# Distributed power flow controller based on fuzzy-logic controller for solar-wind energy hybrid system

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**ABSTRACT**

The demand of electricity globally led to the concept of renewable energy resources for power generation that are eco-friendly and freely available from nature. The solar photovoltaic systems and wind-based power generators are considered as primary renewable resources and are called as Distributed Generation units as they are scattered in nature. These are operated with bidirectional converters by providing auxiliary services at grid side and load side in either mode of microgrid operation. Besides, the DC power generation units' integration gets converted into AC system by means of inverters. These types of systems not only increase voltage and current harmonics, power frequency deviations but also drive the distribution system to risky operating zone. This emphasizes the stipulation of advanced control schemes for microgrid architecture. Consequently, power electronic converters introduce harmonics in the system and affect the system performance. To report these expanded issues, the authors recognized an advanced custom power device entitled distributed power flow controller. The proposed hybrid solar-wind energy system is first studied with a distributed power-flow controller. Later the system is examined by replacing proportional integral controller with fuzzy logic controller (FLC) for shunt control of distributed power-flow controller. To validate the investigations, MATLAB/Simulink software is used.



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## 1. INTRODUCTION

The swift escalation of power electronic equipment and its appliance have vividly altered the distinctiveness in the distribution system. The redundant serious power-quality problems are created in recent distribution system due to power electronic device based nonlinear components. Fascinatingly, it is renowned that the same power electronic devices have the capability to shield utility grid and load either from power quality problems. The flexible AC transmission system (FACTS) device and custom power device (CPD) are considered as the vital compensation devices to be installed in power system for finest control of active and reactive power flow [1]. The development of the FACTS has allowed for the implementation of various novel ideas that are making the power system more dependable, flexible, and providing greater control over power flow without affecting the generating schedule.

In an effort to optimize the performance of the power system network, the authors of this research suggest an unique device termed as distributed-power flow controller (DPFC), which is an improved version of the unified power flow controller (UPFC). The primary distinction between DPFC and UPFC is the lack of

DC connectivity between the converters. The third harmonic frequency component in DPFC connects the two converters so that power may be traded dynamically. As an added advantage, the suggested approach provides superior performance against voltage and current deviations [2]. This paper presents the development and testing of a simulation model of the proposed system in the MATLAB/Simulink environment to evaluate the effectiveness of the suggested control strategy.

Section 2 describes the suggested dynamic system in light of the preceding material. A variety of DPFC control techniques, such as the proportional- integral controller and the fuzzy logic controller, are discussed in section 3. Section 4 presents the work's extensive examination of the Simulation findings, while section 5 presents the work's conclusions.

## 2. PROPOSED DYNAMIC METHOD

Figure 1 shows a block schematic of a hybrid energy system that combines solar PV arrays with wind turbines. In [3]–[8], the event of a failure at the point of common coupling (PCC), both the output power and the grid power would be affected. As a result, in the event that power quality difficulties manifested at the load, a specialized device designated as a DPFC would be implemented. In this study, the converters of a DPFC are controlled using a proportional integral controller and a fuzzy logic controller.

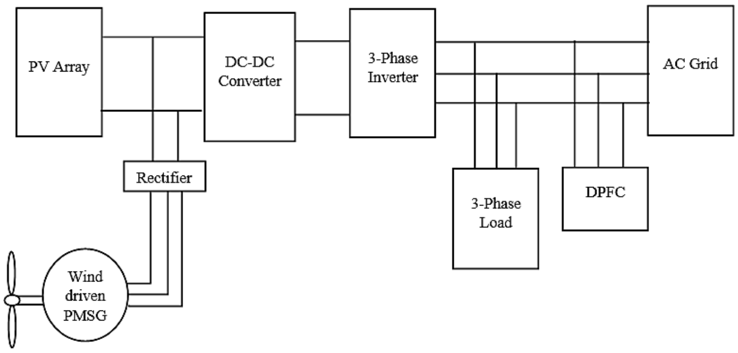


Figure 1. Block diagram of proposed photovoltaic-wind hybrid system

### 2.1. Wind-energy conversion system

Wind energy conversion system key components are permanent magnet synchronous generators, wind turbines, power electronic converters. The function of the wind turbine is to convert the kinetic energy of the wind into mechanical power [9]. The mechanical energy produced by a wind turbine may be expressed as (1).

$$P_m = \frac{1}{2}\rho C_p A_r V_w^3 \quad (1)$$

$$C_p(\lambda, \beta) = 0.73\left(\frac{151}{\lambda_i} - 0.58\beta - 0.002\beta^{2.14} - 13.2\right)e^{\frac{-18.4}{\lambda_i}} \quad (2)$$

$$\text{Where} \quad \boldsymbol{\lambda_i} = \frac{\mathbf{1}}{\frac{\mathbf{1}}{\boldsymbol{\lambda}-\mathbf{0.02}\boldsymbol{\beta}} - \frac{\mathbf{0.003}}{\boldsymbol{\beta}^{\mathbf{3}}+\mathbf{1}}} \quad (3)$$

$$\text{and} \quad \text{TSR}(\boldsymbol{\lambda}) = \frac{\boldsymbol{\omega_r R_r}}{\boldsymbol{V_w}} \quad (4)$$

Assume constant rotor pitch angle and power coefficient Cp = 0.59 according to Betz's Law. Yet, realistic performance coefficients (Cp) vary from 0.2 to 0.4.

– Permanent magnet synchronous generator (PMSG) mathematical model

It is not required to have a separate frame, gearbox, couplings, and shaft lines when using a PMSG with a gearless or single-stage gear configuration [10]-[15]. The mathematical formulation of permanent magnet synchronous generator in synchronous reference frame is indicated by (5)-(7).

$$V_{gd} = R_{sg}i_{gd} + L_{sg}\frac{di_{gd}}{dt} - \omega_e L_{sg}i_{gq} \quad (5)$$

$$V_{gq} = R_{sq}i_{gq} + L_{sg}\frac{di_{gq}}{dt} + \omega_e(L_{sg}i_{gd} + \lambda_m) \quad (6)$$

The electromagnetic torque is given as

$$T_e = \frac{3}{2}\frac{p}{2}\lambda_m i_{gq} \quad (7)$$

### 2.2. Concept of solar PV system

The ideal PV cell is a source of current linked parallel to a diode [16], [17]. In accordance with Kirchhoff's Current Law,

$$I_{ph} = I_d + I_{RP} + I \quad (8)$$

$$I = I_{ph} - (I_{RP} + I_d) \quad (9)$$

The photo - voltaic module's current has been seen as

$$I = I_{ph} - (I_{RP} + I_d) \quad (10)$$

### 2.3. Distributed power flow controller (DPFC)

The DPFC is derived out from UPFC in this research. The DPFC replaces shunt and series converters' common dc links. With the aid of third harmonic component, active power switch over occurs between a shunt and a series converter. The DPFC's series converter uses distributed FACTS (D-FACTS) [18]–[22]. Figure 2 represents the internal circuit of DPFC [23].

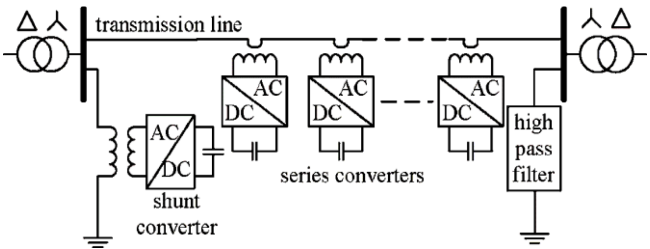


Figure 2. Internal circuit of distributed power flow controller

## 3. CONTROL STRATEGIES OF DPFC

DPFC management systems help to reduce power quality concerns including sag, swell, and harmonics. The controllers must be able to identify and investigate system issues in addition to correction of current and voltage harmonics. In this study, DPFC that incorporates proportional integral controller and fuzzy logic controller is used to alleviate power quality issues such sags, swells, and harmonics. The system's performance is monitored using MATLAB/Simulink.

### 3.1. DPFC with proportional integral controller

Proportional controllers have been used in a power system network to regulate converters for instance grid connected inverters, dc-dc converters, as well as specialized power devices. The controller's performance is impacted by changes in system variables. The PI controller generates pulses for the DPFC shunt controller in the suggested technique. Figure 3 shows a proportional integral controller's fundamental construction [24]. The proportional integral controller output is the sum of the proportional and integral controller outputs. For PI controller, the process inputs are u(t) and the reference inputs are r(t) [25], [26].

$$u(t) = Kp\, e(t) + Ki \int e(t)\, dt \quad (11)$$

Apply LaPlace transform on both sides

$$U(s) = \left( Kp + \frac{Ki}{s} \right) E(s) \tag{12}$$

In order to sort out and reduce the steady-state error, the proportional integral controller is utilized.

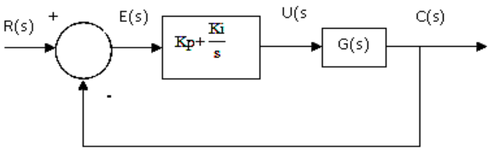


Figure 3. Basic structure of PI controller

### 3.2. DPFC with fuzzy logic controller

The FLC is based on fuzzy-set theory and human reasoning processes. Figure 4 depicts the FLC structure with three essential blocks: fuzzification, rule-base interfacing, and defuzzification. The membership functions used in FLC are triangular membership functions for simplicity as shown in Figure 5. In [27], [28] fuzzification is processed with continuous universe of discourse and Defuzzification is processed using the centroid method

The DC voltage of shunt controller and a reference value are compared in DPFC and error is then provided for FLC to produce required power for regulation of shunt controller. Constructing fuzzy control rules originates with developing rules that correlate the input variables to the attributes of the model. Table 1 gives the rules for constructing FLC [29].

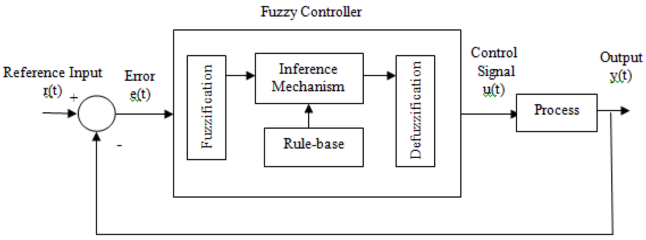


Figure 4. Basic structure of fuzzy logic controller

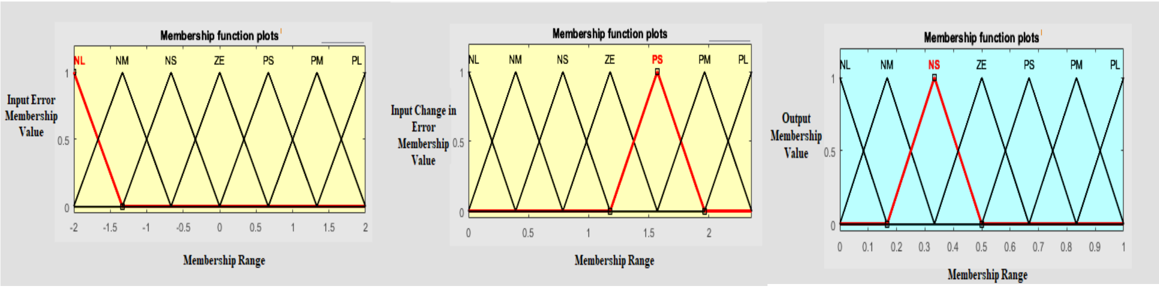


Figure 5. Input and output membership functions

Table 1. Rule base of FLC

| e Δe | NGL | NGM | NGS | ZE | PSS | PSM | PSL |
|---|---|---|---|---|---|---|---|
| NGL | NGL | NGL | NGL | NGL | NGM | NGM | ZE |
| NGM | NGL | NGL | NGL | NGM | NGM | ZE | PSS |
| NGS | NGL | NGL | NGM | NGS | ZE | PSS | PSM |
| ZE | NGL | NGM | NGS | ZE | PSS | PSM | PSL |
| PSS | NGM | NGS | ZE | PSS | PSM | PSL | PSL |
| PSM | NGS | ZE | PSS | PSM | PSL | PSL | PSL |
| PSL | ZE | PSS | PSM | PSL | PSL | PSL | PSL |

## 4. RESULTS AND DISCUSSIONS

The effectiveness of a DPFC device using a proportional integral controller and a fuzzy logic controller is the subject of this study. MATLAB/Simulink is used to create these representations. Firstly, the suggested PV-wind system is constructed and connected into the grid without a DPFC device. The hybrid setup is then used to implement the DPFC device with its proportional-integral controller and FIC. In this study, we investigate at the load-point simulation results of a DPFC device using two distinct controllers. The load point of a system is confronted with a variety of power quality difficulties at varying times.

### 4.1. Simulation results without DPFC device

Figure 6 illustrate the simulation outcomes of the load voltage and load current waveforms the proposed PV-wind hybrid system without DPFC. The power output at the load point is shown in Figure 7. Harmonic spectra of load voltage at various times are shown in Figures 8 and 9. The voltage sag harmonic (%THD) occurs at t=0.2 seconds, while the voltage swell harmonic (%THD) occurs at t=0.6 seconds.

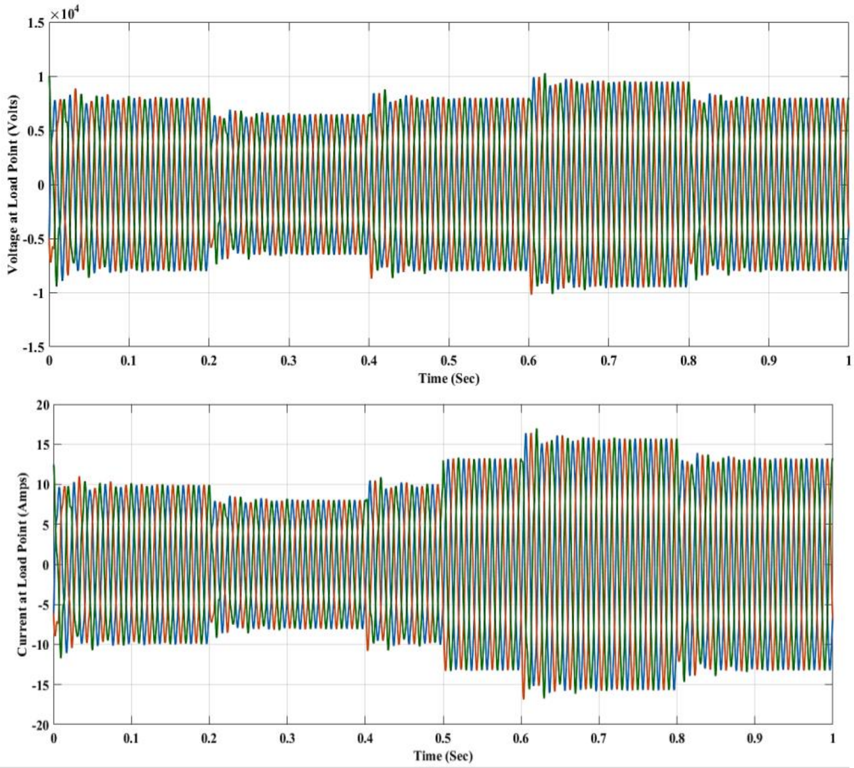


Figure 6. Load voltage and load current waveform before DPFC connected

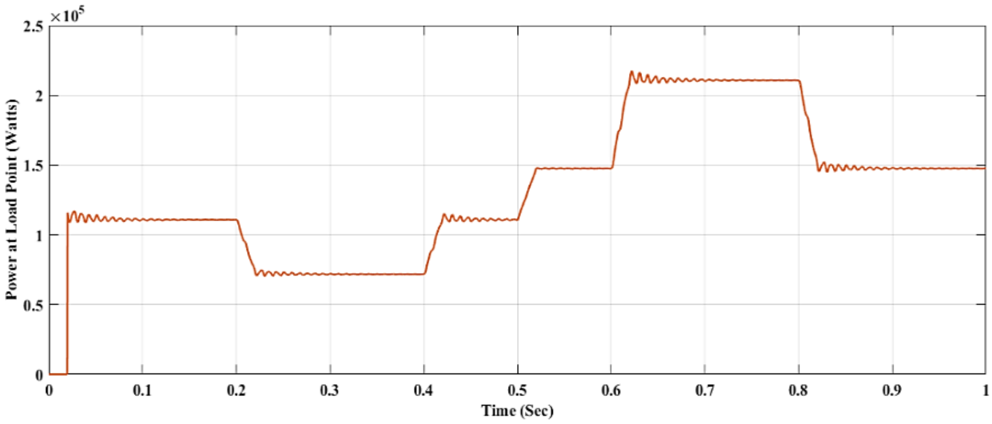


Figure 7. Load active power before DPFC connected

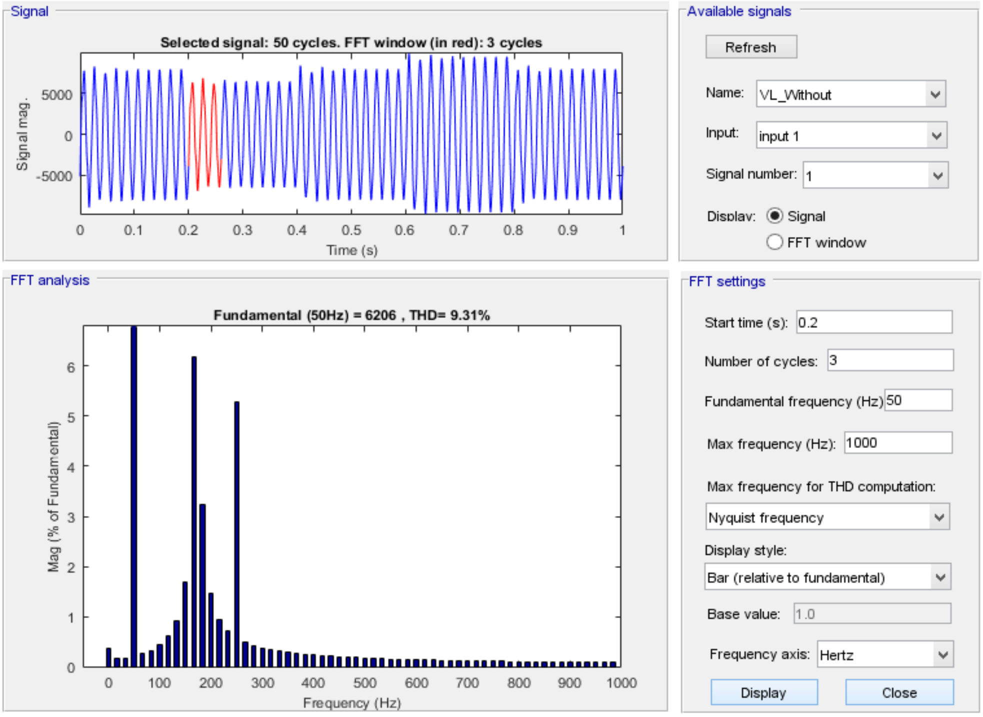


Figure 8. $V_L$ Sag Harmonic spectrum

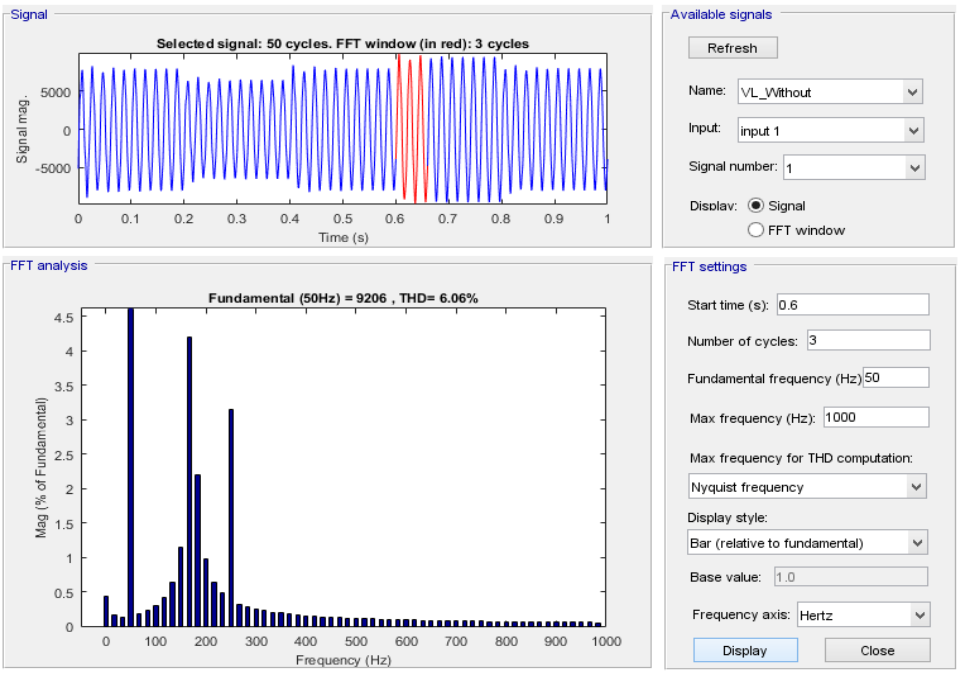


Figure 9. $V_L$ Swell harmonic spectrum

### 4.2. Simulation results of proportional integral controller-DPFC

Figure 10 shows the simulation outcomes of voltage and current at load point of a PV–Wind hybrid system using a DPFC and a PI controller. The power output at the load point is shown in Figure 11. The harmonic spectra of the load voltage are shown in Figure 12 and Figure 13 at two distinct times. At t=0.2 sec (voltage sag harmonic), the %THD is 4.36%, while at t=0.6 sec (voltage swell harmonic), it is 3.80%.

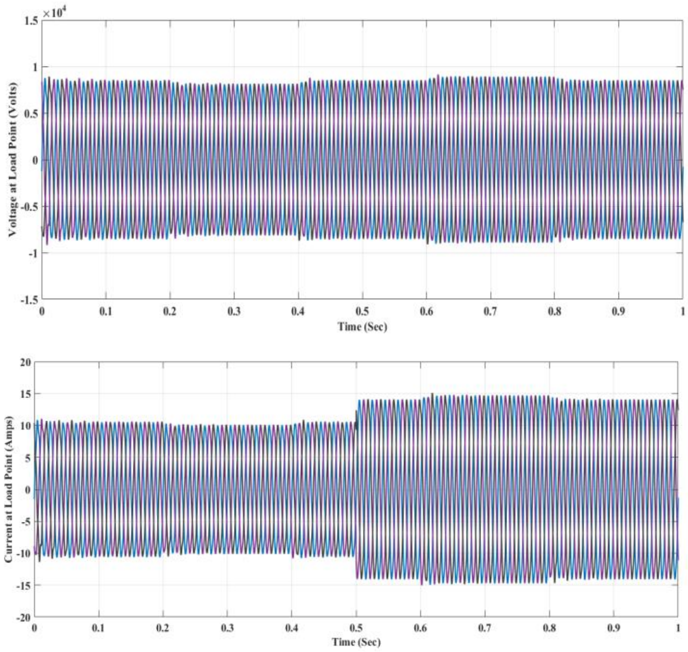


Figure 10. Load voltage and load current waveform with DPFC

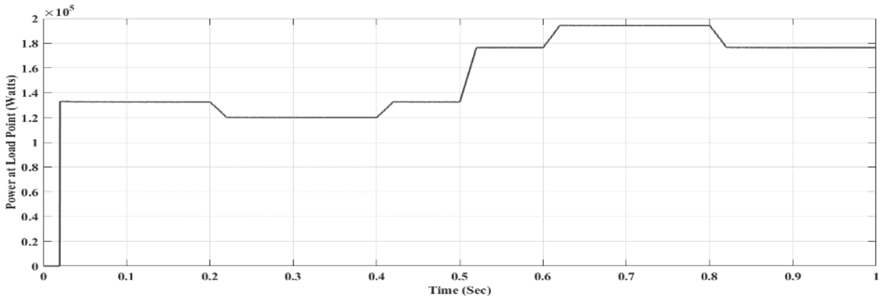


Figure 11. Load active power with DPFC

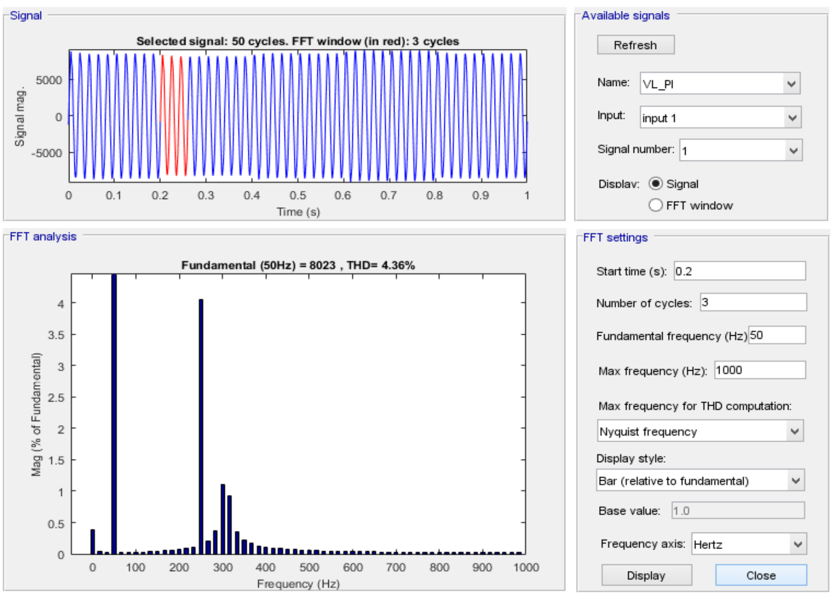


Figure 12. $V_L$ sag harmonic spectrum

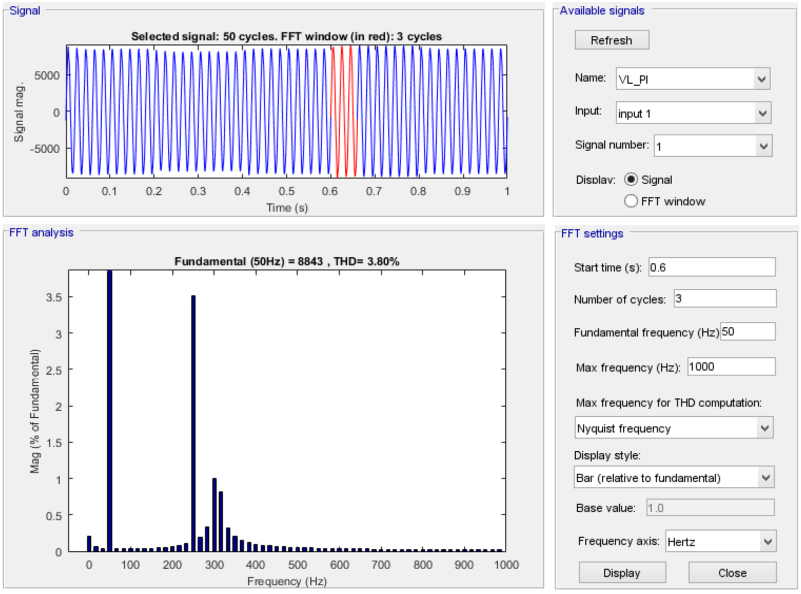


Figure 13. $V_L$ swell harmonic spectrum

### 4.3. Simulation results DPFC device with fuzzy logic controller

The load voltage and load current waveforms for DPFC with FLC is shown in Figure 14 and it can be seen that the FLC-DPFC device has effectively compensated for the varying voltage and current levels in the system. Figure 15 shows that required active power of the load i.e., up to t=0.5 sec it is 150 KW and after t=0.5 sec it is 200 KW. The load voltage harmonic spectra are shown in Figure 16 and Figure 17 at various times. THD% values are 1.89% at t=0.2s (voltage sag harmonic) and 1.69% at t=0.6s (voltage swell harmonic).

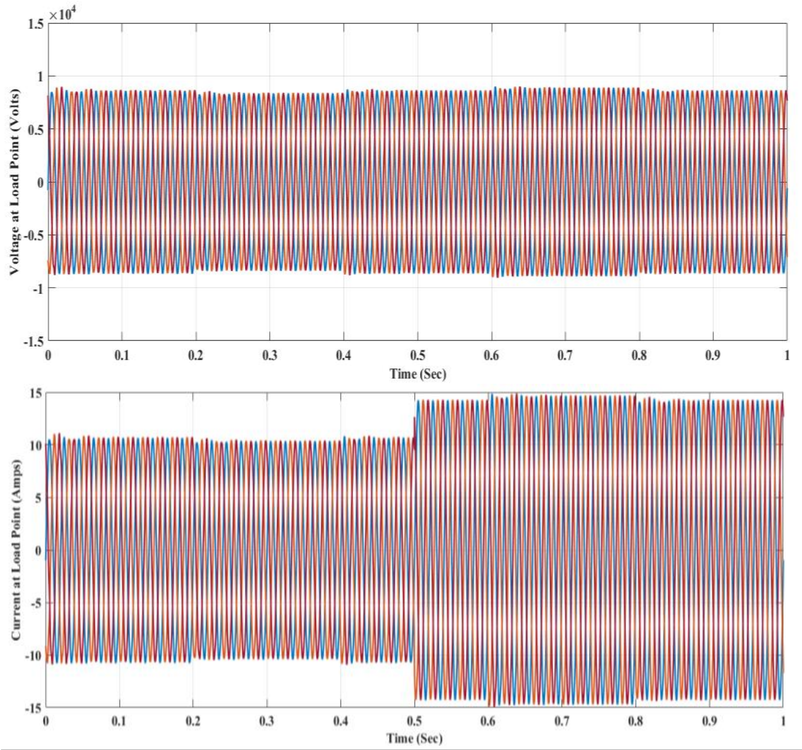


Figure 14. Load voltage and load current waveforms for DPFC with FLC

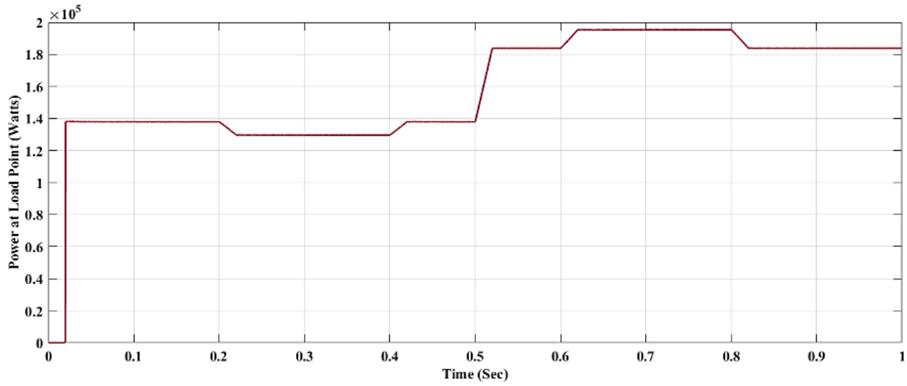


Figure 15. Load active power for DPFC with FLC

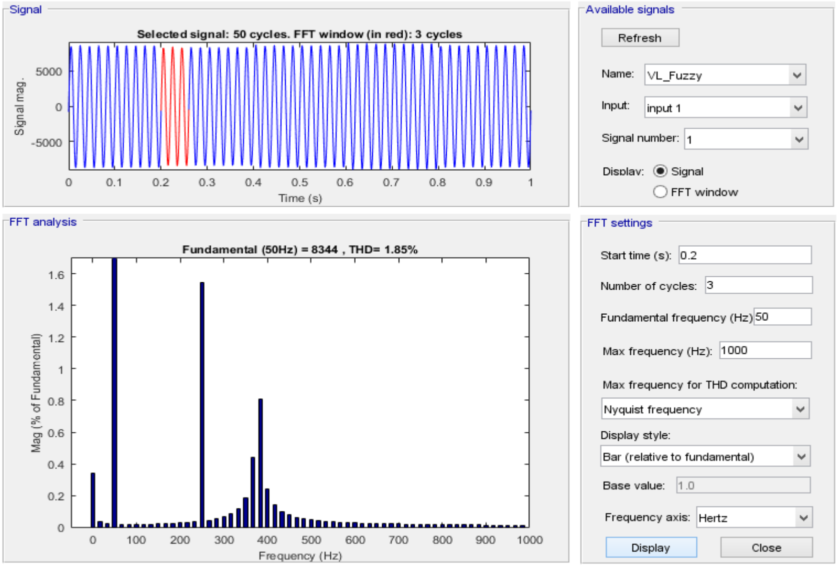


Figure 16. $V_L$ sag harmonic spectrum

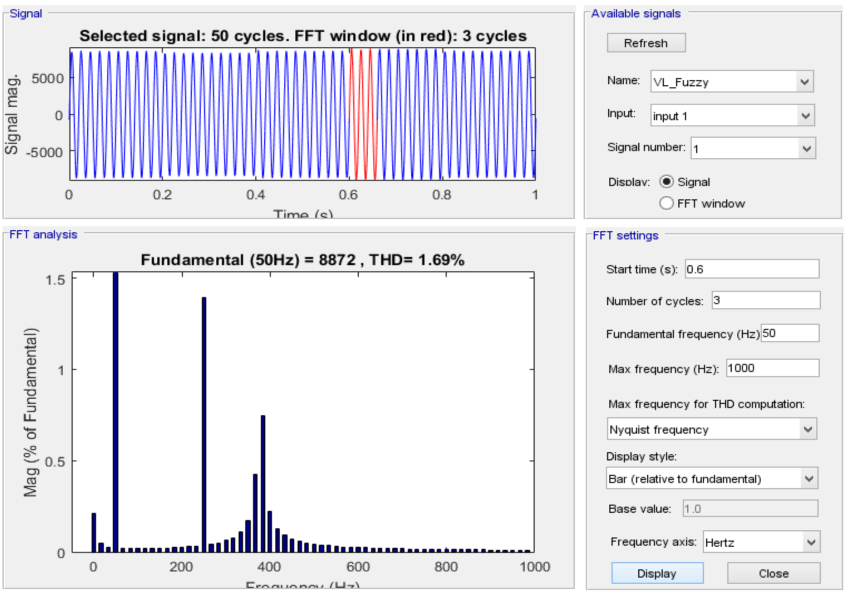


Figure 17. $V_L$ swell harmonic spectrum

### 4.4. Comparative analysis

Table 2 compares the harmonic distortion levels produced from different compensatory approaches. Figure 18 depicts the performance of suggested controllers in percent THD. Table 2 and Figure 18 show that DPFC with FLC reduces voltage sags and swells better than DPFC with FLC under different situations.

Table 2. Load voltage waveforms - %THD

| %THD | With DPFC | DPFC with PI Controller | DPFC with FLC |
|---|---|---|---|
| % THD for Load Voltage (Sag) | 9.31 | 4.36 | 1.85 |
| % THD for Load Voltage (Swell) | 6.06 | 3.80 | 1.69 |

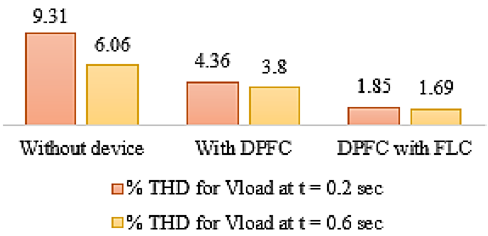


Figure 18. Load voltage %THD values

## 5. CONCLUSION

This article investigated a DPFC device for reducing power quality concerns such as sags and swells. DPFC has a comparable structure to UPFC and may affect system parameters. The DPFC has three control loops: shunt, central and series. The system under investigation is a PV-Wind Hybrid. Swells and sags near the load approximate dynamic performance. The effectiveness of a DPFC device has been studied using proportional integral and fuzzy logic controllers. Time intervals of 0.2 seconds and 0.6 seconds are used to measure harmonic content. The simulation outcomes show that the fuzzy logic controller outperforms the standard PI controller in terms of compensation and harmonic distortion.

## REFERENCES

[1] S. L. Prakash, M. Arutchelvi, and A. Stanley Jesudaiyan, “Autonomous PV-array excited wind-driven induction generator for off-grid application in India,” i*EEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 4, no. 4, pp. 1259–1269, December 2016, doi: 10.1109/JESTPE.2016.2579678.

[2] H. R. Pota, M. J. Hossain, M. A. Mahmud, R. Gadh, R. C. Bansal, “Islanded operation of microgrids with inverter connected renewable energy resources,” *IEEE PES General Meeting Washington DC*, 27-31 July 2014, doi: 10.3182/20140824-6-ZA-1003.01091.

[3] S. ul Hassan, Z. ul Abideen, and T. Izhar, “Advanced control techniques for micro-grids power quality improvement,” *2017 Asian Conference on Energy, Power and Transportation Electrification (ACEPT)*, 24-26 Oct. 2017, pp. 1–6, doi: 10.1109/ACEPT.2017.8168564.

[4] G. Pandu Ranga Reddy and M. Vijaya Kumar, “Analysis of wind energy conversion system employing DFIG with SPWM and SVPWM type converters,” *Journal of Electrical Engineering (JEE)*, vol. 15, no. 4, pp. 95–106, Sep 2015.

[5] Z. Yuan, S. W.H de Haan, B. Frreira and D. Cevoric, “A FACTS DEVICE: Distributed power flow controller (DPFC),” *IEEE Transaction on Power Electronics,* vol. 25, no. 10, pp. 2564 – 2572, October 2010, doi: 10.1109/TPEL.2010.2050494.

[6] A. K. Bahamani, G. M. Sreerama Reddy, and V. Ganesh, “Comparative of performance for UPFC with DPFC,” *2017 International Conference on Electrical, Instrumentation and Communication Engineering (ICEICE2017)*, doi: 10.1109/ICEICE.2017.8191843.

[7] R. Pavan Kumar Naidu, and S. Meikandasivam, “Power quality enhancement in a grid-connected hybrid system with coordinated PQ theory & fractional order PID controller in DPFC,” *Sustainable Energy, Grids and Networks,* vol. 21, March 2020, doi: 10.1016/j.segan.2020.100317.

[8] Ahmed N. Alsammak, and Hasan A. Mohammed, “Power quality improvement using fuzzy logic controller based unified power flow controller (UPFC),” *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS),* vol. 21, no. 1, pp. 1–9, January 2021, doi: 10.11591/ijeecs.v21.i1.pp1-9.

[9] R. Duvvuru, N. Rajeswaran, and T. Sanjeeva Rao, “Performance of distributed power flow controller in transmission system based on fuzzy logic controller,” *International Journal of Recent Technology and Engineering (IJRTE),* vol. 8, no. 3, pp. 2039–2043, September 2019, doi: 10.35940/ijrte.C4530.098319.

[10] Dilip Kumar Pratihar, *Soft Computing: Fundamentals and Applications,* Alpha Science International Ltd. First Edition, 2013.

[11] A. Ananda Kumar, and J. Srinivasa Rao, “Power quality improvement of grid interconnected three phase four wire distribution system using fuzzy logic control,” *International Journal of Engineering Research and Technology*, vol. 1, no. 4, 2012, doi: 10.17577/IJERTV1IS4182.

[12] A. K. Giri, S. Arya, and R. Maurya, “Compensation of power quality problems in wind based renewable energy system for small consumer as isolated loads,” *IEEE Trans. Ind. Electron.*, vol. 66, no. 11, pp. 9023–9031, Nov. 2019, doi: 10.1109/TIE.2018.2873515.

[13] J. He, Y. W. Li, and F. Blaabjerg, “An enhanced islanding microgrid reactive power, imbalance power, and harmonic power sharing scheme,” *IEEE Trans. Power Electron*., vol. 30, no. 6, pp. 3389–3401, 2015, doi: 10.1109/TPEL.2014.2332998.

[14] D. C. Sekhar, P. V. V. R. Rao, and R. Kiranmayi, "A novel efficient adaptive-neuro fuzzy inference system control based smart grid to enhance power quality," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 12, no. 4, pp. 3375–3387, August 2022, doi: 10.11591/ijece.v12i4.pp3375-3387.
[15] N. A. M. Aseri *et al*., "Comparison of meta-heuristic algorithms for fuzzy modelling of COVID-19 illness' severity classification," *IAES International Journal of Artificial Intelligence (IJ-AI)*, vol. 11, no. 1, pp. 50–64, March 2022, doi: 10.11591/ijai.v11.i1.pp50-64.
[16] H. J. Queen, Jayakumar J, Deepika T.J., "Comparative techno-economic analysis of power system with and without renewable energy sources," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 24, no. 3, pp. 1260–1268, December 2021, doi: 10.11591/ijeecs.v24.i3.pp1260-1268.
[17] B. Fatima, C. Mama, and B. Benaissa, "Design methodology of smart photovoltaic plant," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 11, no. 6, pp. 4718–4730, December 2021, doi: 10.11591/ijece.v11i6.pp4718-4730.
[18] A. Khandelwal, and P. Nema, "Application of PI controller based active filter for harmonic mitigation of grid-connected PV-system," *Bulletin of Electrical Engineering and Informatics*, vol. 10, no. 5, pp. 2377–2382, October 2021, doi: 10.11591/eei.v10i5.2907.
[19] H. Ahmadi, Q. Shafiee, and H. Bevrani, "Dynamic modeling and transient stability analysis of distributed generators in a microgrid system," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 11, no. 5, pp. 3692–3703, October 2021, doi: 10.11591/ijece.v11i5.pp3692-3703.
[20] A.K. Kirgizov, S.A. Dmitriev, M.Kh. Safaraliev, D.A. Pavlyuchenko, A.H. Ghulomzoda, J.S. Ahyoev, "Expert system application for reactive power compensation in isolated electric power systems," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 11, no. 5, pp. 3682–3691, October 2021, doi: 10.11591/ijece.v11i5.pp3682-3691.
[21] D. Kucherov, A. Kozub, O. Sushchenko, and R. Skrynkovskyy, "Stabilizing the spatial position of a quadrotor by the backstepping procedure," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 23, no. 2, pp. 1188–1199, August 2021, doi: 10.11591/ijeecs.v23.i2.pp1188-1199.
[22] Aysar M. Yasin, Mohammed F. Alsayed, "Fuzzy logic power management for a PV/wind microgrid with backup and storage systems," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 11, no. 4, pp. 2876–2888, August 2021, doi: 10.11591/ijece.v11i4.pp2876-2888.
[23] E. Radwan, M. Nour, A. Baniyounes, and K. S. Al-Olimat, "Design of type-1 servo controller for grid voltage modulated direct-power control of single-phase grid-connected PV inverter," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 11, no. 3, pp. 1912–1923, June 2021, doi: 10.11591/ijece.v11i3.pp1912-1923.
[24] A. Basma, and O. Benyounes, "A simulation energy management system of a multi-source renewable energy based on multi agent system," *IAES International Journal of Artificial Intelligence (IJ-AI)*, vol. 10, no. 1, pp. 191–199, March 2021, doi: 10.11591/ijai.v10.i1.pp191-199.
[25] M. M. A. Hassan, X. Sun, and A. Ate, "FLC based on static var compensator for power system transient stability enhancement," *TELKOMNIKA Telecommunication, Computing, Electronics and Control*, vol. 18, no. 5, pp. 2665–2673, October 2020, doi: 10.12928/TELKOMNIKA.v18i5.15605.
[26] M. Sh. Aziz, and A. G. Abdullah, "Hybrid control strategies of SVC for reactive power compensation," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 19, no. 2, pp. 563–571, August 2020, doi: 10.11591/ijeecs.v19.i2.pp563-571.
[27] C. Ameur, S. Faquir, and A. Yahyaouy, "Intelligent optimization and management system for renewable energy systems using multi-agent," *IAES International Journal of Artificial Intelligence (IJ-AI)*, vol. 8, no. 4, pp. 352–359, December 2019, DOI: 10.11591/ijai.v8.i4.pp352-359.
[28] Sridhar R, Boopathi C S, D. Das, S. Agrawal, H. Choubisa, "An ingenious invasive weed optimization (IWO) aided maximum power tracking for partially shaded photovoltaic array," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 15, no. 2, pp. 543–553, August 2019, doi: 10.11591/ijeecs.v15.i2.pp543-553.
[29] Z. M. Yusoff *et al*., "Real time robustness test evaluation performance for intelligent fuzzy controller in extraction process," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 15, no. 3, pp. 1290–1296, September 2019, doi: 10.11591/ijeecs.v15.i3.pp1290-1296.

## BIOGRAPHIES OF AUTHORS

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