International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 13 Issue: 03 | Mar 2026 www.irjet.net p-ISSN: 2395-0072

A REVIEW OF DYNAMIC REACTIVE POWER ALLOCATION MECHANISM FOR VOLTAGE PROFILE ENHANCEMENT IN WEAK GRID CONDITIONS

Rahul Kumar Maurya[1], Dr. Imran Khan[2]

[1]Master of Technology, Electrical Engineering (Power System), Azad Institute of Engineering and Technology, Lucknow, India
[2]Professor, Department Electrical Engineering (Power System), Azad Institute of Engineering and Technology, Lucknow, India

---

Abstract - *Voltage instability is a major challenge in modern power systems, particularly in weak grid conditions where low short-circuit capacity, high line impedance, and large penetration of renewable energy sources can significantly degrade voltage profiles. Effective management of reactive power is essential for maintaining system voltage within acceptable limits and ensuring reliable grid operation. This review paper presents a comprehensive analysis of dynamic reactive power allocation mechanisms aimed at improving voltage profiles in weak power networks. The study begins by discussing the fundamental relationship between reactive power and voltage stability, followed by an overview of conventional and advanced reactive power compensation technologies such as capacitor banks, synchronous condensers, Static Var Compensators (SVC), and Static Synchronous Compensators (STATCOM). Furthermore, the review examines various reactive power allocation strategies including optimal reactive power dispatch, sensitivity-based methods, and coordinated Volt-VAR control approaches. Special attention is given to recent developments involving intelligent optimization techniques and artificial intelligence-based controllers for real-time reactive power management. The paper also provides a comparative discussion of existing methods reported in the literature, highlighting their advantages, limitations, and practical implementation challenges in weak grid environments. Finally, key research gaps and future directions are identified, including the integration of distributed energy resources, advanced control frameworks, and hybrid compensation systems. The review aims to provide researchers and power system engineers with a structured understanding of modern reactive power allocation mechanisms for enhancing voltage stability in weak grids.*

Key Words: Reactive Power Allocation; Voltage Stability; Weak Grid; STATCOM; Volt-VAR Control; Reactive Power Compensation.

1. INTRODUCTION

The stability and reliability of modern electrical power systems largely depend on the ability to maintain voltage levels within acceptable operating limits. Voltage instability has become an important issue due to the rapid expansion of interconnected networks, the increasing integration of renewable energy resources, and the growing demand for electricity. In power systems, reactive power plays a fundamental role in controlling voltage magnitude and supporting power transfer capability across transmission and distribution networks. Insufficient reactive power support may lead to voltage deviations, increased transmission losses, and in severe cases, voltage collapse. Consequently, effective reactive power management strategies have become essential for ensuring secure system operation, particularly in networks with high renewable penetration and weak grid characteristics.

1.1 Background of Voltage Stability in Modern Power Systems

Voltage stability refers to the ability of a power system to maintain steady and acceptable voltage levels at all buses under normal operating conditions as well as after disturbances such as faults or load changes. The concept is closely related to the balance between reactive power supply and demand within the electrical network. When reactive power demand exceeds the available supply, the voltage magnitude begins to decline, which may eventually lead to voltage collapse if corrective actions are not taken. Voltage stability problems are particularly significant in long transmission networks and heavily loaded systems where reactive power support becomes limited (Kundur, 1994).

In recent years, the increasing integration of renewable energy sources such as wind and solar power has introduced additional complexity to voltage regulation. Renewable energy generators are often connected to the grid through power electronic converters, which may provide limited reactive power support depending on their control configuration. Moreover, distributed generation units are frequently installed in remote areas where the grid infrastructure is relatively weak, further increasing the risk of voltage instability. These developments have highlighted the need for advanced reactive power control strategies capable of maintaining stable voltage profiles in modern power systems (Bollen and Hassan, 2011).

1.2 Weak Grid Conditions and Their Impact on Voltage Profiles

A weak grid is generally characterized by high system impedance, low short-circuit capacity, and a limited ability to regulate voltage during disturbances or load variations. In such networks, even small changes in load or generation can cause significant voltage fluctuations. The short-circuit ratio (SCR) is commonly used as an indicator of grid strength; a low SCR indicates that the grid is weak and more susceptible to instability problems. Weak grids often occur in remote transmission corridors, islanded systems, and renewable energy integration zones where the network infrastructure is relatively sparse (Milano, 2010).

Under weak grid conditions, the voltage profile becomes highly sensitive to reactive power imbalance. Renewable energy sources such as wind farms and photovoltaic systems may introduce intermittent power output, leading to sudden voltage variations and power quality issues. Additionally, the presence of long transmission lines increases reactive power losses and voltage drops along the network. These factors collectively make weak grids more vulnerable to voltage instability and require efficient reactive power compensation mechanisms to maintain stable operation (Taylor, 1994).

1.3 Importance of Dynamic Reactive Power Allocation

Dynamic reactive power allocation plays a crucial role in improving voltage stability and enhancing the voltage profile of weak power systems. Unlike traditional compensation methods that rely on fixed or mechanically switched capacitor banks, dynamic approaches utilize fast-acting power electronic devices capable of providing real-time reactive power support. Devices such as Static Var Compensators (SVC), Static Synchronous Compensators (STATCOM), and Distribution STATCOM (DSTATCOM) can rapidly inject or absorb reactive power depending on system requirements, thereby stabilizing voltage levels during disturbances (Hingorani and Gyugyi, 2000).

These advanced compensation devices are widely used in modern power systems because of their high response speed, flexible control capability, and ability to operate effectively in weak grid environments. By dynamically allocating reactive power at appropriate locations within the network, these technologies help reduce voltage fluctuations, improve power transfer capability, and enhance overall system reliability. As power systems continue to evolve with increased renewable energy penetration, dynamic reactive power allocation mechanisms are expected to play an increasingly important role in maintaining voltage stability and supporting efficient grid operation (Song and Johns, 1999).

2. FUNDAMENTALS OF REACTIVE POWER AND VOLTAGE REGULATION

Voltage regulation and system stability in electrical power networks are closely related to the effective management of reactive power. In alternating current (AC) power systems, reactive power plays a crucial role in sustaining voltage magnitude, enabling efficient power transfer, and ensuring the proper operation of electrical equipment. Without adequate reactive power support, voltage levels may deviate from acceptable limits, resulting in reduced system reliability and increased operational risks. Understanding the fundamentals of reactive power and its relationship with voltage control is therefore essential for designing effective voltage regulation strategies, particularly in modern grids with high penetration of renewable energy resources and distributed generation.

2.1 Concept of Reactive Power in Power Systems

Reactive power is the component of electrical power that oscillates between the source and reactive elements in an AC system without being converted into useful work. It arises due to the presence of inductive and capacitive components in electrical networks, which cause a phase difference between voltage and current. Inductive devices such as transformers, motors, and reactors require reactive power to establish and maintain magnetic fields necessary for their operation. Capacitive components, on the other hand, can supply reactive power to the system and help balance inductive demand (Grainger and Stevenson, 1994).

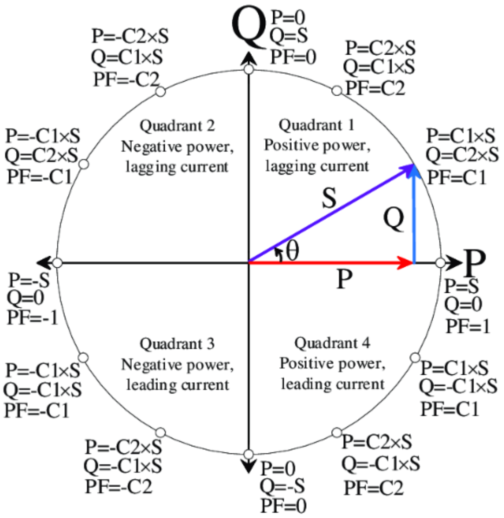

Figure-1: Reactive Power and Voltage Relationship

Although reactive power does not directly contribute to real energy transfer, it is essential for maintaining appropriate voltage levels throughout the network. A sufficient supply of reactive power ensures that voltage magnitudes remain stable at various buses in the power system. If reactive power is not adequately managed, voltage levels may fluctuate significantly, leading to poor power quality and potential instability. Therefore, reactive power compensation and control are critical aspects of power system operation and planning, particularly in large interconnected networks (Wood, Wollenberg and Sheblé, 2013).

2.2 Relationship Between Reactive Power and Voltage Profile

The voltage profile of a power system refers to the variation of voltage magnitude across different buses within the network. Reactive power has a direct influence on the voltage magnitude in transmission and distribution systems. When reactive power demand increases, especially in heavily loaded lines or inductive loads, the voltage magnitude tends to decrease due to increased reactive power losses along transmission lines. Conversely, injecting reactive power into the system can raise voltage levels and improve voltage stability (Glover, Sarma and Overbye, 2017).

In situations where reactive power support is insufficient, higher currents are required to transfer the same amount of real power. This increase in current flow leads to higher I^2R losses in transmission lines and transformers, reducing overall system efficiency. Additionally, excessive voltage drops may limit the amount of power that can be transmitted safely through the network. Proper reactive power management through compensation devices and voltage control strategies helps maintain voltage within acceptable limits, improves transmission capacity, and enhances the overall operational efficiency of the power system (Sauer and Pai, 1998).

2.3 Voltage Stability and Voltage Collapse Mechanisms

Voltage stability refers to the ability of a power system to maintain acceptable voltage levels under normal operating conditions as well as after disturbances such as faults, sudden load increases, or generation outages. Voltage instability occurs when the power system fails to supply the required reactive power to meet demand, resulting in a progressive decline in voltage magnitude. Depending on the time scale and system conditions, voltage stability can be categorized into steady-state voltage stability, transient voltage stability, and long-term voltage stability. Steady-state voltage stability deals with the system’s ability to maintain voltage during gradual load changes, whereas transient voltage stability focuses on system behavior following large disturbances such as faults (Kundur et al., 2004).

Long-term voltage stability involves slower processes such as transformer tap changes, load recovery dynamics, and generator reactive power limits. When the reactive power demand exceeds the available supply for an extended period, the system may experience voltage collapse, a phenomenon characterized by a rapid and uncontrollable drop in voltage levels across the network. Voltage collapse can lead to widespread blackouts if corrective actions are not taken promptly. For this reason, modern power systems employ various reactive power compensation techniques and dynamic control mechanisms to maintain voltage stability and prevent collapse scenarios (Van Cutsem and Vournas, 1998).

3. REACTIVE POWER COMPENSATION TECHNOLOGIES

Reactive power compensation technologies are essential for maintaining voltage stability and improving the operational efficiency of power systems. In electrical networks, reactive power imbalance can lead to voltage fluctuations, increased transmission losses, and reduced power transfer capability. To address these issues, various compensation technologies have been developed to provide reactive power support at different levels of the power system. These technologies range from conventional mechanical devices to advanced power electronic-based compensators that offer fast and flexible voltage control. The selection of appropriate compensation technology depends on system requirements, response speed, economic considerations, and the operating characteristics of the grid (Glover, Sarma and Overbye, 2017).

3.1 Conventional Reactive Power Compensation Devices

Traditional reactive power compensation devices have been widely used in power systems for several decades to maintain voltage levels and improve power factor. These devices generally rely on passive components or rotating machines to provide reactive power support. Conventional compensation methods are relatively simple, reliable, and cost-effective, making them suitable for many transmission and distribution applications. However, their response speed and controllability are limited compared with modern power electronic solutions. As power systems become more dynamic due to renewable energy integration and fluctuating loads, the limitations of conventional devices have become more evident (Grainger and Stevenson, 1994).

3.1.1 Shunt Capacitor Banks

Shunt capacitor banks are among the most commonly used reactive power compensation devices in power systems. They are connected in parallel with the load or transmission line and provide capacitive reactive power to counteract the inductive reactive power demand of loads such as motors and transformers. By supplying reactive power locally, shunt capacitors help improve voltage levels, reduce line losses, and enhance the power factor of the system. Their simple design, low installation cost, and minimal maintenance requirements make them a popular solution in both transmission and distribution networks (Bollen and Hassan, 2011).

Despite these advantages, shunt capacitor banks have certain limitations. Their operation is generally based on mechanical switching, which results in relatively slow response times compared with dynamic compensation devices. Additionally, capacitor banks provide fixed or stepwise reactive power support, which may not be sufficient in systems experiencing rapid voltage fluctuations.

In networks with significant load variations or renewable energy penetration, these limitations can reduce the effectiveness of capacitor banks in maintaining voltage stability.

3.1.2 Synchronous Condensers

Synchronous condensers are rotating synchronous machines that operate without a mechanical load and are specifically designed to provide reactive power support to the grid. By adjusting the excitation current of the rotor winding, the synchronous condenser can either generate or absorb reactive power, thereby regulating the voltage level of the connected bus. This capability makes synchronous condensers highly effective in improving voltage stability and enhancing system reliability (Kundur, 1994).

Another important advantage of synchronous condensers is their ability to contribute to short-circuit power and system inertia, which can be beneficial for maintaining grid stability during disturbances. However, these machines require regular maintenance due to their mechanical components and typically involve higher installation and operational costs compared with passive compensation devices. Consequently, although they provide flexible reactive power support, their application is often limited to large transmission systems or critical grid locations.

3.2 Power Electronic Based Dynamic Compensation Devices

With the increasing complexity of modern power systems, power electronic-based compensation technologies have gained significant importance. These devices are capable of providing fast and continuous reactive power control, making them highly suitable for dynamic voltage regulation. Flexible AC Transmission System (FACTS) devices utilize high-speed power electronic switches and advanced control algorithms to regulate voltage, control power flow, and enhance system stability. Compared with conventional compensation methods, these technologies offer superior response speed, higher controllability, and improved performance under varying system conditions (Hingorani and Gyugyi, 2000).

3.2.1 Static Var Compensator (SVC)

The Static Var Compensator (SVC) is one of the earliest FACTS devices used for reactive power compensation in power systems. It consists of thyristor-controlled reactors (TCR) and thyristor-switched capacitors (TSC), which are connected in shunt with the power system. By controlling the firing angle of thyristors, the SVC can dynamically adjust the amount of reactive power injected or absorbed, allowing it to regulate voltage levels effectively.

SVCs are widely used in transmission networks to improve voltage stability, reduce voltage fluctuations, and increase power transfer capability. Their relatively fast response time compared with conventional devices enables them to respond quickly to load changes and system disturbances. However, since SVC performance depends on the system voltage magnitude, its reactive power capability decreases significantly when the system voltage drops to very low levels (Song and Johns, 1999).

3.2.2 Static Synchronous Compensator (STATCOM)

The Static Synchronous Compensator (STATCOM) is a voltage source converter (VSC)-based FACTS device designed to provide rapid and flexible reactive power support. Unlike SVCs, which rely on passive components such as capacitors and reactors, STATCOM uses a power electronic converter to generate a controllable AC voltage that can exchange reactive power with the grid. This design enables STATCOM to maintain its reactive power output even under low voltage conditions, making it particularly effective in weak grid environments (Zhang, Rehtanz and Pal, 2006).

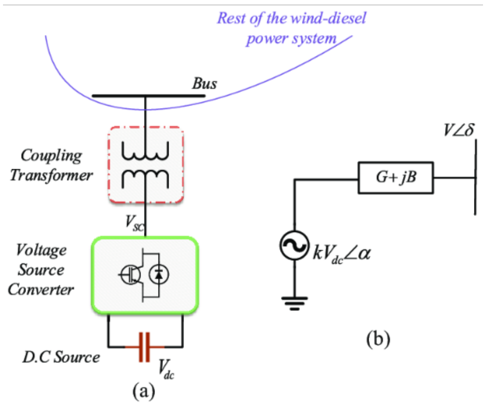

Figure-2: Basic Configuration of STATCOM

STATCOM devices offer several advantages, including fast dynamic response, compact size, and improved voltage regulation capability. They are widely applied in renewable energy integration, transmission system stabilization, and power quality improvement. Due to their superior performance, STATCOMs have become one of the most preferred solutions for dynamic reactive power compensation in modern power systems.

3.2.3 Distribution STATCOM (DSTATCOM)

The Distribution Static Synchronous Compensator (DSTATCOM) is a modified version of STATCOM specifically designed for distribution networks. It is primarily used to improve voltage regulation, correct power factor, and mitigate power quality problems in distribution systems with fluctuating loads and distributed generation sources. DSTATCOM is typically installed near load centers or renewable energy integration points to provide localized reactive power support (Akagi, 2006).

In distribution systems with high penetration of renewable energy sources such as solar photovoltaic systems and wind turbines, voltage fluctuations can occur frequently due to intermittent power generation. DSTATCOM devices help stabilize voltage levels by dynamically adjusting reactive power injection, thereby improving system reliability and power quality. Their fast response and flexible control capabilities make them well suited for modern smart grid applications.

3.3 Hybrid Compensation Systems

Hybrid reactive power compensation systems combine different compensation technologies to achieve improved performance and operational flexibility. These systems typically integrate conventional devices such as capacitor banks with advanced FACTS devices like STATCOM or SVC. In some cases, energy storage systems are also incorporated to provide additional active and reactive power support. The combination of multiple technologies enables hybrid systems to provide both steady-state and dynamic voltage regulation capabilities.

Hybrid compensation systems offer several advantages, including improved voltage control, enhanced reliability, and optimized system operation under varying load conditions. By coordinating different compensation devices, these systems can effectively manage reactive power requirements across multiple time scales. Such integrated solutions are increasingly being adopted in modern power systems, particularly in networks with high renewable energy penetration and weak grid conditions (Padiyar, 2007).

4. DYNAMIC REACTIVE POWER ALLOCATION MECHANISMS

Dynamic reactive power allocation mechanisms are essential for maintaining voltage stability and improving the operational efficiency of modern power systems. As power networks become increasingly complex due to the integration of renewable energy resources, distributed generation, and variable loads, traditional static reactive power compensation methods may not be sufficient to address rapid voltage fluctuations. Dynamic allocation mechanisms enable the real-time distribution of reactive power support across different locations in the power network to maintain acceptable voltage levels and reduce system losses. These mechanisms typically employ advanced optimization techniques, sensitivity analysis, and coordinated control strategies to determine the optimal reactive power injection from various compensation devices and distributed resources (Padiyar, 2007).

4.1 Optimal Reactive Power Dispatch (ORPD) Techniques

Optimal Reactive Power Dispatch (ORPD) is an important optimization problem in power system operation that focuses on determining the optimal settings of reactive power control variables to improve voltage stability and minimize transmission losses. ORPD techniques aim to identify the optimal combination of generator voltages, transformer tap settings, and reactive power injections from compensation devices such as capacitor banks, SVCs, and STATCOMs. The objective functions of ORPD commonly include minimization of real power losses, improvement of voltage profile, and enhancement of voltage stability margins.

To solve the ORPD problem, various mathematical and computational optimization algorithms have been developed. Traditional methods include linear programming, nonlinear programming, and interior-point optimization techniques. In recent years, metaheuristic algorithms such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Differential Evolution (DE), and Ant Colony Optimization (ACO) have gained significant attention due to their ability to handle complex, nonlinear, and multi-objective optimization problems in power systems (Abido, 2002). These techniques enable power system operators to determine the optimal allocation and control of reactive power resources while satisfying system constraints such as voltage limits, generator capability curves, and transmission line capacity.

4.2 Sensitivity-Based Reactive Power Allocation

Sensitivity-based reactive power allocation methods are widely used to identify the most effective locations for reactive power compensation in power networks. These methods rely on sensitivity indices that quantify the relationship between reactive power injections and voltage variations at different buses within the system. By analyzing these indices, system operators can determine which buses are most sensitive to reactive power changes and therefore require compensation devices to improve voltage stability.

Commonly used sensitivity indices include voltage sensitivity factors, reactive power sensitivity indices, and voltage stability indices derived from power flow analysis. These indicators help evaluate the impact of reactive power injections on system voltage and allow for the strategic placement of compensation devices. Sensitivity analysis is computationally efficient and can be applied to large-scale power systems to identify critical buses with high voltage instability risk. Consequently, it has become an important tool for planning reactive power support and improving voltage regulation in weak grid environments (Van Cutsem and Vournas, 1998).

4.3 Distributed and Decentralized Reactive Power Control

With the increasing penetration of distributed energy resources (DERs) such as photovoltaic systems, wind turbines, and battery storage systems, distributed and decentralized reactive power control strategies have gained significant attention. Unlike traditional centralized control approaches, distributed control allows multiple reactive power sources across the network to operate autonomously or collaboratively to maintain voltage stability. This approach improves system flexibility and reduces the reliance on centralized control infrastructure.

In distributed control systems, local controllers installed in inverters or compensation devices can adjust reactive power output based on locally measured voltage conditions. Communication networks may also be used to coordinate reactive power support among different distributed resources to achieve system-wide voltage regulation. Such decentralized control strategies are particularly suitable for microgrids and smart grids, where numerous small-scale generation units are connected to the distribution network. By enabling local decision-making and coordination among distributed resources, these control approaches enhance system resilience and improve voltage regulation in dynamic operating environments (Lasseter, 2002).

4.4 Coordinated Volt-VAR Control Strategies

Coordinated Volt-VAR control strategies focus on managing reactive power resources across different components of the power system to maintain voltage within acceptable limits. Volt-VAR control involves the coordinated operation of voltage control devices such as on-load tap-changing transformers, capacitor banks, voltage regulators, and power electronic compensators. By properly coordinating these devices, system operators can maintain stable voltage profiles across transmission and distribution networks.

In modern power systems, coordinated Volt-VAR control also involves distributed energy resources and inverter-based generation units. Advanced inverter control strategies allow renewable energy systems to provide reactive power support in addition to active power generation. Through coordinated control algorithms, these distributed resources can collectively contribute to voltage regulation and reduce the need for traditional compensation devices. This integrated approach enhances voltage stability, improves power quality, and increases the hosting capacity of renewable energy sources within the power grid (Turitsyn et al., 2011).

5. LITERATURE REVIEW OF DYNAMIC REACTIVE POWER ALLOCATION METHODS

The increasing complexity of modern power systems has encouraged extensive research on dynamic reactive power allocation techniques for improving voltage stability and maintaining reliable grid operation. A significant number of studies have investigated optimization-based methods, intelligent control approaches, and coordinated compensation strategies for efficient reactive power management. These studies aim to address issues such as voltage instability, transmission losses, and fluctuating power generation, particularly in networks with high renewable energy penetration and weak grid conditions. The literature highlights that advanced computational techniques and power electronic devices have significantly improved the capability of power systems to dynamically regulate reactive power and maintain stable voltage profiles (Taylor, 1994).

5.1 Early Research on Reactive Power Optimization

Early research on reactive power allocation primarily focused on mathematical optimization techniques designed to determine optimal reactive power dispatch within power systems. Linear programming and nonlinear programming were among the earliest methods used to solve reactive power optimization problems by minimizing transmission losses and maintaining acceptable voltage levels. These approaches were effective for relatively small and well-structured systems but often faced limitations when dealing with highly nonlinear and complex power system models (Carpentier, 1962).

Subsequent studies introduced more advanced optimization algorithms capable of addressing the nonlinear characteristics of power system operation. Techniques such as particle swarm optimization (PSO), genetic algorithms (GA), and evolutionary programming were widely adopted to solve optimal reactive power dispatch problems more efficiently. These metaheuristic algorithms provided better global search capability and improved convergence performance compared with traditional mathematical programming methods, making them suitable for large-scale power system optimization problems (Abido, 2002).

5.2 Reactive Power Allocation in Renewable Energy Integrated Grids

The integration of renewable energy sources such as wind and solar power has significantly changed the operational characteristics of power systems. Renewable energy generators are typically connected through power electronic converters, which may not inherently provide sufficient reactive power support. As a result, high penetration of renewable energy sources can introduce voltage fluctuations and reactive power imbalances, particularly in weak grid environments. Several studies have emphasized the need for advanced reactive power control strategies to maintain voltage stability in renewable-dominated power networks (Blaabjerg, Teodorescu and Liserre, 2006).

Research has also shown that the variability and intermittency of renewable generation require dynamic reactive power compensation to maintain stable voltage profiles. Coordinated control strategies involving inverter-based generators, flexible AC transmission system devices, and distributed reactive power compensators have been proposed to address these challenges. These approaches enable renewable energy systems to participate in voltage regulation and contribute to overall grid stability (Liserre, Sauter and Hung, 2010).

5.3 Intelligent and AI-Based Reactive Power Control Methods

Recent developments in artificial intelligence have led to the emergence of intelligent reactive power control techniques capable of adapting to changing grid conditions. Machine learning algorithms, neural networks, and adaptive control strategies have been applied to optimize reactive power allocation and improve voltage stability. These intelligent approaches can analyze large volumes of operational data and learn system behavior patterns, enabling faster and more accurate control decisions compared with conventional methods (Zhang and Li, 2007).

Among these techniques, adaptive neuro-fuzzy inference system (ANFIS)-based controllers have gained attention for reactive power control applications. ANFIS combines the learning capability of neural networks with the reasoning mechanism of fuzzy logic to provide adaptive and robust voltage regulation. Several studies have demonstrated that ANFIS-controlled DSTATCOM devices can effectively regulate reactive power in distribution systems, reduce voltage fluctuations, and improve overall power quality under varying load and generation conditions (Singh, Chandra and Al-Haddad, 2015).

5.4 Optimization-Based Dynamic Allocation Techniques

Optimization-based dynamic allocation techniques focus on determining the optimal placement and capacity of reactive power compensation devices within power networks. Researchers have proposed various optimization frameworks that simultaneously consider voltage stability improvement, reduction of transmission losses, and economic cost minimization. These optimization problems are often formulated as multi-objective problems with several operational constraints such as voltage limits, generator reactive power capability, and transmission line capacity (Momoh et al., 1999).

To address these complex optimization challenges, metaheuristic algorithms such as differential evolution, ant colony optimization, simulated annealing, and hybrid optimization techniques have been widely explored in recent studies. These algorithms are capable of handling nonlinear and multi-dimensional optimization problems efficiently and have shown promising results in identifying optimal locations and ratings of compensation devices such as SVC, STATCOM, and capacitor banks. Such techniques have become an important component of modern reactive power planning and voltage stability enhancement strategies (Zhang, Rehtanz and Pal, 2006).

5.5 Comparative Analysis of Existing Methods

The literature on reactive power allocation methods reveals that each technique offers specific advantages and limitations depending on system requirements and operating conditions. Traditional optimization methods are mathematically rigorous and computationally efficient for small systems but may struggle with highly nonlinear and large-scale problems. Metaheuristic algorithms provide better global search capability and flexibility, although they may require higher computational effort and careful parameter tuning.

Intelligent control methods based on artificial intelligence offer adaptive and data-driven solutions that can respond effectively to dynamic grid conditions. However, these methods often require large training datasets and may involve complex implementation procedures. Similarly, coordinated control strategies involving distributed energy resources and power electronic devices provide improved voltage regulation but depend heavily on communication infrastructure and system coordination mechanisms. Consequently, selecting an appropriate reactive power allocation strategy requires careful consideration of response speed, computational complexity, scalability, and practical implementation constraints within the power system environment (Kundur et al., 2004).

6. CHALLENGES IN DYNAMIC REACTIVE POWER ALLOCATION FOR WEAK GRIDS

The implementation of dynamic reactive power allocation mechanisms in weak grid environments presents several technical and operational challenges. Weak grids are typically characterized by low short-circuit capacity, high impedance, and limited voltage regulation capability, which makes them highly sensitive to disturbances and fluctuations in power generation and demand. Although advanced reactive power compensation technologies such as STATCOM, SVC, and distributed inverter-based resources have improved voltage control capabilities, several issues still hinder their effective deployment and coordination. These challenges include variability in renewable energy generation, communication and coordination difficulties among distributed devices, and economic constraints associated with the installation and operation of compensation technologies (Van Cutsem and Vournas, 1998).

6.1 Renewable Energy Variability

One of the major challenges in reactive power management for weak grids is the variability and intermittency of renewable energy sources such as wind and solar power. Unlike conventional power plants, renewable energy generators depend heavily on environmental conditions, which results in fluctuating power output. Variations in solar irradiance or wind speed can lead to sudden changes in active power generation, which in turn affects the reactive power balance and voltage profile of the power system. These fluctuations can cause voltage instability, particularly in weak grid regions where the network has limited capability to absorb disturbances (Ackermann, 2005).

In addition, many renewable energy systems are connected to the grid through power electronic converters, which may have limited reactive power capability depending on their design and control strategy. When large-scale renewable integration occurs in remote areas with long transmission lines, the resulting reactive power deficiency may cause significant voltage drops or oscillations in the network. Consequently, maintaining voltage stability in renewable-rich weak grids requires advanced reactive power control strategies capable of responding rapidly to generation variability and dynamic operating conditions (Blaabjerg et al., 2017).

6.2 Communication and Coordination Issues

Another critical challenge in dynamic reactive power allocation is the coordination of multiple reactive power sources distributed across the power network. In modern smart grids and microgrids, numerous devices such as distributed generators, inverter-based renewable systems, capacitor banks, and FACTS devices contribute to voltage regulation. Effective coordination among these devices requires reliable communication infrastructure and advanced control algorithms capable of managing real-time data exchange and control signals.

However, communication delays, data synchronization issues, and cybersecurity concerns can significantly affect the performance of distributed reactive power control systems. If communication between controllers and compensation devices is disrupted or delayed, the system may fail to respond quickly to voltage fluctuations, potentially leading to instability. Furthermore, coordinating reactive power support among multiple distributed energy resources is computationally complex and requires robust control frameworks to ensure stable system operation (Lasseter, 2002).

6.3 Economic and Operational Constraints

Economic considerations also play an important role in the deployment of reactive power compensation technologies in power systems. Advanced dynamic compensation devices such as STATCOM and SVC require significant capital investment for installation, as well as operational and maintenance costs throughout their service life. Utilities and system operators must carefully evaluate the cost–benefit ratio when planning reactive power compensation infrastructure, particularly in developing regions or small power networks where financial resources may be limited (Hingorani and Gyugyi, 2000).

Operational constraints also influence the effectiveness of reactive power allocation strategies. These include limitations on generator reactive power capability, transformer tap-changing restrictions, and thermal limits of transmission lines. Additionally, integrating multiple compensation devices within the network requires careful planning to avoid control conflicts and inefficient operation. As power systems continue to evolve with increased renewable integration and distributed generation, addressing these economic and operational challenges will be essential for the successful implementation of dynamic reactive power allocation mechanisms in weak grid environments (Wood, Wollenberg and Sheblé, 2013).

7. CONCLUSION

This review paper has presented a comprehensive analysis of dynamic reactive power allocation mechanisms for voltage profile enhancement in weak grid conditions. The study highlighted the fundamental role of reactive power in maintaining voltage stability and ensuring reliable operation of modern power systems. With the increasing penetration of renewable energy sources and distributed generation, maintaining voltage profiles within acceptable limits has become more challenging, particularly in weak grid environments characterized by low short-circuit capacity and high network impedance.

The review discussed various reactive power compensation technologies, including conventional devices such as shunt capacitor banks and synchronous condensers, as well as advanced power electronic-based solutions like Static Var Compensators (SVC), Static Synchronous Compensators (STATCOM), and Distribution STATCOM (DSTATCOM). These technologies provide flexible and dynamic reactive power support, enabling faster response to voltage fluctuations and system disturbances. In addition, several dynamic reactive power allocation strategies were examined, including optimal reactive power dispatch, sensitivity-based allocation techniques, distributed control methods, and coordinated Volt–VAR control strategies.

The literature review revealed that modern optimization algorithms, metaheuristic techniques, and artificial intelligence-based control approaches have significantly improved the effectiveness of reactive power management in complex power networks. However, challenges such as renewable energy variability, communication constraints, and economic considerations still influence the practical implementation of these techniques. Overall, dynamic reactive power allocation plays a crucial role in improving voltage stability, enhancing power system reliability, and supporting the integration of renewable energy sources in weak grid environments. Future research should focus on intelligent control frameworks and coordinated reactive power management strategies to further strengthen voltage stability in evolving power systems.

7.1.Limitations of the Review

Although this review provides a structured overview of dynamic reactive power allocation mechanisms and related compensation technologies, certain limitations should be acknowledged. The study primarily focuses on conceptual and methodological developments reported in the literature and does not include detailed simulation or experimental validation of the discussed techniques. Additionally, the review emphasizes widely adopted compensation devices and optimization methods, while some emerging technologies and region-specific grid management practices may not be fully covered. Another limitation is that the comparative analysis is based on findings reported in existing publications, which may vary in terms of system configuration, assumptions, and evaluation metrics. Therefore, the practical performance of different reactive power allocation strategies may differ depending on specific power system conditions and operational requirements.

REFERENCES

1. Abido, M.A. (2002) 'Optimal power flow using particle swarm optimization', International Journal of Electrical Power & Energy Systems, 24(7), pp. 563–571.
2. Ackermann, T. (2005) Wind Power in Power Systems. Chichester: John Wiley & Sons.
3. Akagi, H. (2006) 'Modern active filters and traditional passive filters', Bulletin of the Polish Academy of Sciences: Technical Sciences, 54(3), pp. 255–269.
4. Blaabjerg, F., Teodorescu, R. and Liserre, M. (2006) 'Overview of control and grid synchronization for distributed power generation systems', IEEE Transactions on Industrial Electronics, 53(5), pp. 1398–1409.
5. Blaabjerg, F., Yang, Y., Yang, D. and Wang, X. (2017) 'Distributed power-generation systems and protection', Proceedings of the IEEE, 105(7), pp. 1311–1331.
6. Bollen, M.H.J. and Hassan, F. (2011) Integration of Distributed Generation in the Power System. Hoboken: John Wiley & Sons.
7. Carpentier, J. (1962) 'Contribution to the economic dispatch problem', Bulletin de la Société Française des Électriciens, 3(8), pp. 431–447.
8. Glover, J.D., Sarma, M.S. and Overbye, T. (2017) Power System Analysis and Design. 6th edn. Boston: Cengage Learning.
9. Grainger, J.J. and Stevenson, W.D. (1994) Power System Analysis. New York: McGraw-Hill.
10. Hingorani, N.G. and Gyugyi, L. (2000) Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems. New York: IEEE Press.
11. Kundur, P. (1994) Power System Stability and Control. New York: McGraw-Hill.
12. Kundur, P., Balu, N.J. and Lauby, M.G. (2004) 'Definition and classification of power system stability', IEEE Transactions on Power Systems, 19(2), pp. 1387–1401.
13. Lasseter, R.H. (2002) 'Microgrids', IEEE Power Engineering Society Winter Meeting, pp. 305–308.
14. Liserre, M., Sauter, T. and Hung, J.Y. (2010) 'Future energy systems: Integrating renewable energy sources into the smart power grid', IEEE Industrial Electronics Magazine, 4(1), pp. 18–37.
15. Momoh, J.A., El-Hawary, M.E. and Adapa, R. (1999) 'A review of selected optimal power flow literature to 1993', IEEE Transactions on Power Systems, 14(1), pp. 96–104.
16. Padiyar, K.R. (2007) FACTS Controllers in Power Transmission and Distribution. New Delhi: New Age International.
17. Sauer, P.W. and Pai, M.A. (1998) Power System Dynamics and Stability. Upper Saddle River: Prentice Hall.
18. Singh, B., Chandra, A. and Al-Haddad, K. (2015) Power Quality: Problems and Mitigation Techniques. Hoboken: John Wiley & Sons.
19. Song, Y.H. and Johns, A.T. (1999) Flexible AC Transmission Systems (FACTS). London: Institution of Engineering and Technology.
20. Taylor, C.W. (1994) Power System Voltage Stability. New York: McGraw-Hill.
21. Turitsyn, K., Sulc, P., Backhaus, S. and Chertkov, M. (2011) 'Options for control of reactive power by distributed photovoltaic generators', Proceedings of the IEEE, 99(6), pp. 1063–1073.
22. Van Cutsem, T. and Vournas, C. (1998) Voltage Stability of Electric Power Systems. Boston: Springer.
23. Wood, A.J., Wollenberg, B.F. and Sheblé, G.B. (2013) Power Generation, Operation, and Control. 3rd edn. Hoboken: John Wiley & Sons.
24. Zhang, X.P., Rehtanz, C. and Pal, B. (2006) Flexible AC Transmission Systems: Modelling and Control. Berlin: Springer.

25. Zhang, Y. and Li, Y. (2007) ‘Application of neural networks to reactive power optimization’, Electric Power Systems Research, 77(3–4), pp. 285–291.
26. Abdelaziz, A.Y., Ali, E.S. and Elazim, S.M.A. (2010) ‘Combined economic and emission dispatch solution using Flower Pollination Algorithm’, International Journal of Electrical Power & Energy Systems, 80, pp. 264–274.
27. Abdelaziz, A.Y. and Ali, E.S. (2016) ‘Cuckoo search algorithm for optimal reactive power dispatch problem’, Energy, 95, pp. 33–40.
28. Abido, M.A. (2000) ‘Optimal power flow using evolutionary algorithms’, Electric Power and Energy Systems, 24(7), pp. 563–571.
29. Abdul-Rahman, K.H. and Shahidehpour, S.M. (1994) ‘Application of fuzzy sets to optimal reactive power planning with security constraints’, IEEE Transactions on Power Systems, 9(2), pp. 589–597.
30. Ajjarapu, V. and Lee, B. (1998) ‘Bibliography on voltage stability’, IEEE Transactions on Power Systems, 13(1), pp. 115–125.
31. Ajjarapu, V., Lau, P.L. and Battula, S. (1994) ‘An optimal reactive power planning strategy against voltage collapse’, IEEE Transactions on Power Systems, 9(2), pp. 906–917.
32. Aoki, K., Fan, M. and Nishikori, A. (1988) ‘Optimal VAr planning by approximation method for recursive mixed integer linear programming’, IEEE Transactions on Power Apparatus and Systems, PAS-107(7), pp. 1741–1747.
33. Bhattacharya, K. and Zhong, J. (2001) ‘Reactive power as an ancillary service’, IEEE Transactions on Power Systems, 16(2), pp. 294–300.
34. Chang, N.E. (1969) ‘Locating shunt capacitors on primary feeder for voltage control and loss reduction’, IEEE Transactions on Power Apparatus and Systems, PAS-88(10), pp. 1574–1577.
35. Conejo, A.J., Galiana, F.D. and Kockar, I. (2001) ‘Z-bus loss allocation’, IEEE Transactions on Power Systems, 16(1), pp. 105–110.
36. Devaraj, D. and Yegnanarayana, B. (2005) ‘Genetic algorithm based optimal power flow for security enhancement’, Electric Power Systems Research, 73(2), pp. 215–222.
37. El-Hawary, M.E. and Mohamed, A.A. (2000) ‘Reactive power management using evolutionary programming’, IEEE Transactions on Power Systems, 15(4), pp. 1242–1248.
38. Farhat, I.A. and El-Hawary, M.E. (2010) ‘Dynamic reactive power planning using evolutionary programming’, Electric Power Systems Research, 80(4), pp. 453–460.
39. Gandomkar, M., Vakilian, M. and Ehsan, M. (2005) ‘A combination of genetic algorithm and simulated annealing for optimal reactive power dispatch’, Electric Power and Energy Systems, 27(6–7), pp. 419–423.
40. Hatziargyriou, N. (2014) Microgrids: Architectures and Control. Hoboken: Wiley-IEEE Press.
41. Hassan, M.Y., Majid, M.S. and Rahman, H.A. (2009) ‘Optimal placement and sizing of distributed generation using particle swarm optimization’, Energy Conversion and Management, 50(4), pp. 115–121.
42. Jabr, R.A. (2013) ‘Radial distribution load flow using conic programming’, IEEE Transactions on Power Systems, 21(3), pp. 1458–1459.
43. Lee, K.Y., Paru, Y.M. and Oritz, J.L. (1985) ‘A united approach to optimal real and reactive power dispatch’, IEEE Transactions on Power Apparatus and Systems, PAS-104(5), pp. 1147–1153.
44. Li, Y., Wu, Q., Oren, S. and Li, Z. (2014) ‘Distribution locational marginal pricing for optimal electric vehicle charging management’, IEEE Transactions on Power Systems, 29(1), pp. 203–211.
45. Liu, Q., Li, Y. and Shen, X. (2017) ‘A new approach for reactive power optimization using multi-objective particle swarm optimization’, Electric Power Systems Research, 152, pp. 265–275.
46. Lu, Z., Wen, F. and Ledwich, G. (2004) ‘Optimal siting and sizing of distributed generators in distribution networks’, Electric Power Systems Research, 63(3), pp. 235–244.
47. Moghaddam, A.A., Seifi, H. and Sheikh-El-Eslami, M.K. (2010) ‘Multi-objective reactive power planning’, Energy Conversion and Management, 51(9), pp. 1926–1933.
48. Moradi, M.H. and Abedini, M. (2012) ‘A combination of genetic algorithm and particle swarm optimization for optimal DG location and sizing’, Electric Power and Energy Systems, 34(1), pp. 66–74.
49. Nguyen, T.T. and Mohammadi, F. (2020) ‘Optimal placement of TCSC for congestion management’, Energy Reports, 6, pp. 166–174.

50. Ongsakul, W. and Tantimaporn, T. (2006) 'Optimal power flow by improved evolutionary programming', Electric Power Components and Systems, 34(1), pp. 79–95.

51. Pandya, S. and Joshi, S. (2008) 'A survey of optimal reactive power dispatch methods', Journal of Electrical Engineering, 59(5), pp. 248–254.

52. Roy, P.K. and Ghoshal, S.P. (2012) 'Optimal reactive power dispatch using biogeography-based optimization', International Journal of Electrical Power & Energy Systems, 43(1), pp. 830–838.

53. Sinsuphan, N., Leeton, U., Kulworawanichpong, T. and Pothiya, S. (2013) 'Optimal power flow using cuckoo search algorithm', Energy Conversion and Management, 69, pp. 75–82.

54. Sode-Yome, A., Mithulananthan, N. and Lee, K.Y. (2007) 'A comprehensive comparison of FACTS devices for enhancing voltage stability', Electric Power Systems Research, 77(5–6), pp. 695–703.

55. Talebi, N., Hosseini, S.H. and Aghaei, J. (2014) 'Voltage stability improvement using optimal allocation of FACTS devices', Energy Conversion and Management, 85, pp. 281–290.

56. Varadarajan, M. and Swarup, K.S. (2008) 'Differential evolution approach for optimal reactive power dispatch', Applied Soft Computing, 8(4), pp. 1549–1561.

57. Venkatesh, B., Ranjan, R. and Gooi, H.B. (2004) 'Optimal reconfiguration of radial distribution systems', IEEE Transactions on Power Delivery, 19(2), pp. 524–529.

58. Wang, Q., Li, F. and Tang, Y. (2016) 'Optimal Volt-VAR control in active distribution networks', IEEE Transactions on Smart Grid, 7(2), pp. 635–645.

59. Zhang, Y., Wang, J. and Liu, X. (2018) 'Optimal reactive power planning in distribution networks', Electric Power Systems Research, 155, pp. 218–225.

60. Zhu, J. (2009) Optimization of Power System Operation. Hoboken: Wiley-IEEE Press.