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Research Article

# UPQC With Fuzzy Controlled Based Wind Farm To Weak-Grid Connection For Power Quality Improvement

**Budiga Rakesh[1*], T. Anil Kumar[2]**

***Abstract***

Wind energy producing facilities are often located based on the presence of wind resources, resulting in their construction in remote places that are far from high voltage power transmission lines and large consumption centers. Wind farms that use squirrel cage induction generators (SCIG) directly linked to the power grid constitute a substantial proportion of wind energy conversion systems worldwide. However, in situations when wind farms are linked via medium voltage (MV) distribution lines because of controlled electricity output, a prevalent problem occurs called Wind Farm to Weak Grid Connection. This scenario is characterized by power production that is similar to the capacity of the grid for transportation, leading to inadequate control of voltage at the point where the grid is connected (PCC). This work presents a new compensation method that utilizes the Unified Power Quality Compensator (UPQC) with a unique internal control system based on fuzzy logic controllers. The aim is to tackle the difficulties related to connecting Wind Farms to weak grids. The UPQC, which is a Custom Power System (CUPS) device, presents a possible alternative for improving power quality in such situations. The suggested compensation technique entails the use of the UPQC series converter to regulate voltage at the WF terminals, while using the shunt converter to filter power provided by the WF and reduce voltage swings at the grid side. The internal control approach prioritizes the regulation of active and reactive power in converters and the transfer of power between them via the UPQC DC-Link. The suggested technique differs from traditional tactics by using both reactive power and DC-bus energy storage to optimize compensating capabilities. Additionally, it involves active power sharing amongst UPQC converters. The efficacy of the fuzzy logic improved UPQC compensating technique in enhancing both Power Quality and Wind Farm stability is proven via meticulous simulations.

**Keywords**— wind energy, Wind Farms, squirrel cage induction generators, grid connection, Unified Power Quality Compensator, fuzzy logic controllers, power quality

## I. INTRODUCTION

Integrating wind farms into fragile grid systems presents substantial difficulties in preserving electricity quality [1]. Researchers have investigated the use of UPQC with Fuzzy Control in wind farm connections to unstable power networks [2]. This technique signifies a crucial breakthrough in the realm of power systems and renewable energy. In the past, weak-grid connections have had voltage sags, harmonics, and other power quality problems mostly because of the intermittent nature of wind power output [3]. The notion of UPQC has gained popularity as a solution to these difficulties. The UPQC is a multifunctional device that can effectively address both voltage and current disturbances at the same time [4]. Nevertheless, in order to enhance its efficiency in wind farm connections,

[1*]PG Scholar, Department of EEE, Anurag University, Hyderabad, Telangana.
rakeshgoudbudiga@gmail.com
[2]Professor and Head, Department of EEE, Anurag University, Hyderabad, Telangana.
thalluruanil@gmail.com

researchers have resorted to using Fuzzy Control. Fuzzy Control, which incorporates the handling of uncertainty and imprecision, is well-suited to complement UPQC in this particular situation [5]. The use of the fuzzy logic controller facilitates instantaneous modifications and decision-making, enabling the UPQC to promptly conform to the ever-changing wind power output and grid circumstances. This connection not only improves the effectiveness of power quality adjustment [6], but also guarantees a smooth interaction between the wind farm and the vulnerable grid [7]. The historical development of this study includes a detailed investigation of UPQC technology, its use in situations with inadequate power grids, and the following enhancement achieved by integrating Fuzzy Control. Extensive researches [8] and real trials have been undertaken by researchers to confirm the effectiveness of this combination method. The findings demonstrate a significant improvement in the quality of electricity, characterized by minimal variations in voltage, decreased levels of harmonics, and improved stability in a weak-grid setting [9].

The integration of UPQC with Fuzzy Control for wind farm connections to weak grids is a major advancement in the field of power systems engineering. This novel approach not only tackles the inherent difficulties linked to feeble power grid connections, but also drives the renewable energy industry towards a more dependable and environmentally-friendly future.

## II. Literature Survey

The authors of [10] provided the theoretical principles, which included mathematical modelling of MG, fundamental lemmas, and the design approach of both primary controllers and mixed H2/H controllers. In the end, the performance of the controller was assessed in terms of small- and large-signal disruptions, nonlinear load, and imbalanced load based on offline data. In [11], the authors developed a model predictive control method for AC-MGs that are based on real applications of renewable energy without using any proportional-integral-differential regulators. The model predictive power control scheme (MPPC) and the model predictive voltage control scheme (MPVC) make up the suggested technique. This allows stable dc-bus voltages to be maintained as inputs to the inverters, which allows the fluctuating output from the RESs to be maintained.

In [12], the authors suggested the construction of a complete inverter-BESS main control that would be able to provide adequate performances. In these topologies because of dc-linking, only sources with nearly close operating voltages can be connected through a common ground. The non-isolated multiport topologies are normally derived from basic topologies such as buck, boost, or buck/boost converters. Since they don’t employ a transformer for isolation and share some devices among the ports, usually results in a structure that is compact and small and aids in attaining high power density.

In [13], a hybrid MPVC-MPPC based control system was introduced. Here, the voltage gain of nonisolated topologies depends only on the duty cycle of the switches and is limited. So voltage lifting techniques are required for improving the gain which again complicates the circuit structure. Further, these topologies are only applicable for systems that don’t require safety standards because of the absence of transformer isolation.

In [14], A main control loop, an inner control loop, and a secondary control loop are included in the control system were introduced. Finite Control Set (FCS-DMPC) is integrated in the inner loop of each Distributed Generator (DG) unit so that it can follow the reference voltage and fix the capacitor voltage. Controlling the flow of power and the distribution of that power among the DG systems is the responsibility of the primary control, which is made up of virtual impedance loop and droop control. Further, to overcome the power control problems, the multiple ports of the converter [15] are connected through magnetic coupling i. e., by using a multi winding transformer. Here all the ports of the converter are isolated from one another through this multi winding transformer and hence called fully-isolated topologies. These topological structures are derived from half-bridge converter circuits, full-bridge converter circuits, or a combination of both. Since in this topological structure the ports are connected through a multi-winding transformer, voltage sources or loads that have widely varying voltage levels can be easily integrated.

In [16], authors have developed comprises of two-level structures: primary and secondary control. The suggested technique, which differs from the distributed control systems that are already in use, is based on the pragmatic assumption that the impedance of the network is resistive. The principal control level is made up, and GPS timing is what's employed to synchronize the control agents with one another. The method that has been suggested involves adjusting the component of the voltage known as the d-axis in order to bring the average AC-MG voltage up to the rated value while simultaneously ensuring that the DERs share active power in an appropriate manner.

Since these topologies use bridge circuits, they are naturally capable of transferring power from both sides i. e., from source to load side and vice versa [17]. Also because of the bridge circuit structure achieving zero voltage switching in all active switches is possible in these topologies. But the major limitation is the use of so many active switches and no sharing of devices by the multiple ports of the converter which further result in complex driving and control circuits. The use of many active switches also affects the reliability and performance of the converter. To overcome the limitations of dc-linking and magnetically coupled topology, combined dc link and magnetic coupled topologies are developed in [18]. This category of converter uses both electrical and magnetic coupling for connecting different ports. In this topology, the voltage sources that have closer operating voltages are connected through dc-linking with common grounding and the load is connected through a transformer providing isolation and flexible voltage handling capability. Since in these topologies, only some ports are isolated, normally load port. It assures that three DER units will share active power in an equal manner, with each unit tracking the time-varying average demand, and it achieves this convergence in a limited amount of time.

In [19], authors developed hybrid control systems with multi-layer environment. This layer makes it possible to perform an efficient power allocation operation across multiple MG clusters. The lower control layer of the framework is made up of all the DGs that are not cluster heads and makes it possible to adjust the power distribution within each MG cluster. The main control is responsible for generating the frequency and voltage nominal set-points, and it receives all the power mismatches that occur throughout the TLC architecture. Multiple renewable energy sources are integrated into one or more loads through non-isolated direct link connection or through time-sharing of devices concept. In the direct link method [20], multiple sources are connected to a common bus through converter cells. This method is offered to cope with these issues. The suggested control method can simultaneously assure economic dispatch and frequency restoration control. This lowers the cost of operation for AC-MGs by bridging the time-scale difference between the two control strategies.

## III. Proposed System Model

Figure 1 visually depicts the power system being studied, with a thorough overview of its components and connections. The central element of this representation is the WF, which consists of 36 wind turbines, each using squirrel cage induction generators. Together, these wind turbines provide a combined electrical power output of 21.6 megawatts (MW). The selection of squirrel cage induction generators is in line with the typical technology used in several wind energy conversion systems. Each wind turbine in the WF design has fixed reactive compensation capacitor banks, each having a rating of 175 kilovolt-amperes reactive (kVAr). The capacitor banks have a vital function in improving the power factor of the wind turbines, maximizing their reactive power production, and strengthening the overall stability of the power system. Each turbine is connected to the electrical grid using a 630-kilovolt-ampere (KVA) transformer with a step-up ratio of 0.69/33 kilovolts (kV). This transformer plays a crucial role in regulating the voltage levels to facilitate the effective transfer of electricity between the wind turbines and the larger power grid. The use of genuine system characteristics provides credibility to the research, enabling a more accurate examination of the obstacles and dynamics related to the integration of wind farms into the larger power grid. The illustration in Figure 1 highlights a significant parameter referred to as "connection weakness," which is essential for comprehending the system's resilience and possible difficulties. The ratio of short-circuit power to rated power of the Wind Farm is a crucial indicator for evaluating the vulnerability of this link. The system being discussed refers to the short-circuit power in MV6, which is represented by the acronym SSC and has an estimated value of 120 megavolt-amperes (MVA). The ratio (r) is determined by dividing the short-circuit power by the rated power of the Wind Farm (PW F), yielding an estimated value of 5.5. The ratio (r) is an indicative measure of the system's connection weakness, providing insights into its ability to manage short-circuit circumstances relative to its rated power. Values below 20 for this ratio are often classified as indicative of a "weak grid" connection, in accordance with established norms in the area. Regarding the shown power system, its connection weakness ratio has been assessed to be 5.5, placing it in the category of a poor grid connection.

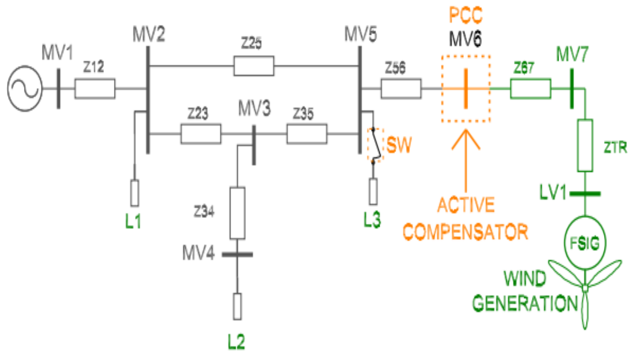


**Fig. 1.** Study case power system.

***A. Turbine rotor and associated disturbances model***

The work explores the modeling of the turbine rotor and its related disturbances, aiming to get a thorough knowledge of the elements that affect the power generated by a wind turbine in the given WF setup. The power extraction, represented by the symbol P, is explained as a mathematical function including several factors. This equation serves as a key principle that regulates the process of converting energy in wind turbines. The equation, shown

$$P = \frac{1}{2} \cdot \rho \cdot \pi \cdot R^2 \cdot v^3 \cdot C_P \qquad (1)$$

The calculation incorporates variables such as air density (ρ), the radius of the swept region (R), wind speed (v), and the power coefficient (CP). The given characteristics for the turbines under consideration, which have a power rating of 600 kilowatts (kW), include the following precise values: R=31.2 meters, ρ=1.225 kilograms per cubic meter (3kg/m3), and CP computed based on a reference source. After calculating the power of each individual turbine, the research presents the notion of turbine aggregation, highlighting the creation of a comprehensive model for the whole Wind Farm. By treating the whole Wind Farm as a single equal wind turbine, this aggregation simplifies the intricate system. The power produced by each individual turbine is calculated by adding them together using arithmetic summation, as shown by the equation.

$$P_T = \sum_{i=1 \cdots 36} P_i \qquad (2)$$

This modeling methodology enables a more efficient examination of the overall performance of the Wind Farm by simplifying the complexity of the individual turbines into a single, similar entity. The research subsequently examines the influence of disruptions on wind speed, recognizing that deviations from the normal wind flow might arise from both deterministic and random variables. The occurrence of deterministic disturbances, which are marked by imbalances in the movement of wind, may be related to the phenomenon known as the "tower shadow" effect and the atmospheric boundary layer. Concurrently, arbitrary disruptions, referred to as "turbulence," bring about unforeseeable alterations to the movement of air. The research explicitly examines the deterministic disruption induced by the support structure, namely the tower, for the purpose of analysis.

The deterministic disturbance is represented by a sinusoidal modulation that is added to the average wind speed. The modulation frequency of a three-bladed wind turbine is obtained by multiplying the number of rotor blades, Nrotor, by 3. The magnitude of this modulation depends on the tower's shape. In this research, a mean wind speed of 12m/s and an amplitude modulation of 15% are being evaluated. This modeling methodology seeks to accurately represent the effects of tower-induced disturbances on wind speed, considering the influence of the turbine support structure on the overall efficiency of the wind farm. In most situations, the research emphasizes that the shadow effect of the tower has a far greater influence than the border layer. This differentiation emphasizes the significance of considering tower-induced disruptions as a fundamental determinant of wind flow fluctuations. The sinusoidal modulation effectively incorporates the predictable disruption created by the tower, resulting in a more precise depiction of real-world circumstances.

Significantly, the research highlights that the total disturbances accumulate when all turbines function simultaneously and in alignment. Although this may not accurately reflect the typical operating condition, it is recognized as the most extreme situation with the most power fluctuations. The turbine aggregation approach is considered legitimate, since it aligns with the worst-case scenario that has the most effect on the electricity system. This modeling methodology optimizes the study process while maintaining precision, allowing for a targeted examination of the Wind Farm's performance under difficult circumstances. The turbine aggregation approach is proposed to streamline the system for thorough examination. Incorporating deterministic disturbances, particularly those caused by the tower, enhances the authenticity of the modeling process. The research meticulously addresses the intricacies of wind flow fluctuations by specifically examining the most unfavorable situation, in which turbines operate simultaneously and in perfect synchronization, hence intensifying their influence on the power system. This part provides a strong basis for future investigations, including detailed information on the complexities of wind farm dynamics and their impact on electricity output and grid stability.

***B. Model of induction generator:***

The modeling of the squirrel cage induction generator is dependent on the functionalities provided by the MATLAB/Simulink Supersystems library. This decision highlights the use of a widely used and well-established modeling system, which provides a strong basis for accurately representing the behavior of the induction generator. The model used in MATLAB/Simulink Supersystems libraries is distinguished by its extensive framework, which includes both electrical and mechanical components. The electrical model is expressed as a state-space representation of fourth order, which accurately captures the complex dynamics of the electrical components of the generator. This model explores the interaction of electrical variables, such as voltage and current, and how they change over time. The model's fourth-order nature implies a sophisticated representation, enabling a thorough analysis of the generator's reaction to different situations and inputs.

The electrical model is complemented by the second-order mechanical model, which expands the simulation to include the mechanical features of the squirrel cage induction generator. This aspect of the model offers a deep understanding of the mechanical dynamics of the generator, taking into account variables such as rotational velocity and inertia. By using a second-order mechanical model, there is an emphasis on accurately capturing the fundamental dynamics of the generator's mechanical parts, resulting in a comprehensive depiction of its overall performance. The integration of electrical and mechanical models in the MATLAB/Simulink Supersystems libraries provides a unified and coordinated simulation environment. This environment enables the examination of the induction generator's performance under various operating situations, offering a dynamic simulation that accurately depicts the intricacies seen in real-world scenarios. State-space modeling improves the precision and accuracy of the simulation, enabling a thorough analysis of the generator's reaction to variations in input parameters and external factors. The utilization of MATLAB/Simulink Supersystems libraries for the induction generator model offers several benefits to the investigation. MATLAB/Simulink is a very popular platform used for modeling and simulating dynamic systems. It provides an intuitive interface and a comprehensive collection of libraries for a broad range of

engineering applications. The Supersystems libraries in MATLAB provide a specific set of tools for modeling complex electrical and mechanical systems, simplifying the task of creating precise and efficient simulations.
In addition, the fourth-order electrical model corresponds to the need for a comprehensive depiction of the electrical dynamics of the induction generator. Precision at this level is especially important in wind energy systems, since the generator's ability to adapt to changing wind conditions and interact with the grid necessitates a very accurate model for precise forecasts and analysis. By including a second-order mechanical model, the electrical model is enhanced, resulting in a more thorough comprehension of the induction generator's behavior. The simulation considers mechanical factors such as rotational speed and inertia to accurately model the generator's reaction to mechanical disturbances and variations. This provides valuable information about the generator's overall performance and stability.

### *C. Dynamic compensator model*

The primary objective of this study is to analyze the dynamic compensator model, with a special emphasis on the techniques used to mitigate voltage fluctuations in the MV6 busbar, which serves as the Point of Common Coupling (PCC). The compensation is accomplished by injecting voltage in series and actively controlling both active and reactive power, using a Unified Power Quality Compensator (UPQC). Figure 2 provides a graphical depiction of the fundamental structure of this compensator, specifically referring to the busbars and impedances identified in Figure 1. The UPQC, seen in Figure 2, functions by producing three-phase voltages via the use of electronic converters, either Voltage Source Inverters (VSI) or Current Source Inverters (CSI). The compensator's functionality relies on the use of electronic converters, and the comparison between VSI and CSI converters is examined, favoring VSI converters owing to their reduced DC link losses and quicker responsiveness within the system. The importance of maximizing the efficiency and responsiveness of the compensator is highlighted by this decision, since they are critical components in dynamic voltage compensation. The compensator's structure has two crucial elements: the shunt converter, which injects current at the PCC (Point of Common Coupling), and the series converter, which generates voltages between the PCC and U1, a designated reference point. Figure 2 presents a phasor diagram that provides more clarity on the functioning of the UPQC. The shunt converter introduces current at the point of common coupling (PCC), affecting the current behavior throughout the system, whereas the series converter produces voltages between the PCC and U1. This graphic depiction facilitates the communication of the complex interconnections and associations among the many components of the compensator. It functions as a reference for comprehending the phasor correlations and the influence of the compensator on the electrical characteristics inside the system.

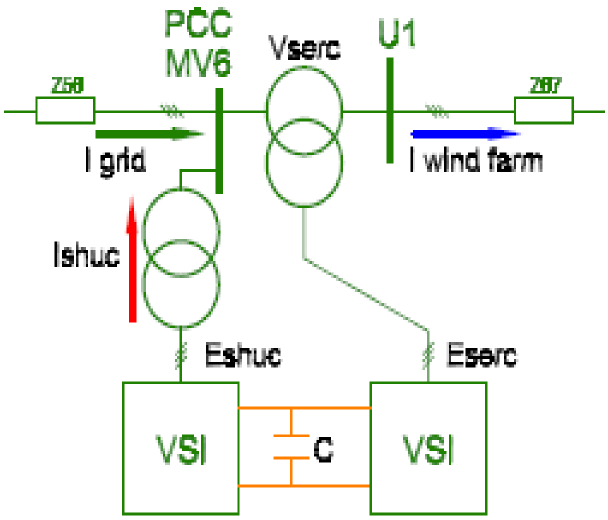


**Fig. 2.** Block diagram of UPQC.

The UPQC compensator is notable for its capacity to distribute the operation of both VSI converters, whether in series or shunt topologies. The sharing mechanism improves the efficiency and efficacy of the compensator by enabling synchronized measures to mitigate voltage fluctuations in the MV6 busbar. The compensator's capacity to adjust and synchronize the functioning of its constituents enhances its dynamic reaction and appropriateness for alleviating power quality problems. The shunt converter has the important function of injecting current at the point of common coupling (PCC), while the series converter produces voltages between the PCC and the reference voltage (U1), as seen in the phasor diagram shown in Figure 3. The UPQC compensator is visually shown, illustrating its essential components and interactions. It functions as a great instrument for comprehending the intricate connections between voltage and current elements in the system. The graphic depicts the interaction of vectors representing voltages and currents, indicating the dynamic nature of the compensator's functioning.

An important aspect emphasized in the description of the compensator is the use of a common DC-bus that is shared by both the series and shunt converters. The common DC-bus enables active power transfer between the two converters, which is a crucial feature of the compensator's operation. The shared use of the same DC-bus by both Voltage Source Inverter (VSI) converters improves the overall performance and efficiency of the compensator. The rationale for using an idealized depiction of the converters, whereby they are simulated as regulated voltage sources, is elucidated. The simulation model, although not including the complexities of switching control often linked with converters, effectively captures the fundamental dynamics of the UPQC system. Furthermore, the fact that the simulation research does not take into account the higher order harmonics produced by VSI converters supports the choice of this simplified model.

The phasor diagram provides a visual representation that helps to understand the linkages and interactions between the series and shunt converters in the UPQC compensator. The diagram illustrates the phase relationships and magnitudes of important electrical variables, providing a deeper understanding of how the compensator functions to control the power quality at the PCC. The graphic physically depicts the shared DC-bus, highlighting its function in facilitating active power exchange between the converters. The dynamic compensator model, discussed in this part, serves as a fundamental framework for analyzing the performance of the UPQC in wind farm connections to weak grids. Although the model may not accurately represent the complex aspects of switching control or the subtle characteristics of higher order harmonics, its simplicity enables a computationally efficient simulation that may provide valuable insights into the compensator's effects on power quality and stability.

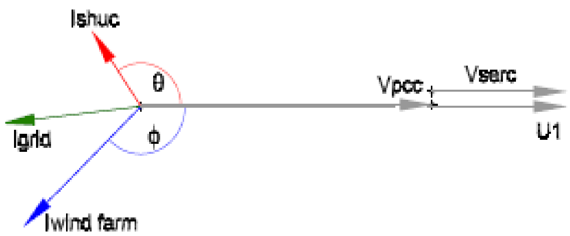


**Fig. 3.** Phasor diagram of UPQC.

Figure 4 is shown as a visual depiction of the model that was used, offering a detailed understanding of the complexities of the power stage compensator on the AC side. The model plays a crucial role in the UPQC system, adding to its capacity to improve power quality and reduce disruptions in the grid. The power side compensator model demonstrates the essential components of the functioning of the UPQC. The illustration emphasizes the use of a rotating frame dq0 for implementing control techniques. This method entails using Park's transformation, as indicated by equations (3) and (4). The transformation matrix T enables the translation of values from the abc phase domain (fa, fb, fc) to the dq0 domain (fd, fq, f0), where "d" and "q" indicate the rotating reference frame and "0" signifies the zero-sequence component.

$$T = \frac{2}{3} \cdot \begin{bmatrix} \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} f_d \\ f_q \\ f_0 \end{bmatrix} = T \cdot \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \quad (4)$$

The matrix T, as specified in equation (3), encompasses the trigonometric functions of the angle θ, so establishing a mathematical foundation for the transformation. Aligning a rotating reference frame with the positive sequence of the PCC voltages space vector is essential for this transformation. The angle θ is synced with the PCC positive sequence fundamental voltage space vector and is determined by the use of a PLL technology. This work has successfully constructed a PLL based on the "instantaneous power theory". This implementation has significantly improved the precision in determining the reference angle. The values fd, fq, and f0 in the synchronous reference frame correspond to magnitudes in the dq0 space. This transformation enables a consistent analysis and independent management of the UPQC system. Especially when the system is in a balanced steady-state, the voltage and current vectors in this synchronous reference frame stay unchanged, providing stability and predictability in the analysis.

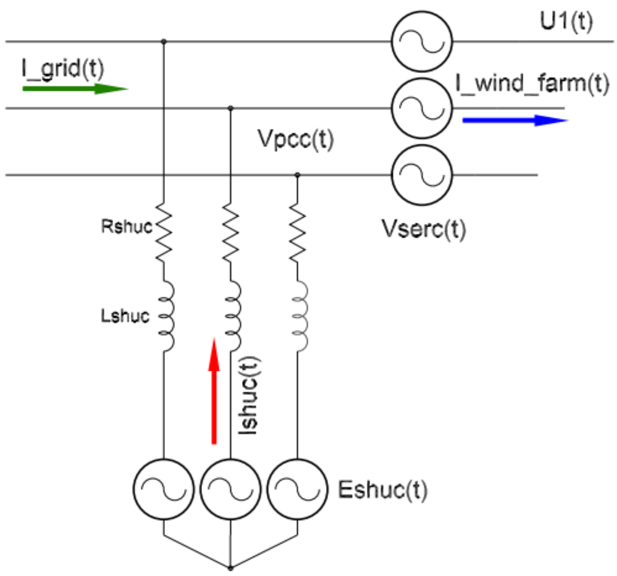


**Fig. 4.** Power stage compensator model-AC Side.

By using a rotating frame and Park's transformation, one may adopt a methodical and effective approach to control techniques, guaranteeing synchronization with the positive sequence of PCC voltages. The alignment of the UPQC is crucial for its efficacy in reducing power quality problems and disruptions in the system. The controller has a vital function in overseeing the voltage and current regulation in the series compensator of the UPQC. Its purpose is to guarantee accurate and quick modifications in accordance with changes in the grid circumstances. The integration of the power stage compensator model and the Series Compensator Controller creates a resilient control system that improves the overall performance of the UPQC in practical scenarios.

## IV. Results and Discussion

Figure 5 presents a thorough representation of the Simulink model illustrating the complete integration of the FLC and UPQC system. The Simulink model functions as a graphical depiction of the interrelated components and control mechanisms that make up the FLC-UPQC system. Gaining insights into how the FLC strengthens the compensatory capacities of the UPQC is crucial for comprehending this paradigm. The FLC-UPQC system functions as a closed-loop control system, whereby the Fuzzy Logic Controller consistently evaluates the parameters of the system and modifies the operation of the UPQC in real-time. The Simulink model represents the interaction between the FLC, the UPQC, and the various components of the power system. The system's architecture is graphically portrayed, providing a comprehensive perspective of key components such as the shunt and series converters, DC-Bus, and the feedback loop from the FLC.

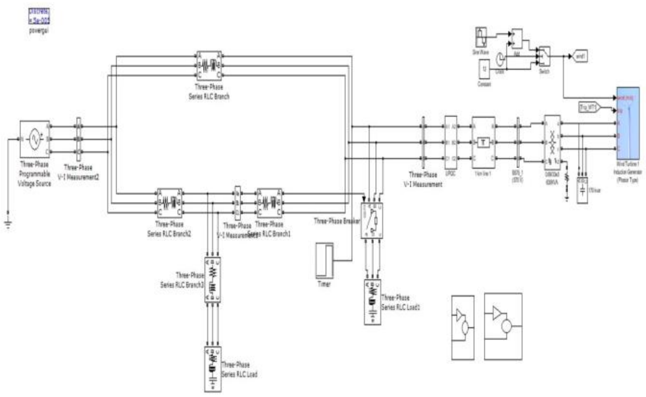

**Fig. 5.** Overall Simulink Model of FLC-UPQC System.

Figure 6 presents an intricate depiction of the internal subsystem inside the FLC-UPQC system, with a special emphasis on the Simulink model that integrates the Fuzzy Logic Controller. The internal subsystem functions as the central intelligence of the system, where the FLC analyzes system inputs, makes determinations, and produces control signals to enhance the performance of the UPQC. This Simulink model contains the membership functions, rule base, and defuzzification process that are essential components of the FLC. Membership functions establish the linguistic variables and their corresponding fuzzy sets, allowing the FLC to interpret input signals in a linguistic manner. The rule base defines the logical connections between input and output fuzzy sets, providing guidance for the decision-making process. The defuzzification procedure transforms the imprecise output into precise control signals for the UPQC. An analysis of the internal subsystem model provides insight into the information processing and decision-making process of the FLC to decide the suitable corrective measures. The FLC utilizes linguistic principles to make sophisticated judgments by considering the dynamic circumstances of the system. The Simulink model provides a graphical depiction of the decision-making logic of the FLC, enhancing comprehension of how fuzzy logic enhances the flexibility and intelligence of the UPQC system.

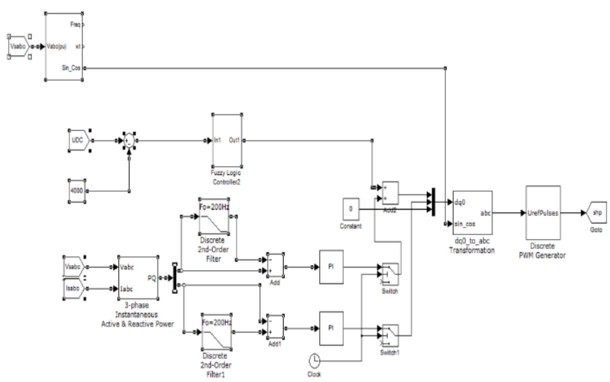


**Fig. 6.** Internal Subsystem using Fuzzy Logic Controller Simulink Model.

Figure 7 provides a close-up view of the Simulink model that is particularly designed for the Fuzzy Logic Controller in the FLC-UPQC system. This comprehensive perspective offers a deep understanding of the fundamental mechanisms of the FLC, presenting the distinct components and linkages that constitute the fuzzy control logic. The Simulink model of the Fuzzy Logic Controller comprises input blocks that represent system variables, fuzzification blocks that convert precise inputs into fuzzy variables, a rule base that defines the logical connections between inputs and outputs, and defuzzification blocks that translate fuzzy outputs into precise control signals. The FLC's decision-making process is comprised of several components, which work together to evaluate the system's condition and provide accurate control signals for the UPQC.

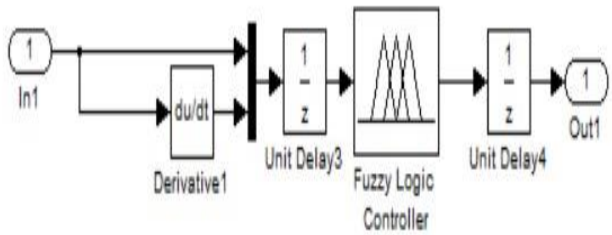


**Fig. 7.** Fuzzy Logic Controller Simulink Model.

Figure 8 illustrates the precise depiction of the active and reactive power requirements at the power grid side in the FLC-UPQC system. Figure (a) illustrates the active power demand, displaying a waveform with a magnitude of 0.5 x 10^7. This signifies the immediate need for actual electricity at the power grid, highlighting the dynamic nature of power use or production. Subfigure (b) depicts the reactive power demand, showcasing a waveform with a magnitude of -2 x 10^7. Reactive power plays a vital role in the regulation of voltage levels and facilitating the transfer of active power. The presence of the negative sign signifies the need for the power grid side to receive assistance in the form of reactive power, which may be attributed to voltage fluctuations or the requirement for power factor adjustment. Figure 9 specifically examines the PCC voltage in the FLC-UPQC system. The electricity Conversion Center (PCC) serves as the intermediary between the Wind Farm (WF) and the wider electricity grid. Figure 6.16 depicts the PCC voltage, which has a magnitude of 2.8 x 10^4. The PCC voltage is a crucial factor since it has a direct impact on the quality of electricity that is supplied to the grid. A consistent and well managed PCC voltage serves as evidence of the UPQC's efficient compensation and control procedures. Variations or variations in PCC voltage may result in power quality problems, impacting the overall stability of the linked power grid. Examining this diagram yields valuable information about how the FLC-UPQC system effectively controls and monitors the voltage at the PCC in order to comply with grid regulations and provide dependable power distribution.

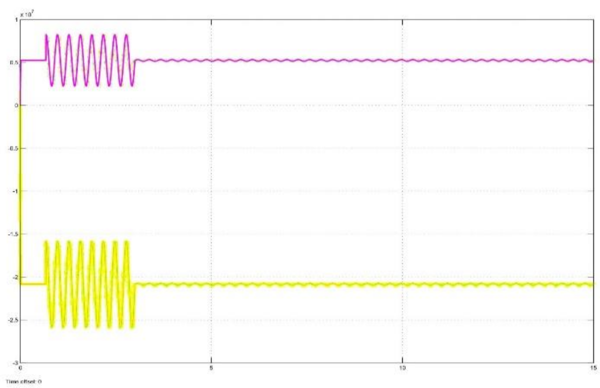

**Fig. 8.** Active and reactive power demand at power grid side. a) Active Power. b) Reactive Power.

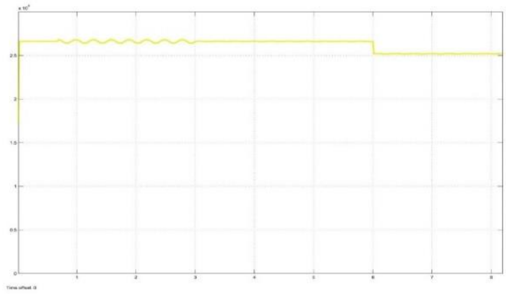

**Fig. 9.** PCC Voltage.

Figure 10 depicts the power characteristics of the capacitor in the DC–Bus of the FLC-UPQC system. The figure illustrates a sine wave exhibiting oscillations that vary between positive and negative values of 4.3 x 10^6. The DC–Bus capacitor is an essential component for storing and exchanging energy in the UPQC. Its power profile reflects the dynamic energy flow into and out of the DC–Bus. The sinusoidal waveform of the capacitor power emphasizes the periodic process of storing and releasing energy. During the positive phase, the capacitor accumulates energy, while during the negative phase, the stored energy is released back into the system. The magnitude of the sine wave, in this instance ±4.3 x 10^6, offers valuable information about the energy levels sustained by the capacitor, showcasing the UPQC's capacity to control and stabilize the DC-Bus power for efficient compensation.

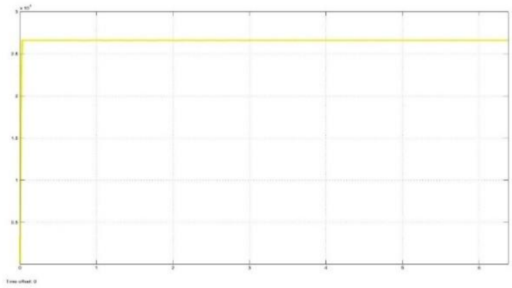

**Fig. 10.** WF Terminal Voltage.

Figure 11 presents a dual depiction of voltage, both at the WF and the PCC. Figure (a) shows the waveform voltage in pink, with a magnitude of 2.64 x 10^4. Subfigure (b) displays the PCC voltage in yellow, represented as a square wave with variations ranging from + or – 2.55 to 2.65 x 10^4. The WF voltage signifies the electrical potential at the terminals of the Wind Farm, but the PCC voltage is vital as it serves as the interface between the WF and the wider power grid. The pink waveform seen at WF illustrates the function of the UPQC in controlling and maintaining the voltage levels in the Wind Farm, hence ensuring the dependable performance of the turbines. The presence of a yellow square wave at PCC signifies the UPQC's diligent endeavors to effectively regulate and govern the voltage at this pivotal location, in accordance with grid norms, hence guaranteeing optimal power quality.

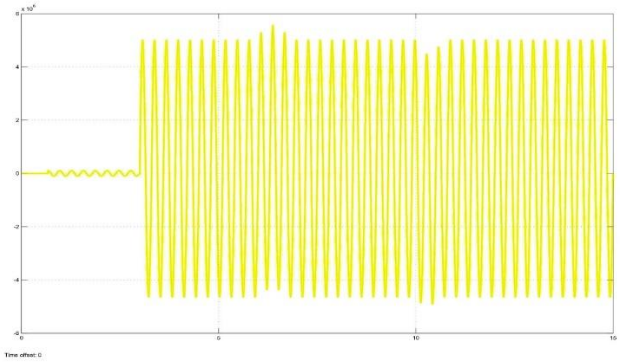

**Fig. 11.** Power of the capacitor in the DC–Bus.

## V. CONCLUSION

The use of a Fuzzy Logic Controller (FLC) in a shunt converter, which is based on a Voltage Source Inverter (VSI), provides several notable benefits in the field of power system management. FLC demonstrates exceptional performance in scenarios where conventional control techniques encounter difficulties arising from inaccurate data, uncertainties, and nonlinearities that are inherent in power systems. An important benefit of FLC is its capacity to adapt to different operating circumstances, enabling it to intelligently respond to dynamic variations in active and reactive power. The accuracy of FLC in promptly detecting and responding to variations in power characteristics is a crucial advantage. FLC employs a well defined set of rules to provide customized control actions that specifically target the distinct features of the VSI-based shunt converter. This results in enhanced stability and optimum performance, even in the presence of fluctuations. The utilization of linguistic phrases and fuzzy sets improves the comprehensibility, facilitating a more distinct comprehension of the controller's actions for operators and system engineers. The capability of FLC to manage nonlinearities in the system is essential in power systems that demonstrate nonlinear behavior as a result of variables such as transformer saturation and load characteristics. The strong resilience of this system guarantees consistent and reliable operation, even when faced with uncertainties and disruptions. This degree of dependability is essential for power systems in real-world scenarios, where unexpected occurrences are certain to occur. The versatility of FLC in adapting to different situations is emphasized, particularly in power systems with fluctuating demand and generation patterns. The fuzzy logic rules may be constructed to accommodate many circumstances, guaranteeing that the controller adapts its operations according to particular conditions at each given moment. FLC, when applied to a shunt converter using a VSI, guarantees efficient control of controller voltages by promptly responding to variations in active and reactive power. This prevents excessive or insufficient compensation.

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