

Intelligent control for distributed smart grid: comprehensive system integrating wave, fuel cell, and photovoltaic power generation

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ABSTRACT

The intermittent supply from renewable energy sources reckons integration of different renewable sources that can provide robust and uninterrupted energy supply to the grid. This paper applies an intelligent control method to such hybrid power generation involving a wave generator, fuel cell, and solar power generator integrated into the distribution power grid. A common DC link that supplies the voltage source converter (VSC) is powered by the output from the hybridized wave, fuel cell and photovoltaic (PV) output. Wave generator uses the rectifier DC-DC converter, PV uses a maximum power point tracking (MPPT)-controlled DC-DC converter and fuel cell uses a DC-DC converter. All DC sources converge at the DC link, connecting to an inverter featuring another voltage source controller for controlled AC voltage. In instances of power unavailability from renewable resources, the fuel cell seamlessly provides power. The inverter controls the integration of power from these sources to the grid and maintains stable DC link voltage due to the dynamic nature of the DQ controller. MATLAB-based simulation is developed for the proposed controller and a comparison between both proportional integral and adaptive neuro-fuzzy inference system (ANFIS) controller in the DC link voltage regulation loop is observed. An ANFIS controller is employed as an alternative to the proportional integral (PI) controller and found that the ANFIS controller outperformed the PI controller in voltage regulation at the DC link.

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1. INTRODUCTION

The surge in renewable energy sources (RES), driven by environmental concerns and the escalating costs of fossil fuels, has been substantial. The incorporation of these sources into the utility grid is contingent upon the scale of power generation, with large-scale projects linked to transmission systems and smaller-scale distributed power generation integrated into distribution systems. The direct integration of both systems poses challenges. Wave energy with unpredictable nature of wave dynamics poses challenges in achieving consistent power quality. Generators output from the wave generator is affected by the changes or dynamics in the wave. Photovoltaic (PV) generation also is dependent on the irradiation that falls on the panels which affects the voltage at the DC link of the inverter, which indirectly affects the power delivery to the utility

grid. Literature [1] discusses the challenges in integrating RES into the grid, power quality issues and their causes, the impact on the stability of the power system and strategies that can manage these issues and leverage the (RES) integration to the grid. An assessment framework has been designed for the empirical validation of a prototype featuring a double-sided linear permanent magnet synchronous generator (PMSG) in regular and irregular wave conditions [2]. The study employs a linear PMSG anticipating buoy motion and extracting parameters conducive to optimal power generation, especially in scenarios involving both regular and irregular wave conditions. A technique that enhances the stability of electrical energy in the direct drive wave generator using the virtual synchronous generator (VSG).

ANSYS Maxwell based simulation model of the permanent magnet linear generator (PMLG) whose output is connected to the rectifier and regulated using the pulse width modulation (PWM) is developed. Integration of a battery energy storage system (BESS) helps mitigate variations in active power. By emulating the inertia and damping characteristics of synchronous generators, inverters actively contribute to frequency adjustment and provide inertial support, facilitated by the VSG method, that is validated from the simulation results [3]. With the limited maximum power point tracking (MPPT) methods for the wave energy converters (WECs) the literature [4] the effectiveness of damping control through various MPPT methods for WECs using DC-DC boost converter and evaluate optimal parameters that maximize the power delivery. Integration of WECS to the grid requires the circuits that are employed with the features that can sense the power take-off mechanism inherent in PMLG. Both the magnitude and frequency of the WECS vary and the incorporation of the circuit that adapts both magnitude and frequency include a three-phase rectifier, DC-DC converter, three-phase inverter and a step-up transformer. The harmonic distortion of the microgrid is regulated by applying both voltage and frequency regulation in the microgrid [5]. Active rectifier design is used for the WECs using the field-oriented control to control the dynamics of the power generator at the output itself [6]. Power take-off (PTO) which is responsible for mechanical energy to electrical energy conversion in the WECs, power conversion system that rectifies the voltage with different amplitude and frequency and power conditioning systems, all have dynamics involved in its operations. From wave to grid, there are power processing units that affect the overall performance of the system. Thus, the literature [7] introduces the comprehensive wave-to-grid control approach that involves linear permanent magnet generator (LPMG), a back-to-back power converter to enhance power quality and a short time energy storage using the ultra-capacitors for a steady operation of the WECs using Lyapunov-based nonlinear controllers.

Although wave energy is abundant in nature the promising conversion technology, stability and predictability of resources make it less competitive in the energy market [8]. Aspects including the converters that need to be incorporated for the WECs energy conversion and grid integration techniques for the WECs devices are elaborated in [9]. Thus, the WECs have to be teamed up with other RES sources including PV, fuel cell to get a stable power delivery to the Microgrid. A setup which includes linear permanent magnet synchronous generator (LPMSG) and the rectifier called as Archimedes wave swing (AWS) device introduced in [10] for power conversion in WECs is combined with the photovoltaic (PV) system with the supercapacitor energy storage system. The golden jackal optimization algorithm (GJOA) is applied to optimize the PI gains to improve transient stability in the hybrid wave and PV generator integration to the grid. GJOA obtained better optimization performance compared to the particle swarm optimization (PSO) and Cuckoo search algorithm. The higher dynamics of supercapacitor compared to the batteries makes it a better choice for RES applications. A hybrid power generation encompassing energy storage system (ESS), Supercapacitor and WEC is combined to supply a constant power load (CPL) which is controlled by improved direct model predictive control (I-DMPC). The objective function that reduces the steady state error is developed using the MATLAB Simulink environment to enhance fault tolerance during regular and irregular waves [11]. Compared to DMPC the I-DMPC performed better in reducing d-axis and q-axis errors. Apart from other hybrid generation systems wind and wave energy combine naturally due to geological factors. Locating both sources is a layout optimization problem involving wave wake analysis. The recursive layout optimization algorithm is applied for hybrid wave wind farm locations using the historical meteorological data from 1979 till 2015 [12]. The algorithm selected locations for optimal wind and wave energy for generation that provided capacity factors required for commercial viability. To ensure a robust energy supply for critical loads, integrating multiple energy sources is essential criteria. While multiple multi-input converters (MICs) are in use, a common limitation is their time-sharing scheme, utilizing one source while leaving others idle. A dual input single output (DISO) DC-DC converter is used to compensate the under-utilization of both the converter and input energy sources [13].

A 240 W DISO converter is developed for experimental verification. Choosing an appropriate wave energy conversion system from the extensive variety in the literature poses a challenging task. The study [14] consolidates information on six widely utilized WECs, extensively examined in past, including the Archimedes wave swing (AWS), wave dragon (WD), pelamis wave power (PWP), Aquabouy (AB), Oyster, and the oscillating water column (OWC). Higher power density-based analysis is developed to find the most

suitable WECS installation in Egypt with mathematical analysis. A hybrid power generation unit combining both the wind and wave energy sources is checked for its dynamic performance [15]. The minimal number of converters involved in the setup demonstrates effectiveness under various operating conditions. Steady-state analysis on the hybrid setup of LPMG-based WECS and doubly-fed induction generator (DFIG)-based wind generators has shown an improved voltage profile in the distribution feeder [16] without the use of a voltage regulator. The voltage support to the wind-wave energy conversion system assisted by the droop control by obtaining the droop gains from the (Q-V) characteristics [17] is found to be effective. A hybrid offshore wind-wave conversion system (HOW-WECS) using DFIG and direct drive LPMG (DDLPMG) is developed with improved dynamic and transient performance during fault conditions [18]. The frequency and the voltage deviation that disturb the stable operation of the grid is kept under control during the fault condition in the distribution system by using appropriate controller.

Hydrogen generator which supplies hydrogen to fuel is supplied from the inverter that is connected to the DC link which is supplied from the hybrid generation unit combining the PV, hydrogen, and fuel cell generators with batteries [19]. Thus, while hybrid generation is used in the microgrid environment it is important to have advanced controllers. Load frequency controller in a microgrid environment using a feed-forward fractional order proportional-integral-derivative (FFOPID) control strategy is developed [20] with the evaluation of performance using the frequency deviation criteria of integral of time squared error (ITSE). The simulation included diesel generators, loads, solar cells and wind farms in a microgrid environment [21]. Proportional-integral-derivative (PID) controller is improved using the cascade PID controller to manage frequency deviation.

Further, the PID gain parameters are optimized using the optimization techniques including PSO and firefly algorithm (FA) with the integral of time multiplied by absolute error (ITAE) as its fitness function. MATLAB/Simulink-based hybrid PV Wind energy generation which supplies DC to the common DC link is used as the supply to the grid-connected inverter [22]. Space vector pulse width modulation (SVPWM) controller is used to switch the three-phase inverter and supply the grid-tied load. Enhancing the efficiency of PV wind hybrid sources using the WECs characterized by augmented swept area is developed [23]. Advanced controllers in hybrid renewable energy integration to the grid is evident in [24], [25] for better performance evaluation. In this paper, Wave power generation, Fuel cells, and Solar power generation are interconnected at the DC link. This integration is linked to a distribution smart power grid, introducing dynamic transient challenges arising from the inherent fluctuations in wave generators. To address this issue, a novel control approach incorporating a PI controller has been implemented. However, the conventional use of PI controllers in this control technique tends to induce oscillations. To mitigate this concern and enhance control precision, an exploration into the application of neuro-fuzzy logic has been undertaken as an alternative solution.

2. METHOD

The problem of intermittent power supply by the different renewable energy source is dealt using the hybrid integrated energy source which would combine the different renewable energy sources. Intelligent control that can manage the dynamics of different energy sources is considered for the integrated source connected to a power distribution grid connected via DC link. A unified power source that combines the energy from PV, fuel cell and wave generators at the DC link. Voltage and frequency control of the power generated from this unified power source while connecting to the distribution grid is managed using the voltage source converter (VSC) which offers the dynamics of a synchronous generator. The decoupled controller which is used for the real and reactive power controlled in an orthogonal manner is applied for the integration of this unified power to the distributed grid. Controller uses both traditional PI controller and highly dynamic adaptive neuro-fuzzy inference system (ANFIS) controller for the comparative analysis of the voltage regulation results at the DC link. MATLAB Simulink model is developed for the same and results are tabulated for the analysis.

Since the source for all the RES are at the DC link the power is processed to be available as the DC source. PV source uses MPPT method, while wave generator uses rectifier along with the fuel cell for hybrid power source to connect at the DC link. Considering the highly dynamic operation of the supercapacitor, it is used to regulate the power fluctuations at the point of common coupling (PCC). DC voltage regulation at the DC link is carried out using the PI controller, while ANFIS is used as an alternative for the PI controller considering its dynamics. The dynamics of the system is learnt by the ANFIS controller and the complex characteristics of the system is emulated with the fuzzy logic controller's ability to dynamically control the parameters under study. Since the characteristics of the wave generator is complex the ability of ANFIS to adapt to the nonlinear characteristics is an advantage in the implementation. The complete block diagram of the implementation is as shown in the Figure 1.

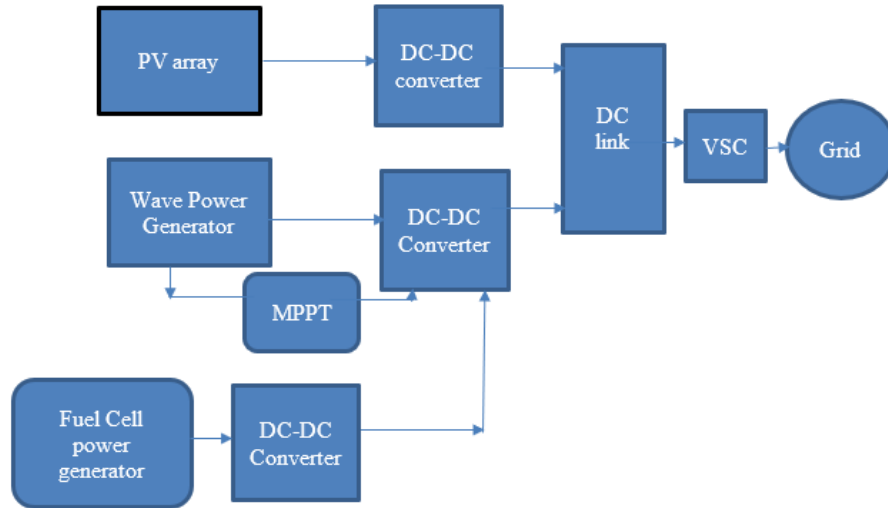


Figure 1. Proposed block diagram

3. DQ CONTROL SYNCHRONIZATION

The orthogonal controller is meant to decouple both the real and reactive portion of the power for better control in the grid connected RES systems. The stochastic nature of the VSC which can handle the voltage and the frequency of the power connected to the grid is the prime component of the whole controller. The conversion of the abc phasor components to direct and quadrature components makes the control very easier since the decoupled nature of the controller separately control both the direct and quadrature components. Decoupling of real and reactive power is done using parks transform as (1).

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\omega t) & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \\ -\sin(\omega t) & -\sin(\omega t - \frac{2\pi}{3}) & -\sin(\omega t + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (1)$$

All the reference voltage that belongs to real and reactive power correction is generated in the real and reactive mode and that reference is converted to abc voltages that would be used as the reference for the PWM generation in the VSC controller. Equation (2) defines the reference abc voltage generated from the direct and quadrature axis voltage also known as inverse park's transform.

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\omega t) & -\sin(\omega t) & 1 \\ \cos(\omega t - \frac{2\pi}{3}) & -\sin(\omega t - \frac{2\pi}{3}) & 1 \\ \cos(\omega t + \frac{2\pi}{3}) & -\sin(\omega t + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} \quad (2)$$

The direct axis reference current and quadrature reference current are generated as per the block diagram as given in Figure 2. The DC link voltage reference voltage is calculated according the grid voltage amplitude. The difference between the actual voltage at the DC link and the reference voltage that must be maintained at the DC link needs to be equal. This condition generates the reference direct axis current as given in Figure 2. Since the reactive power must be equal to zero the reference quadrature axis current is kept at zero. The error of the actual DC link voltage and reference DC link voltage is given to the PI controller, thus generating the reference direct axis current.

The process involves transforming voltage regulation at the DC link into current regulation at the inverter. This comprehensive control strategy integrates both the DC voltage regulation and the voltage and frequency control achieved through a phase-locked loop (PLL). The synergy of these elements contributes to the development of a holistic grid synchronization algorithm, ensuring a cohesive and effective approach to managing both voltage and frequency parameters within the system.

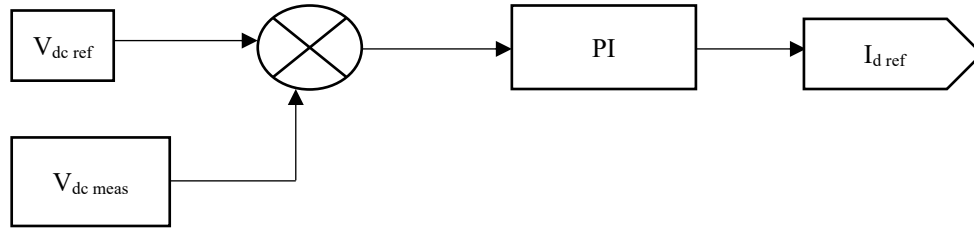


Figure 2. DC voltage regulation

Utilizing the proportional-integral (PI) regulator, the conversion of direct and quadrature currents (I_{dq}) into voltage (V_{dq}) is facilitated. Figure 3 illustrates the regulation of current in the system. The expression for $V_{dq\ conv}$, according to the DQ0 theory, is depicted below:

$$V_{d\ conv} = V_{d\ meas} + I_d R - I_q L + dI_d/dt(L/\omega_{base}) \quad (3)$$

$$V_{q\ conv} = V_{q\ meas} + I_d L - I_q R + dI_q/dt(L/\omega_{base}) \quad (4)$$

Here,

$V_{d\ conv}$ and $I_{d\ conv}$: controller direct voltage and current

$V_{q\ conv}$ and $I_{q\ conv}$: controller quadratic voltage and current

R: grid resistance

L: grid inductance

ω_{base} : Angular frequency

The transformed $V_{dq\ conv}$ is input into (2), resulting in its conversion back to V_{abc} . This reconstructed waveform serves as the modulation input for pulse width modulation. The control exerted by this converter ensures the maintenance of voltage at the PCC.

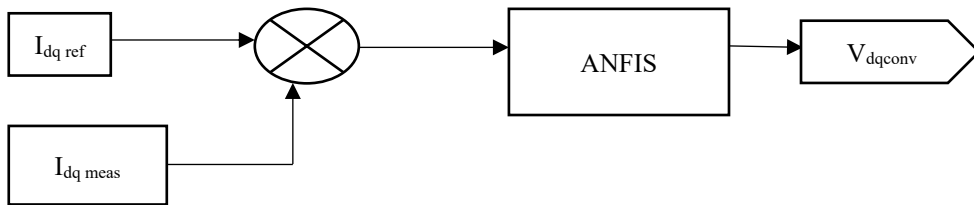


Figure 3. Current regulation

4. RESULTS AND DISCUSSION

The chosen rating for the hybrid power generation system in the context of the smart grid is illustrated in the Table 1. This hybrid system is integrated into the distribution power grid. The output generated by the wave power generator is linked to a VSC. Concurrently, solar power is connected to a DC/DC converter equipped with MPPT. Both DC sources are then connected to a common DC link voltage. Subsequently, an inverter, alongside another VSC, facilitates controlled AC voltage output. To enhance energy storage capabilities, a boost converter is strategically positioned at the point of common DC link, allowing energy storage in supercapacitors. In instances where power from renewable resources is unavailable, the supercapacitors seamlessly supply the required power. The system employs a DQ control logic to ensure the maintenance of stable power. Notably, ANFIS technology is employed in lieu of a PI controller for enhanced control and adaptability.

The power generated from solar, wave generator and fuel cells are integrated to the DC link and connected Figure 4 illustrates the power generation from the PV source. Notably, during periods of high irradiation, it reaches its peak power output of 25 kW. The power output fluctuates in response to changes in irradiation levels. In Figure 5, the power generated by the fuel cell is depicted. It becomes evident that the fuel cell steps in to supply power whenever there is a decline in PV power. Figure 6 showcases the power output from the wave power generator, which remains stable at 2 kW.

Moving on to Figure 7, it presents the real and reactive power at the grid connection. The graph indicates that a maximum of 60 kW is supplied to the grid with zero reactive power. Figure 8 provides insights into the grid's voltage and current characteristics. An enlarged view of the wave observed in Figure 5 is detailed in Figure 9. Additionally, Figure 10 displays the stability of the DC link voltage and modulation index and a zoomed waveform is depicted in Figure 10.

Table 1. Simulation specification

PV parameters	Value
Module type	Sun power SPR305WHT
Number of cells/modules	96
Number of series connected module/string	5
Number of parallel strings	17
V_{oc} (V)	64.2
I_{sc} (A)	5.96
V_{mp} (V)	54.7
I_{mp} (A)	5.58
Wave generator parameters	Value
Voltage in V	500
Current in A	8
Power in Watts	2000
Fuel cell parameters	Value
Type	PEMFC
Voltage in V	48×(6 fuel cells)
Power in W	6 kW

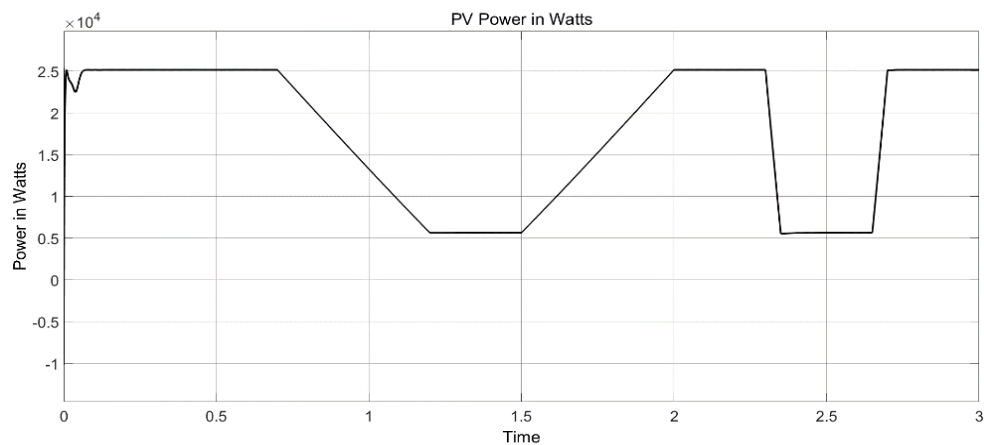


Figure 4. PV power generation profile

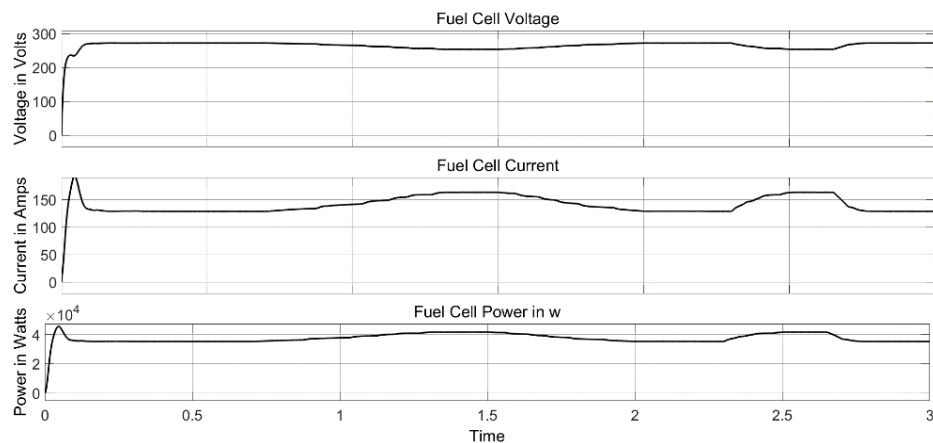


Figure 5. Fuel cell power generation profile

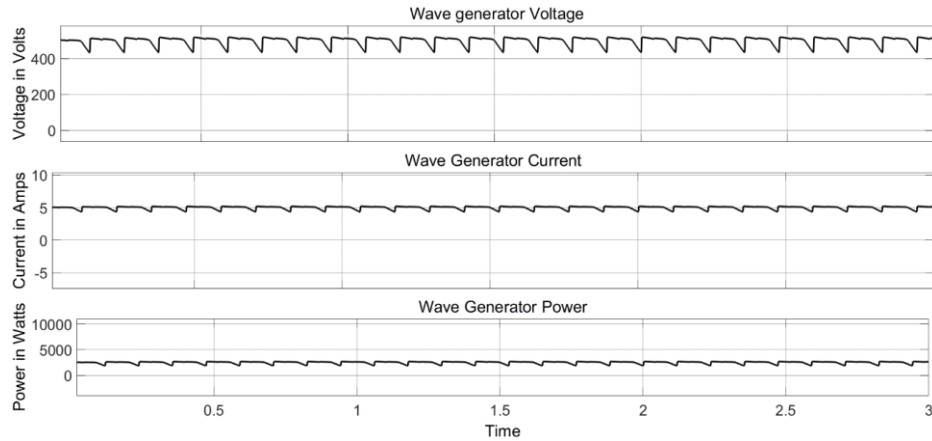


Figure 6. Wave power generation profile

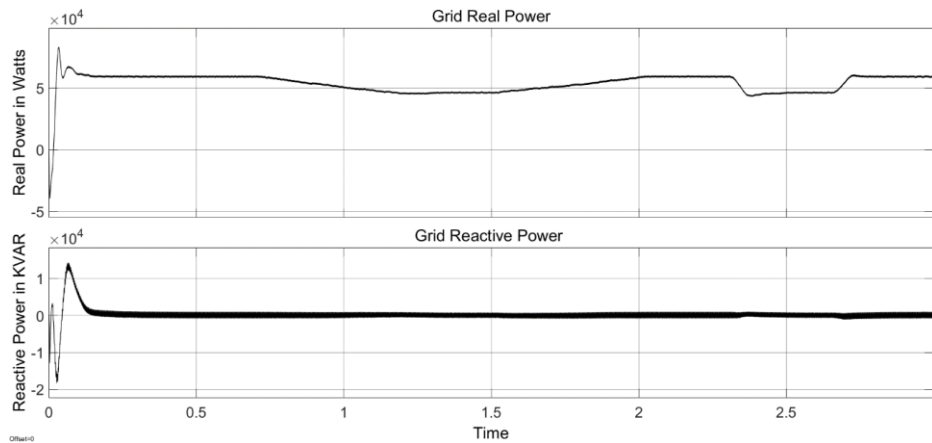


Figure 7. Grid side real and reactive power

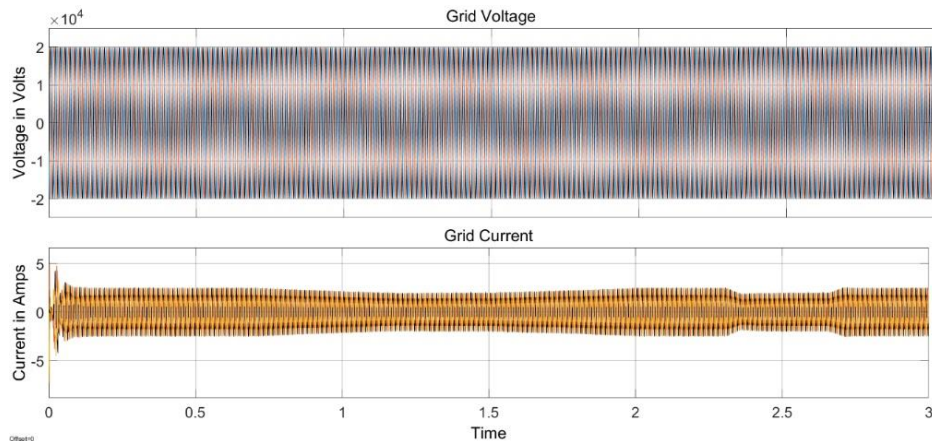


Figure 8. Grid side voltage and current response

The overall performance of the system is assessed with the ANFIS-based DQ control strategy, demonstrating effective operation in the context of hybrid power generation. The smart power transfer dynamics are evident in the seamless coordination between various power sources, ensuring a reliable and stable power supply to the grid. Notably, both fuzzy logic controllers (FLC) and AN-FIS employ the same set of fuzzy rules, emphasizing the role of these rules in determining the system's behavior and output in various

fuzzy logic-based approaches. Both fuzzy and ANFIS specifications is as given in Table 1. Since the ANFIS controller is used the Sugeno type is the only choice for the FLC controller. Thus, the number of output membership variables will be equal to the number of rules used for the FLC. The fuzzy rules used for the implementation are given in Table 2. Three membership (MF1, MF2, MF3) variables for two inputs are low, medium and high. And the output will be a constant since it is the Sugeno method.

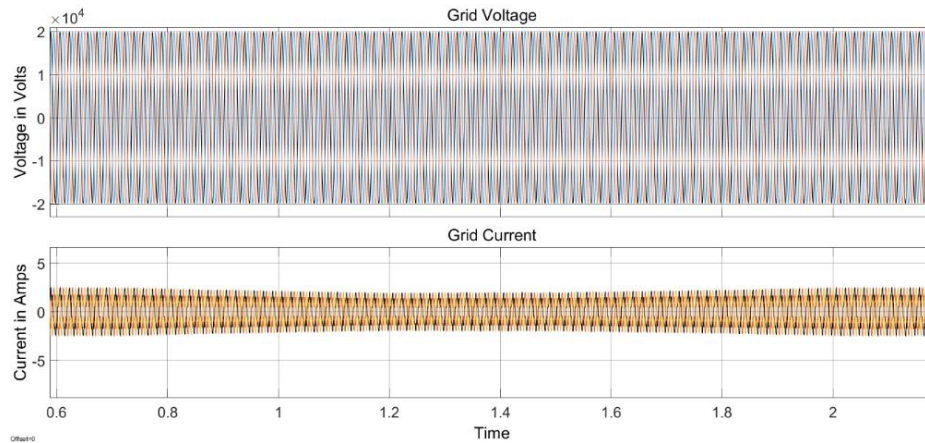


Figure 9. Grid side voltage and current response (zoomed)

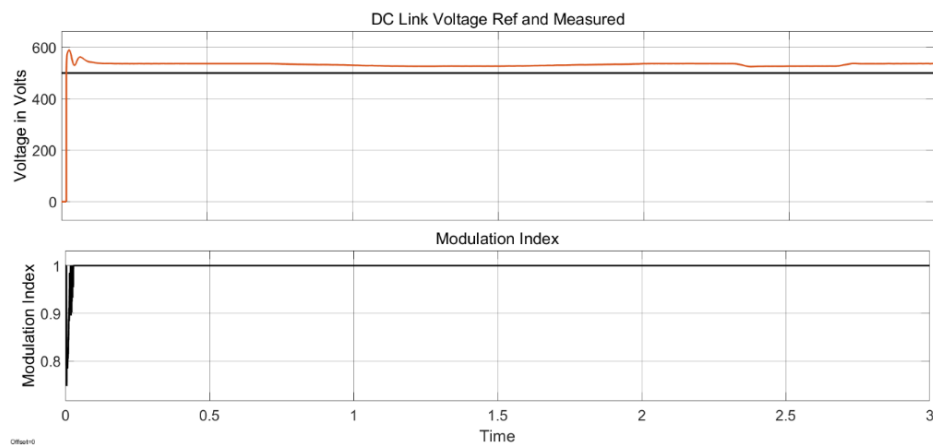


Figure 10. Reference V_{dc} versus measured and modulation index

Table 2. Fuzzy rules for both FLC and ANFIS

Input 1	Input 2	Output
MF1	MF1	MF1
MF1	MF2	MF2
MF1	MF3	MF3
MF2	MF1	MF4
MF2	MF2	MF5
MF2	MF3	MF6
MF3	MF1	MF7
MF3	MF2	MF8
MF3	MF3	MF9
MF1	MF1	MF1
MF1	MF2	MF2
MF1	MF3	MF3
MF2	MF1	MF4
MF2	MF2	MF5
MF2	MF3	MF6
MF3	MF1	MF7

Since ANFIS employs a Sugeno-type inference system, the FLC was also designed accordingly. This led to a setup where the number of output membership functions matches the number of rules, each producing constant outputs, enhancing computational efficiency. Voltage regulation at the DC link is important since it defines the stability of the grid connected systems. The regulation of the voltage observed using the ANFIS controller is less than 5% as can be seen in Figure 11. The reference voltage of 500 is fixed at the DC link and it is observed that the ANFIS controller brings it to around 535 V which is maintaining a regulation of 3.5%. The regulation at the DC link can be compared for the power quality improvement in the overall grid integrated power system. The trained surface of the ANFIS model is as shown in Figure 12.

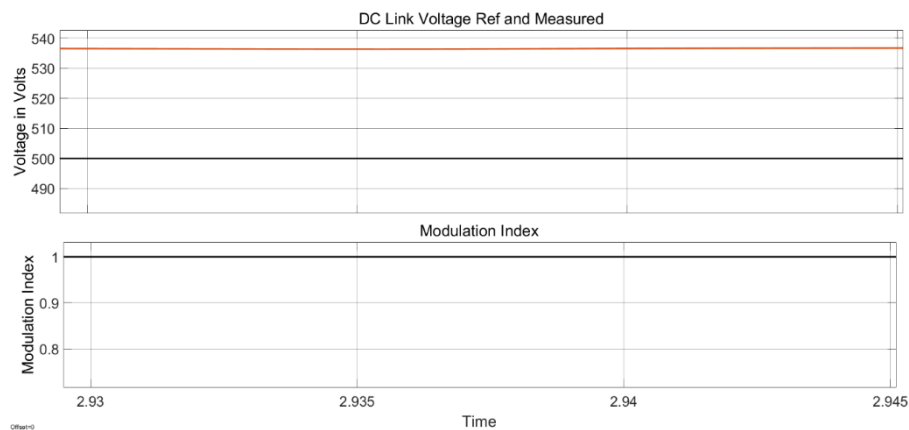


Figure 11. Reference V_{dc} versus measured and modulation index (zoomed)

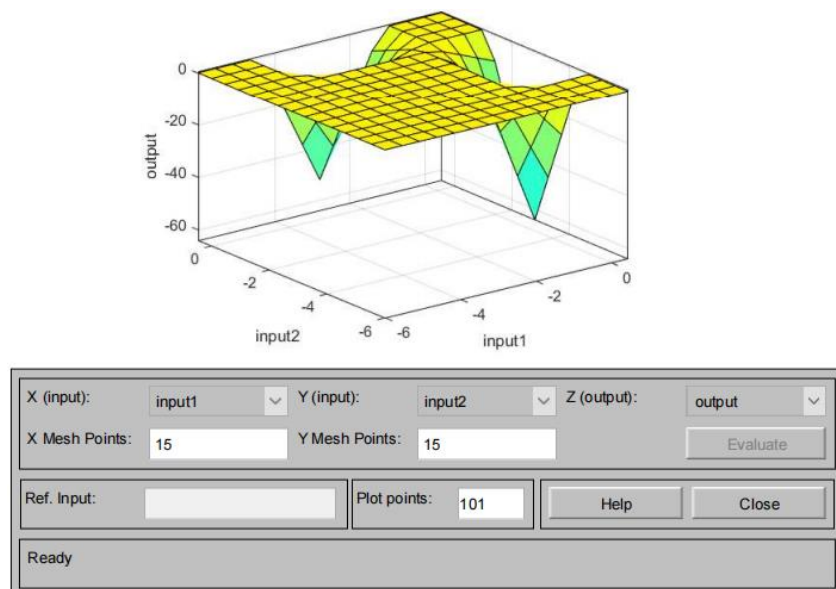


Figure 12. Trained surface of ANFIS model

5. CONCLUSION

Within the smart grid environment, a hybrid power generation system is deployed, integrating PV power, fuel cell technology, and wave power generation. The system's power response is thoroughly examined to assess its effectiveness. Employing a combination of DQ control and ANFIS control, the fuel cell becomes instrumental in providing power support during periods of unavailability in the PV system. The connection of the grid to this hybrid power system results in an overall improvement in power quality and reliability. The DC link voltage was successfully regulated by the ANFIS controller with a deviation of just 3.5% from the reference value of 500 V (observed at ~535 V). This level of regulation is within acceptable limits (below 5%), highlighting improved stability and power quality in the grid-connected hybrid system.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Manohar B S	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
Basavaraja Banakara						✓				✓		✓		

C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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