

Integration of renewable source with reactive power control using modified power factor control

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Abstract

This research proposes a novel control strategy for reactive power sharing among distributed BESSs in smart grids. Conventional droop control is widely employed for sharing active and reactive power among parallel-connected renewable sources. However, conventional droop control does not explicitly consider the operating power factor of individual units, which can result in unequal reactive power distribution, increased power losses, and higher equipment ratings and costs. To address these limitations, the proposed methodology focuses on achieving balanced reactive power distribution while maintaining the operating power factors of all parallel-connected renewable units at nearly the same value and as close to unity as possible. A controller based on an MPF control strategy is developed to synchronize the power factors of the individual energy storage units. The effectiveness of the proposed approach is evaluated through MATLAB/Simscape Power Systems simulations using a microgrid comprising three parallel-connected sources (BESS, PV and wind farm). The simulation results demonstrate the improvement in reactive power sharing and power-factor coordination achieved by the proposed control strategy compared with the conventional operating condition.

Keywords: MPF (Modified Power Factor), MATLAB/Simulink, BESS (Battery Energy Storage System), PV (PhotoVoltaic).

1. Introduction

The increasing penetration of renewable energy sources has become an important approach for reducing dependence on conventional fossil-fuel-based power generation and supporting the transition toward sustainable electrical power systems. Among various renewable technologies, solar photovoltaic (PV) and wind energy systems are widely deployed because of their scalability, low operating emissions, and suitability for grid-connected applications [1]. However, the intermittent and weather-dependent nature of solar irradiance and wind speed can introduce fluctuations in generated power, making reliable integration with the utility grid a significant technical challenge.

A grid-connected solar and wind farm system combines photovoltaic generation and wind energy conversion systems through appropriate power electronic converters and transformers to supply active power to the utility grid. Solar PV systems generally employ DC–DC converters for maximum power point tracking (MPPT) and voltage regulation, followed by voltage-source inverters (VSIs) for DC-to-AC power conversion [2]. Similarly, wind farms commonly employ permanent-magnet synchronous generators (PMSGs) with power electronic converters to regulate active and reactive power and facilitate grid synchronization. The

generated power from both renewable sources can be integrated through a common DC or AC bus before being delivered to the grid.

Despite their advantages, renewable sources exhibit significant power variations due to changes in solar irradiance, temperature, wind speed, and other environmental conditions. These variations can affect DC-link voltage, grid voltage, frequency, active and reactive power, and power quality. Furthermore, sudden changes in renewable generation can create a mismatch between generation and demand, particularly when the renewable sources are operating below their rated power. Therefore, an energy storage system is often integrated with renewable generation to improve the controllability and reliability of the overall system.

A BESS provides an effective solution for managing the variability of solar and wind generation. A BESS is generally connected to the DC bus or AC grid through a bidirectional DC–DC converter and a voltage-source inverter, enabling both charging and discharging operations. During periods of excess renewable generation, the BESS can absorb surplus energy, whereas during periods of insufficient renewable generation, stored energy can be supplied to the grid. In addition to energy balancing, BESSs can provide functions such as peak-load support, power smoothing, voltage regulation, reactive power compensation, frequency support, and improvement of grid power quality.

The integration of solar PV, wind farms, and BESS therefore provides a flexible renewable-energy-based grid interface. The overall system requires coordinated control of the renewable-energy converters, BESS, and grid-side inverter to maintain stable operation under changing generation and load conditions. Maximum power extraction, DC-link voltage regulation, active/reactive power control, battery state-of-charge (SOC) management, grid synchronization, and power-quality improvement are important control objectives [3]. Conventional PI-based controllers are widely used because of their simple implementation; however, their performance can deteriorate under rapid changes in operating conditions and system parameters.

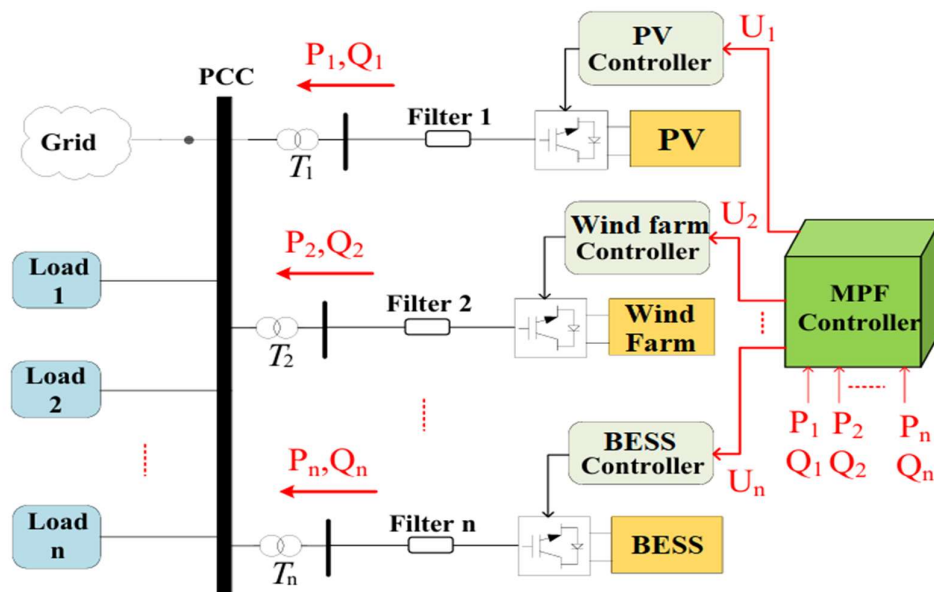


Figure 1: Grid connected PV, wind farm and BESS units

A typical grid-connected solar–wind–BESS system consists of PV arrays, wind turbines/generators, DC–DC converters, AC–DC converters, a BESS with a bidirectional converter, grid-side VSI, filters, and a step-up transformer. The coordinated operation of these components enables renewable energy to be efficiently transferred to the grid while the BESS compensates for short-term variations in renewable power [4]. Such an integrated configuration can contribute to improved renewable-energy utilization, reduced power fluctuations, enhanced grid stability, and increased flexibility of future smart grids.

Overall, the integration of solar PV, wind energy, and BESS with the utility grid represents an important architecture for high-penetration renewable-energy systems. The combination of complementary renewable resources with controllable battery storage can mitigate the limitations associated with renewable intermittency while providing additional grid-support capabilities. The development of advanced energy-management and converter-control strategies is therefore essential for achieving stable, efficient, and reliable operation of grid-connected hybrid renewable-energy systems.

Therefore, the primary contribution of this research is the development of a control strategy that enables distributed units to operate close to their maximum available power factor while ensuring appropriate reactive power sharing. The proposed approach employs the modified power-factor concept which was originally developed for controlling the output power factor of parallel-connected generators in power plants [5]. In the proposed methodology, the modified power-factor control strategy is applied to regulate the operating power factors of individual units and, consequently, control their reactive power contribution. The performance of the proposed controller is evaluated against conventional droop control in a microgrid comprising three parallel-connected BESS units. The comparative analysis is conducted using MATLAB/Simscape Power Systems to demonstrate the effectiveness of the proposed control strategy in improving reactive power distribution and power-factor coordination among the renewable and BESS units.

2. System configuration

As mentioned previously in section I the renewable micro-grid is included with three source modules which operate as per the grid connection condition. From the three sources, PV module and wind farm module are the major renewable sources which generate power utilizing solar irradiation and natural winds. The powers from these two sources (PV and wind farm) are completely extracted in any operating condition of the grid. As these sources generate power from natural resources it is recommendable to extract the total power that they are generating which can be either fed to load, grid or can be stored in battery module [6]. The third source is otherwise called as energy storage module which comprise of battery pack. This battery pack can store power from excess generation by the PV and wind farm modules. The complete structure of the three sources with their controllable power electronic devices is shown in figure 2 below.

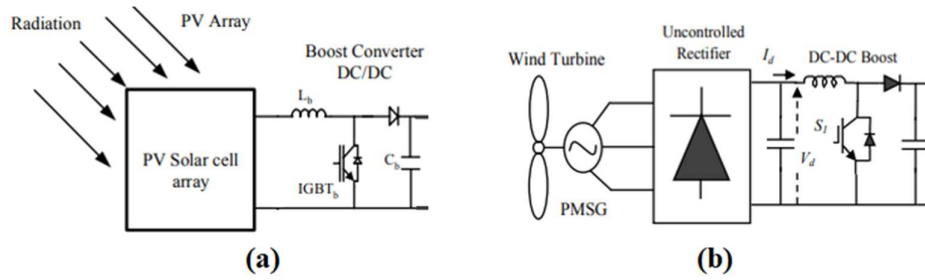


Figure 2: Source modules (a) PV source (b) Wind farm

As per the figure 2 micro-grid configuration the PV source is connected to boost converters for boosting the voltage as per the requirement. The wind farm module has a PMSG which is an independent power generation machine. Even the wind farm uses boost converter but with a diode bridge rectifier between PMSG and the converter for AC-DC conversion [7]. The battery module comprises of a bidirectional DC-DC converter which has the capability to store and extract power from battery during excess and deficit conditions respectively. All these converters are connected to common DC link for power sharing to the grid through a 3-ph inverter.

The boost converter of the PV unit is controlled using traditional P&O (Perturb and Observe) MPPT (Maximum Power Point Tracking) control algorithm. This technique is most adopted control in many systems because of its simple logic with respect to PV source voltage and current. The duty ratio of the boost converter is either increased or decreased as per the change in PV voltage and current parameters which are impacted by solar irradiation [8].

$$D = D_1 + \Delta D; \begin{cases} \text{If } P(k) > P(k-1) \text{ and } V(k) > V(k-1) \\ \text{If } P(k) < P(k-1) \text{ and } V(k) < V(k-1) \end{cases} \quad (1)$$

$$D = D_1 - \Delta D; \begin{cases} \text{If } P(k) > P(k-1) \text{ and } V(k) < V(k-1) \\ \text{If } P(k) < P(k-1) \text{ and } V(k) > V(k-1) \end{cases} \quad (2)$$

Here, D is the updated duty ratio, D_1 is past duty ratio value, ΔD is the fraction update to the past value, $P(k)$ and $P(k-1)$ are the present and past powers of PV source, $V(k)$ and $V(k-1)$ are the present and past voltages of PV source.

The wind farm boost converter is also controlled by MPPT algorithm with feedback from PMSG rotor angular speed w_r [9]. The MPPT adopted for the wind farm unit is power signal feedback (PSF) control which generates optimal power estimation P_{opt} using PMSG rotor speed. The equation for the same is given below.

$$P_{opt} = K_{opt} w_r^3 \quad (3)$$

Here, K_{opt} is MPPT multiplication factor and w_r is the rotor speed of PMSG.

From the above optimal power reference generation required torque (T^*) is generated which is compared to measured electro-magnetic torque (T_e) of the machine. The error generated is fed to PI torque controller which generates duty ratio for the wind farm unit boost converter [10]. The variable DC voltage generated by converting 3-ph PMSG voltages using diode bridge rectifier is now stabilized using boost converter operated by PSF MPPT algorithm.

3. Inverter control and MPF control

The proposed controller is capable of regulating the amount of reactive power supplied to the power system by multiple battery energy storage systems (BESSs). To achieve coordinated reactive power control, the controller regulates the reactive power contribution of each battery connected to the grid. The power factor (PF) serves as an effective indicator for evaluating whether individual BESS units are operating within their desirable operating conditions. The PF of each battery can be readily calculated from the measured active and reactive power components [11]. Based on the calculated PF, the controller can determine whether each battery is contributing an appropriate amount of reactive power relative to its rated power capacity. If a particular battery supplies a relatively large amount of reactive power and approaches its maximum permissible operating capability, its reactive power contribution should be reduced to prevent excessive loading. The reactive power allocation among the BESS units is achieved using the modified power factor (MPF) control method proposed [12].

Conventionally, the power factor is defined over the range of $([-1,1])$. A positive PF within the range $((0,1])$ generally corresponds to reactive power generation, whereas a negative PF within the range $([-1,0))$ represents reactive power absorption. However, this conventional representation introduces a discontinuity at zero when the operating condition changes between reactive power generation and absorption. To overcome this limitation, the method proposed redefines the power factor as a modified power factor over the interval $([0,2])$. In this formulation, the range $([0,1])$ represents reactive power generation, while the range $((1,2])$ represents reactive power consumption [13]. The transformed MPF provides a continuous and monotonically decreasing relationship with reactive power, thereby eliminating the discontinuity associated with the conventional PF representation.

Figure 1 illustrates the relationship between the conventional power factor and reactive power, as well as the corresponding relationship between the modified power factor and reactive power. Based on this modified definition, the MPF can be expressed as:

$$\bar{PF} \triangleq PF \times \text{sign}\{Q\} + (1 - \text{sign}\{Q\}) \quad (4)$$

where (PF) represents the modified power factor of the (i)-th battery. The MPF control algorithm is designed to coordinate the operation of all connected battery energy storage systems (BESSs) such that they operate at approximately the same modified power factor. This coordinated operation ensures that the reactive power demand is appropriately distributed among the individual batteries according to their operating conditions and available capacity.

To implement the proposed control strategy, a feedback loop is established to provide the local controllers with the instantaneous active power ($P_i(t)$) and reactive power ($Q_i(t)$) supplied by each battery to the grid at time (t). The overall control structure of the investigated system is illustrated in Figure 3.

Using the measured values of ($P_i(t)$) and ($Q_i(t)$), the conventional power factor ($PF_i(t)$) of each battery, where ($i=1,2,\dots,N$), is calculated using (2). Subsequently, the modified power factor ($MPF_i(t)$) is determined from the calculated power factor and the sign of the corresponding reactive power, ($\text{sign}\{Q_i(t)\}$), according to (3). The reference modified power factor, ($MPF_r(t)$), representing the average operating condition of all connected batteries, is then calculated from the individual modified power factors using (4).

The deviation between the modified power factor of each battery, ($MPF_i(t)$), and the average modified power factor, ($MPF_r(t)$), is subsequently determined. This deviation indicates the difference between the reactive power contribution of an individual battery and the coordinated operating condition of the overall BESS network. Each deviation is multiplied by a global control gain (K), and the resulting signal is used as the correction input ($u_i(t)$) for the corresponding battery, as expressed in (5). Thus, the controller continuously adjusts the reactive power contribution of individual batteries to minimize the differences in their modified power factors and achieve coordinated reactive power sharing among the connected BESS units [14].

$$PF_i(t) = \frac{P_i(t)}{\sqrt{P_i(t)^2 + Q_i(t)^2}} \quad (5)$$

$$\bar{P}F_i(t) = PF_i \times \text{sign}\{Q_i(t)\} + (1 - \text{sign}\{Q_i(t)\}) \quad (6)$$

$$\bar{P}F_r(t) = \frac{1}{n} \sum_{i=1}^n \bar{P}F_i(t) \quad (7)$$

$$u_i(t) = K(\bar{P}F_i(t) - \bar{P}F_r(t)) \quad (8)$$

The correction signal ($u_i(t)$) is added to the voltage reference of the corresponding battery (i), thereby modifying its control reference voltage ($V_i(t)$). The basic hierarchical control structure of a vector-controlled battery energy storage system (BESS), incorporating primary and secondary voltage/frequency droop controllers, is illustrated in Figure 3.

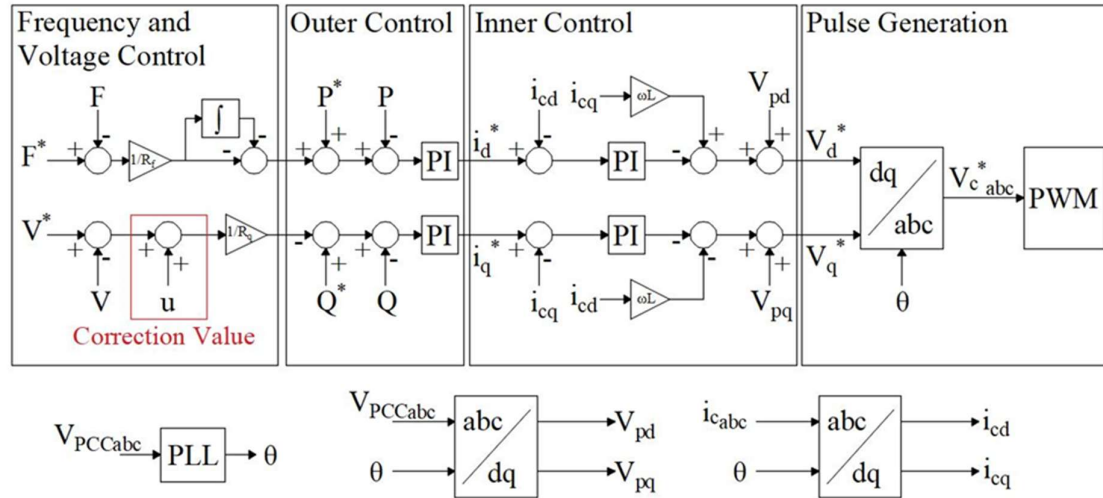


Figure 3: Schematic diagram of the vector controlled converter battery model

The addition of the correction signal ($u_i(t)$) to the voltage reference results in a corresponding adjustment of the reactive power ($Q_i(t)$) supplied by battery (i). The magnitude and dynamic response of this correction signal are primarily determined by the global control gain (K). A higher value of (K) increases the rate at which the power-factor deviations are corrected, resulting in faster convergence of the individual battery power factors toward their coordinated operating values. Conversely, a lower value of (K) produces a slower correction response.

However, (K) must be selected within an appropriate range because an excessively high gain can cause the voltage droop controller to reach its saturation limit, thereby adversely affecting the control performance and voltage regulation [15]. Defining (K) as a global gain also ensures

that the net voltage-reference correction remains zero across the interconnected BESS units. This coordinated correction prevents unnecessary changes in the overall voltage reference and contributes to maintaining voltage stability of the grid. The schematic representation of the proposed MPF-based controller is presented in Figure 4.

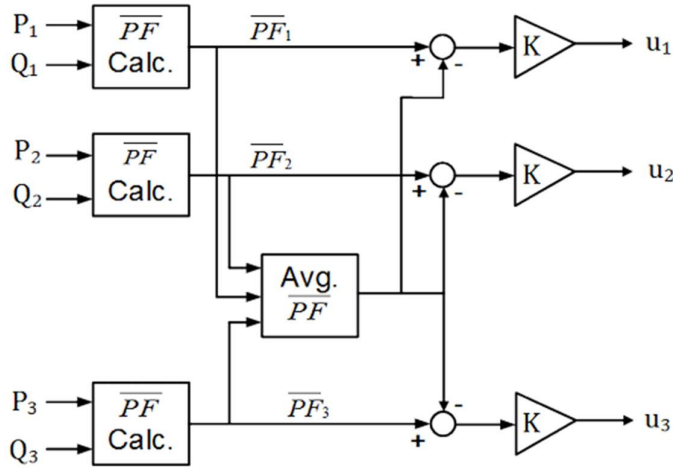


Figure 4: Schematic of the modified power factor controller

4. Simulation results

The simulation of the proposed system is modelled in MATLAB Simulink environment using blocks from library browser. The parameters of the simulation are updated as per the given table 1.

Table 1: System parameters

Name of the parameter	Values
Grid rating	11kV 50Hz 100MVA
PV module	$V_{mp} = 33.3V$, $I_{mp} = 7.2A$, $V_{oc} = 42V$, $I_{sc} = 7.8A$, $N_p = 8$, $N_s = 50$. $P_{pv\ total} = 96kW$, Boost converter – $L_b = 1mH$, $C_{in} = 100\mu F$, $C_{out} = 12mF$.
Wind farm module	PMSG – 126N-mt, 560Vdc, 3000rpm Turbine – 36kW, Base wind speed = 12m/s, base rotational speed = 1.2pu Boost converter – $L_b = 100\mu H$, $C_{in} = 1000\mu F$, $C_{out} = 1000\mu F$
BESS module	Lithium-Ion $V_{nom} = 250V$, Capacity = 100Ah
VSI LC filter	$L_f = 2.5mH$, $C_f = 3.6\mu F$

All the modules are connected at PCC and the simulation is run for 2s simulation time. Different operating conditions are included in the model and the results are observed. At 0.5s MPF is activated and the power factors of the modules are corrected. At 1s the solar irradiation is dropped from 1000W/m² to 600W/m² and the wind speed is dropped from 13m/s to 12m/s at 1.5s. The graphs generated from the simulation are presented below.

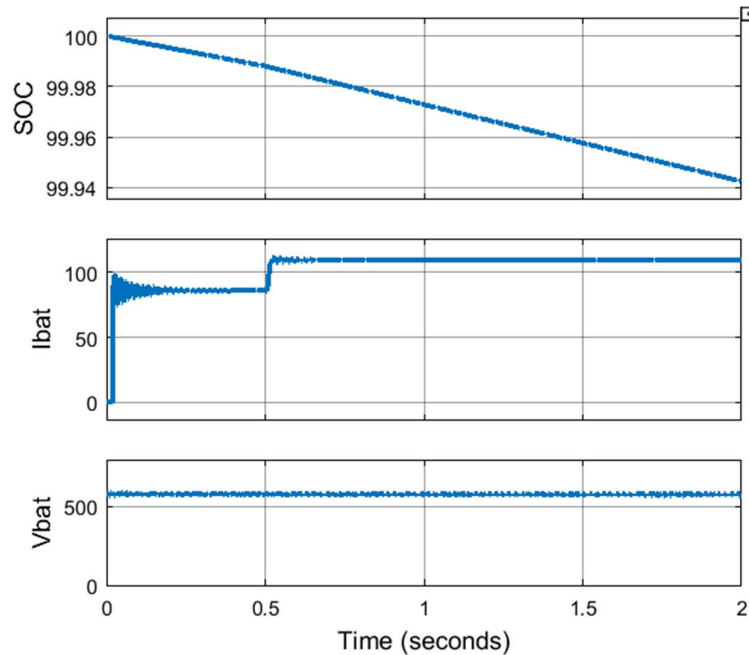


Figure 5: Battery characteristics

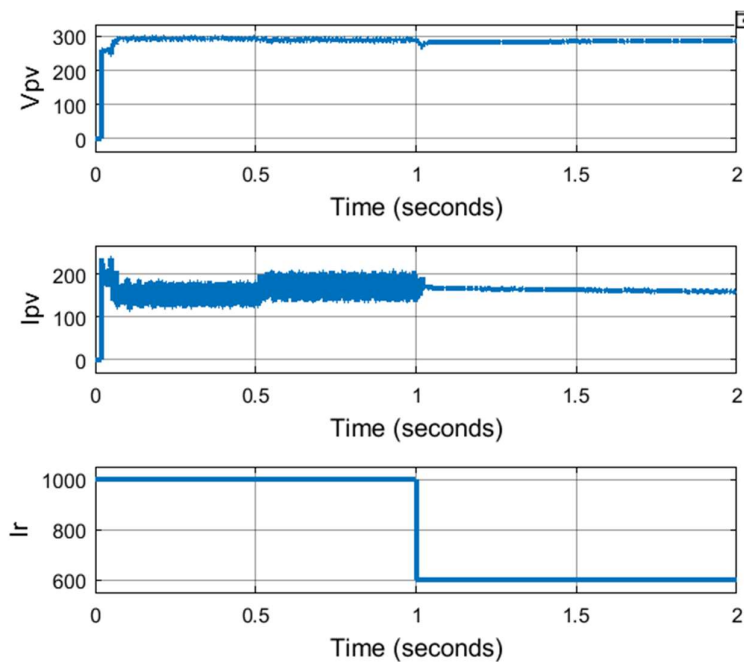


Figure 6: PV array characteristics

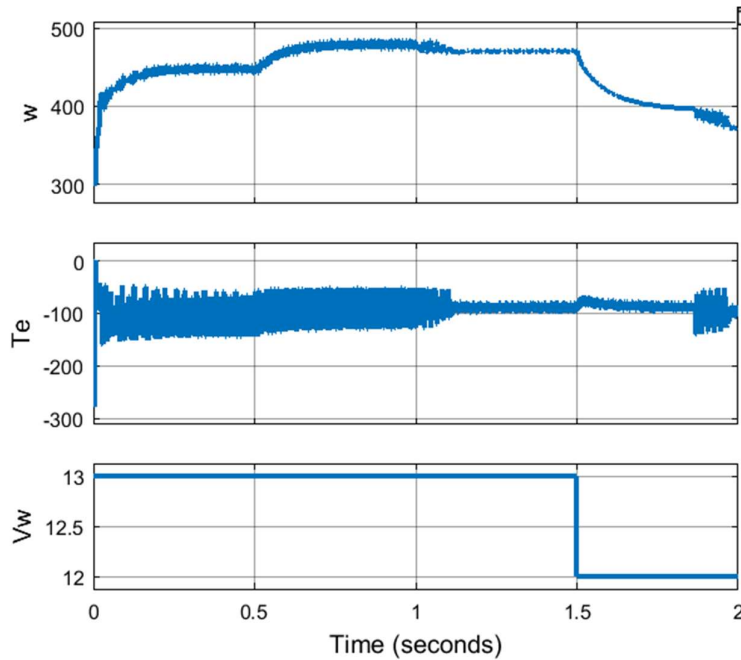


Figure 7: Wind farm characteristics

The figure 5, 6 and 7 are the characteristics of the battery, PV and PMSG recorded with respect to the dynamic conditions created in the simulation. The figure 8 presents the PCC three phase voltages and three phase injected currents from the three phase inverter.

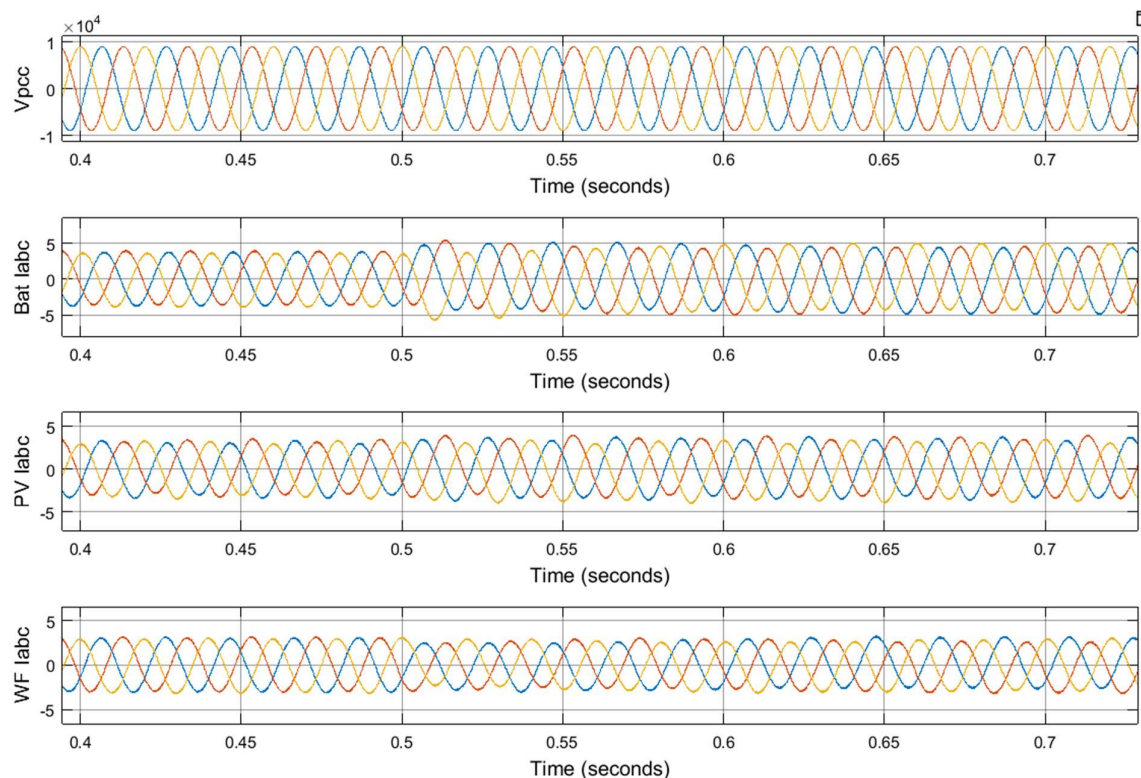


Figure 8: V_{pcc} three phase voltages and individual inverter injected three phase currents

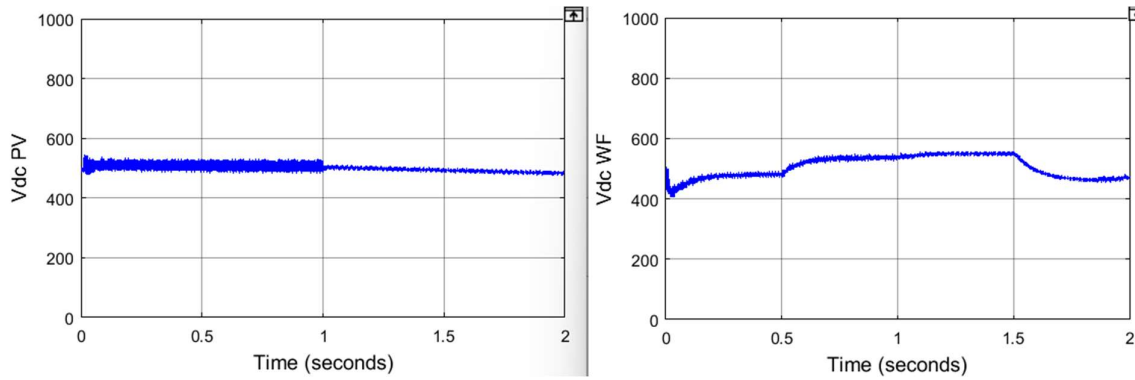


Figure 9: DC voltage at PV and WF modules inverter input

The figure 9 depicts the DC voltages of the PV and wind farm at the input of the inverter. It is observed that the voltages are slightly disrupted during different operating conditions at 0.5s, 1s and 1.5s. With respect to the conditions the active, reactive and power factor of all three modules (1. Battery 2. PV 3. WF) are presented in figure 10.

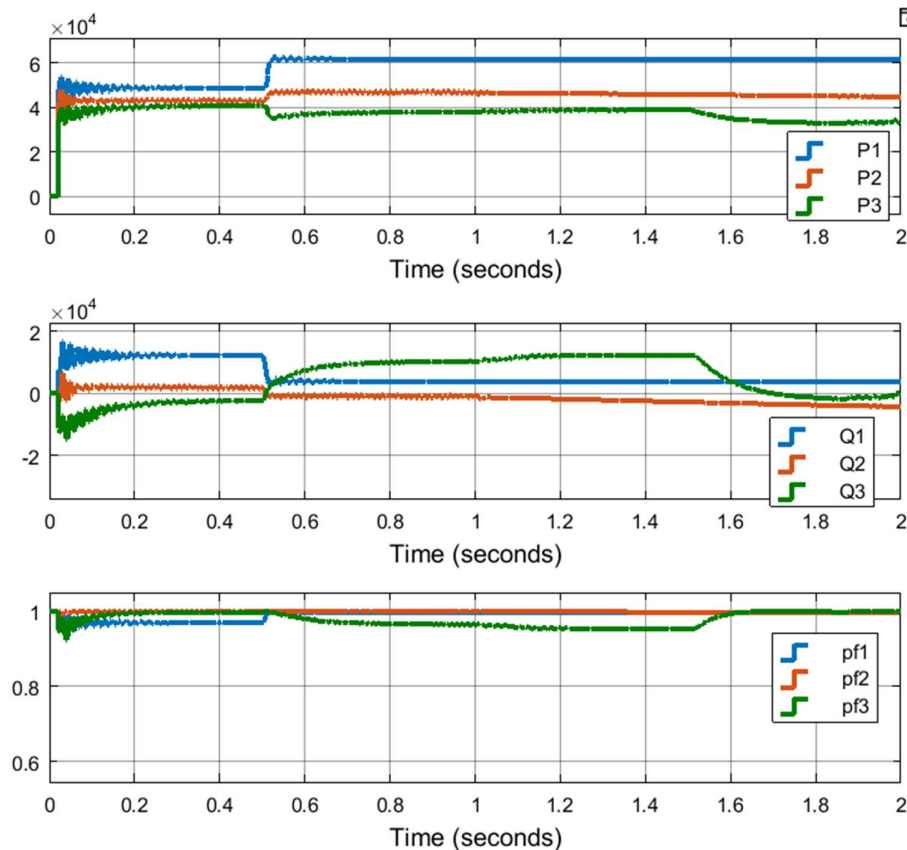


Figure 10: Active, reactive powers and power factor of all three modules

As presented in figure 10 the PF of Battery module is lower as compared to PV and WF before MPF activation as the renewable source inject mostly active power. When MPF is activated at 0.5s the PF of the wind drops and the PV battery modules PFs are maintained near to 1. At 1.5s the MPF ensures all the PFs attain near to unity value making the reactive powers near to zero.

5. Conclusion

The integration of renewable energy sources with reactive power control using modified power factor control provides an effective approach for improving the voltage regulation, power quality, and overall performance of grid-connected renewable energy systems. The proposed modified power factor control regulates the reactive power contribution of the energy storage or renewable energy interface according to the operating conditions, while maintaining the desired power factor at the point of common coupling. This enables better utilization of the converter capacity and reduces unnecessary reactive power circulation in the grid. Compared with conventional reactive power and droop-based control methods, the modified power factor control provides improved coordination between active and reactive power control, resulting in enhanced voltage stability and reduced power fluctuations during changes in renewable generation and load demand. The control strategy also supports stable operation under varying irradiance, wind power, and loading conditions. Furthermore, effective reactive power compensation contributes to improved power factor and reduced voltage deviations at the grid interface. Overall, the proposed approach demonstrates that combining renewable energy integration with modified power factor-based reactive power control can enhance grid-supporting capability and system stability.

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