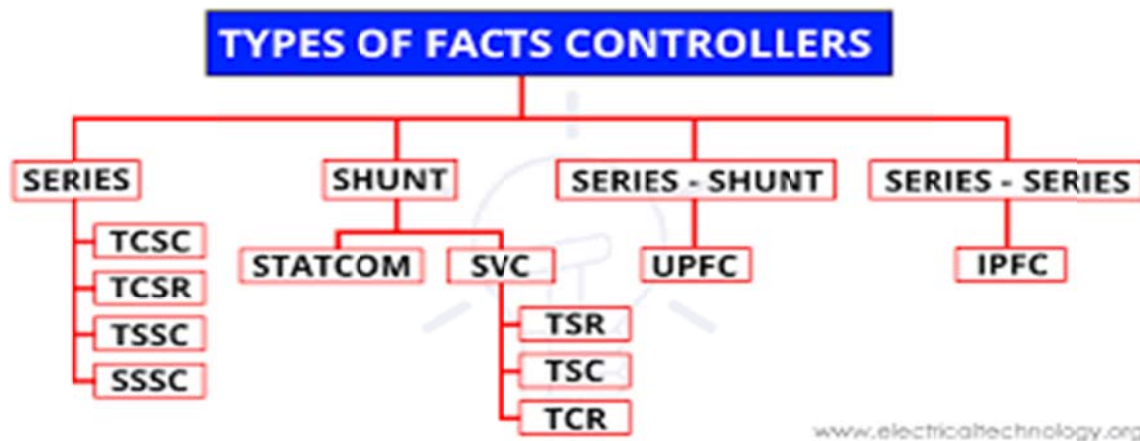


Figure 1: Classification of FACTS Devices (Source : Electrical Technology, 2024)

2.1.4 Role of FACTS Devices in Power Compensation and Control

By dynamically compensating and controlling power flow, Flexible AC Transmission Systems (FACTS) devices are essential in enhancing the performance, reliability and flexibility of modern power systems. They allow for quick change of important system parameters like voltage magnitude, phase angle and line impedance to improve stability, quality and efficiency of the system (Hingorani & Gyugyi, 2000).

Stability and voltage control are more challenging in power networks in a rapidly changing environment that is incorporating an increasing amount of distributed generation (DG), renewable energy sources and bidirectional power flows. FACTS can effectively address these problems and offer rapid reactive power compensation, real-time voltage control, and power flow control in both medium-voltage distribution network and transmission lines (Kundur 1994, Padiyar 2007).

In AC systems, the process of controlling active (P) and reactive (Q) power flow for optimum voltage levels, minimum losses, and maximum power transfer capability is termed power compensation. In particular, reactive power influences the level of voltage, the line load and system losses. If not properly compensated, reactive power causes voltage drops, higher currents and low transmission efficiencies (Bollen & Hassan, 2011). FACTS devices act as dynamic compensating devices which inject or absorb the reactive power on real-time basis. This function will help keep voltage/generation level within statutory limits, improve power factor and reduce transmission losses to achieve a more stable and efficient network (Kumar & Ghosh, 2009).

2.2 Review of Related Works

In the early and foundational studies, the effectiveness of different FACTS, including shunt connected FACTS (particularly STATCOM/D-STATCOM) and SVC at fast reactive power support and local voltage regulation has been pointed out, and hence they were used to address the issue of overvoltage at the point of common coupling (PCC) caused by DGs. In Alajrash, et al., (2024), a comparative study of static and dynamic performance analysis of STATCOM type devices was done and the result indicates the superiority of using STATCOM devices over conventional capacitor banks, showing superior dynamic performance (faster response and better voltage regulation under rapidly changing generation).

Feeder level FACTS devices like D-STATCOM have been always proposed in the literature for local generation support for high Photovoltaic or wind energy penetration in low and medium voltage networks due to their ability to absorb and injecting reactive power, or compensate voltage locally in real-time. Relic et al. (2020), performed a comparison between D-STATCOMs and Distribution Voltage Regulators (DVRs) in simulation studies to determine how both can be used to ensure voltages are within statutory limits, enabling higher levels of DGs to be hosted and reducing forced curtailment. Their effectiveness, however, is highly dependent on the size of devices, the location of connection and the control strategy.

Much of the research on DG and D-FACTS devices has been on how to optimally position and size these devices to achieve the greatest benefit in terms of reduction of losses, voltage profile and cost of operations. Studies present different methodologies such as the deterministic optimization based on mixed integer programming, the metaheuristic algorithms based on particles swarm, bacterial foraging, GA, etc., and the hybrid approach based on power-flow and global optimizers. All the recent comparative studies and surveys provide a great deal of evidence as to why metaheuristics are still popular, given the nonconvex and combinatorial nature of the placement problem, despite the need for rigorous benchmarking and formulations based on multiple objectives (lost time, cost, reliability, power quality) (Santamaria-Henao et al., 2023.).

Prystupczuk et al. (2022) studied the topology and control-method and point out new concepts other than classical reactive compensation techniques; these consisted of inverter-based active power curtailment, dynamic operating techniques and local storage, which can often be compared to the FACTS based solution. The overwhelming opinion in the review is that FACTS are still a valuable and versatile option particularly when retrofitting with an inverter is not possible. When combined with the control by the inverter and network-level dispatch, effectiveness is increased and reduction of the required FACTS capacity can be achieved

Unified Power Flow Controller (UPFC) can be considered as an advanced FACTS device that combines the features of a Static Synchronous Compensator (STATCOM) and a Static Synchronous Series Compensator (SSSC). Moreover, required placement of the Unified Power Flow Controller (UPFC) in the desired network is one of the issues that has been subject to much consideration by scholars. As the UPFC is placed in the network, its performance varies from one to another depending on the location of the UPFC in the grid. Many efforts have been done to achieve an agreement in this regard, such as (Zhang, Tomsovic and Dimitrovski, 2018; Ghahremani and Kamwa, 2013).

When observing the optimum location of UPFC in larger networks, some areas were always unsuitable for UPFC operation which is seen in (Dutta et al., 2016) while other areas were always favourable as can be seen in (Singh, 2018). To decrease subjectivity, the whole search space (the network) was used to find the optimal distribution of the UPFC. In (Albatsh et al., 2017), this procedure was conducted with fuzzy logic controllers, in (Miotto et al., 2018), while developing power system stabilizers, in (Kamel et al., 2018) in connection with the reliability analysis, and in (Galvani et al., 2019), at the time of optimizing the power loss.

Adhvaryyu et al. (2017), clarifies how the SCOPF simulation helped to determine the location of the UPFC in a typical network for a higher demand condition. The UPFC use will have a larger cost benefit compared to the previous method, and may be beneficial to alleviate the N-1 congestion problem of the North to South transmission channels, according to Li et al. (2019).

Ebeed et al. (2019), proposed the idea of using a Newton-Raphson load flow in conjunction with UPFC. The developed model of UPFC is implemented based on power injection strategy under four control modes, in which the usable power and MVAR power of a certain node can be injected into a line concurrently or selectively for controlling the voltage amplitude of a certain node.

In Chakravorty and Saraswat (2019), the optimum placement of Distribution Power Flow Controller (DPFC) in a power system and optimum location of two DPFCs in a power system have been suggested, respectively. Using the artificial algae technique, DPFC is positioned in the best location of the electrical system.

Asihene, Effah and Normanyo (2020) presented and experimented a model 161 kV UPFC on 11-bus network. FVSI is utilized to identify the weakest bus while MLA is utilized for identifying the most important line.

Vijay, Kumar and Srikanth (2015) did the study on Dynamic Stability and proposed a hybrid approach to select optimum location and optimum size of UPFC. Singh, Singh and Srivastava (2007) used traditional technique to decide the best location of the TCSC and UPFC to maximize the system security at optimum FACTS parameter values and for different operating conditions. .

Kamel et al. (2018), presented a comprehensive, reliable and flexible model of ESS and UPFC. Zohrabad (2018) provides an optimization problem for a power grid with the Tabu search algorithm based on an improved HS approach to reduce the overall loss of the grid. Khan et al. (2019), discussed the enhancement of a transmission line's ability to handle power and voltage using FACTS devices. Amirtham and Uma, (2016) have also investigated the best location of UPFC.

Rajderkar and Chandrakar (2013) have identified the optimum placement of UPFC device by using sensitivity and GA approach. Test results indicate that either sensitivity factor or GA can be used to successfully deploy UPFCs to meet the desired goals. If congestion reasons arise in the network, option can be to position the UPFC. Once determining the ideal location of the UPFC, a detailed model of UPFC should be considered to remove congestion, and improve the security of the system, when using PWS.

Osama abed el-Raouf et al. (2023) used a Unified Power Flow Controller (UPFC) to enhance the performance and reliability of renewable energy systems connected to the power grid. This system comprises of two renewable energy sources: PV cells and WTs. The UPFC was selected, due to its unique advantage to manage both the reactive power and active power. An optimized

Fractional Order Proportional–Integral–Derivative (FOPID) controller controls the UPFC. This controller's parameters were adjusted with the aid of an Atomic Search Optimization (ASO) technique. Simulations results validate the effectiveness of the proposed controller to maintain the reliability and performance of the hybrid power system under different disturbance conditions (e.g., voltage sag/swell and unbalanced load).

To maximize the effectiveness of D-STATCOM and the Unified Power Flow Controller (UPFC) in the power system, it is necessary to have the objectives for the placement of the controllers, and then use these to determine where and how large to install the devices in the system. By applying optimization method, the optimal location of D-STATCOM and the Unified Power Flow Controller (UPFC) can be found to obtain the best results. When placed in appropriate locations, the D-STATCOM and UPFC can reduce or even eliminate overloaded lines, and help to regulate the network's voltage levels during severe disturbances. Also, reduced system losses result to more efficient networks. For optimal power flow, particle swarm optimization (PSO) algorithm can be used to find the best location for the placement of D-STATCOM and UPFC on the network

2.3 Research Gap

The integration of distributed generation (DG) into medium voltage (MV) distribution networks has been extensively studied in recent years, particularly with respect to voltage rise issues. Several studies have analyzed the technical challenges associated with high DG penetration and proposed mitigation techniques ranging from reactive power compensation to active power curtailment and network reconfiguration (Coster et al., 2011; Bollen & Hassan, 2011). While these works provide a foundation, notable gaps remain that necessitate further investigation. For example, most works done so far arbitrarily placed DGs on the network using trial and error method, rather than optimal placement of DGs on the network.

From the review of existing studies, it is evident that while the voltage rise problem in DG-integrated MV distribution networks is well recognized, gaps remain in comprehensive evaluation, optimal application, and techno-economic feasibility of FACTS devices as a solution. This study addresses these gaps through:

- I. DG placement and voltage rise analysis
- II. Modeling and comparison of different FACTS devices
- III. Deployment strategies in developing power system

3. METHODOLOGY

3.1 Case Study Network

The study employs the 33-bus, 11-kV radial distribution network of the Port Harcourt Electricity Distribution Company (PHED), Nigeria. The network topology is shown in Figure 2. The system has a total active power demand of 3,715 kW and reactive power demand of 2,300 kVar. Line parameters and load data are derived from field measurements and utility records.

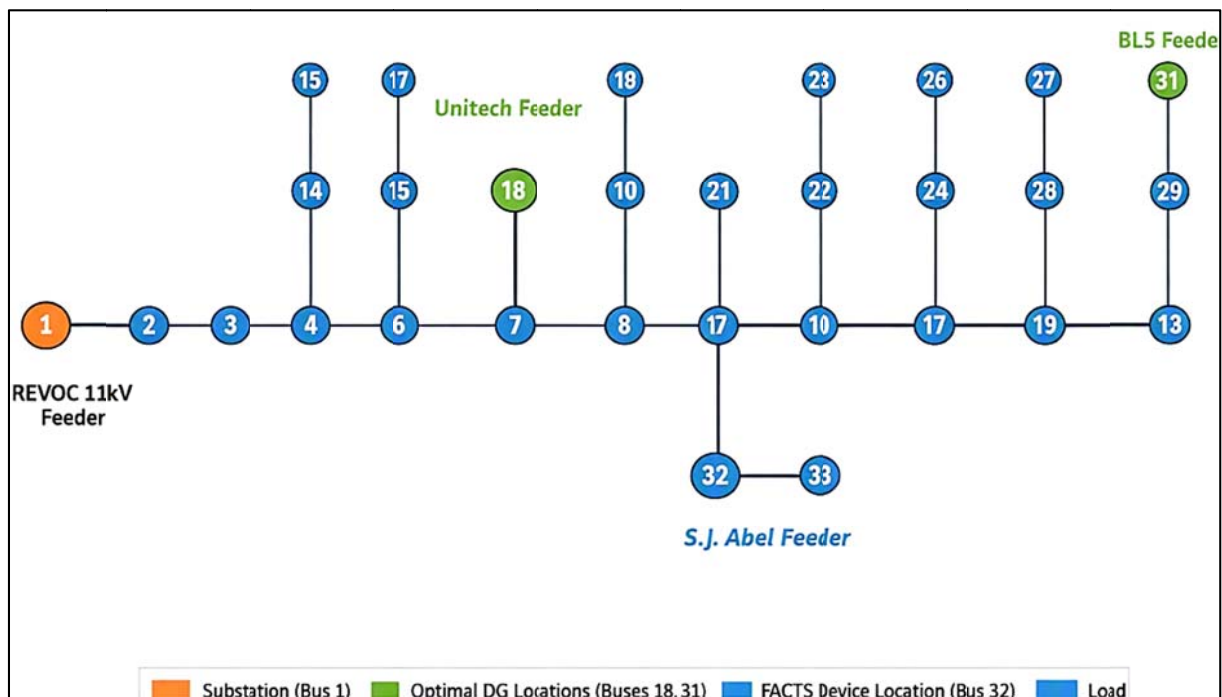


Figure 2: 33-Bus Radial Distribution Network Diagram (Port-Harcourt Electricity Distribution Company)

3.2 Modeling of the Different FACTS Devices

In this study two FACTS devices such as Distribution Static Synchronous Compensator (DSTATCOM) and Unified Power Flow Controller (UPFC) were modeled in Simulink to compensate for voltage changes in the distribution network. The modeling equations for STATCOM and UPFC are described in the sub-sections below

3.2.1 Modeling of STATCOM

The Distribution Static Synchronous Compensator (DSTATCOM) is one of the most widely applied Distribution Flexible AC Transmission System (D-FACTS) devices used for power quality enhancement and voltage regulation in distribution networks. It is a shunt-connected, solid-state compensator designed to inject or absorb reactive power at the point of common coupling (PCC) to regulate voltage magnitude, improve power factor, mitigate harmonics, and enhance overall system stability (Kumar & Ghosh, 2009; Hingorani & Gyugyi, 2000).

A DSTATCOM operates based on the voltage source converter (VSC) principle, where a DC capacitor supplies controllable AC output voltages of variable magnitude and phase through power electronic switches (e.g., IGBTs or MOSFETs). By dynamically controlling the output current, the DSTATCOM can provide rapid reactive power compensation, offering superior performance compared to conventional static VAR compensators (SVCs) (Padiyar, 2007).

The DSTATCOM injects a current into the distribution network that can be leading or lagging, depending on whether the system requires capacitive (voltage boost) or inductive (voltage reduction) compensation.

- a. When the system voltage is low, the DSTATCOM generates reactive power (capacitive mode) to raise the voltage.
- b. When the system voltage is high, it absorbs reactive power (inductive mode) to lower the voltage.

The injected current I_{inj} is controlled by adjusting the phase angle δ and magnitude of the converter's output voltage V_c relative to the system voltage V_s .

The basic relationship governing reactive power exchange is:

$$Q = V_s(V_s - V_c)X \quad (1)$$

Where Q = reactive power exchanged, V_s = system voltage, V_c = converter output voltage, X = coupling reactance between the converter and the system.

When $V_c > V_s$, the DSTATCOM supplies reactive power (capacitive mode), and when $V_c < V_s$, it absorbs reactive power

The performance of a DSTATCOM depends largely on its control algorithm, which determines the reference current or voltage signals to maintain desired power quality parameters.

The DSTATCOM is modeled as a shunt-connected voltage source converter (VSC) linked to the distribution feeder through a coupling transformer or reactance. Its primary function is to inject controllable currents into the distribution system to compensate for reactive power, correct voltage deviations, and mitigate power quality issues.

The controller used in this dissertation is the PI Controller-based Control and Instantaneous Reactive Power Theory (p-q Theory). The control method generates a reference source current for the 3-phase system using the modulating signal of the inverter.

The mathematical model of a DSTATCOM can be derived using Kirchhoff's voltage and current laws (KVL and KCL) and represented in the abc (three-phase) or dq0 (synchronous reference) frame for ease of control.

A simplified single-phase equivalent circuit of the DSTATCOM connected at the Point of Common Coupling (PCC) is shown conceptually as:

$$V_s = V_c + jX_c I_s \quad (2)$$

Where I_s = DSTATCOM current injected into the system, and X_c = equivalent reactance of the coupling inductor. The DSTATCOM injects current I_s depending on the difference between V_c and V_s .

The DSTATCOM Converter Voltage-Current Dynamics is modeled using the three-phase voltage equations of the DSTATCOM in the abc frame given by applying Kirchhoff's Voltage Law (KVL):

$$V_{sa} = V_{ca} + R_s i_a + L_s \frac{di_a}{dx} \quad (3)$$

$$V_{sb} = V_{cb} + R_s i_b + L_s \frac{di_b}{dx} \quad (4)$$

$$V_{sc} = V_{cc} + R_s i_c + L_s \frac{di_c}{dx} \quad (5)$$

Where V_{sa}, V_{sb}, V_{sc} = source voltages, V_{ca}, V_{cb}, V_{cc} = converter output voltages, i_a, i_b, i_c = phase currents, R_s = resistance of coupling inductor, L_s = inductance of coupling inductor.

To simplify control and eliminate time-varying components, the above equations are transformed into the synchronous rotating reference frame (dq-frame) using the Park transformation:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta - 120^\circ) & \cos(\theta + 120^\circ) \\ -\sin\theta & -\sin(\theta - 120^\circ) & -\sin(\theta + 120^\circ) \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (6)$$

After transformation, the dynamic model in the dq-frame become;

$$V_{sd} = R_s i_d + L_s \frac{di_d}{dx} - \omega L_s i_q + V_{cd} \quad (7)$$

$$V_{sq} = R_s i_q + L_s \frac{di_q}{dx} - \omega L_s i_d + V_{cq} \quad (8)$$

Where V_{sd}, V_{sq} = d-axis and q-axis components of the source voltage, V_{cd}, V_{cq} = d-axis and q-axis components of converter voltage, i_d, i_q = d-axis and q-axis components of the converter current, ω = angular frequency of the supply.

The d-axis controls active power, and the q-axis controls reactive power, enabling independent regulation of both power components through feedback control.

The instantaneous active (P) and reactive (Q) power exchanged between the DSTATCOM and the distribution system are expressed as:

$$P = \frac{3}{2} (V_{sd} i_d + V_{sq} i_q) \quad (9)$$

$$Q = \frac{3}{2} (V_{sq} i_d - V_{sd} i_q) \quad (10)$$

In steady-state operation, if the DSTATCOM is primarily used for reactive compensation, the d-axis current component i_d is minimized (≈ 0), and reactive power Q is controlled through, i_q . Hence, the reactive current reference can be adjusted to maintain the desired PCC voltage.

The DC link capacitor provides the necessary DC voltage for converter operation. The energy balance in the DC link is governed by the following equation:

$$C_{dc} \frac{dV_{dc}}{dx} = i_{dc} - \frac{P_{Loss}}{V_{dc}} \quad (11)$$

Where C_{dc} = DC link capacitance, V_{dc} = DC link voltage, i_{dc} = current flowing into the DC link, P_{Loss} = power loss in converter and coupling components.

3.2.1.1 DSTATCOM Proposed Controlled Strategy

The PI Controller-based Control and Instantaneous Reactive Power Theory (p-q Theory) is used for grid voltage regulation. The control method generates a reference source current for the 3-phase system using the modulating signal of the inverter. In Figure 3, I is the inverter output current, I_p is the active current vector, and I_q is the reactive current vector. V_{inv} is the inverter output voltage, V_s is the grid voltage, and φ is the phase angle. Changes in the active and reactive current vector determine the inverter's capacity to absorb and inject reactive power.

By creating various reactive power references using a regulated DC link capacitor current value known as I_c , the amplitude of the inverter's modulating signal was controlled.

It is assumed in the analysis that the DC link voltage and the inverter input current are inversely proportional. Consequently, the V_{dc} needs to be raised in order to ramp down the inverter input current. As previously mentioned, lowering the modulating signal will lengthen the transistor off time, which will raise the DC link voltage. To achieve this, it is assumed that the inverter produces a reactive current, as indicated:

$$I_{qref} = \frac{1}{V_{dc}} - I_c \quad (12)$$

The regulated DC capacitor current (I_c) is subtracted from the DC source current, which is thought to be proportional to the reciprocal of the DC link voltage (V_{dc}), to determine the assumed reactive reference current component (I_{qref})

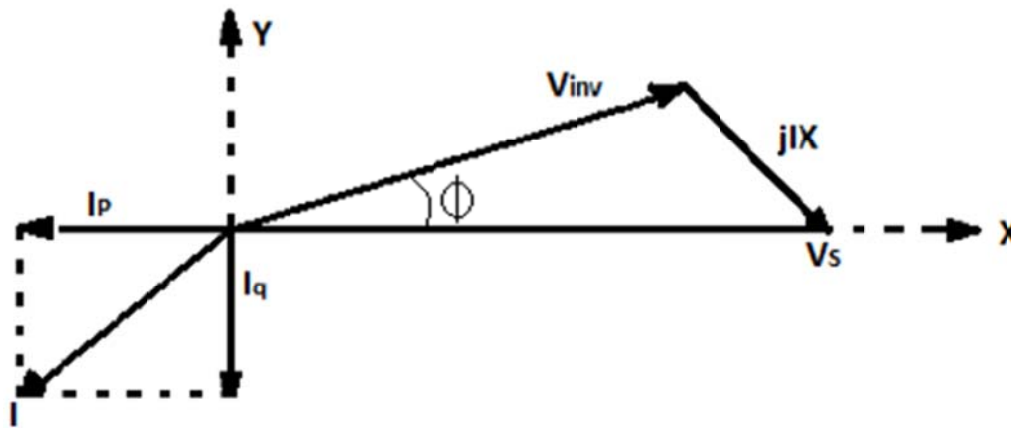


Figure 3: Phasor Diagram of Inverter Injecting and Absorbing Reactive Current

From an assumed position, the reactive power reference component produced is expressed as follows:

$$Q_{ref} = I_{qref} * V_s \quad (13)$$

where V_s is the system voltage.

The generated reactive reference component (Q_{ref}) is used to control the VSI switching pattern, which in turn controls the reactive power absorbed by the inverter.

Hence, the reactive power compensation is given as as;

$$Q_{ref} = \left(\frac{1}{V_{dc}} - I_c \right) \sqrt{V_d^2 + V_q^2} \quad (14)$$

Reactive power control determines the inverter's active power curtailment. Consequently, the measured voltage at the PCC determines the activation of the reactive power reference component (Q_{ref}), as indicated:

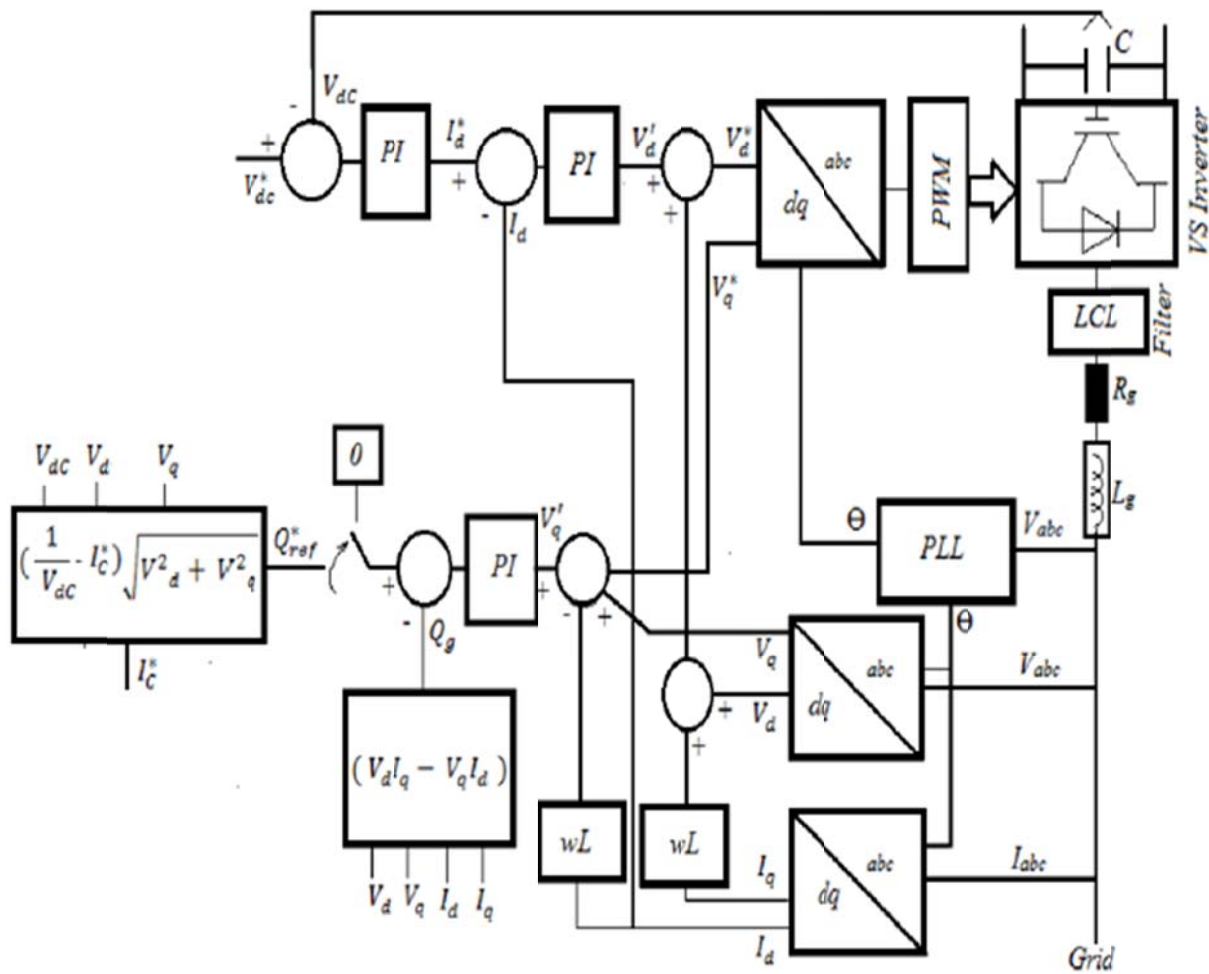
$$Q_{ref} = \begin{cases} \left(\frac{1}{V_{dc}} - I_c \right) \sqrt{V_d^2 + V_q^2} & V_{measured} > V_{upper_limit} [Q_{ref} \neq 0] \\ 0 & V_{measured} > V_{lower_limit} [Q_{ref} = 0] \end{cases} \quad (15)$$

Reactive current is subsequently injected or absorbed using the reactive power error produced, which is subject to I_c value.

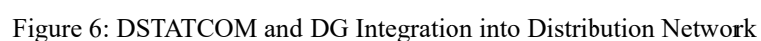
$$Q_{er} = Q_{ref} - Q_a \quad (16)$$

Where Q_{er} is reactive power error and $Q_a (V_d I_q - V_q I_d)$

The control techniques enable the DSTATCOM to correct voltage sags/swells, maintain unity power factor, and reduce current harmonics effectively. The DSTATCOM control diagram is shown in Figure 4. The controller is modeled in MATLAB/Simulink as shown in Figure 5. Figure 6 shows the D-STATCOM integration into the network.



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The Unified Power Flow Controller (UPFC) is one of the most versatile and advanced members of the Flexible AC Transmission System (FACTS) family. It was introduced to achieve simultaneous control of voltage, impedance, and phase angle of a transmission line, enabling comprehensive power flow management.

A UPFC combines the functions of series and shunt compensation within a single device, using two voltage source converters (VSCs) that share a common DC link. This configuration allows it to regulate real and reactive power flow, control bus voltage, and improve system stability

The UPFC consists of shunt converter (Converter 1) and series converter (Converter 2). Both converters are linked through a common DC-link capacitor, which allows real power exchange between the two converters while maintaining independent control of reactive power at each converter terminal.

The equivalent circuit of a UPFC connected between two buses (sending-end i and receiving-end j) can be represented as follows:

$$V_s + V_{se} = V_j + I_{line}(R + jX) \quad (17)$$

where: V_s = sending-end bus voltage, V_j = receiving-end bus voltage, V_{se} = injected series voltage by the UPFC, I_{line} = distribution line current, R , X = resistance and reactance of the transmission line, respectively.

The series converter injects a voltage V_{se} with controllable magnitude and phase angle δ :

$$V_{se} = |V_{se}| < \delta \quad (18)$$

By adjusting $|V_{se}|$ and δ , the UPFC can control both real power (P) and reactive power (Q) flow through the line.

3.3.1 Shunt Converter (STATCOM) Model

The shunt converter maintains the DC-link voltage and provides reactive power support to the bus. The voltage equation at the shunt side is expressed as:

$$V_{bus} = V_{sh} + R_{sh}I_{sh} + L_{sh} \frac{dI_{sh}}{dx} \quad (19)$$

where: V_{bus} = bus voltage, V_{sh} = shunt converter voltage, I_{sh} = shunt current, R_{sh} , L_{sh} = resistance and inductance of the shunt transformer.

The active and reactive power exchanged between the shunt converter and the AC system are:

$$P_{sh} = V_{bus}I_{sh}\cos(\phi_{sh}) \quad (20)$$

$$Q_{sh} = V_{bus}I_{sh}\sin(\phi_{sh}) \quad (21)$$

The shunt converter draws or supplies real power to maintain the DC-link voltage and injects reactive power for bus voltage regulation.

3.3.2 Series Converter (SSSC) Model

For the series converter, the voltage and current relationship along the transmission line can be written as:

$$V_i - V_j = (R + jX)I_{line} - V_{se} \quad (22)$$

The injected voltage V_{se} can be resolved into in-phase and quadrature components with respect to the line current I_{line}

$$V_{se} = V_{se,p} + jV_{se,q} \quad (23)$$

where: $V_{se,p}$ controls the real power flow (active power exchange). $V_{se,q}$ controls the reactive power flow (series compensation).

Thus, the instantaneous active and reactive power exchanged by the series converter are:

$$P_s = R_e(V_{se}I_{line}) \quad (24)$$

$$Q_{se} = I_m(V_{se}I_{line}) \quad (25)$$

These equations show that the series converter can directly control line power flow by injecting a voltage of desired phase and magnitude.

Transforming the voltage and current equations into the synchronous rotating reference frame (dq-frame) simplifies the control design. For the shunt converter:

$$V_{s,d} - V_{j,d} = R_{se}i_d + L_{se} \frac{di_d}{dx} - \omega L_{se}i_q + V_{se,d} \quad (26)$$

$$V_{s,q} - V_{j,q} = R_{se}i_q + L_{se}\frac{di_q}{dx} - \omega L_{se}i_d + V_{se,q} \quad (27)$$

where: $V_{s,d}$, $V_{s,q}$ = d- and q-axis components of sending-end voltage, $V_{j,d}$, $V_{j,q}$ = d- and q-axis components of receiving-end voltage, i_d , i_q = line current components, $V_{se,d}$, $V_{se,q}$ = d- and q-axis components of the injected series voltage, R_{se} , L_{se} = line resistance and inductance, respectively.

The d-axis component primarily controls the active power flow, while the q-axis component regulates the reactive power.

3.3.3 DC-Link Dynamics

The DC-link capacitor serves as the common energy storage between the two converters. The DC-link voltage dynamics are given by:

$$C_{dc}\frac{dV_{dc}}{dx} = I_{dc,sh} - I_{dc,se} \quad (28)$$

where: C_{dc} = DC-link capacitance, V_{dc} = DC-link voltage, $I_{dc,sh}$ = current contribution from the shunt converter, $I_{dc,se}$ = current drawn by the series converter.

To maintain stable operation, the shunt converter controls V_{dc} by exchanging active power with the AC system to balance the power drawn by the series converter.

3.3.4 Power Flow Control Equations

Assuming a lossless system and neglecting resistance, the real and reactive power flow between sending and receiving buses can be expressed as:

$$P = \frac{V_i V_j}{X} \sin(\delta + \delta_{se}) \quad (29)$$

$$Q = \frac{V_i (V_i - V_j \cos(\delta + \delta_{se}))}{X} \quad (30)$$

where: V_i , V_j = sending and receiving end voltages, X = line reactance, δ = phase angle difference between V_i and V_j , δ_{se} = phase angle of the injected voltage,

The MATLAB/Simulink UPFC model, UPFC control, SSSC block, UPFC power flow controller block and UPFC network integration, are shown in Figures 7, 8, 9, 10 and 11 respectively.

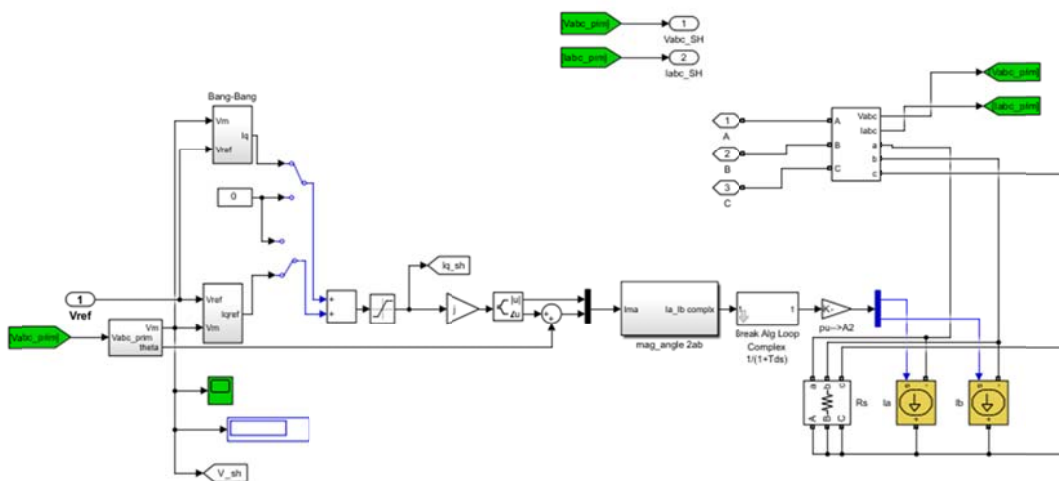


Figure 7: UPFC Model

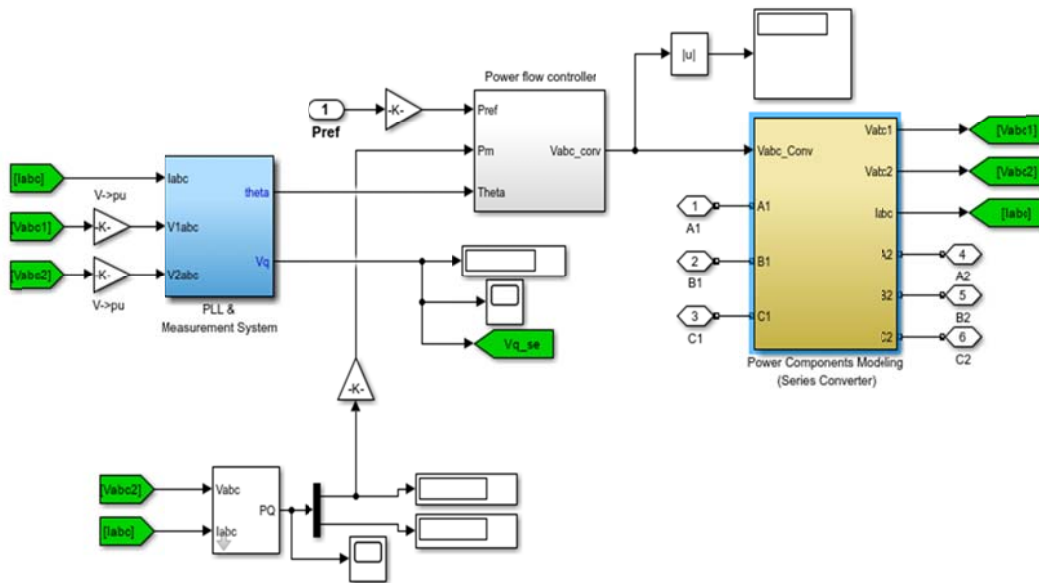


Figure 8: UPFC Controller

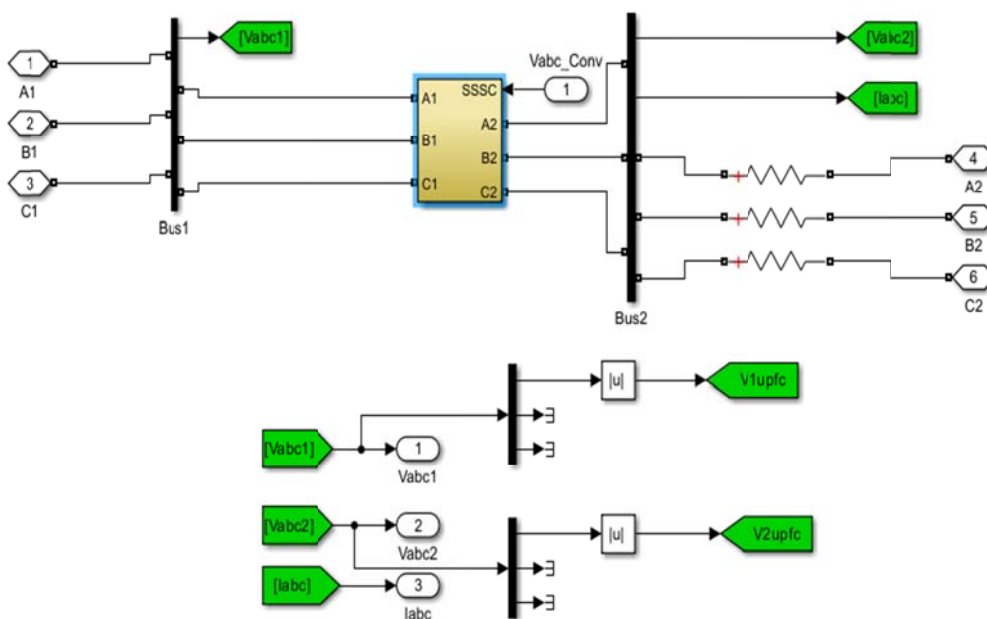


Figure 9: Series Static Synchronous Compensator (SSSC) Block

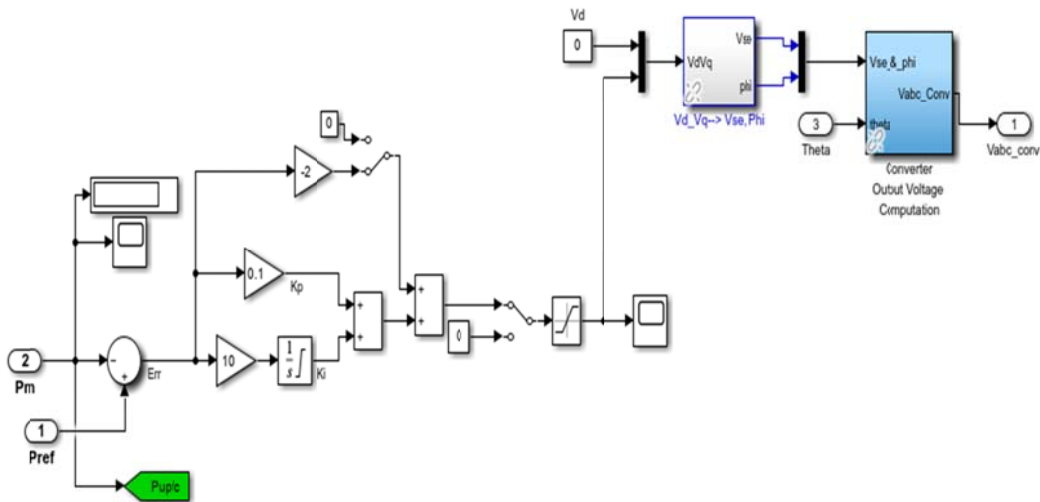


Figure 10: UPFC Power Flow Controller Block

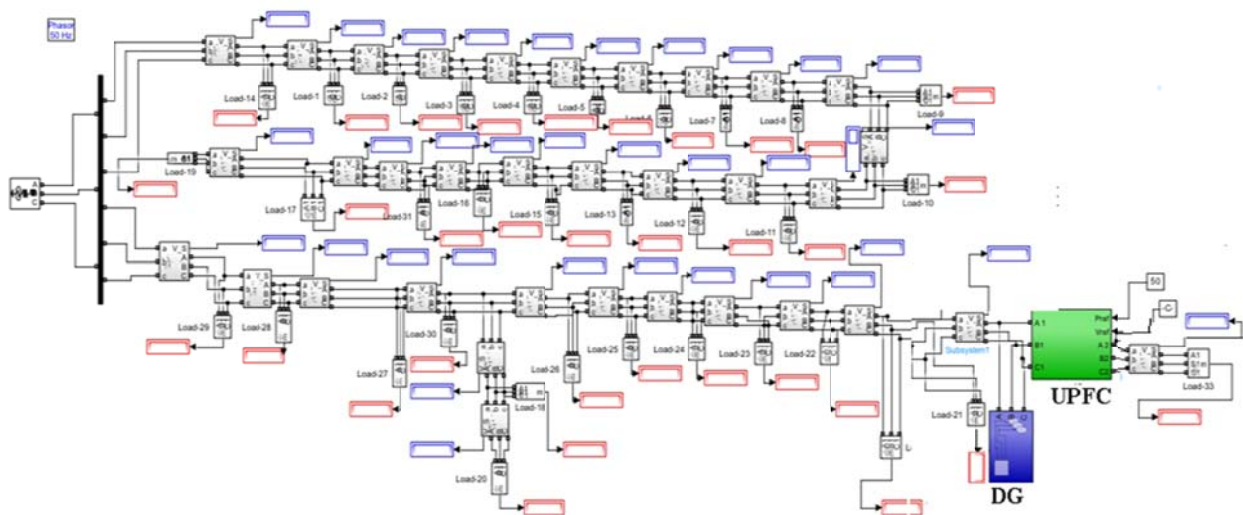


Figure 11: Integration of UPFC and DG on the Distribution Network

4. RESULTS

4.1 Simulation of FACTS Devices (STATCOM and UPFC) Incorporating DG on the Distribution Network

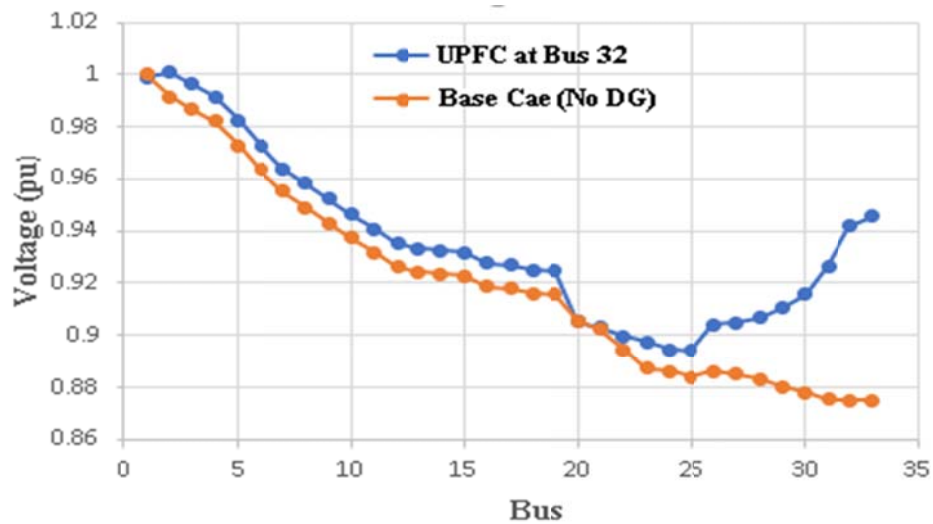


Figure 12: Voltage Profile with UPFC at Bus 32 (S.J. Abed Feeder) and without DG

Table 1: Distribution Network Voltage Profile with UPFC at Bus 32 (S.J. Abed Feeder) and Base Case

Bus	Voltage with UPFC at bus 32 (pu)	Voltage at Base Case (pu)	Bus	Voltage with UPFC at bus 32 (pu)	Voltage at Base Case (pu)
1	0.999	1	18	0.9249	0.916
2	1.001	0.9917	19	0.9248	0.9158
3	0.9965	0.9868	20	0.9051	0.9055
4	0.9917	0.9822	21	0.9031	0.9021
5	0.9825	0.973	22	0.8995	0.8945
6	0.9728	0.9634	23	0.8973	0.8873
7	0.964	0.9553	24	0.8944	0.8863
8	0.9583	0.9491	25	0.894	0.884
9	0.9523	0.9431	26	0.904	0.8863
10	0.9464	0.9373	27	0.905	0.8849
11	0.9407	0.9316	28	0.9067	0.8832
12	0.9352	0.9261	29	0.9106	0.8803
13	0.9334	0.9244	30	0.9156	0.878
14	0.9325	0.9235	31	0.9266	0.8754
15	0.9317	0.9227	32	0.942	0.875
16	0.9276	0.9186	33	0.9457	0.8749
17	0.927	0.918			

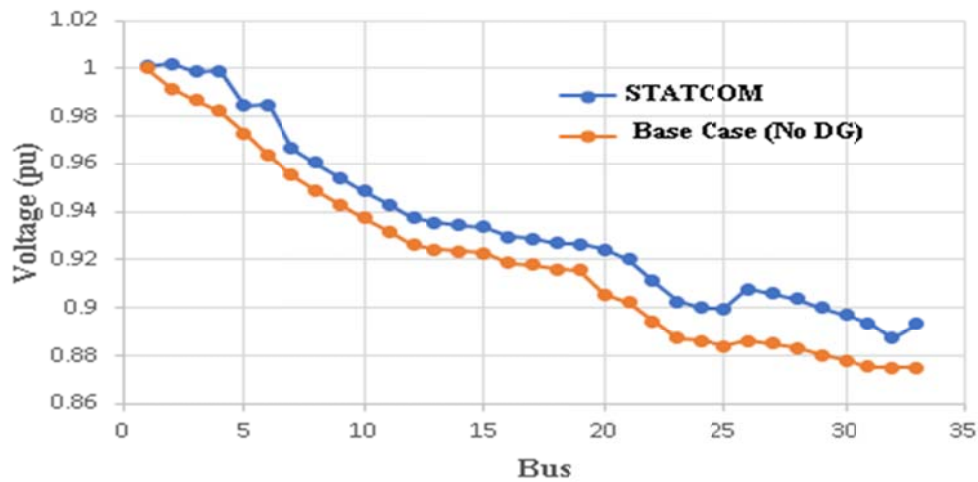


Figure 13: Voltage Profile with STATCOM at Bus 32 (S.J. Abed Feeder)

Table 2: Distribution Network Voltage Profile with STATCOM at Bus 32 (S.J. Abed Feeder) and Base Case

Bus	Voltage with STATCOM at bus 32 (pu)	Base Case	Bus	Voltage with STATCOM at bus 32 (pu)	Base Case
1	1.001	1	18	0.9269	0.916
2	1.002	0.9917	19	0.9267	0.915
3	0.9986	0.9868	20	0.9242	0.905
4	0.999	0.9822	21	0.9202	0.902
5	0.9846	0.973	22	0.9113	0.894
6	0.9849	0.9634	23	0.9028	0.887
7	0.9666	0.9553	24	0.9	0.886
8	0.9604	0.9491	25	0.8995	0.884
9	0.9543	0.9431	26	0.9078	0.886
10	0.9484	0.9373	27	0.906	0.884
11	0.9429	0.9316	28	0.9036	0.883
12	0.9372	0.9261	29	0.8999	0.880
13	0.9354	0.9244	30	0.8969	0.878
14	0.9345	0.9235	31	0.8937	0.875
15	0.9337	0.9227	32	0.8872	0.875
16	0.9296	0.9186	33	0.8932	0.874
17	0.9289	0.918			

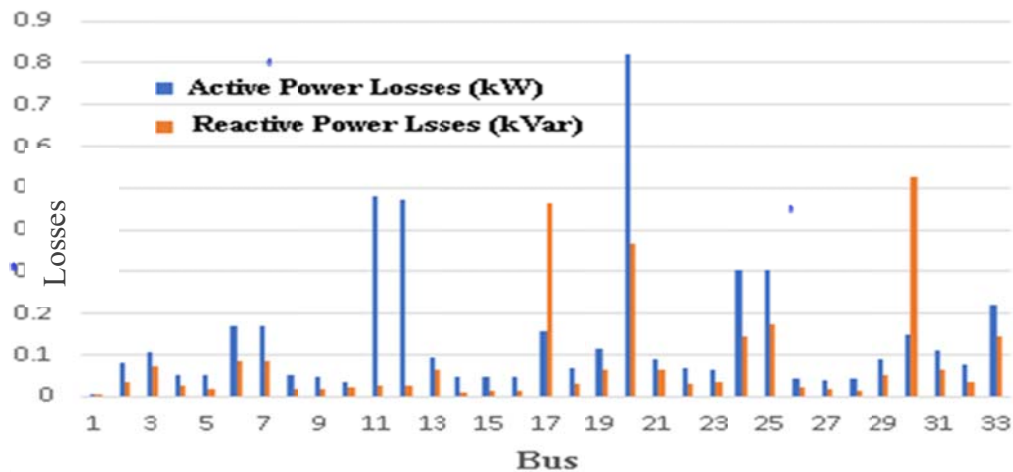


Figure 14: Active and Reactive Power Losses with UPFC at Bus 32 (S. J. Abed Feeder) (4.7191kW and 2.788kVar)

Table 3: Active and Reactive Power Losses with UPFC at Bus 32 (S. J. Abed Feeder)

Bus	Active Power Losses(KW)	Reactive Power Losses (KVar)	Bus	Active Power Losses(KW)	Reactive Power Losses (KVar)
1	0.0018	0.0011	18	0.0694	0.0308
2	0.0813	0.0361	19	0.1157	0.0647
3	0.1074	0.0716	20	0.8227	0.3657
4	0.0532	0.0266	21	0.0900	0.0630
5	0.0522	0.0174	22	0.0666	0.0296
6	0.1706	0.0853	23	0.0658	0.0365
7	0.1678	0.0838	24	0.305	0.1454
8	0.0496	0.0165	25	0.305	0.1743
9	0.0490	0.0163	26	0.0438	0.0219
10	0.0363	0.0242	27	0.0384	0.0182
11	0.4787	0.0279	28	0.0438	0.0146
12	0.4731	0.0276	29	0.0877	0.0511
13	0.0942	0.0628	30	0.1467	0.5281
14	0.0470	0.0078	31	0.1112	0.0622
15	0.0469	0.0156	32	0.0782	0.0363
16	0.0465	0.0155	33	0.2178	0.1452
17	0.1549	0.4648	Total	4.718	2.788

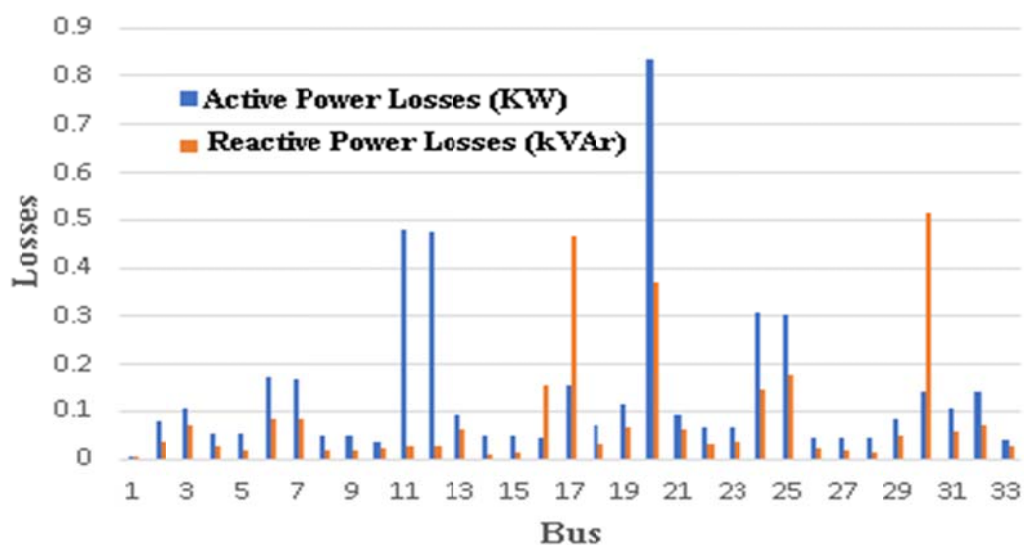


Figure 15: Active and Reactive Power Losses with STATCOM at Bus 32 (S.J.Abed Feeder) (4.6232kW and 2.8386kVar)

Table 4: Active and Reactive Power Losses with STATCOM at Bus 32 (S.J.Abed Feeder)

Bus	Active Power Losses (kW)	Reactive Power Losses (KVar)	Bus	Active Power Losses (kW)	Reactive Power Losses (KVar)
1	0.0018	0.0011	18	0.0695	0.03091
2	0.0815	0.03623	19	0.1159	0.06488
3	0.1076	0.07174	20	0.8366	0.3718
4	0.0533	0.02665	21	0.0913	0.06397
5	0.0523	0.01744	22	0.0672	0.02987
6	0.1709	0.08567	23	0.0659	0.03665
7	0.1681	0.08403	24	0.306	0.1457
8	0.0497	0.01659	25	0.3056	0.1746
9	0.0491	0.01638	26	0.0438	0.02193
10	0.0364	0.02427	27	0.0436	0.0182
11	0.4795	0.02797	28	0.0434	0.01449
12	0.4739	0.02765	29	0.0862	0.05029
13	0.0944	0.06275	30	0.1427	0.5137
14	0.0471	0.0078	31	0.1063	0.05951
15	0.0470	0.01568	32	0.1416	0.07079
16	0.0466	0.1554	33	0.0424	0.02833
17	0.1552	0.4656	Total	4.6224	2.8386

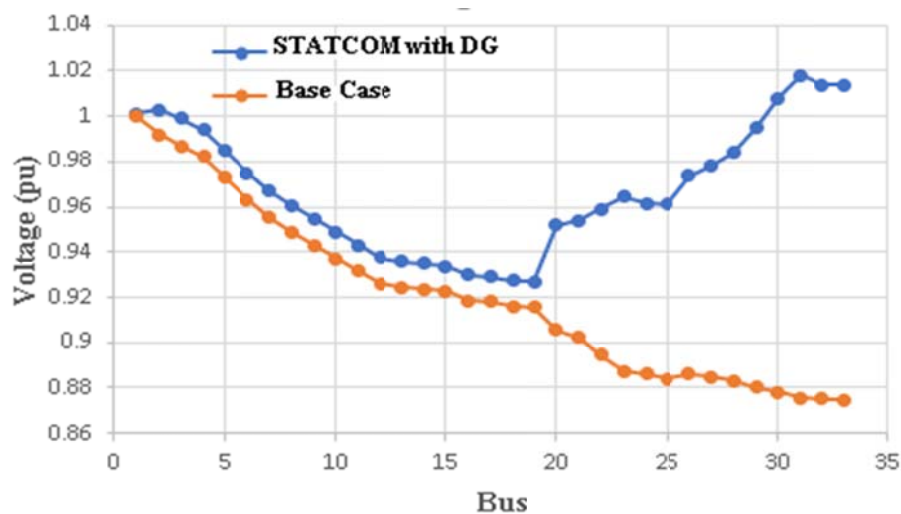


Figure 16: Distribution Network Voltage Profile with STATCOM and DG

Table 5: Distribution Network Voltage with STATCOM and DG

Bus	Voltage Level for STATCOM with DG (pu)	Voltage level for Base Case (pu)	Bus	Voltage Level for STATCOM with DG (pu)	Voltage level for Base Case (pu)
1	1.001	1	18	0.9272	0.916
2	1.003	0.992	19	0.927	0.915
3	0.998	0.987	20	0.952	0.905
4	0.994	0.982	21	0.954	0.902
5	0.984	0.973	22	0.959	0.894
6	0.975	0.963	23	0.9646	0.887

7	0.966	0.955	24	0.9616	0.886
8	0.961	0.949	25	0.9611	0.884
9	0.9546	0.943	26	0.9738	0.886
10	0.9487	0.937	27	0.9781	0.885
11	0.943	0.932	28	0.984	0.883
12	0.9374	0.926	29	0.9949	0.880
13	0.9357	0.924	30	1.008	0.878
14	0.9348	0.924	31	1.018	0.875
15	0.9339	0.922	32	1.014	0.875
16	0.9298	0.918	33	1.014	0.875
17	0.9292	0.918			

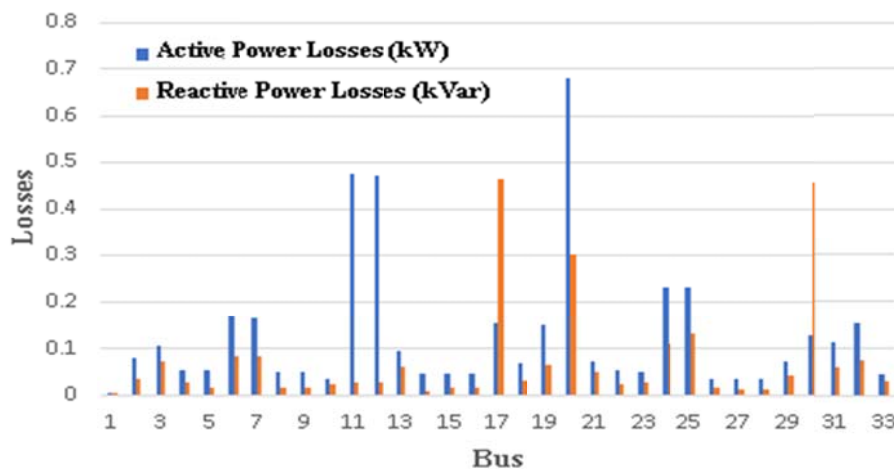


Figure 17: Active Losses (4.25432 KW) and Reactive Power Losses (2.453603kVar) with STATCOM and DG

Table 6: Active Losses and Reactive Power Losses with STATCOM and DG

Bus	Active Power losses (KW)	Reactive Power losses (KVar)	Bus	Active Power losses (KW)	Reactive Power losses (KVar)
1	0.0018	0.00109	18	0.0691	0.03071
2	0.081	0.036	19	0.151	0.06447
3	0.106	0.07129	20	0.6809	0.3026
4	0.0529	0.02648	21	0.0727	0.05091
5	0.0519	0.01733	22	0.0516	0.02296
6	0.1699	0.08493	23	0.0502	0.02792
7	0.167	0.0835	24	0.2331	0.111
8	0.0494	0.01648	25	0.2328	0.1331
9	0.0488	0.01628	26	0.0335	0.01675
10	0.0361	0.02412	27	0.0336	0.01401
11	0.4765	0.0278	28	0.0340	0.01136
12	0.4709	0.02747	29	0.0713	0.0416
13	0.0938	0.06256	30	0.1274	0.4587
14	0.0468	0.00780	31	0.1115	0.06247
15	0.0467	0.01558	32	0.1546	0.07728
16	0.0463	0.01544	33	0.0463	0.0309
17	0.1542	0.4627	Total	4.2536	2.4536

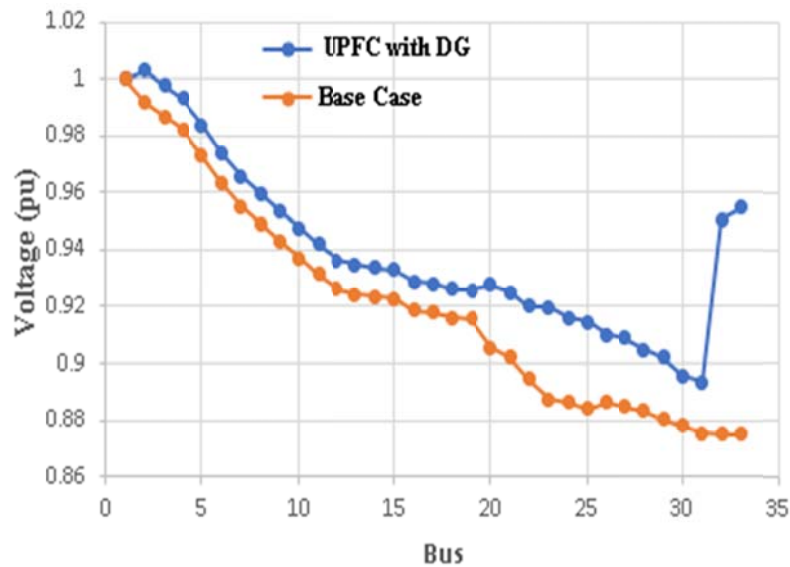


Figure 18: Voltage Profile of UPFC with DG

Table 7: Distribution Network Voltage with UPFC and DG

Bus	Voltage Level for UPFC with DG (pu)	Voltage Level for Base Case (pu)	Bus	Voltage Level for UPFC with DG (pu)	Voltage Level for Base Case (pu)
1	1	1	18	0.9262	0.916
2	1.003	0.9917	19	0.926	0.9158
3	0.9978	0.9868	20	0.9278	0.9055
4	0.9931	0.9822	21	0.9252	0.9021
5	0.9839	0.973	22	0.92	0.8945
6	0.9741	0.9634	23	0.9198	0.8873
7	0.9659	0.9553	24	0.916	0.8863
8	0.9596	0.9491	25	0.9145	0.884
9	0.9536	0.9431	26	0.91	0.8863
10	0.9477	0.9373	27	0.9087	0.8849
11	0.942	0.9316	28	0.9047	0.8832
12	0.9364	0.9261	29	0.902	0.8803
13	0.9347	0.9244	30	0.8957	0.878
14	0.9338	0.9235	31	0.8935	0.8754
15	0.933	0.9227	32	0.9508	0.875
16	0.9289	0.9186	33	0.9547	0.8749
17	0.9282	0.918			

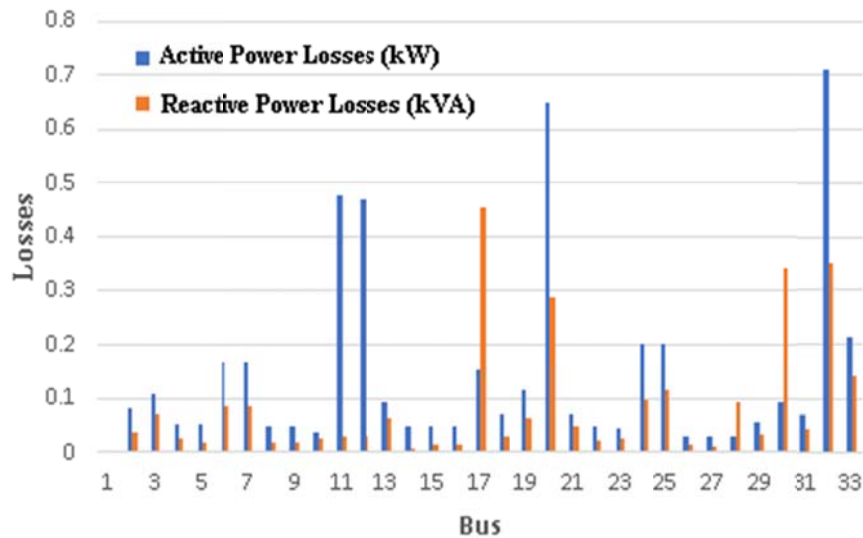


Figure 19: Active power losses (**4.72589kW**) and Reactive power losses (**2.70718 kVar**) with UPFC and DG

Table 8: Active Losses and reactive Power Losses with UPFC and DG

Bus	Active Power losses (kW)	Reactive Power losses (KVar)	Bus	Active Power losses (kW)	Reactive Power losses (KVar)
1	0.00183	0.001098	18	0.0690	0.0307
2	0.08099	0.03599	19	0.1151	0.0644
3	0.1069	0.07127	20	0.6508	0.2893
4	0.05294	0.02647	21	0.0685	0.0480
5	0.05196	0.01732	22	0.0469	0.0208
6	0.1698	0.0849	23	0.0436	0.0242
7	0.1669	0.08347	24	0.2023	0.0963
8	0.04944	0.01648	25	0.2021	0.1155
9	0.04882	0.01627	26	0.0287	0.0143
10	0.03616	0.02411	27	0.0282	0.0117
11	0.4763	0.02779	28	0.0277	0.0926
12	0.4708	0.02746	29	0.0553	0.0327
13	0.0938	0.06253	30	0.0944	0.3401
14	0.04681	0.007802	31	0.0707	0.0437
15	0.04673	0.01558	32	0.7089	0.3544
16	0.04632	0.01544	33	0.2126	0.1417
17	0.1542	0.4525	Total	4.7255	2.7069

4.2 Discussion

Figure 12 and Table 1, present the voltage profile of the 33-bus distribution network with the integration of a Unified Power Flow Controller (UPFC) at Bus 32 (S. J. Abed feeder). The simulation results reveal a considerable improvement in the voltage magnitude, increasing from 0.8749 pu in the base case to approximately 0.9457 pu after the installation of the UPFC. This notable enhancement underscores the UPFC's superior capability in reactive power compensation, voltage support, and dynamic control of power flow within the distribution network.

However, it is observed that the resulting voltage magnitude of 0.9457 pu within the upper boundary of the acceptable voltage range, which is generally set at $\pm 6\%$ of the nominal value (i.e., between 0.94 pu and 1.06 pu). This indicates that, although the UPFC successfully mitigates voltage drops and improves system stability, excessive reactive power injection may lead to

overcompensation. Consequently, fine-tuning of the UPFC's control parameters or the optimization of its placement is essential to achieve voltage regulation within the statutory limits, ensuring both voltage quality and operational efficiency.

Figure 13 and Table 2 illustrate the voltage profile when a Distribution Static Synchronous Compensator (DSTATCOM) was introduced at Bus 32 (S. J. Abed feeder). The network voltage improved from 0.8749 pu to 0.8932 pu, indicating a modest yet positive enhancement in the voltage level. Although the DSTATCOM contributed to improved voltage support, the overall performance comparison reveals that the UPFC exhibited superior voltage regulation capability due to its combined series shunt compensation features. This demonstrates that while both devices enhance voltage stability, the UPFC provides a more comprehensive solution for voltage control and reactive power management in medium-voltage distribution networks.

Figure 14 and Table 3 illustrate the variation of active and reactive power losses in the 33-bus distribution network following the integration of a Unified Power Flow Controller (UPFC) at Bus 32 (S.J. Abed). The simulation results reveal a substantial improvement in system efficiency, with the active and reactive power losses reduced to 4.718 kW and 2.788 kVAr, respectively. These values represent a remarkable reduction from the base case losses of 453.618 kW (active) and 11.089 kVAr (reactive) recorded in the network without DG or FACTS device integration. The significant loss reduction indicates the UPFC's strong ability to control both voltage magnitude and phase angle, thereby optimizing power flow and minimizing network losses.

Furthermore, Figure 15 and Table 4 present the active and reactive power losses when a Distribution Static Synchronous Compensator (DSTATCOM) was installed in the same network. In this case, the system experienced a moderate improvement, with the active and reactive losses recorded as 4.6224 kW and 2.8386 kVAr, respectively. Although both compensation devices demonstrated positive impacts on system performance, the DSTATCOM achieved a slightly better reduction in losses compared to the UPFC.

Overall, the comparative analysis reveals that the DSTATCOM outperforms the UPFC in terms of power loss reduction, while the UPFC gives a better voltage improvement. This can be attributed to the UPFC dual control functionality providing both series and shunt compensation which allows for simultaneous management of voltage, power flow, and reactive power support.

Figure 16 and Table 5 illustrate the voltage profile of the 33-bus distribution network when both a Distributed Generator (DG) and a Distribution Static Synchronous Compensator (DSTATCOM) were integrated into the system. The results show a notable enhancement in voltage performance, particularly at the remote end of the network, where the voltage magnitude improved from 0.8749 pu (base case) to 1.014 pu. This improvement demonstrates the effective voltage support provided by the combined operation of the DG and STATCOM. Correspondingly, Figure 17 and Table 6 present the associated system losses, indicating that the active and reactive power losses decreased significantly to 4.2536 kW and 2.4536 kVAr, respectively. These results confirm that the coordinated operation of DG and STATCOM enhances voltage regulation and reduces system losses, thereby improving the overall efficiency of the distribution network.

Similarly, Figure 18 and Table 7 depict the voltage profile of the distribution network when the DG was integrated in conjunction with a Unified Power Flow Controller (UPFC). The results reveal that the combined configuration further improved the system voltage from 0.8749 pu (in the base case) to 0.9547 pu, representing a substantial increase in voltage stability and network reliability. As shown in Figure 19 and Table 8, the active and reactive power losses for this configuration were recorded as 4.7255 kW and 2.7069 kVAr, respectively. Although the UPFC and DG combination yielded slightly higher losses compared to the STATCOM–DG configuration, it demonstrated moderate voltage control capabilities due to the UPFC's ability to simultaneously regulate voltage magnitude, phase angle, and reactive power flow.

Overall, the comparative analysis indicates that the integration of DG with either STATCOM or UPFC significantly enhances system voltage stability and minimizes power losses. However, the STATCOM–DG configuration exhibited slightly better efficiency in reducing losses, whereas the UPFC–DG combination provided improved voltage control and system robustness. This highlights the importance of selecting appropriate compensation and control strategies based on the specific performance objectives of the distribution network.

5. CONCLUSION

This study investigated the technical and economic impact of integrating Distributed Generation (DG) and Flexible AC Transmission System (FACTS) devices, specifically the DSTATCOM and Unified Power Flow Controller (UPFC), on a 33-bus medium voltage distribution network. The primary objective was to enhance voltage stability, minimize power losses, and improve the overall efficiency of the distribution system through optimal placement and sizing of DG units and compensation devices.

The inclusion of FACTS devices further enhanced the network performance. When a DSTATCOM was installed at Bus 32 (S. J. Abed feeder), the voltage improved substantially from 0.8749 pu to 1.014 pu, reflecting its ability to supply reactive power support and correct voltage sags. In contrast, the integration of a UPFC at Bus 32 (S. J. Abed feeder), produced a moderate improvement, increasing the voltage from 0.8752 pu to 0.9547 pu. This result highlighted the superior voltage regulation and reactive power compensation capability of the UPFC compared to the DSTATCOM.

The introduction of FACTS devices further enhanced system performance. The DSTATCOM provided superior voltage regulation capabilities and power flow capabilities, while the UPFC demonstrated moderate voltage regulation.

The combined application of DG and FACTS devices proved to be an effective strategy for achieving both technical and economic improvements in distribution networks with 99% power loss reduction for STATCOM and 98% power loss reduction for UPFC. The coordinated operation of these technologies improved voltage stability, reduced total power losses, and enhanced overall power quality and reliability.

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