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Optimized control strategy for enhanced stability in grid-connected photovoltaic-wind hybrid energy systems

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ABSTRACT

To improve stability in grid-connected photovoltaic-wind (PV-wind) hybrid energy systems, this research presents optimized model predictive control (MPC) and proportional resonant (PR) control algorithms. The proposed MPC strategy enhances power management by forecasting future system behavior and optimizing control actions accordingly, while the PR controller effectively handles grid-synchronized voltage regulation and harmonic compensation. Together, these advanced control techniques significantly improve grid stability, ensure optimal utilization of renewable energy resources (RER), and maintain power quality under varying operating conditions. The performance of the hybrid system is evaluated through extensive simulations that consider a range of real-world scenarios, including fluctuating load demands and diverse climatic conditions. The results confirm the effectiveness of the proposed MPC and PR-based control in dynamically adjusting power output from wind and photovoltaic sources, thereby ensuring reliable and efficient grid integration. These findings highlight the potential of intelligent control systems in enabling the secure, stable, and long-term adoption of renewable energy within modern power grids.

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1. INTRODUCTION

The necessity for alternative energy sources to meet present demand and avert future energy crises due to the growing depletion of the world's fossil fuel supplies. Finding solutions that limit environmental harm while also meeting the expanding energy needs is a problem. In addition, renewable energy sources (RES) like wind and solar power are infrequent; wind energy changes due to fluctuating conditions in the environment, while solar energy is seasonal. It can be difficult for standalone solar or wind energy systems to supply constant electricity because of this intermittency. A hybrid system that combines solar and wind energy has been proposed as a solution to intermittency. This strategy seeks to balance the power generation from the two sources while optimizing the use of renewable energy. Solar and wind energy both have intermittency problems; solar energy is reliant on the weather and time of day, whilst wind energy fluctuates with the environment. The production of electricity varies as a result, which may lead to power supply instability. The intermittent nature of solar and wind energy results in fluctuations in supply and demand, frequency, and voltage, which can lead to grid issues. To provide consistency, solutions need complex grid management, energy storage, and forecasting. In this work, a novel hybrid controller is proposed to enhance the grid stability.

This article highlights the current opportunities, challenges, and policy implications of hybrid renewable energy systems, which integrate solar and wind technology [1]. A method for simulating and managing a hybrid grid-connected power system is provided in [2]. Betha *et.al* [3] regulate frequent grid delays like uncontrolled voltages, harmonic distortions, and balanced voltage reduction. The photovoltaic/wind (PV/wind) system generates an output that powers every connected appliance. The text delineates the modeling and control methods for a grid-connected wind-photovoltaic hybrid system [4]. To achieve optimal maximum power point (MPP) and high tracking efficiency during problematic operational instances, a maximum power point tracking (MPPT) approach based on hybrid fractional-order particle swarm optimization (FPSO) [5] has been employed. Agrawal *et.al* [6] A grid-connected solar PV/wind hybrid in Kumasi, Ghana the techno-economic viability of a system that can manage a typical commercial load must be assessed. Investigations into the dynamic modeling, control, and simulation of electrical grid-connected RES are carried out in [7]. Utilizing an active power filter (APF) can raise the power standard and mitigate reactive power. In low and medium-voltage electrical systems, a shunt active power filter (SAPF) is primarily used to lower the harmonics and correct for voltage distortions like sags. Flickers and notches SAPF can lower total harmonic distortion (THD) by infusing the line's voltage to reduce inaccurate information [8]. Sawle *et.al* [9] Offer a review of the software used for accurate sizing, control, and optimization guidelines for hybrid system configuration, modeling, RES, and combination systems.

The hybrid fuzzy-neural controller [10] is able to supply unique dynamical stability, an earlier rate of convergence, and fewer oscillations in the location around the functioning location MPP. It is also more effective than conventional techniques at tracking global maxima under a variety of scenarios. In different circumstances and with different quantities of solar radiation, a grid-connected MATLAB model is studied [11]. Ultra-lift converters generate an incredibly high transfer of output gains leveraging geometric expansion in contrast to earlier voltage elevate techniques like classical boost converters and super lift converters. In addition, it is smaller and more effective than other options. The operation of the converter is examined in ultra-lift continuous conduction mode [12]. Describes a well-thought-out hybrid renewable energy system that combines wind and solar energy with a converter and batteries. The system has been optimally simulated by employing the iterative heuristic optimization genetic algorithm (IHOGA) tools. Model predictive control (MPC) for drives and power converters is one control technique that has drawn focus from scientists throughout the world [13], [14].

MPC and an inverter's finite control set model predictive current control (FCS-MPCC) are the core components of a novel MPPT protocol for PV modules that have been released [15]. Rai *et.al* [16] focus on developing and simulating an efficient MPPT solar photovoltaic system. In order to increase the power level, [17] recommend PV power connections to the grid-producing system with APF capability. Gada *et.al* [18] provides a detailed overview of the components of the system, including the incremental conductance maximum power point tracking (IC-MPPT) algorithm, the inverter, the solar generator, and the proportional-integral (PI) regulator for direct current (DC) bus voltage control. Utilizing a PI as a distribution static compensator (DSTATCOM), cascaded h-bridge multilevel inverter (CHBMLI) to minimize source harmonics of the distribution system PI controller's source current is addressed [19]. The PI controller holds the power factor of the distribution system at unity, minimizes the original current's harmonics, and substitutes reactive power.

In [20], three-phase, two-level DC-AC inverters, a boost converter converting DC to DC, and an AC load system hooked up to the grid authority mechanism have been studied and shown. In order to assess traits a grid-connected two-stage photovoltaic array with an extended Kalman filter (EKF) capability has been recommended in [21]. Ahmed *et.al* [22] discuss finite set model predictive control (FS-MPC), based MPPT for PV systems. Particle swarm optimization model predictive control (PSO-MPC) is a novel hybrid incremental conductance-based MPPT control algorithm for grid-connected solar systems [23]. Lekouaghet *et.al* [24] addressed the chain of PV power generation's control problem so that the grid-connected system gets the most power without being obliged for extra steps of the module. In [25], a predictive model is the controller. Advised to use a control-based method to optimize energy conservation in the PV power process. By modifying the default cost function, MPC selects the optimal control action for the DC/AC converter at each sample moment. We can increase grid power stability and achieve precise results by using model predictive and proportional resonant control strategies in simulation. Enhancing grid stability during both seasonal and non-seasonal seasons by using a multitude of energy sources that involve wind and solar energy systems.

2. HYBRID OF PHOTOVOLTAIC AND WIND

A hybrid energy system made up of a wind turbine (WT) and PV array is depicted in Figure 1. Consequently, the solar panels would provide the highest production throughout the summer, while the WT would generate more in the winter. A hybrid solar PV WT system is the most successful lead to leverage many RES instead of just one locally accessible resource. A tiny electric "hybrid" system that connects home solar PV and residence wind Technology for electricity has many benefits over either system alone, according to many renewable energy (RE) specialists.

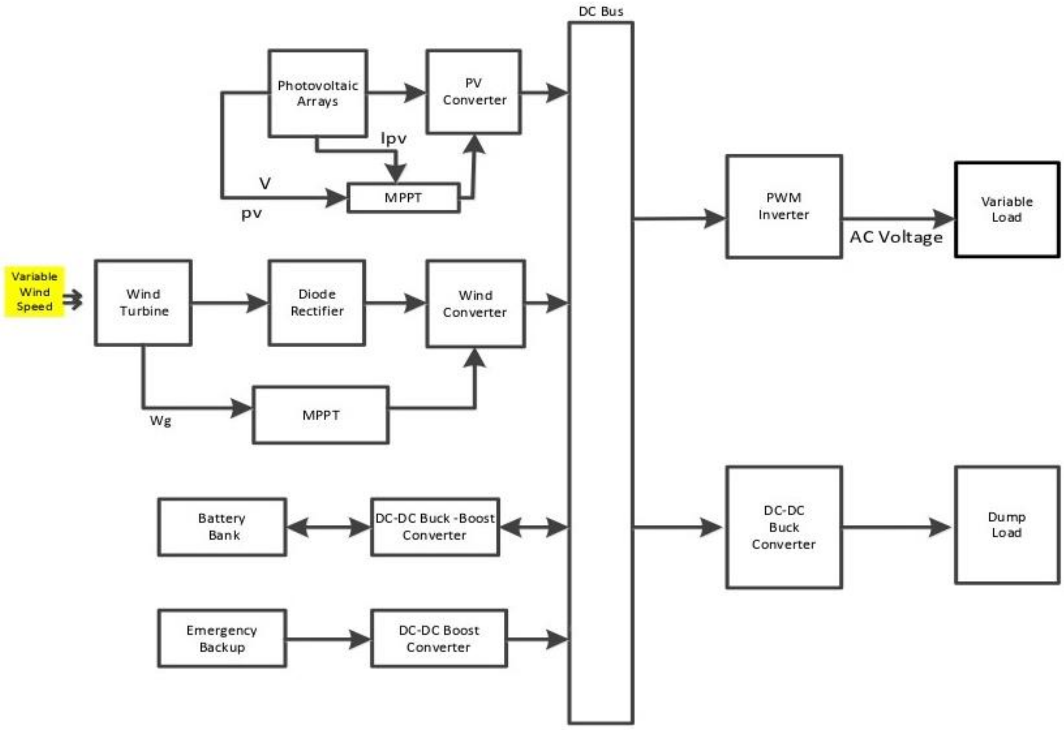

Figure 1. The Hybrid of photovoltaic and wind system block diagram

3. MODEL PREDICTIVE CONTROL

A sophisticated control approach that forecasts and optimizes future behavior across a finite horizon using a model of the system. Because it can manage multi-variable systems with restrictions, it is frequently utilized in power systems, robotics, process control, and hybrid energy systems. This is a summary of how the model would describe the dynamics of the photovoltaic array, WT, converters, and grid interface within the scenario of a hybrid photovoltaic wind power system. The MPC To determine the optimal set of control actions over the prediction horizon, the MPC solves an optimization problem after defining an objective function for the control input optimization. To guarantee the system runs securely and effectively, limitations such as power restrictions, voltage, current, or state bounds are incorporated.

4. PROPORTIONAL RESONANT CONTROL

Especially in grid-connected applications like wind and PV systems, because of its efficient tracking of AC signals. The proportional resonant (PR) controller is very good for lowering steady errors in AC reference tracking because it can manage the periodic nature of AC signals, unlike a conventional PI controller, which is better suited for DC applications. The proportional component speeds up the system's response to disruptions by providing a response proportionate to the discrepancy between the real and reference signals. In particular, the resonant term is made to monitor sinusoidal reference signals at a set frequency, usually the grid frequency, such as 50 or 60 Hz. Figure 2 represents the MATLAB/Simulation of a proportional resonant controller block diagram.

4.1. Mathematical representation

A PR controller's transfer function is provided by (1).

$$G(s) = K_p + \frac{K_r.S}{S^2+\omega_0^2} \quad (1)$$

Where K_p is the proportional gain, K_r is the resonant gain, and ω_0 is the resonant frequency (usually the grid frequency, such as 2π×50 or 2π×60rad/s).

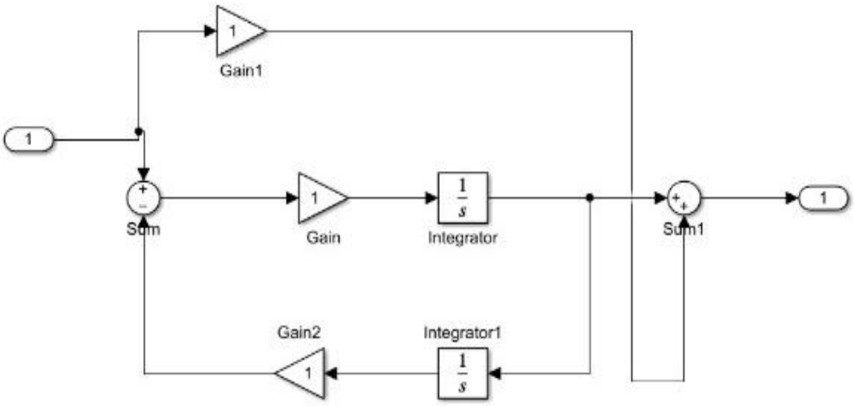

Figure 2. Proportional resonant controller

5. SIMULATION OUTCOMES AND DISCUSSION

MATLAB/Simulink is used to model the entire PV and wind energy hybrid power system with an autonomous rectifier. The block sets for the sim power system are used to model the control techniques required in the MATLAB/Simulink surroundings to generate the signal-enabling tracking. In this, we control the MPC to combine the wind-powered power source and photovoltaic assets. Runtime in seconds is displayed on the X-axis in Figure 3, while the Y-axis displays the voltage of the grid supply. In Figure 3, The voltage ranges from peak to summit at 25,000 V. Phase shifts between three phases should be 120 degrees across. Runtime in seconds is displayed on the X-axis in Figure 4, while the Y-axis displays the current of the grid supply. Furthermore, the grid's supply has remained unchanged, as seen by the voltage source inverter (VSI) controller's supplied current value is the sole way to switch the controllers for the MPC controller, which uses wind and photovoltaic hybrid energy.

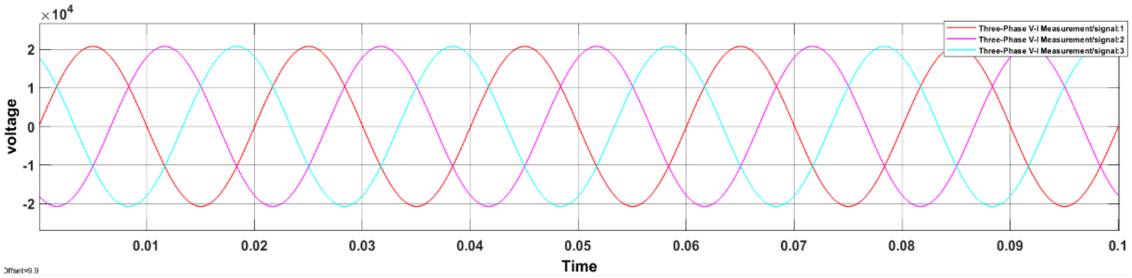

Figure 3. Supply voltage from grid

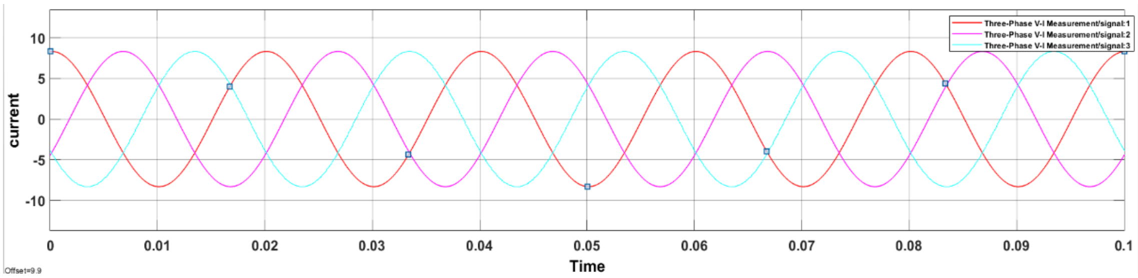

Figure 4. Supply current from grid

The current and voltage of trains 1 and 3 as determined by the MPC controller are displayed in Figures 5 and 6. Bus 1's voltage and current are shown in Figures 5 and 6. Consequently, bus 3's voltage and current are shown in Figures 7 and 8. Figure 5 displays oscillating voltage and nearly zero current over a 0-to-0.1-time interval. Additional voltage variations from 0 to 0.001 are shown in Figure 6. The amplitude of the voltage changes with time. Similar to this, the current varies from 0 to 0.001. The MPC controller will move higher and stay firm till the very end, reaching its maximum during the R and Y phases, because it does not take into consideration changes in photovoltaic-wind (PV-wind) integration.

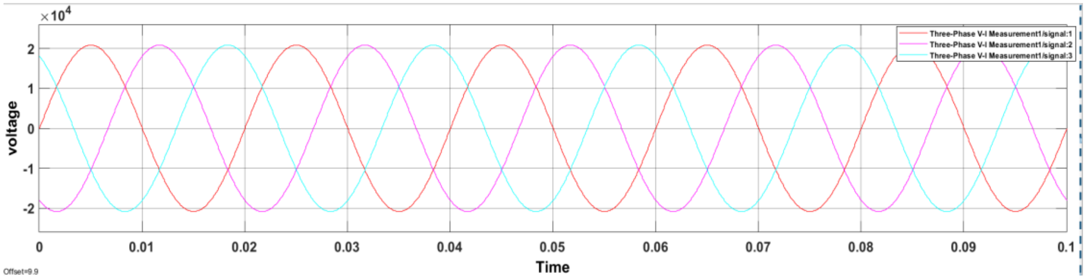

Figure 5. Bus 1 in voltage using MPC controller

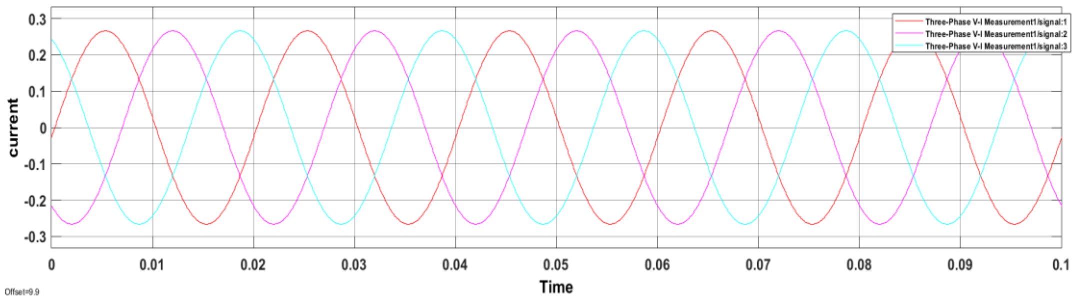

Figure 6. Bus 1 in current using MPC controller

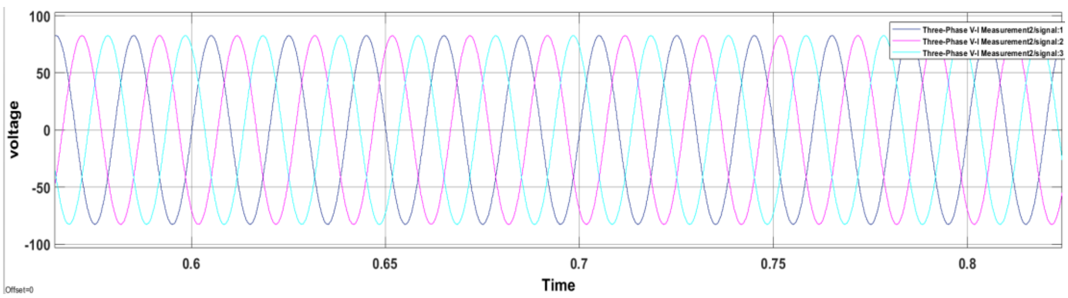

Figure 7. Bus 3 voltage using MPC controller

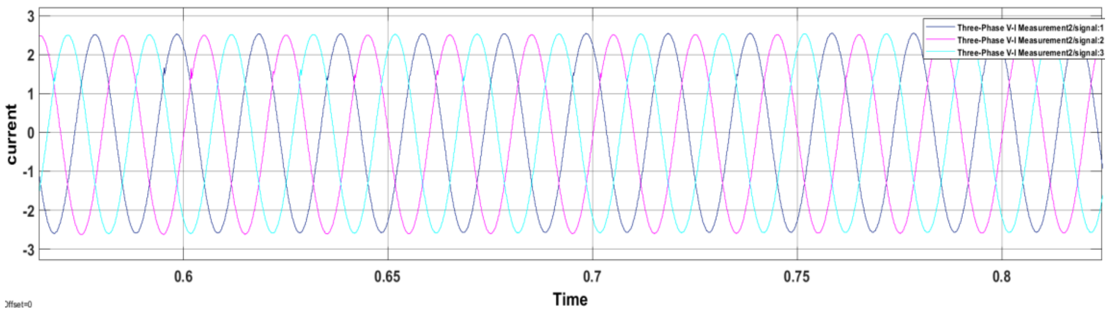

Figure 8. Bus 3 current using MPC controller

Figures 9 and 10 show the bus 3 voltage and current using optimized MPC with PR controllers. There are no fluctuations or changes in amplitude. Any load can be efficiently handled by it. Between 0 and 0.001, the time variation has improved. Inputs and outputs are efficiently arranged by the optimized model predictive and proportional resonant controller, which also generates refinements to alter iterations and achieve the best possible result. Both controllers will have comparable circuit breaker times. Any nonlinear requirement is accommodated.

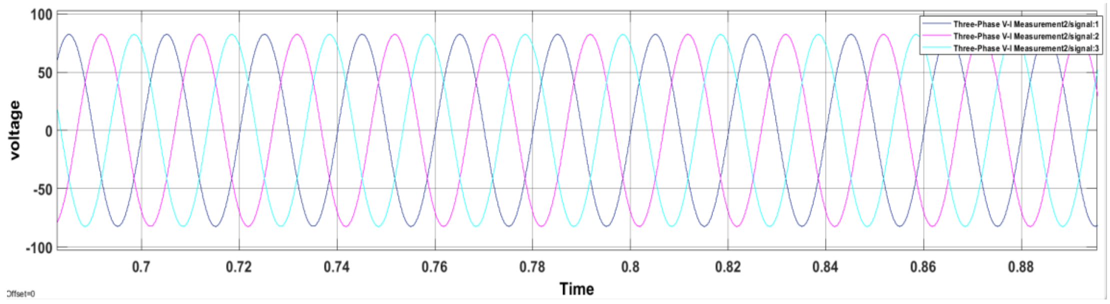

Figure 9. Bus 3 voltage using optimized MPC with PR controllers

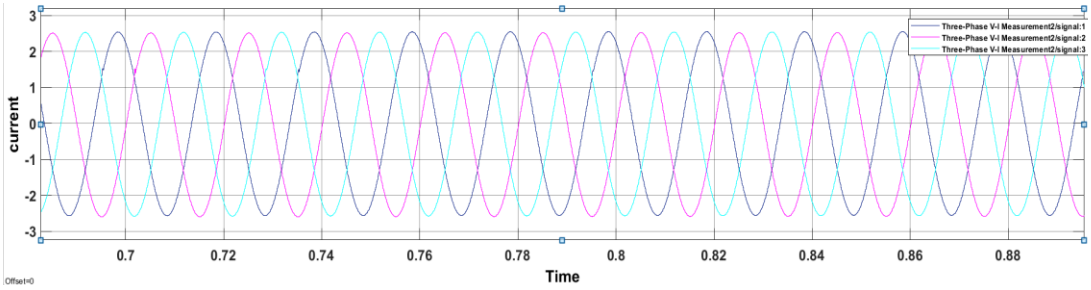

Figure 10. Bus 3 current using optimized MPC with PR controllers

Through a number of interface, testing, and training iterations, the optimized MPC and PR controller will be set up to produce the intended outcomes, boost stability, and handle quality in power issues the voltage of the DC of the combined wind and photovoltaic systems is displayed in Figure 11. The grid can be connected and integrated with this combination. It will be able to increase grid voltage while maintaining power. PR and optimized MPC controllers are comparable to the complicated controller and alter the outcomes when a block that controls current is employed.

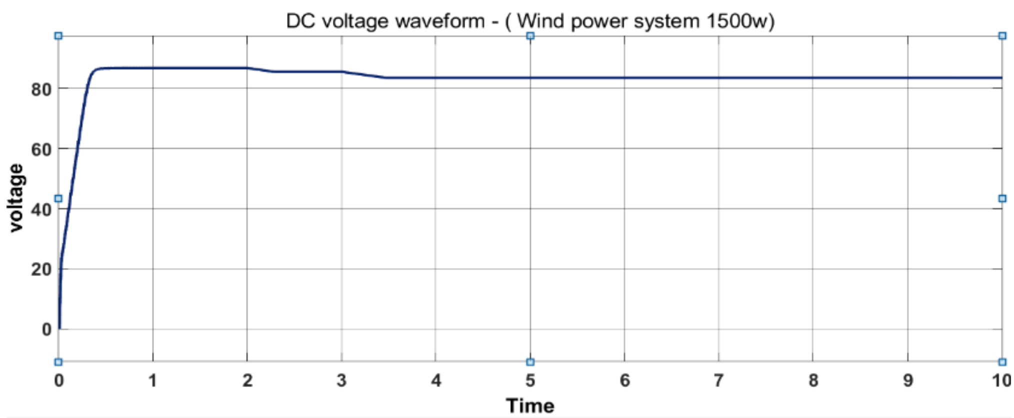

Figure 11. Paired outputs of wind and PV (DC voltage)

6. CONCLUSION

This research conveys how well the optimized model predictive controller with proportional resonance (MPC-PR) works to increase the effectiveness and reliability of hybrid photovoltaic WE systems that are related to the electrical grid. This control strategy maximizes the utilization of RES while maintaining reliable grid integration. It is proven to be flexible, accurate, and effective. In comparison, traditional MPC-PR controllers struggle with consistent performance, especially when faced with the system's non-linearity and unpredictability. This constraint can result in ineffective control, potentially destabilizing the grid. Future research should focus on improving the optimized MPC-PR controller's incorporation of RES that provides power to the grid, addressing system dynamics and changing conditions.

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AUTHOR CONTRIBUTIONS STATEMENT

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Asokan Kaliyamoorthy	✓	✓		✓	✓	✓				✓		✓	✓	
Kosara Sravani		✓	✓			✓	✓	✓	✓		✓	✓	✓	✓
Murgam Sharath Yadav	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are openly available in [IJASIS] at http://doi.org/10.29284/IJASIS.8.1.2022.1-8.

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