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Power Quality Enhancement of Standalone PV-Wind Hybrid Power Supply System with 3DOF-PID Controller

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Abstract
Microgrids serve as primary links for diverse loads, while numerous locally situated power supply systems are concurrently established in various locations. Grid-integrated hybrid renewable energy power conversion systems have gained significant popularity in recent years. However, a novel and effective control methodology must be implemented to supply high-quality power at the local load bus. The 3rd Order Degree of Freedom – PID (3DOF-PID) controllers stand out among numerous controllers, demonstrating exceptional performance across a wide range of operating conditions. In this paper, a hybrid system comprising a solar power plant and a wind power plant is examined, with a focus on its benefits to the power grid. Furthermore, Sliding Mode Control (SMC) techniques are applied to all photovoltaic (PV) and wind power conversion systems to facilitate the operation of the boost converter as Maximum Power Point Tracking (MPPT) devices. A shared DC bus is created by combining all converters in the solar power facility and the wind energy conversion plant. An inverter is integrated between the DC bus and the utility grid's point of common coupling (PCC). The study presents a robust control strategy utilizing 3DOF-PID controllers to ensure high-quality power delivery at the PCC while accommodating a diverse range of load combinations, including both linear and nonlinear loads, as well as single-phase and three-phase reactive power loads. 3DOF-PID controllers have been created for each converter and incorporated using OPAL-RT technology and modules within a Real-Time Simulator (RTS). The results are presented through RTS to evaluate the suggested control methodologies for the power supply system that integrates grid-connected hybrid renewable energy sources (RESs).

Keywords: 3DOF-PID, Wind, PV, Power Quality, Grid connected system

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1. Introduction

The utility power grid is a widely established system designed to deliver electricity to various power loads. Multiple electric power sources are typically incorporated into the UPG for different purposes. Hybrid REPSs have gained increased popularity, particularly when integrated with UPG. The application of REPS in electricity generation presents a viable method to address the challenges posed by global warming. Incorporating various REPS can aid in developing highly reliable power supply systems connected to the grid. The power generation from REPS is subject to variations caused by changing weather conditions [1]. An effective control methodology is obtainable in this article, which is essential for ensuring consistent power quality for consumers in the face of variations in loads and generating units. Various renewable energy power systems (REPS) favour PVS-based solar plants and PMSG-coupled wind power conversion systems (WPCSs) for establishing different configurations of electric power supply units [2]. Loads typically operate at the PCC, exhibiting unbalanced, nonlinear, and reactive characteristics. Consequently, these loads may negatively impact power quality, particularly when connected to a utility power grid (UPG). To guarantee a high-quality power supply to loads, it is crucial to implement suitable control methods that align with the load requirements for generation. Separate MPPT converters are incorporated into each REPCS to maximize their efficiency.

This article presents a novel control methodology for inverters. In contrast to traditional PI and Mamdani fuzzy controllers, a 3DOF-PID controller demonstrates superior performance during swift fluctuations in the grid-connected power supply system. The following outlines the diverse objectives of the paper:

- Develop a grid-connected REPS that incorporates hybrid technologies.
- Apply SMC-based MPPT techniques to both WPCSs and PVSs.
- Create an innovative control technique for the inverter.
- The suggested control methods integrate 3DOF-PID controllers to achieve optimal responses across various operating conditions.
- Two OPAL-RT devices illustrate HIL's functionality, highlighting countless results from numerous case studies.

The article is prepared into subsequent segments. An indication of the complete system is offered in Part II. The methodologies for MPPT in PVSs and WPCSs utilizing SMCs are detailed in Section III. The proposed control procedure for the inverter is elaborated upon in Section IV. Different outcomes derived from HIL are presented and examined in Section V. The conclusion is given in Section VI.

2. System Description

The block diagram illustrating the hybrid REPS connected to the Uninterruptible Power Grid (UPG) is depicted in Fig. 1. This diagram illustrates a wind farm comprising multiple wind power conversion systems (WPCSs), a solar plant featuring several photovoltaic systems (PVSs), a direct current (DC) link, various power electronic converters, a transformer, a point of common coupling (PCC), a unified power flow controller (UPFC), and several local loads. Using suitable converters, REP's power sources are typically linked to the DC bus. Each solar power facility consists of multiple PV arrays. In contrast, each wind power station comprises several Permanent Magnet Synchronous Generators (PMSG) units linked to their corresponding wind turbines. The arrangement of the wind and solar plants, along with their corresponding MPPT converters, is demonstrated in Fig2 (a) and (b), respectively. To achieve maximum efficiency of REPS, it is crucial to implement effective MPPT methods across all wind turbines and photovoltaic systems (PVSs).

Numerous algorithms are available for enhancing the energy output from wind turbines and photovoltaic systems (PVSs); however, SMC offers the most effective solution among these. To eliminate the necessity for multiple sensors, SMCs are designed to rely solely on the devices' C-link voltage and corresponding currents. Consequently, speed sensors for wind turbines and voltage measurements across PVSs are rendered unnecessary. This enables the utilization of the voltage and currents from the boost converter to develop the MPPT algorithm (specifically, SMC) for the respective turbines and PVSs.

Numerous investigators have developed systems of an equivalent nature, with only a restricted numeral of notable systems highlighted in references [3] and [4]. The authors proposed a novel control methodology expected to improve power quality in hybrid REPSs within microgrids [5].

Additionally, the authors discussed strategies for augmenting hydrogen production. Balu et al. [2], the authors are a standalone Microgrid that operates independently of UPG. Katta et al. [4], the authors propose a control methodology utilizing an H∞ controller for single-stage grid-integrated PVSs; however, the authors do not address the inclusion of the WPCS.

Malla et al. [5], the authors created a coordinated power management system by proposing a hybrid

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REPS integrated with a smart grid. In the previous work of [6], Pradhan et al. developed a coordinated power management system for a hybrid REPS connected to a standalone power supply system; however, this system does not incorporate the WPCS and is not linked to the UPG. Elmorshedy et al. [7] introduced an enhanced performance methodology for grid-connected hybrid PVSs and WPCSs. The authors introduced a grid-connected hybrid PVS and a WPCS to address uncertainty issues, as discussed [8].

The authors introduced a grid-connected hybrid power supply system that integrates PVSs, WPCSs, and battery storage [9]. A synchronous scalar control methodology is introduced for grid-connected PVSs to operate induction machines [10]. The authors introduced an advanced mechanism strategy for a grid-connected hybrid system comprising photovoltaic systems (PVSs), wind power conversion systems (WPCSs), fuel cells, and batteries [11]. Rolán et al. [12] discuss the integration of distributed REPS into unbalanced grids.

In the studies of Balu et al. [2], Katta et al. [4], and Rolán et al. [12], the authors do not classify 3DOF-PID controllers as effective for enhancing power quality at the load bus, particularly in the connection of REPS to UPG. A novel control technique for an inverter is introduced in this paper, utilizing 3DOF-PID controllers to enhance power quality in hybrid RESs connected to the utility grid. Different responses are examined and showcased using HIL [13] and [14].

The equations (1) and (2-5) are utilized to develop the models for the PVS and WPCS, respectively. The parameters associated with a single PVS are detailed in Table 1, while the parameters for a single WPCS are presented in Table 2.

$$I_{pv} = I_{ph} - \frac{(V_{pv}+I_{pv}R_s)}{R_{sh}} - I_{rs}\left[exp\left(\frac{q(V_{pv}+I_{pv}R_s)}{AKT}\right)-1\right] \quad (1)$$

Were,

$$I_{rs} = I_{rr}\left[\frac{T}{T_r}\right]^3 exp\left(\frac{qV_D}{AK}\left[\frac{1}{T_r}-\frac{1}{T}\right]\right) \text{ and } I_{ph} = [I_{sc}+k(T-T_r)]\frac{G}{1000} \quad (2)$$

$$2A_t\frac{d\omega_t}{dt} = B_m - B_{sh} \quad (3)$$

$$\frac{1}{\omega_{elb}}\frac{d\theta_{tw}}{dt} = \omega_t - \omega_r \quad (4)$$

$$2A_g\frac{d\omega_r}{dt} = B_{sh} - B_g \quad (5)$$

Where inertia constants of the turbine and PMSG are denoted by A_t and A_g correspondingly, θ_{tw} represents the shaft twist angle, the rotor speed of the PMSG is ω_r in p.u., the angular speed of the turbine is signified by ω_t in p.u., and ω_{elb} signifies electrical base speed., The shaft torque (B_{sh})is

$$B_{sh} = C_{sh}\theta_{tw} + D_c\frac{d\theta_{tw}}{dt} \quad (5)$$

Table 1 Ratings of a PV Module.

S. No	Name	Value
1	Current during short-circuit (Amp).	8.01.
2	Voltage when the circuit opens (V).	36.9.
3	$V_{MPP.}$	30.3.
4	$I_{MPP.}$	7.1.

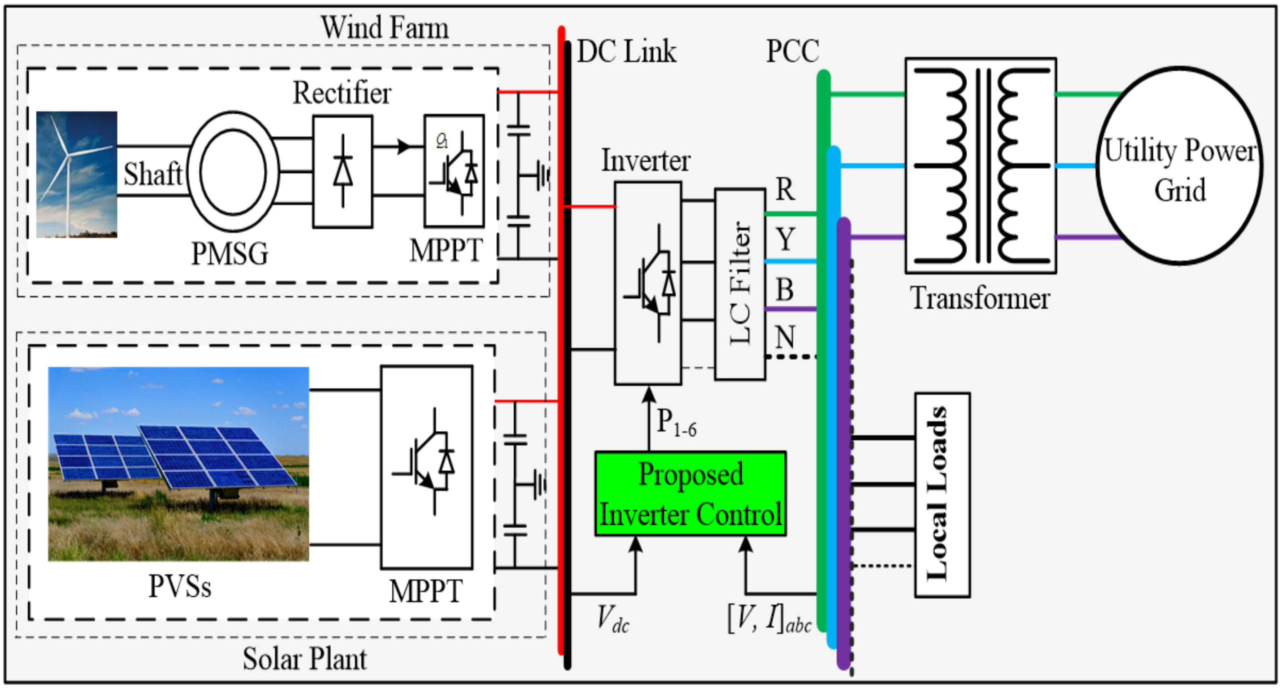

Fig. 1 UPG-connected hybrid REPS

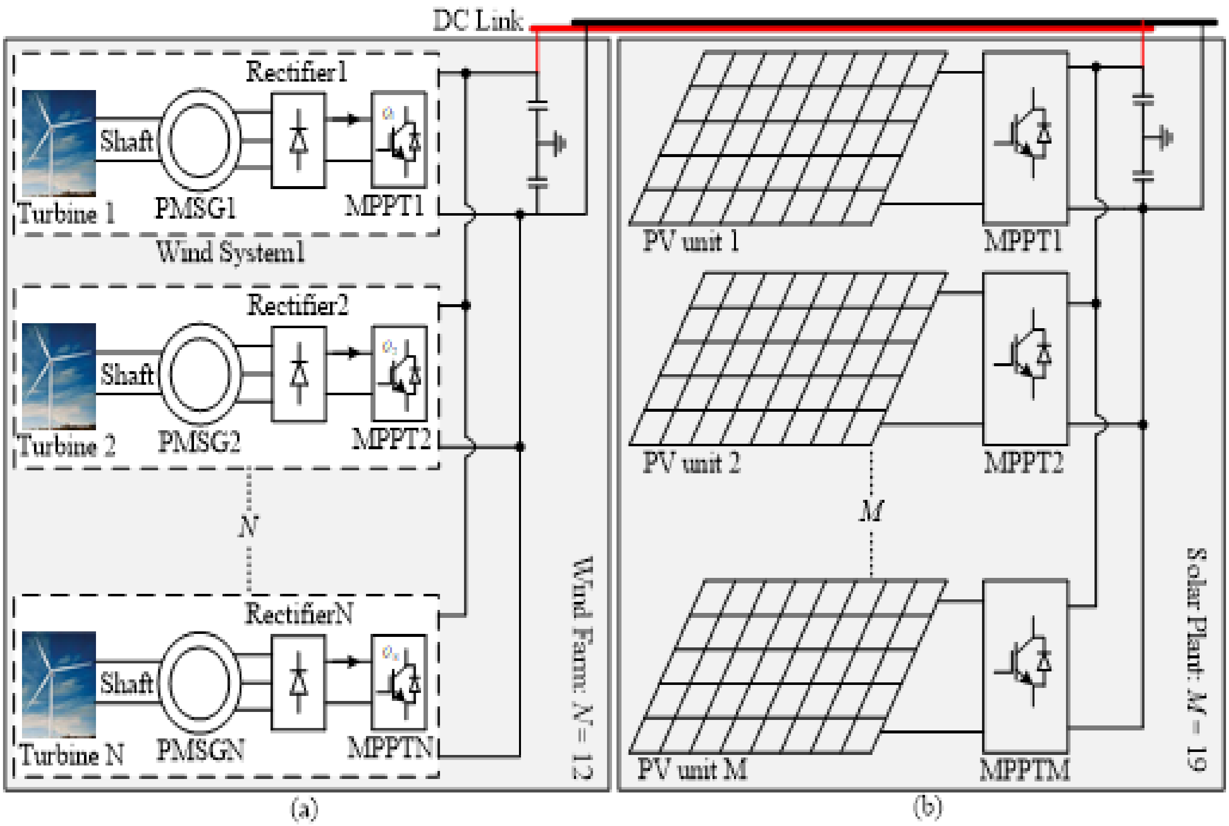

Fig. 2 Size of (a) WPCS, (b) PVSs.

Table 2: Parameters of WPCS.

$A_t$andA_g	4s and 0.1A_t
C_{sh} (p.u./el.rad)	0.3
D_c (p.u.s/el.rad)	0.7
Number of poles	10
Rated speed (rad/s)	153
Armature resistance (Ohm)	0.425
Stator inductance (Ls)	0.0084
Magnetic flux linkage (Wb)	0.433
Rated torque (Nm)	40.0
Rated power	6000

3. MPPT of PVS and WPCS with SMC

Numerous algorithms and control techniques are available to function as MPPT for PVS and WPCS. Ismeil et al. [15] and Pandey et al. [16] work to implement SMC on the boost converter of each PVS and WPCS to optimize power extraction across various operating conditions. To achieve improved performance comparable to that of conventional PI and Fuzzy controllers, a 3DOF-PID controller.

Guo [17], the author is employed within the MPPT control strategy. The fundamental block diagram of a 3DOF-PID controller is illustrated in Fig. 1. The block diagram illustrated in Fig. 3 comprises systems for converting wind energy into electricity using a Permanent Magnet Synchronous Generator (PMSG), photovoltaic units (PVUs), and various loads. Each WPCS is connected to a shared DC link via a boost converter that operates as a maximum power point tracker (MPPT). Each PV array has its own MPPT converter, specifically a boost circuit connected to a shared DC link. The control strategies for all MPPT converters are developed to minimize the number of required voltage sensors, utilizing the DC link voltage (i.e., V_{dc}) as a reference. Therefore, it is necessary to use only current sensors to measure the current of the respective power units, WPCS or PVU. The suggested control strategies for MPPTs are formulated based on transferring current into a shared DC link via the boost converter. It is essential to note that the SMC controller operates independently of measuring the wind turbine's speed.

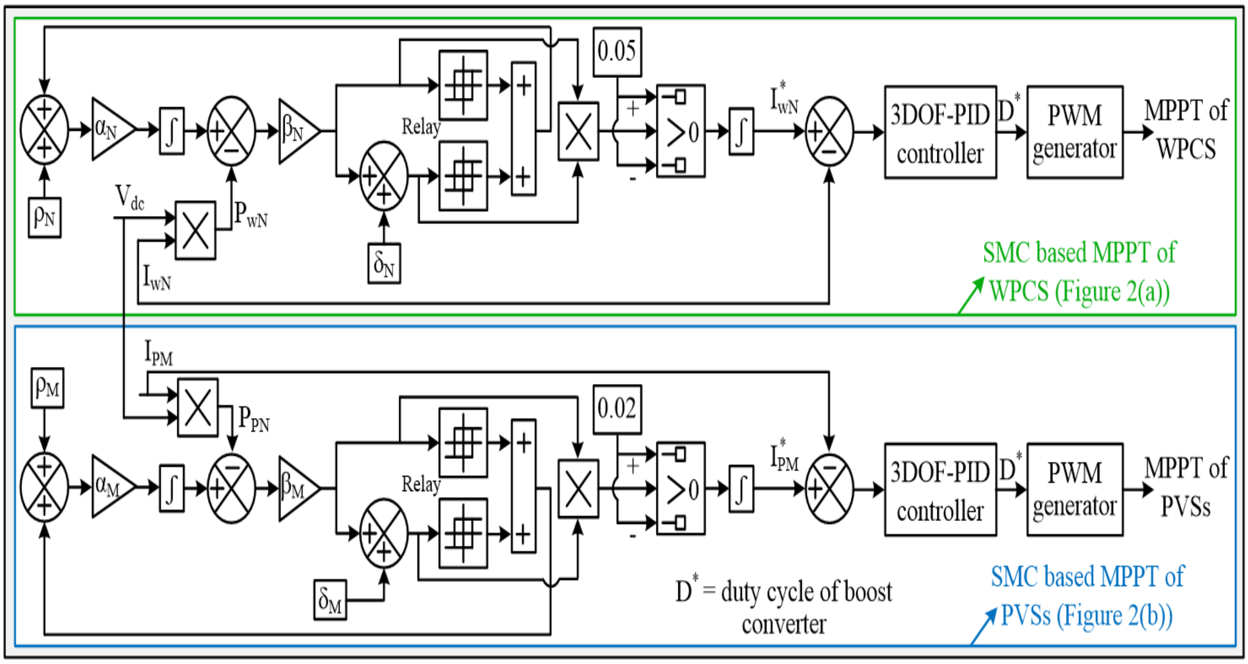

Fig. 3 The methodology of MPPT of PVU and WPCS with SMC and 3DOF-PID controllers.

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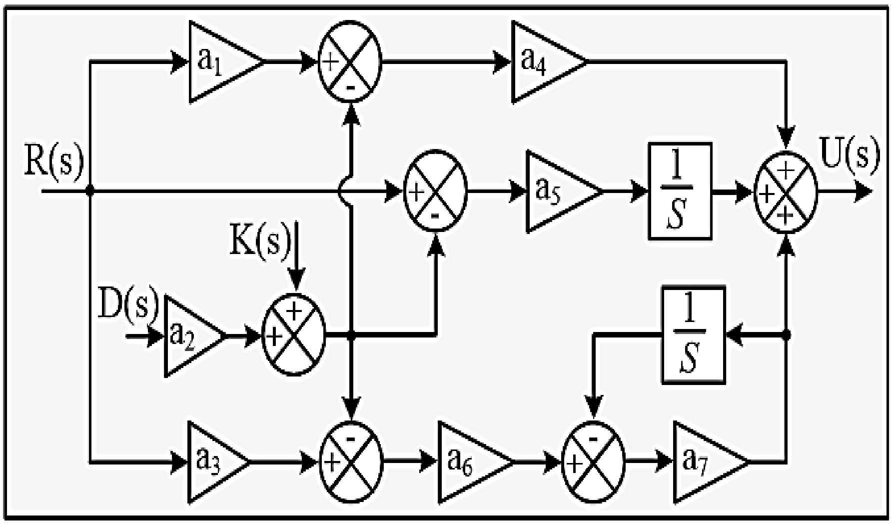

Fig. 4 Basic controller block diagram of a 3DOF-PID system [20].

The control methodology suggested for MPPT of PVUs and WPCS is demonstrated in Fig. 4. The recommended control procedure uses SMC and incorporates a 3DOF-PID regulator to generate an efficient duty cycle (D*) for the corresponding MPPT device, specifically the boost converter. The PWM generator can generate the corresponding pulse b using this D*. The duty cycle of the boost converter can be modified until the MPPT device supplies the necessary current to the DC link. The parameters of the proposed control technique are modified through a tuning process.

4. AC Side Controllers

An inverter must be positioned between the DC link and the PCC to provide AC power to the UPG system. An efficient control strategy should be established for the converter to regulate active power, minimize reactive power, and mitigate the impacts of unstable loads. This inverter is required to deliver currents to the PCC/UPG by regulating the voltages at the DC link and the PCC. Several AC burdens are operating at the PCC, and injecting high-quality power into the UPS is crucial [18]. The suggested control of the inverter must enhance power quality in all dimensions. Numerous loads necessitate reactive power for their operation and to meet their requirements; however, delivering reactive power via UPG is inefficient. Simultaneously, the impact of nonlinear loads must also be mitigated. Most of the load's functioning at PCC is single-phase, necessitating the provision of unbalanced currents from UPG. Supplying an unbalanced load through UPG may result in unbalanced voltages affecting other loads, particularly three-phase loads [19].

The suggested inverter control is considered to mitigate the impact of nonlinear loads by compensating for the reactive power required by local loads at the PCC. Additionally, it ensures the maintenance of balanced voltages at the PCC by injecting unbalanced currents, thereby managing the balanced currents of the UPG.

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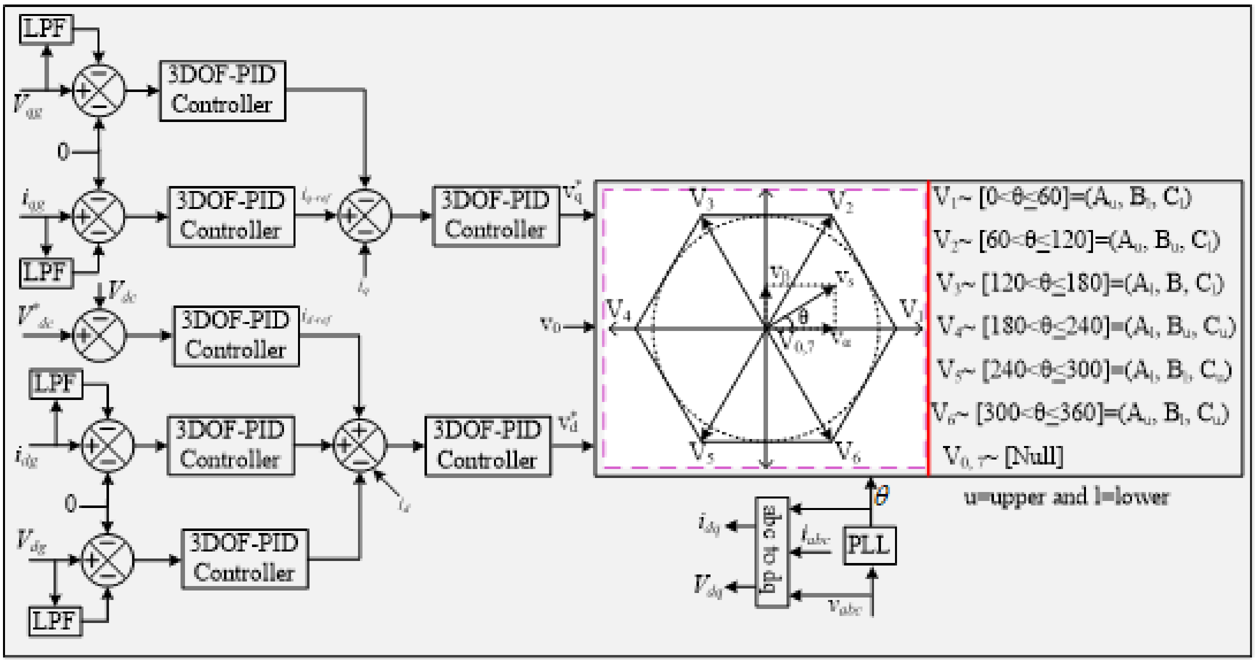

Fig. 5 Control methodology of inverter.

The mechanism methodology for the inverter is demonstrated in Fig. 5. The real power can be introduced into the PCC by confirming that the voltage of the DC join leftovers at its nominated orientation value. The reactive components of grid current (i_qg) and voltage (V_qg) are evaluated against zero to regulate reactive power flow and mitigate the impact of unbalanced loads. The direct-axis components also significantly enhanced power quality. The corresponding reference currents are obtained using 3DOF-PID controllers.

The space vector modulation technique is retained to create the necessary pulses through synchronization with the UPG. It also guarantees that oscillations resulting from nonlinear and unbalanced loads at the PCC do not propagate into PVSs and WPCS. Consequently, the temperature at the terminals of the PVS will be diminished, and the fatigue life of the turbine's shaft will be extended by eliminating the impact of second-frequency oscillations. To address this issue, the proposed control method eliminates the oscillating components in the DQ. When irradiance is absent, such as during nighttime or when the WPCS supplies no power, the inverters will function as DSTATCOMs to provide reactive power compensation and maintain the RMS voltage at the PCC.

5. Results

The configuration illustrated in Fig. 1 is developed on a real-time simulation platform that employs OPAL-RT machinery. The HIL setup involves linking two OPAL-RT units. One module occupation as an HSMS block, while the other is utilized to enhance control organizations, as displayed in Fig. 6. The configuration of the HIL system is accomplished by transmitting analogue signals from the OPAL RT-1 module to the mechanism unit module, known as OPAL RT-2. Similarly, digital signals are transmitted from unit 2 to unit 1.

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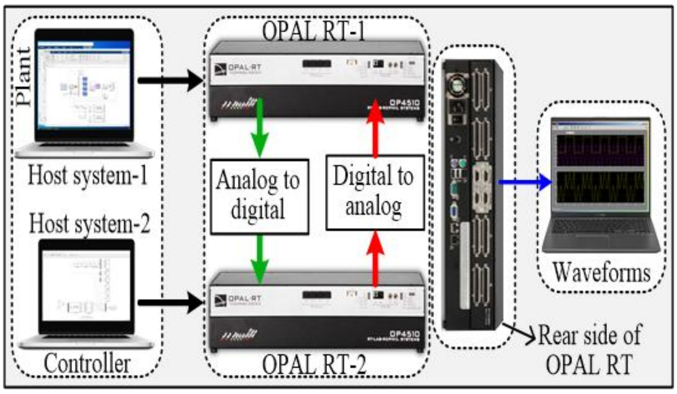

Fig. 6 HIL Configuration [21].

To create a HIL simulation, it is essential to divide the system into two primary elements: the controller and the plant. The Plant block, as illustrated in Figures 1 and 2, comprises a comprehensive array of components, including PVSs, wind energy systems, UPG, converters, voltage sensors, current sensors, and more. The controller unit, in contrast, consists exclusively of the proposed control models, Figures 4 and 5, and produces digital signals for pulses. The plant uses 'OPAL-RT'-1, whereas the regulator block is modelled with 'OPAL-RT'-2. Numerous case studies have been carried out to estimate the consequences and confirm the system's effectiveness. Numerous additional parameters of the system are derived from [19].

Case A: MPPT operation of PVS.

The individual PV array, consisting of three PV strings, is evaluated under varying irradiance conditions in this scenario. Initially, the irradiance is regarded as being at its maximum, declining to 900.0W/m² at t = 1 second. The model's corresponding responses during this operation are demonstrated in Fig. 7. The voltage across the PVS, specifically the input voltage at the boost converter, denoted as VPV, is illustrated in Fig. 7 (b). This voltage is regulated at its MPP V_{mpp}.

The proposed method, which employs SMC with three degrees of freedom PI-derivative (3DOF-PID) controllers, is compared with traditional PI and Mamdani fuzzy controllers. The corresponding powers of PVS are illustrated in Fig. 7 (c). Fig. 7 (d) illustrates the DC link's voltage. The current of the PVS is regulated to adjust the voltage across the PVS at its maximum power point (MPP) voltage, Vmpp, in response to variations in irradiance. The analysis of Fig. 7 indicates that the proposed control methodology offers considerable advantages and priority over traditional PI and Fuzzy controllers. A rapid and valuable response is accomplished done the use of 3DOF-PID regulators.

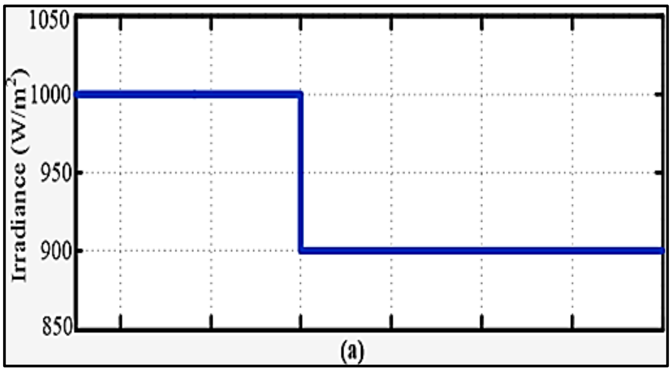

Fig. 7 (a) Irradiances [22].

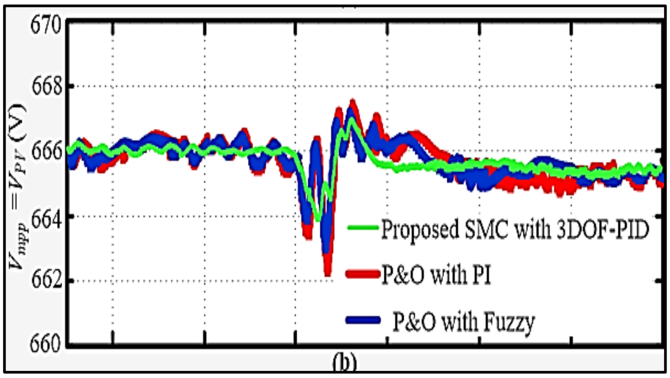

Fig. 7 (b)V_{mpp}

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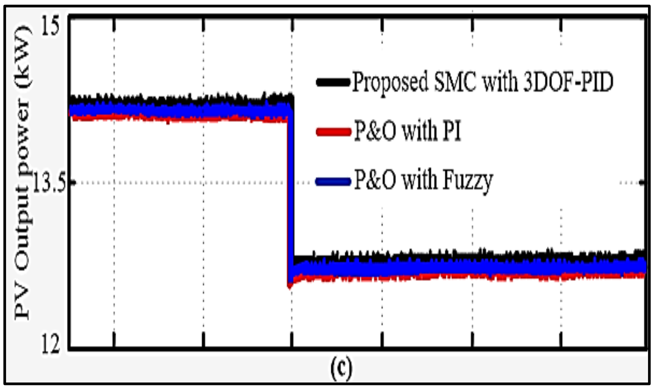

Fig. 7 (c) Powers

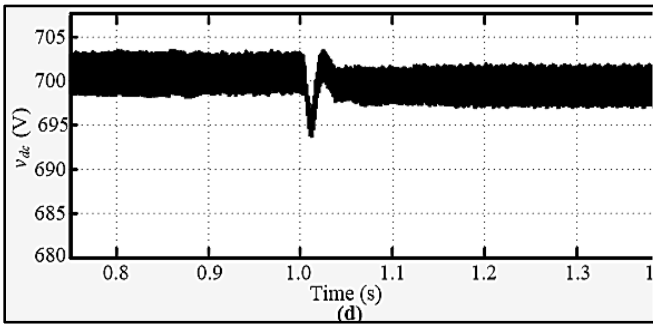

Fig. 7 (d)Voltage.

Case B: Performance of WTS's MPPT.

A two-mass wind turbine model has been established to improve the accuracy of MPPT outcomes. The model considers fluctuations in wind speed, decreasing from 12.0 m/s at t = 1.5 seconds to 7 m/s and subsequently increasing to 10 m/s at t = 4 s, as demonstrated in Fig. 8. Throughout these conversions, the torque of the wind turbine consistently aligns with the orientation torque derived from wind turbine data [1] and [3]. The graphical depiction in Fig. 8 demonstrates the characteristics of the mechanical and orientation torques within the wind turbine system. An abrupt reduction in wind speed, a defining property of the two-mass model, leads to a gradual decrease in torque. As illustrated in Fig. 8, the WTS operates at its maximum power point tracking (MPPT) [1]. The synchronization of the PMSG torque with the orientation torque is accomplished by regulating the current of the boost circuit.

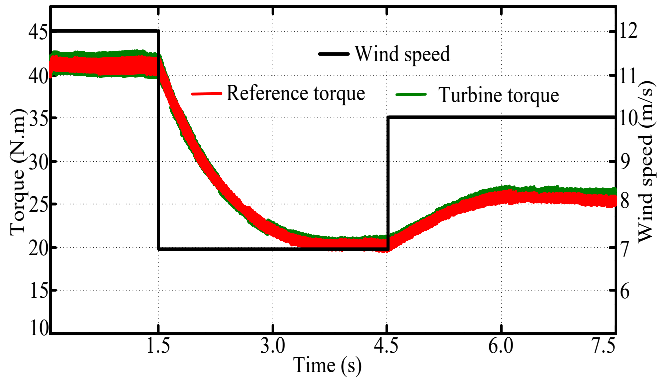

Fig. 8 MPPT action of WPCS with SMC and 3DOF-PID regulators.

Case-C Operation with unstable burdens.

Fig. 9 (a) illustrates the unstable currents associated with a 3-phase burden at the PCC. When an unbalanced load is functioning at the PCC, the UPG is required to provide unbalanced currents. This scenario results in uneven currents within the grid, attributed to irregular voltage drops occurring along the transmission lines. The proposed inverter regulator will produce counter-phase currents and introduce them into the PCC to achieve an equilibrium in the currents of the UPG. The balanced grid currents are illustrated in Fig. 9(b). In the absence of power from the REPS, the inverter operates as an interline power flow regulator, maintaining balanced currents for the UPG. Fig. 9 (c) depicts the balanced characteristics of the associated voltages at the PCC.

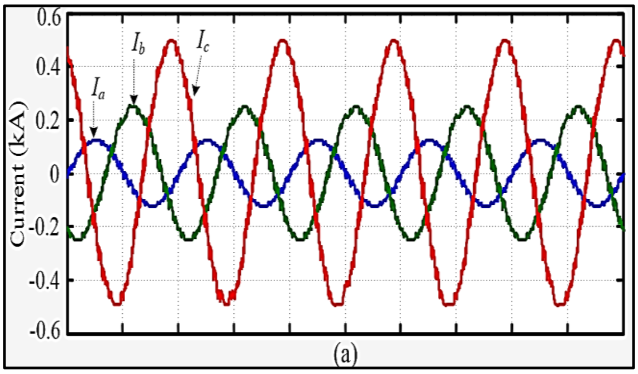

Fig. 9 (a) illustrates the unstable currents associated with a 3-phase load at the PCC

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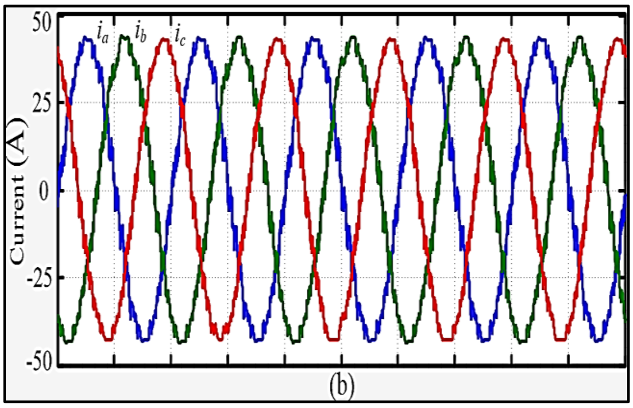

Fig. 9 B) illustrates the balanced grid currents

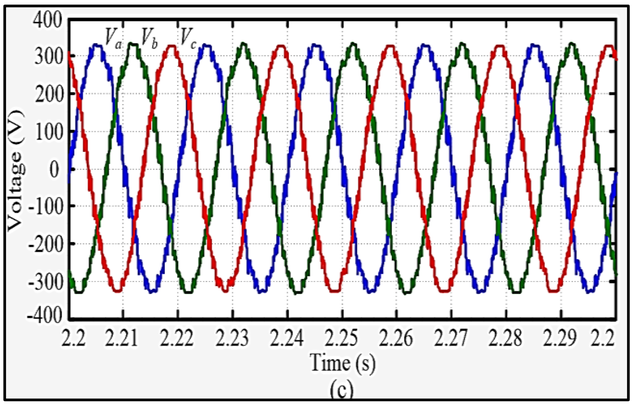

Fig. 9 C) depicts the balanced characteristics of the associated voltages at the PCC.

In this specific case study, an unstable burden was examined at a time of 2.0 s. The fluctuations produced in the wind farm and solar plants as a result of unbalanced currents are illustrated in Fig. 10, which compares the conventional and proposed control strategies of the inverter. The controller under review is also tested with nonlinear loads.

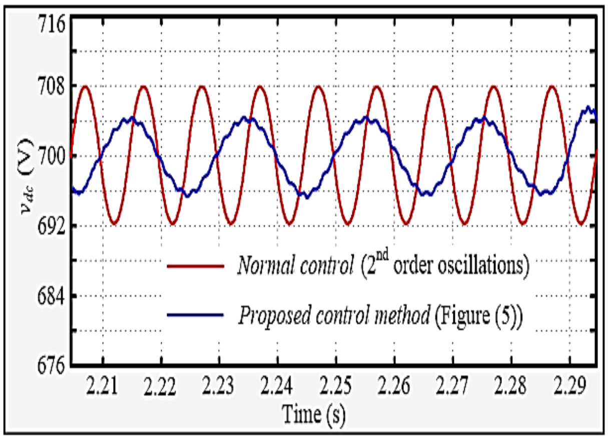

Fig.10: Voltage at DC link.

6. Conclusion

A comprehensive control methodology for grid-integrated REPS is presented in this paper, designed to enhance the power quality supplied at the point of common coupling (PCC). Control methodologies based on SMC have been employed for MPPT in PVS and WPCS, utilizing three-degree-of-freedom PI-Derivative 3DOF-PID controllers. The suggested control scheme can facilitate active power transfer to the UPG, compensating for reactive power and unstable loads while extenuating the impact of nonlinear burdens. The findings derived from OPAL-RT illustrate the effectiveness of this methodology and highlight the capabilities of the 3DOF-PID-based regulator in regulating a REPS-based grid-associated system through a Real-Time Simulator. A HIL arrangement has been implemented to provide a more realistic simulation and assessment of the regulator.

References

[1] Bahar, S. T., & Omar, R. G. (2023). PERMANENT MAGNET SYNCHRONOUS MOTOR TORQUE RIPPLE REDUCTION USING PREDICTIVE TORQUE CONTROL. *Journal of Engineering and Sustainable Development*, *27*(3), 394-406. **DOI:** https://doi.org/10.31272/jeasd.27.3.9

[2] Balu, V., Krishnaveni, K., Malla, P., & Malla, S. G. (2023). Improving the power quality and hydrogen production from renewable energy sources based microgrid. Engineering Research Express, 5(3), 035037. DOI:10.1088/2631-8695/acecdb

[3] Cao, W., Xing, N., Wen, Y., Chen, X., & Wang, D. (2021). New Adaptive Control Strategy for a Wind Turbine Permanent Magnet Synchronous Generator (PMSG). Inventions, 6(1), 3. **https://doi.org/10.3390/inventions6010003**

[4] Katta, N., Kumar, M. P., Mahender, K., Malla, D. N. S. R. P., & Malla, S. G. (2022, October). Whale Optimization based MPPT of Single Stage Grid Connected PV System with $\mathbf {H}\infty $ Controller. In 2022 1st IEEE International Conference on Industrial Electronics: Developments & Applications

(ICIDeA) (pp. 220-226). IEEE. DOI:10.1109/ICIDeA53933.2022.9970020

[5] Malla, S. G., Malla, J. M. R., Malla, P., Ramasamy, S., Doniparthi, S. K., Sahu, M. K., ... & Awad, H. (2022). Coordinated power management and control of renewable energy sources based smart grid. International Journal of Emerging Electric Power Systems, 23(2), 261-276. DOI: 10.1515/ijeeps-2021-0113

[6] Pradhan, C., Senapati, M. K., Malla, S. G., Nayak, P. K., & Gjengedal, T. (2020). Coordinated power management and control of standalone PV-hybrid system with modified IWO-based MPPT. IEEE Systems Journal, 15(3), 3585-3596.

[7] Elmorshedy, M. F., Habib, H. U. R., Ali, M. M., Sathik, M. J., & Almakhles, D. J. (2022). Improved performance of hybrid pv and wind generating system connected to the grid using finite-set model predictive control. IEEE Access, 10, 110344-110361. DOI:10.1109/ACCESS.2022.3214996

[8] Ahmed, M. M. R., Mirsaeidi, S., Koondhar, M. A., Karami, N., Tag-Eldin, E. M., Ghamry, N. A., ... & Sharaf, A. M. (2024). Mitigating uncertainty problems of renewable energy resources through efficient integration of hybrid solar PV/wind systems into power networks. IEEe Access, 12, 30311-30328. DOI:10.1109/ACCESS.2024.3370163

[9] Bhattacharyya, S., Phallically, S., & Singh, B. (2022). Operation of grid-connected PV-battery-wind driven DFIG. based system. IEEE Transactions on Industry Applications, 58(5), 6448-6458. DOI:10.1109/TIA.2022.3181124

[10] Bahar, S. T., & Neama, D. R. (2024). Improved Direct Torque Control Utilizing Model Predictive Control Approach for Permanent Magnet Synchronous Motor. Al-Iraqia Journal for Scientific Engineering Research, 3(2), 57-64.
DOI: https://doi.org/10.58564/IJSER.3.2.2024.179

[11] Gulzar, M. M., Iqbal, A., Sibtain, D., & Khalid, M. (2023). An innovative converter less solar PV control strategy for a grid connected hybrid PV/wind/fuel-cell system coupled with battery energy storage. IEEE Access, 11, 23245-23259. **DOI:** 10.1109/ACCESS.2023.3252891

[12] Rolán, A., Bogarra, S., & Bakkar, M. (2021). Integration of distributed energy resources to unbalanced grids under voltage sags with grid code compliance. IEEE Transactions on Smart Grid, 13(1), 355-366. DOI:10.1109/TSG.2021.3107984

[13] Karad, S. G., Thakur, R., Alotaibi, M. A., Khan, M. J., Malik, H., Márquez, F. P. G., & Hossaini, M. A. (2024). Optimal design of fractional order vector controller using hardware-in-loop (hil) and opal rt for wind energy system. IEEE Access, 12, 35033-35047. DOI:10.1109/ACCESS.2024.3357504

[14] Lin, F. J., Liao, J. C., Zhang, Y. M., & Huang, Y. C. (2023). Optimal economic dispatch and power generation for microgrid using novel lagrange multipliers-based method with HIL verification. IEEE Systems Journal, 17(3), 4533-4544. DOI:10.1109/JSYST.2023.3283996

[15] Ismeil, M. A., Alfouly, A., Hussein, H. S., & Hamdan, I. (2023). Hardware in the loop real-time simulation of improving hosting capacity in photovoltaic systems distribution grid with passive filtering using OPAL-RT. IEEE Access, 11, 78119-78134. DOI:10.1109/ACCESS.2023.3298547

[16] Pandey, S. K., Patil, S. L., & Phadke, S. B. (2017). Regulation of nonminimum phase DC–DC converters using integral sliding mode control combined with a disturbance observer. IEEE Transactions on Circuits and Systems II: Express Briefs, 65(11), 1649-1653. DOI:10.1109/ACCESS.2023.3298547

[17] Guo, J. (2022). The load frequency control by adaptive high order sliding mode control strategy. IEEE access, 10, 25392-25399. **DOI:** 10.1109/ACCESS.2022.3152259

[18] Goud, B. S., Kalyan, C. N. S., Keerthi, N., Reddy, C. R., Bajaj, M., & Reddy, B. N. (2021, October). AGC of multi area multi fuel system with water cycle algorithm based 3DOF-PID controller and integration of PEVs. In 2021 International Conference on Data Analytics for Business and Industry (ICDABI) (pp. 464-469).

ISSN: 2073-9524
Pages:1-12

IEEE. DOI:10.1109/ICDABI53623.2021.9655899

[19] Bahar, S. T., & Rashid, Y. G. (2024). A Study on An MPPT Control Approach Using Artificial Intelligence and the Perturb and Observe Method. Diyala Journal of Engineering Sciences, 131-143. **DOI:** https://doi.org/10.24237/djes.2024.17210

[20] Chakraborty, S., Mondal, A., & Biswas, S. (2024). Application of FUZZY-3DOF-PID controller for controlling FOPTD type communication delay based renewable three-area deregulated hybrid power system. Evolutionary Intelligence, 17(4), 2821-2841. **DOI:** https://doi.org/10.1007/s12065-024-00914-x

[21] Fnaiech, M. A., Guzinski, J., Trabelsi, M., Kouzou, A., Benbouzid, M., & Luksza, K. (2021). MRAS-Based Switching linear feedback strategy for sensorless speed control of induction motor drives. Energies, 14(11), 3083. **DOI: https://doi.org/10.3390/en14113083.**

[22] Chellakhi, A., El Beid, S., Abouelmahjoub, Y., & Mchaouar, Y. (2024). An efficient implementation of three-level boost converter with capacitor voltage balancing for an advanced MPPT approach in PV Systems. e-Prime-Advances in Electrical Engineering, Electronics and Energy, 9, 100688. DOI: **https://doi.org/10.1016/j.prime.2024.100688.**