iJournals: International Journal of Software & Hardware Research in Engineering
ISSN:2347-4890, ijournals.in/ijshre
Volume 13 Issue 4, April 2025

Hybrid Wind-Solar Cogeneration Back-to-Back Converters

Authors: Pankaj Kumar Shukla[1]; Dr. Imran Khan[2]; Anwar Ahmad[3]

[1]M. Tech Student, Azad Institute of Engineering & Technology, Lucknow
[2]Profeesor, Azad Institute of Engineering & Technology, Lucknow
[3]Profeesor, Azad Institute of Engineering & Technology, Lucknow

ABSTRACT

This paper introduces a new topology, yet simple and efficient, for a grid-connected wind-solar cogeneration system. A permanent magnet synchronous generator-based full-scale wind turbine is interconnected to the utility-grid via back-to-back voltage-source converters (VSCs). The dc-link capacitor has been utilized to directly interface a photovoltaic solar generator. No dc/dc conversion stages are required, and hence, the hybrid system is simple and efficient. Moreover, the proposed topology features an independent maximum power point tracking for both the wind and the solar generators to maximize the extraction of the renewable energy. The regulation of the VSCs is achieved via the vector control in the rotating reference frame. The detailed small-signal models for the system components are developed to characterize the overall stability. The influence of the utility-grid faults on the performance of the proposed system is also investigated. Nonlinear time-domain simulation results under different operating conditions are presented to validate the effectiveness of the proposed topology.

Key words: permanent magnet synchronous generator (PMSG); dual stator winding induction generator (DWIG); wind energy; grid isolated operation

1.1 INTRODUCTION

This research presents a novel yet straightforward & highly effective topology for a grid-connected hybrid wind-solar cogeneration structure. The structure incorporates a full-scale wind turbine equipped with a PMSG, which is linked to the utility grid through a pair of back-to-back VSCs. A photovoltaic solar array is directly coupled to the structure's DC-link capacitor, eliminating the need for additional DC/DC converter stages. This direct integration not only simplifies the structure architecture but also enhances overall efficiency. A key benefit of the projected configuration is its ability to implement independent MPPT algorithms for both wind & solar energy sources, ensuring optimal renewable energy extraction. Control of the VSCs is managed using vector control strategies within the synchronous reference frame, enabling precise dynamic performance. To analyze the structure’s stability & dynamic behavior, comprehensive small-signal models for all major mechanisms are established. Additionally, the impact of utility grid disturbances & faults on structure operation is thoroughly examined. The effectiveness & reliability of the projected hybrid configuration are demonstrated through nonlinear time-domain simulations conducted under various operating scenarios.

Over the past years, the price of wind & solar energy generation has witnessed a significant decline. Owing to their growing economic feasibility & technological benefits, global installed capacities have seen a remarkable increase—solar & wind rule capacities reached approximately 303 GW & 487 GW, respectively, by the year 2016, in contrast to 6 GW & 74 GW recorded in 2006 [1]. However, the variable & unpredictable nature of these renewable energy sources necessitates the use of rule electronic converters, which serve as essential interfaces between the renewable energy sources & either the utility grid or local loads, enabling the creation of distributed generation structures [2], [3].

Traditionally, research & development in distributed generation structures have predominantly focused on single-source renewable structures—either solar-based [4], [5] or wind-based structures [6]–[8]. To leverage the complementary nature of these two resources, recent studies have explored the integration of both wind & solar generators within a single hybrid structure [9]–[22]. Hybrid cogeneration structures that combine wind & solar sources offer several key benefits: (1) the accessibility patterns of wind & solar energy often complement each other, thereby enhancing overall energy production efficiency [23]; (2) co-locating these structures leads to more efficient l& usage, optimizing infrastructure investments [24]; (3) compared to static photovoltaic installations, hybrid structures involving wind turbines can provide better grid support due to the mechanical inertia associated with the turbine's rotating components [8]; & (4) the dual energy inputs improve structure reliability & reduce dependence on any single source [9], [10].

3 MODELING & CONTROL

The suggested setup consists of a Voltage Source Inverter that connects the hybrid cogeneration structure to the utility grid & a Voltage Spring Rectifier that communicates with the wind energy conversion structure, as shown in Fig. 1. As described in [27], a DC cable is used to connect the photovoltaic structure directly to the DC-link capacitor of the BtB VSCs. With six switching units each, the VSR & VSI are both implemented as two-level converters. An IGBT & a freewheeling diode are linked in parallel in each unit. The next subsections provide specifics on the modeling & control methodologies for the entire structure.

3.2 Discrete PI Controller

Digital controllers operate based on discrete time intervals, requiring a discretized version of the PI control law to replace the continuous-time integral with a numerical approximation. In this approach, the integral term is estimated using a summation of the error values over time. The interval between successive samples is denoted by Δt\Delta tΔt, & the total number of samples up to time ttt is represented by ntn_tnt. The discrete-time PI control equation is thus designed to accommodate this sampling structure, enabling accurate control implementation in digital structures.

u(t)=ubias+Kce(t)+KcτInt∑i=1ei(t)Δt

3.2.1 Overview Of Pi Control

PI control is primarily applied to non-integrating (self-regulating) processes, which are structures that naturally stabilize at a specific output level when subjected to constant inputs & disturbances. In contrast, P-only control is more suitable for integrating processes, where the output continuously changes over time unless actively corrected. The integral term in PI control is essential for eliminating steady-state error, effectively serving as a dynamic offset or adjustable bias.

To determine suitable controller settings, tuning methods such as ITAE & IMC are commonly used. IMC tuning, in particular, is an extension of lambda tuning that incorporates process time delay, enhancing control performance for structures with lag. These tuning techniques rely on estimating model parameters — the process gain KcK_cKc, the time constant τp\tau_pτp, & the time delay θp\theta_pθp — by approximating the process with a FOPDT model.

The structure & function of the PI speed controller can be illustrated using the general block diagram shown in Figure X.

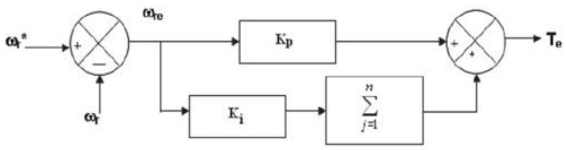

Fig.1.Block diagram of PI speed controller

The torque communication at the nth sampling moment, which is the speed controller's output, may be mathematically written as:

$$Te\,(n) = Te(n-1) + Kp\ \omega re(n) + Ki\omega re(n) \quad (10)$$

where Te (n) is the torque output of the controller at the n-th instant, and Kp and Ki are the proportional and integral gain constants, respectively.

A limit of the torque comm& is imposed as

$$T_{e(n+1)} = \begin{cases} T_{emax} & \text{for} \quad T_{e(n+1)} \geq T_{emax} \\ -T_{emax} & \text{for} \quad T_{e(n+1)} \leq -T_{emax} \end{cases}$$

The Ziegler-Nichols approach, the trial-and-error method, and searching based on evolutionary methodology are some of the techniques used to choose the PI controller gains in (10) as well. The motor ratings establish the numerical values of various controller upgrades.

4 RESULTS& DISCUSSIONS

4.1 SIMULATION CIRCUITS

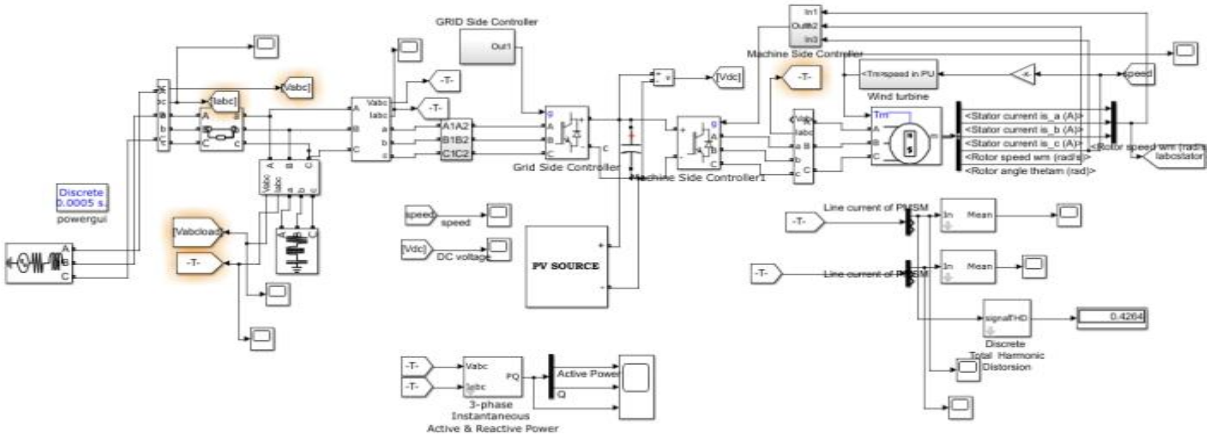

Figure 2: Simulation Circuit of Simulink Model

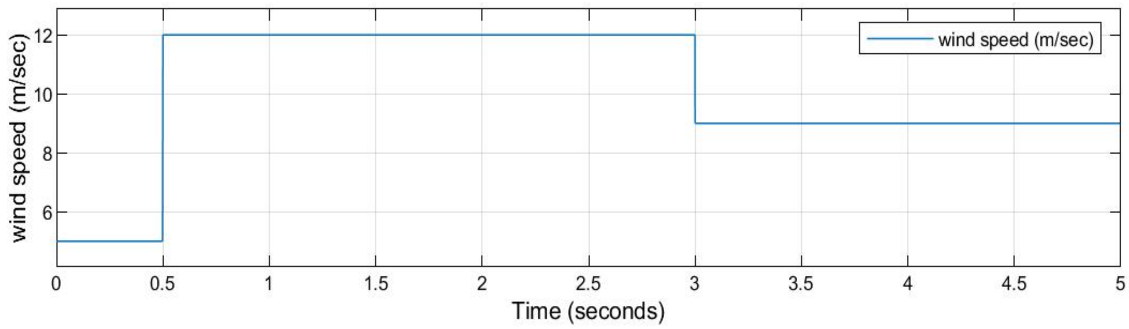

Figure 3: Wind Speed variation with respect to time

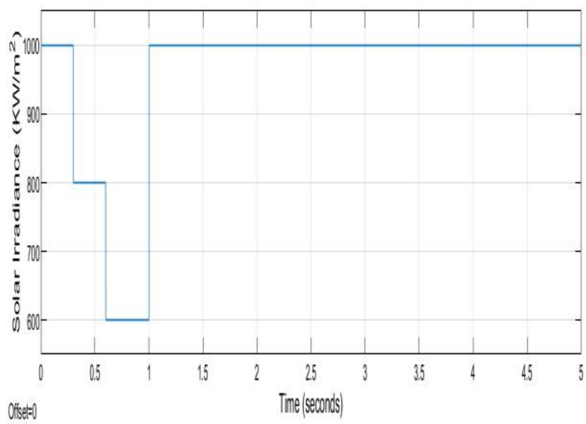

Figure 4: Solar irradiance variation with respect to time

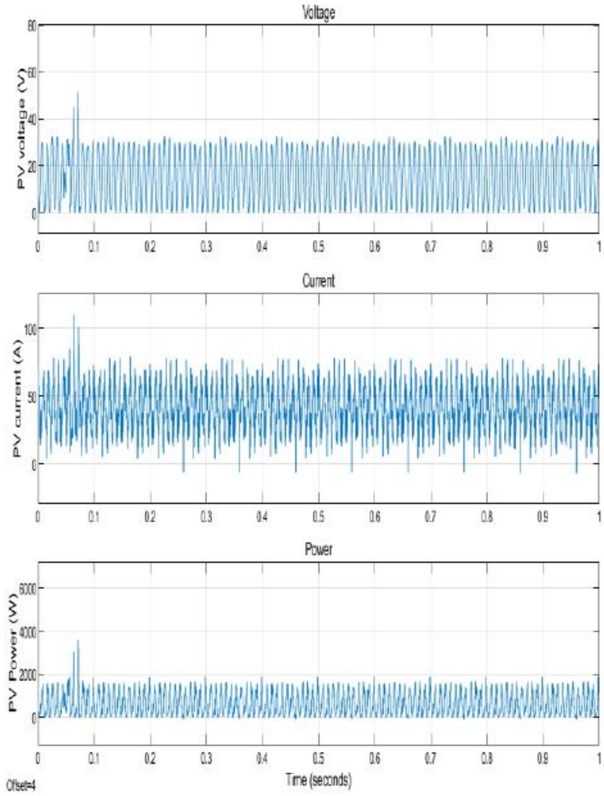

Figure 5: Grid side converter current variation with respect to time

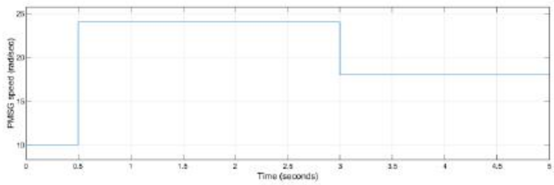

Figure 6: PV array model voltage (top), current (middle), & rule (bottom) variation with respect to time

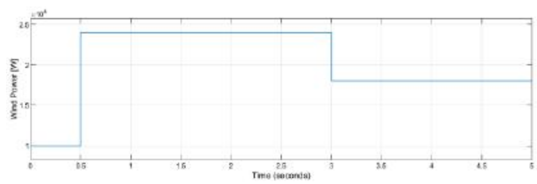

Figure 7: PMSG speed (radian / sec) variation with respect to time

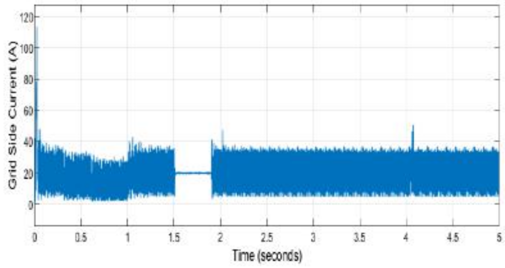

Figure 8: Wind Rule (W) variation with respect to time

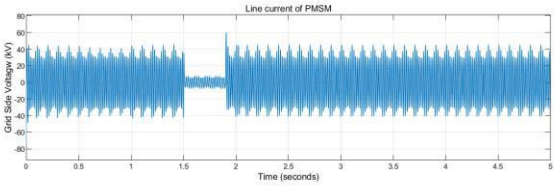

Figure 9: Variation in grid side converter voltage over time

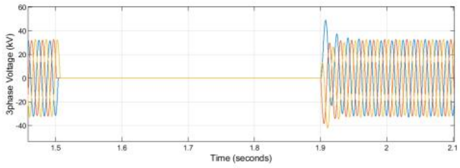

Figure 10: Three phase voltage variation with respect to time

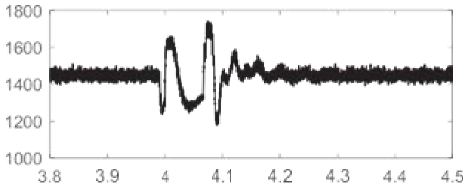

Fig.11. Voltage response to a 3PG fault at t = 4.0 s for 4.0 cycles – 1.0 p.u. with fault protection measures in place for wind & solar rule generation.

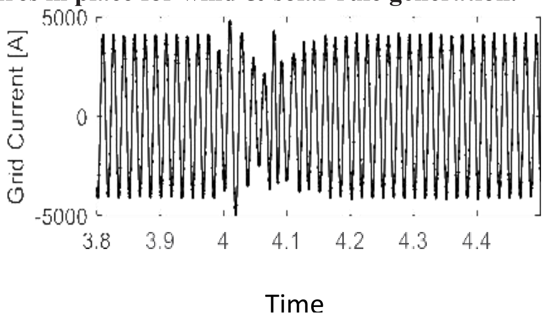

Fig. 12.Current response of wind & solar rule generation with fault protection systems in place to a 3PG fault at t = 4.0 s for 4.0 cycles – 1.0 p.u.

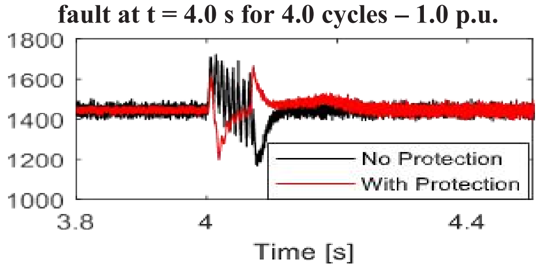

Fig. 13. Response of 1.0 p.u. wind & solar rule generation with & without the fault protection methods to a 1PG fault at t = 4.0 s for 4.0 cycles

5 CONCLUSIONS

This thesis offerings the integration of solar & wind energy structures using vector-controlled, grid-connected back-to-back VSCs. The VSR, connected to the wind turbine, is responsible for maximizing rule extraction by tracking variations in wind speed. On the grid side, the Voltage Source Inverter performs multiple functions, including maintaining a unity rule aspect at the PCC under different operating conditions, ensuring rule balance across the DC-link capacitor, & optimizing energy capture from the photovoltaic (PV) source.

To assess the dynamic behavior of the projected system, a detailed small-signal linearization has been carried out, resulting in the complete development of a state-space model. The proposed configuration offers several noteworthy advantages in terms of performance, stability, & efficiency:

1. Enhanced reliability & efficiency due to the hybrid configuration of wind & solar energy sources;
2. Independent MPPT control, with the VSR & VSI dedicated to wind & PV rule extraction, respectively;
3. Effective regulation of the dc-link voltage across all operating conditions, contributing to improved damping characteristics;
4. Simplified structure architecture & ease of controller design; &
5. Capability to achieve fault ride-through using existing protection mechanisms.

Time-domain simulation results, conducted in the MATLAB/Simulink environment, confirm the structure's well-damped dynamic response & efficient operation under a range of operational scenarios.

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