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DESIGN, REGULATION, AND ENERGY MANAGEMENT OF A HYBRID GRID-CONNECTED SYSTEM THAT INCORPORATES AN ELECTROLYZER AND FUEL CELL

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ABSTRACT

The proposed work addresses the modelling, control, energy management and operation of hybrid grid connected system with wind-PV-Battery Energy Storage System (BESS) integrated with Fuel Cell (FC) and Electrolyser. A hybrid PV-Wind-FC with electrolyser consisting of BESS with the least number of control loops and converters has been proposed. The proposed hybrid system presents a cost-efficient solution for integrating PV into a hybrid system by eliminating the PV converter. This includes the design of controllers for grid-connected hybrid systems with a renewable distributed generator (Wind and PV) as a primary source, BESS as a secondary source and FC with Electrolyser as a tertiary source. In addition, the lead compensator along with integrator is used for obtaining enough phase margin and removing steady state error completely. It increases the stability of the controller and adds phase shift ϕs at a cross gain frequency (ωcut). The Grid Side Controller (GSC) can provide frequency support to the utility grid, when it is linked to the grid. In the proposed configuration, PV power is maximized and injected into grid through GSC. Rotor Side Converter (RSC) and GSC ensure the support for sharing the burden of the grid station. Moreover, the proposed controller of BESS with coordination of FC eliminates the effect of intermittency of power generated from wind and PV. Excess power production by renewable distribution generation is used by Electrolyser to generate hydrogen. This hydrogen is further used by FC when there is not enough power generation due to unfavourable weather conditions. The energy management has been presented to fulfil the load profile, avoid BESS overcharging and to minimize the intermittency and fluctuation of Wind and PV sources. This method guarantees steady power flow and service continuity. The Simulink model of the proposed system results validate the efficiency of the proposed hybrid system as compared to the conventional hybrid system reported in the literature. The modelling of the proposed system and analysis has been demonstrated using the MATLAB Simulink model. Lastly, the energy management of the system has also been examined and compared with the conventional power system.

Keywords: Grid-connected system, energy management system, battery energy storage system, electrolyser, fuel cell, doubly fed induction motor, maximum power point tracking.

1. INTRODUCTION

Due to the considerations of environment condition, applications of renewable energy sources (RESs) are more promising; that makes environment pollution free. Also, their availability is cost free and continuous [1], [2]. Numerous RESs consist of photovoltaic system (PV), wind turbine system (WT) and micro-turbines, etc. which are considered as components of hybrid energy systems in the literature and also demonstrate applications of micro-grid [3], [4]. Due to the various seasonal and bad weather conditions such as temperature, wind speed, solar radiation and also geographical conditions, these structures are not worked properly. So, the solutions must be needed and find out. Hence, energy storage systems (ESSs) are suitable for the solution of the mitigation of wind effects, solar radiation fluctuations and also ESSs uphold the power and energy balance. Power quality also improves due to ESSs. Due to the fast variations of power, ESSs must contain a high power density as well as high energy density. So, it is required to keep more than one storage system for a hybrid energy storage system (HESS) [5]-[7]. The ESSs and battery banks (BBs) are efficiently used in hybrid energy systems (HESs). But, lifetime of batteries decreases due to the charging and discharging cycles [8], [9]. A secondary energy sources is required to enhance the supply energy reliability of HESs. Hence, a fuel cell (FC) is required to combine with the electrolyzer by giving a continuous supply to the load [10], [11]. The strategies of energy management consist of combination of PV, WT and FC comprising with electrolyzer as well as battery storage. These are most effective practice for quality of higher energy requirement. Further, micro-grid comes into interface with the distributed generation and for the decentralized management, the grid is connected with this micro-grid [12]. Now a day’s DC loads are increasing in electric vehicles, residential, commercial and industrial buildings. So, the loads in power system might be DC dominated in the subsequent time. If AC grid supplies these type of DC loads, then AC/DC as well as DC/DC converters are required in near future. These converter equipments combine with the individual DC or AC grid, so the cost is increased as well as cause the additional losses. In the meantime the overall efficiency is reduced for the particular system. Numerous studies and configurations have been suggested in [13]-[16] for the application of the hybrid energy system. A HES normally consists of individual DC grid or AC grid that can beat the fact that DC loads connect with the DC grid [17] and AC loads connect with the AC grid, also DC or AC grids are associated with the bidirectional converter [18].

From [18], a hybrid system includes PV system, WT system as well as FC. So, the hybrid system reduced the power electronics equipments such as AC/DC or DC/AC converters in the separate DC or AC grid applications. Also, FC is operated separately without batteries. But, robustness, vector control, advantages of WT-DFIG are not suggested, also their operations modes are not considered and further pitch angle control is not considered. Amongst other, Tamalouzt *et al.* [19] have discussed a direct torque and reactive power control of grid connected doubly fed induction generator for the wind energy conversion. Tazerart *et al.* [20] have described a direct torque control implementation method with losses minimization of induction motor for electric vehicle applications with high operating life of the battery. Bhende *et al*. [21] have designed a permanent magnet synchronous generator-based standalone wind energy supply system. Onar *et al*. [22] have described dynamic modeling, design and simulation of a wind/fuel cell/ultra-capacitor-based hybrid power generation system. In HES though wind integration looks attractive in terms of requirement of active power still the cost and control technique are the major drawbacks of this technology in addition to noisy environment.

The major contribution of this paper is modeling of a new configuration of grid connected HES consisting of PV, electrolyzer, storage tank and SOFC which are simulated together. Particularly, the detailed modeling of hydrogen flow from electrolyzer to SOFC through storage tank which is not available in the literature has also been provided in this paper. Advantage of this technology shows the accessibility of grid (AC and DC). Hence, hybrid system increases power management capability of the grid. This paper provides the overall description of the proposed methodology. Further, detailed modeling and control strategy of each equipment of the system is described. A supervisory control strategy and also a management strategy of the system are presented. Finally, the effectiveness of the proposed HES is confirmed through the simulation under several situations such as variation in power demand and various meteorological conditions.

2. LITERATURE SURVEY

1. Renewable Energy Systems and Storage Challenges

Renewable energy systems, such as photovoltaic (PV) and wind turbine systems, have been extensively explored due to their environmentally friendly and cost-free nature. However, challenges like variability due to weather conditions necessitate energy storage solutions. Energy storage systems (ESS) and battery banks are commonly employed to balance power but suffer from reduced lifespan due to frequent charge-discharge cycles. To enhance reliability, fuel cells (FC) combined with electrolyzers are proposed, ensuring continuous energy supply and environmental benefits.

Industrial Engineering Journal
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2. **Hybrid Energy Systems (HES) in Literature**
   Numerous studies have focused on hybrid systems incorporating various combinations of PV, wind turbines, fuel cells, and electrolyzers. For instance:
   - Tamalouzt et al. demonstrated the performance of WT-DFIG integrated with PV and fuel cells.
   - Tazerart et al. explored the direct torque control of induction motors for EVs, emphasizing energy efficiency.
   - Onar et al. detailed wind/fuel cell/ultra-capacitor hybrid power systems, showcasing their dynamic capabilities.
3. **Key Contributions in Hybrid System Configurations**
   Previous configurations highlighted the challenges of integrating multiple energy sources:
   - DC and AC grid combinations often involve higher costs due to the need for converters.
   - Systems with PV, WT, and FCs addressed robustness issues but lacked a detailed operational framework for integrating hydrogen storage.
4. **Advances in Modeling and Control**
   - PV systems are commonly optimized using Maximum Power Point Tracking (MPPT) for efficiency. However, hybrid systems integrate MPPT with hydrogen generation through electrolyzers to manage excess energy effectively.
   - SOFCs have gained attention as clean alternatives to batteries. Their operation involves hydrogen produced by electrolyzers, with PID controllers ensuring optimal flow based on load demands.
5. **Grid Integration of HES**
   Many studies underline the importance of interfacing hybrid systems with the grid to maintain voltage and frequency stability. Voltage Source Converters (VSC) play a pivotal role in synchronizing DC/AC converters for seamless grid integration.
6. **Proposed System Contributions**
   The paper addresses gaps in previous research by:
   - Developing a detailed model for hydrogen flow between electrolyzers and SOFCs, ensuring efficient storage and utilization.
   - Implementing advanced power management strategies that dynamically balance load demands under varying meteorological conditions.
   - Demonstrating the system's effectiveness through

Industrial Engineering Journal
ISSN: 0970-2555
Volume: 54, Issue 1, January:2025

MATLAB/Simulink simulations, ensuring the proposed system's adaptability to real-world scenarios.

Environmental and Economic Benefits The proposed HES provides clean, renewable energy solutions, reducing reliance on conventional batteries and minimizing environmental impact. Moreover, the system's modularity and efficiency promise cost-effective solutions for consumers.

3. PROPOSED SYSTEM

The proposed model is shown in Figure 1. In this model the PV system is regulated by the maximum power point tracking algorithm (MPPT) and it is also interfaced with the boost converter to boost up the DC voltage. Then this DC voltage (Vpv_boost) is applied to DC/AC converter to convert DC voltage to AC voltage. Solar energy depends upon the weather conditions; so when the solar radiation is weak or it is absence for sometimes, then the SOFC comes into interface because integration of the system with SOFC makes it more sustainable. Further, when power generation is more from Sun for a long period, then the electrolyzer takes part to consume the excess electric power and generate hydrogen. This hydrogen is stored in storage tank in compressed manner and further utilized as a fuel of the SOFC. Therefore, the power management strategy of this HES is developed to minimize the effect of daily as well as seasonal variations due to the conditions containing climatic and geographical. So, RES results a polished output power, also satisfy the power requirement. Operating performances of HES depend on stability of the voltage of DC bus when disturbances/faults occur or when power demand fluctuation is rapid. When, voltage fluctuations is more, then power converters show more power losses and more injection of harmonics towards the grid.

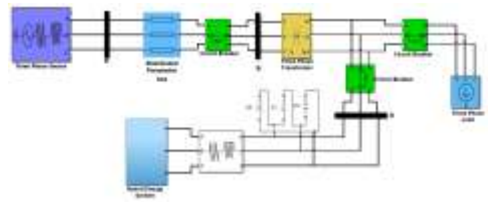

Figure 1. Hybrid system connected to grid (Proposed Model)

2.1. Modeling of photovoltaic (PV) system

Mathematical model of the PV system is shown in [15], [16]. The power characteristic of the PV system is represented in [2]. To draw out the maximum power which is available in PV array, it is useful to operate the PV system at MPPT. Maximum power point tracking (MPPT) is a process where PV array, inverters which are connected to grid and other similar devices are employed to extract the maximum amount power. Hence, the PV module is designed with the help up MATLAB/SIMULINK by considering the following Equation (1). Also Table 1 contains specifications of the photovoltaic (PV) array.

$$V_{pv} = \frac{N_s a k T}{q} \ln\left[\frac{I_{sc} - I_{pv} + N_p}{N_p I_0}\right] - \frac{N_s}{N_p} R_s I_{pv} \qquad (1)$$

Parameters considered to design the PV system such as I0 is the reverse saturation current of PV cell in [A], ISC is the short-circuit PV cell current in [A], IPV/Iph is the output current of PV cell in [A], k is the boltzmann's constant in [J/oK], a is the completion or ideality factor, q is the electron charge in [C], RP is the PV cell containing parallel resistance in [Ω], RS is the PV cell containing series resistance in [Ω], NS is the no. of series cells in a string of the PV cell, NP is the No. of parallel strings, T is the temperature of the PV cell in [K], VPV is the PV cell terminal voltage in volt in [V],VMP is the voltage related to maximum power

Industrial Engineering Journal
ISSN: 0970-2555
Volume: 54, Issue 1, January:2025

of the PV cell in [V],VOC is the PV cell open-circuit voltage in volt in [V].

Table 1 Specifications of Photovoltaic (PV) array

Specification	Value
No. of series connected PV cell	96
No. of Modules in parallel	66
No. of Modules in series	05
Open circuit voltage (V_{OC})	64.2 V
Short circuit current (I_{SC})	5.96 A
Maximum Power of PV cell	305W
Temperature (T)	25
Irradiance	1000

2.2. Modeling of electrolyzer

Electrolyzer is used to decompose the water (H2O) into two elements, first one is hydrogen and another one is oxygen by circulating the electric current in the electrolyzer containing two separate electrodes. The process is called electrolytic process or electrolysis [11].

The electrolysis equation of water is shown below:

$$H_2O(l) + electrical\ energy = H_2(g) + \frac{1}{2}O_2(g) \tag{2}$$

Parameters used for modeling of an electrolyzer are ie is the current of an electrolyzer in [A], nc is the no. of series connected electrolyzer cells, nH2 is the amount of hydrogen generated in moles per second in [mol s−1], F is the faraday constant in [C kmol−1],ηF is the Faraday efficiency.

Electrical current is directly related to the rate of production of hydrogen of the electrolyzer as shown in Faraday's law given below [22].

$$nH_2 = \frac{\eta_F n_c i_e}{2F} \tag{3}$$

The ratio of the actual amount of hydrogen generated by the electrolyzer to the theoretical value is represented as Faraday efficiency.

$$\eta_F = 96.5e^{\left(\frac{0.09}{i_e} - \frac{75.5}{i_e^2}\right)} \tag{4}$$

From the Equations (3) and (4), an electrolyzer model is designed through the help of Simulink that is shown in Figure 2.

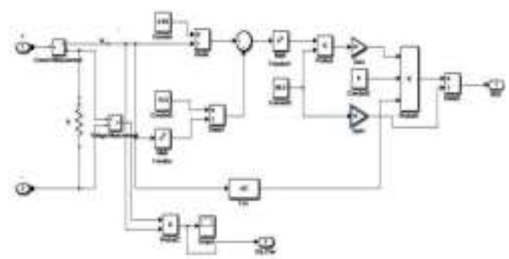

Figure 2. A brief model of electrolyzer using Simulink

2.3. Modeling of storage tank

Hydrogen is produced by the electrolyzer, then this generated hydrogen acts as fuel of the SOFC. According to the output power, SOFC consumed the required amount of hydrogen. The difference between the generated hydrogen and required amount of hydrogen is stored in the storage tank in storage tank.

In the hydrogen storage tank, the hydrogen is stored in compressed liquid or gaseous form. The hydrogen storage tank is designed according to the Equation (5) and tank pressure is directly calculated by considering the difference amount of hydrogen flow to the storage tank [22]. Figure 3 shows the brief model of hydrogen storage tank using Simulink.

$$P_b - P_{bi} = z\frac{NH_2RT_B}{MH_2V_b} \tag{5}$$

Parameters used for modeling of the storage tank such as Z is the pressure compressibility factor, NH2 is the amount of hydrogen stored in the storage tank in moles per second in [kmol s−1], MH2 is the hydrogen molar mass in [kg kmol−1], Tb is the operating temperature in [oK], Pbi is the storage tank pressure at initial stage, Pb in storage tank pressure, R is the rydberg/Universal gas constant in [J (kmol oK) −1], Vb is the storage tank volume in [m3].

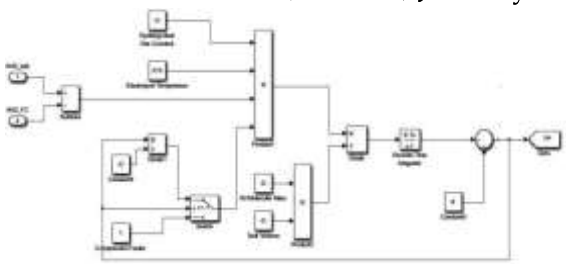

Figure 3. A brief model of hydrogen storage tank using Simulink

4. RESULTS

In this paper, the FC and Electrolyser have been added to WTG-DFIG, PV and BESS systems connected in a hybrid grid system. The hybrid grid-connected system has been implemented and power management for the proposed system is performed in the Simulink environment of MATLAB. The entire system was simulated under different environmental conditions and variable loads. This emphasizes the impacts of this hybrid system on the efficiency and quality of the injected and/or necessary energy.

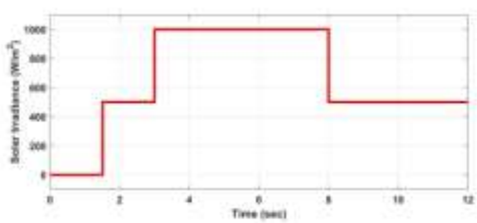

FIGURE 60. Solar Irradiance (W/m2).

The capacity of the DFIG is taken as 2 MW along with the solar system that has a capacity more than GSC rating. Generally, GSC and RSC ratings are supposed to be 24% to 31% of the rating of the generator. Thus, GSC and RSC ratings are taken as 340 kVA and 250 kVA, respectively. Contrarily, the PV system rating is taken as 1.1 MW. To emphasize the benefits of chosen system, the capacity of the system is considerably taken larger than its GSC rating. A 100-Ah BESS is connected to this system to protect the GSC from overloads. FC of 50 kW and 625 V with an electrolyser of 35V is added to the system. The DFIG, WT and GSC parameters are given in Table 1.

The proposed system is simulated under various scenarios and the results are provided and analysed in this section. Solar irradiance is considered to vary across a day as shown in Fig. 60.

The PV system is protected by using diode (D1) and circuit breaker (SP). The circuit breaker is initiated at t = 0. Till t = 2 sec, solar irradiance is 0 W/m 2, then it changes to 500 W/m 2 during t = 2sec to 3 sec, 1000 W/m 2 during 3 to 8 sec and come back to 500 W/m 2 for rest of the time. PV power depends upon the solar irradiance. Fig. 61 shows the PV array type current and power at MPPT. The PV, BESS,

TABLE 1. DFIG, Wind turbine and GSC parameters.

Industrial Engineering Journal
ISSN: 0970-2555
Volume: 54, Issue 1, January:2025

Symbol	Parameter	Values
f	Frequency (Hz)	50
P_s	Rated Stator power (W)	2e6
n	Rated Rotational Speed (rpm)	1500
I_s	Rated Stator current (A)	1760
V_s	Rated Stator voltage (V)	690
T_{em}	Rated Torque (N.m)	12732
p	Pole pair	2
u	Stator/Rotor Turn Ratio	1/3
V_r	Rotor rated voltage (Non-Reached) (V)	2070
s_{max}	Maximum Slip	1/3
C_b	Rated Rotor voltage reference to stator	$(V_r * S_{max}) * u$
R_s	Stator leakage	$2.6e-3$
L_{ls}	Leakage Inductance (stator and rotor) (H)	$0.087e-3$
L_m	Magnetization Inductance (H)	$2.5e-3$
R_r	Rotor resistance referred to stator (Ω)	$2.6e-3$
-	Stator Inductance (H)	$L_s = L_m + L_{ls}$
-	Rotor Inductance (H)	$L_r = L_m + L_{ls}$
V_{dc}	DC link voltage	$1050-1150$
J	Inertia	127
f_{sw}	Switching Frequency	4e3
N	Gearbox ratio	100
ρ	Air Density	1.225
β	Pitch angle	0
-	C_{pmax}	0.44
C_{bus}	DC bus capacitance	$80e^{-3}$
R_g	Grid side filter resistance	$20e^{-6}$
L_g	Grid side filter inductance	$400e^{-6}$

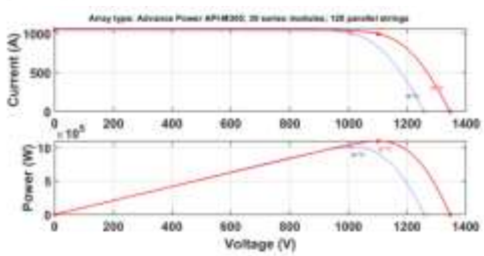

FIGURE 61. Current and Power at MPPT for array type (temperature variation).

FC and Electrolyser design parameters have been given in Table 2.

PV generation during 3 to 8 sec is maximum and achieved its maximum power of 1.1 MW while operating at MPP. During this internal, PV is supposed to infuse energy into the bus (DC). At this stage, power from the PV and the rotor goes to GSC. This huge power should be utilized well to avoid GSC overheating. The output power of PV for the proposed system is presented in Fig. 62. Therefore, BESS continues to start charging and absorb the extra power until

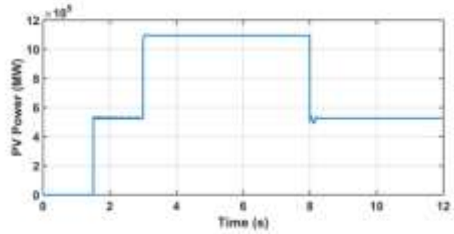

FIGURE 62. PV power (MW).

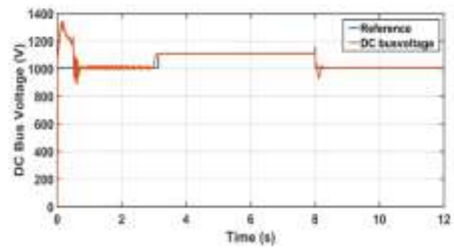

FIGURE 63. DC Bus Voltage (V).

its SOC goes greater than 80%. After 8 sec, solar irradiance drops due to which power generation from the PV goes down, BESS released stored energy to DC link in low solar irradiance condition. DC link waveform has been illustrated in Fig. 63. Before the operation of PV power generation, some initial transients occur but soon DC link voltage maintains at the value of 1000 V due to the BESS power supply. Between 3 to 8 sec, DC link voltage achieves its reference level of 1158 V due to injection of power by PV.

The charging and discharging behaviour of BESS when PNET is positive at the DC link, has been demonstrated. Fig. 64 shows the BESS power when the DC link is not getting surplus power from PV. It depicts that BESS is fully discharged between 1 to 2 sec and after 8 sec. Negative power shows the charging behaviour of BESS when PV generation track MPP power between 3 to 8 sec. BESS SoC is limited between 20% and 80%. AT SoC ≥ 80%, the

Industrial Engineering Journal
ISSN: 0970-2555
Volume: 54, Issue 1, January:2025

purpose of BESS at this stage is to discharge the power to the DC link until its SoC comes to 20%. During the initial transient behaviour of the system, the BESS is charged. During the second phase, the BESS started discharging till 3 sec to support the power at the DC link and it gets charged when enough power from the PV side ensures the power demand at the DC link.
When BESS is charged at 80% and there is still excess power at the DC link, Electrolyser starts dissipating power to produce and stored H2 in the hydrogen tank. When BESS is at 20%, FC gets connected to ensure system stability and service continuity. FC then used the stored H2 from the hydrogen

TABLE 2. PV, BESS, FC, and Electrolyser design parameters.

Parameter	Values
PV parallel strings	60
Series connected modules per strings	30
Maximum power PV array (W)	213.15
Open circuit voltage V_{oc} (V)	36.3
Short circuit current I_{sc}	7.84
BESS nominal voltage (V)	800
BESS rated capacity (Ah)	100
Initial SoC BESS	50
FC Power (kW)	50
FC Voltage	625
Nominal hydrogen utilization	99.56

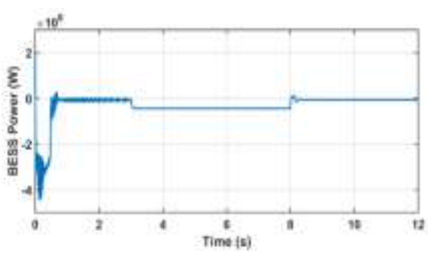

FIGURE 64. BESS discharging power (kW).

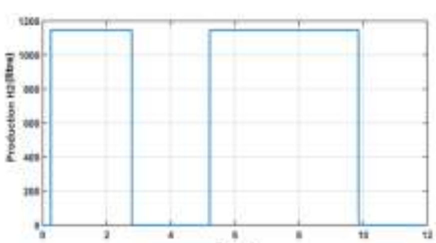

FIGURE 65. H2 production (litre).

tank to generate power for the supply to the DC link. Figs. 65 and 66 show the H2 production and storage in hydrogen tank during charging phase of BESS. Fig. 67 illustrated H2 usage by Fuel Cell in discharging phase of BESS when SoC came down to 20%. Similarly, H2 production by Electrolyser and consumption by FC when BESS starts charging are shown in Figs. 68 and 69.
The plots of the rotor powers (Active Pr) and the (Reactive Qr) are presented in Figs. 70 and 71. In the sub synchronous span, both powers are positive and these powers are being drawn from the RSC while in the super synchronous span, when both powers are negative, it supplies power to the DC links. Figs. 72 and 73 illustrate the behaviour of stator active and reactive powers respectively. Reactive power is negligible, equals to zero and the active power is positive and delivered to the grid.

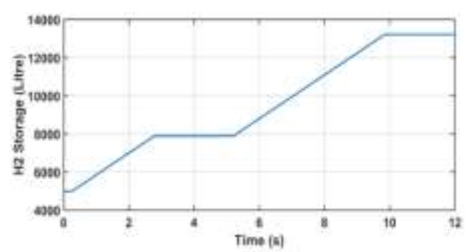

FIGURE 66. H2 storage (litre).

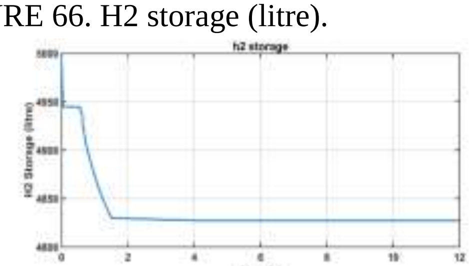

FIGURE 67. H2 storage (litre) used in discharging case of BESS.

Industrial Engineering Journal
ISSN: 0970-2555
Volume: 54, Issue 1, January:2025

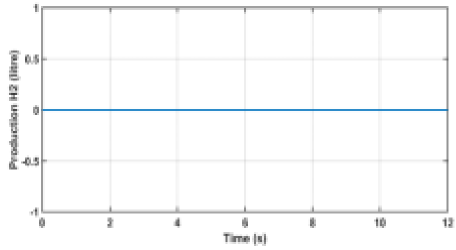

FIGURE 68. H2 production (litre) in charging state of BESS

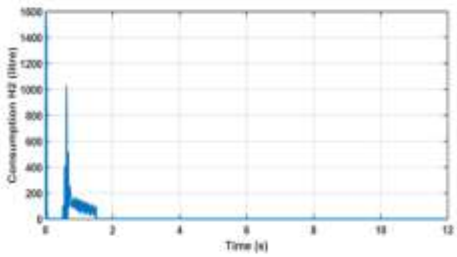

FIGURE 69. H2 consumption (Charging case).

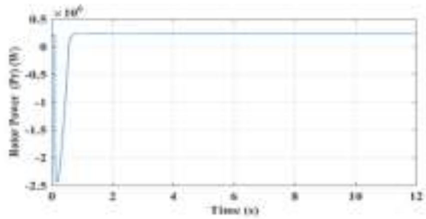

FIGURE 70. Rotor (Pr) power (W).

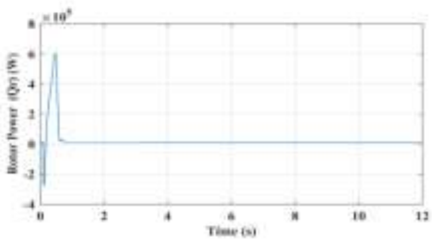

FIGURE 71. Rotor (Qr power (W).

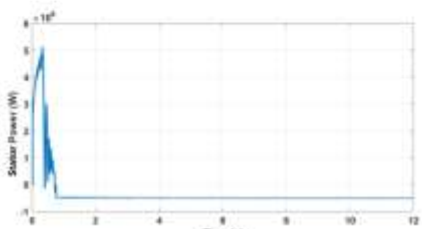

FIGURE 72. Stator (Ps) power (W).

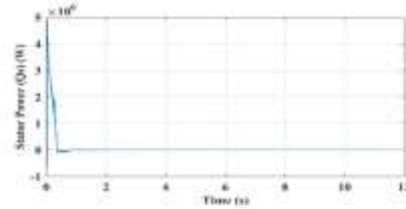

FIGURE 73. Stator (Qs) power (W).

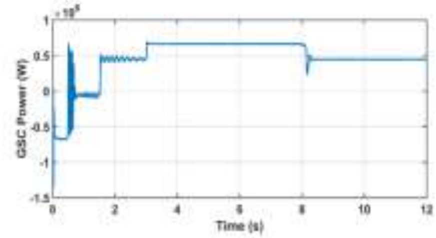

Fig. 74 shows the GSC power waveform. Its value is smaller than its rated value in sub-synchronous mode when PV irradiance or wind velocities are low. However, for proper control of BESS and GSC, its value is kept near to the value which is rated. The performance of this grid voltage is represented in Fig. 75. The main objective of the proposed system is to keep the system and its voltage stable, thus the zoom-in also shows the stable AC grid voltage.

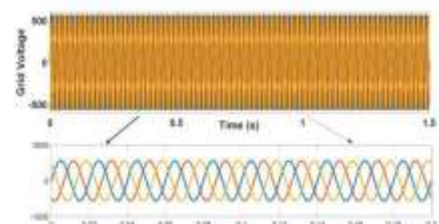

FIGURE 75. Grid Voltage (V).

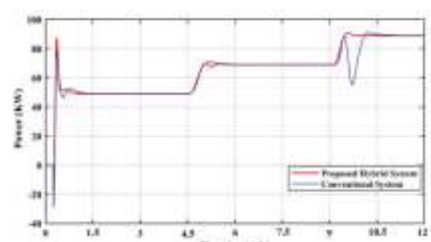

FIGURE 76. Comparative analysis of proposed hybrid and conventional power system.

Fig. 76 shows the output power response of the proposed hybrid system and the conventional system. In the proposed design fuel cell and PV contribute to achieving the reference target by meeting the energy

5. CONCLUSION

5.1 CONCLUSION

In this paper, FC and Electrolyser as an energy source have been added to the PV-DFIG and BESS hybrid grid connected system with the least number of converter and control loops is proposed. The characteristics of all system components and main configuration of the proposed system are explained. This paper includes the design of controllers for grid-connected hybrid systems with renewable distributed generators (Wind and PV) as a primary source, BESS as a secondary source and FC with Electrolyser as a tertiary source. The proposed hybrid system presents a cost-efficient solution for integrating PV into a hybrid system by eliminating the converter of the PV. The system that is being proposed is controlled by introducing power management for better power sharing between proposed sources. PV power is maximized and injected into the grid through GSC. BESS with coordination of FC and Electrolyser eliminates the effect of intermittency of power generated from wind and PV. Excess power production by renewable distribution generation is used by Electrolyser to generate hydrogen. This hydrogen is further used by FC when there is not enough power generation due to unfavourable weather conditions. The power management is presented to fulfil the load profile, avoid BESS overcharging and to minimize the intermittency and fluctuation of Wind and PV sources. This method guarantees a steady power flow and service continuity. Significant improvement has been observed by introducing FC with Electrolyser to the Wind/PV/BESS-based hybrid grid connected system. Better power management, DC link voltage tracking and MPP of PV power from the GSC side have been observed.

This work can be further improved by introducing non-linear controllers to better cater nonlinearities presented in Wind, Fuel Cell, Electrolyser and BESS for the proposed hybrid grid-connected system. Moreover, an Artificial intelligence-based algorithm can be implemented for Energy Management

REFERENCES

[1] J. M. Carrasco, L. G. Franquelli, J. T. Bailiwick, E. Galván, R. C. Portillo Guisado, M. M. Prats, J. I. León, and N. Moreno-Alfonso, ‘‘Power-electronic systems for the grid integration of renewable energy sources: A survey,’’ IEEE Trans. Ind. Electron., vol. 53, no. 4, pp. 1002–1016, Jun. 2006.

[2] H. Hassanzadeh Fard, F. Toor yan, E. R. Collins, S. Jin, and B. Ramezani, ‘‘Design and optimum energy management of a hybrid renewable energy system based on efficient various hydrogen production,’’ Int. J. Hydrogen Energy, vol. 45, no. 55, pp. 30113–30128, Nov. 2020.

[3] M. Xie, M. M. Gulzar, H. Tehreem, M. Y. Javed, and S. T. H. Rizvi, ‘‘Automatic voltage regulation of grid connected photovoltaic system using Lyapunov based sliding mode controller: A finite—Time approach,’’ Int. J. Control, Autom. Syst., vol. 18, no. 6, pp. 1550–1560, Jun. 2020.

[4] F. U. Khan, M. M. Gulzar, D. Sibtain, H. M. Usman, and A. Hayat, ‘‘Variable step size fractional incremental conductance for MPPT under changing atmospheric conditions,’’ Int. J.

Nummer. Model., Electron. Newt., Devices Fields, vol. 33, no. 6, p. e2765, Nov. 2020.

[5] K. A. Khan and M. Khalid, ‘‘Improving the transient response of hybrid energy storage system for voltage stability in DC microgrids using an autonomous control strategy,’’ IEEE Access, vol. 9, pp. 10460–10472, 2021.

[6] J. Yao, H. Li, Y. Liao, and Z. Chen, ‘‘An improved control strategy of limiting the DC-link voltage fluctuation for a doubly fed induction wind generator,’’ IEEE Trans. Power Electron., vol. 23, no. 3, pp. 1205–1213, May 2008.

[7] B. Bellambi, N. Baroudi, S. Makhila, D. Abdel Jalil, T. Abdelkrim, F. Bukhara, and A. Lakhdari, ‘‘Experimental investigation of power management and control of a PV/wind/fuel cell/battery hybrid energy system microgrid,’’ Int. J. Hydrogen Energy, vol. 45, no. 53, pp. 29110–29122, Oct. 2020.

A. Khan, H. Ahmad, S. M. Ahsan, M. M. Gulzar, and S. Murowa, ‘‘Coordinated LVRT support for a PMSG-based wind energy conversion system integrated into a weak AC-grid,’’ Energies, vol. 14, no. 20, p. 6588, Oct. 2021.

[8] J. P. Da Costa, H. Pinheiro, T. Degner, and G. Arnold, ‘‘Robust controller for DFIGs of grid-connected wind turbines,’’ IEEE Trans. Ind. Electron., vol. 58, no. 9, pp. 4023–4038, Sep. 2011.

[9] C. Liu, F. Blaabjerg, W. Chen, and D. Xu, ‘‘Stator current harmonic control with resonant controller for doubly fed induction generator,’’ IEEE Trans. Power Electron., vol. 27, no. 7, pp. 3207–3220, Jul. 2011.

[10] H. Xu, J. Hu, and Y. He, ‘‘Operation of wind-turbine-driven DFIG systems under distorted grid voltage conditions: Analysis and experimental validations,’’ IEEE Trans. Power Electron., vol. 27, no. 5, pp. 2354–2366, May 2012.

[11] H. Nian and Y. Song, ‘‘Direct power control of doubly fed induction generator under distorted grid voltage,’’ IEEE Trans. Power Electron., vol. 29, no. 2, pp. 894–905, Feb. 2014.

[12] M. M. Gulzar, D. Sibtain, A. F. Murtaza, S. Murowa, M. Saadi, and A. Jameel, ‘‘Adaptive fuzzy based optimized proportional-integral controller to mitigate the frequency oscillation of multi-area photovoltaic thermal system,’’ Int. Trans. Electra. Energy Syst., vol. 31, no. 1, 2021, Art. no. e12643.

[13] Z. Dejia, Z. Zhenmin, M. Entail, and Y. Lijiang, ‘‘Design and control of a three-phase grid-connected photovoltaic system with developed maximum power point tracking,’’ in Proc. 23rd Annu. IEEE Appl. Power Electron. Conf. Expo., Feb. 2008, pp. 973–979.

[14] M. Gulzar, S. Rizvi, M. Javed, D. Sibtain, and R. S. Udo Din, ‘‘Mitigating the load frequency fluctuations of interconnected power systems using model predictive controller,’’ Electronics, vol. 8, no. 2, p. 156, Feb. 2019.

[15] M. Maaruf, K. Khan, and M. Khalid, ‘‘Robust control for optimized islanded and grid-connected operation of solar/wind/battery hybrid energy,’’ Sustainability, vol. 14, no. 9, p. 5673, May 2022.

[16] M. Hanan, X. Ai, M. Y. Javed, M. Majid Gulzar, and S. Ahmad, ‘‘A twostage algorithm to harvest maximum power from photovoltaic system,’’ in Proc. 2nd IEEE Conf. Energy Internet Energy Syst. Integer. (EI2), Oct. 2018, pp. 1–6.

[17] H. Ghadami, M. B. DeGrave, and A. Yazdani, ‘‘An integrated wind-photovoltaic-battery system with reduced power-electronic interface and fast control for grid-tied and off-grid applications,’’ Renew. Energy, vol. 45, pp. 128–137, Sep. 2012.

[18] R. G. Wand hare and V. Agarwal, ‘‘Novel integration of a PV-wind energy system with enhanced efficiency,’’ IEEE Trans. Power Electron., vol. 30, no. 7, pp. 3638–3649, Jul. 2015.

[19] M. Y. Javed, M. M. Gulzar, S. T. H. Rizvi, and A. Arif, ‘‘A hybrid technique to harvest maximum power from PV systems under partial shading conditions,’’ in Proc. Int. Conf. Emerg. Technol. (ICET), Oct. 2016, pp. 1–5.

[20] S. Diaf, G. Norton, M. Bechamel, M. Haddadi, and A. Louche, ‘‘Design and techno-economical optimization for hybrid PV/wind system under various meteorological conditions,’’ Appl. Energy, vol. 85, no. 10, pp. 968–987, Oct. 2008.

[21] B. N. Alazani, B. H. Jasim, Z.-A.-S. A. Rahman, and P. Siano, ‘‘A novel robust smart energy management and demand reduction for smart homes based on internet of energy,’’ Sensors, vol. 21, no. 14, p. 4756, Jul. 2021.

[22] S. Dorayaki, R. Dashti, and H. R. Shaker, ‘‘Optimal energy management in the smart microgrid considering the electrical energy storage system and the demand-side energy efficiency program,’’ J. Energy Storage, vol. 28, Apr. 2020, Art. no. 101229.

[23] T. M. Gür, ‘‘Review of electrical energy storage technologies, materials, and systems: Challenges and prospects for large-scale grid storage,’’ Energy Environ. Sci., vol. 11, no. 10, pp. 2696–2767, 2018.

[24] Y. Alhumaid, K. Khan, F. Alis mail, and M. Khalid, ‘‘Multi-input nonlinear programming based deterministic optimization framework for evaluating microgrids with optimal renewable-storage energy mix,’’ Sustainability, vol. 13, no. 11, p. 5878, May 2021.

[25] M. Khalid, ‘‘A review on the selected applications of battery-supercapacitor hybrid energy storage systems for microgrids,’’ Energies, vol. 12, no. 23, p. 4559, Nov. 2019.

[26] H. T. Dinh, J. Yun, D. M. Kim, K. Lee, and D. Kim, ‘‘A home energy management system with renewable energy and energy storage utilizing main grid and electricity selling,’’ IEEE Access, vol. 8, pp. 49436–49450, 2020.

A. Katariina, M. Khalid, A. V. Savkin, and V. G. Angelides, ‘‘Improving wind farm dispatch in the Australian electricity market with battery energy storage using model predictive control,’’ IEEE Trans. Sustain. Energy, vol. 4, no. 3, pp. 745–755, Jul. 2013.

[27] D. Sibtain, A. F. Murtaza, N. Ahmed, H. A. Sher, and M. M. Gulzar, ‘‘Multi control adaptive fractional order PID control approach for PV/wind connected grid system,’’ Int. Trans. Electra. Energy Syst., vol. 31, no. 4, 2021, Art. no. e12809.

[28] C. Ghenea, M. Bettayeb, B. Braining, and A. K. Hamid, ‘‘Hybrid solar PV/PEM fuel cell/diesel generator power system for cruise ship: A case study in Stockholm, Sweden,’’ Case Stud. Thermal Eng., vol. 14, Sep. 2019, Art. no. 100497.

[29] M. Çolak and İ. Kaya, ‘‘Multi-criteria evaluation of energy storage technologies based on hesitant fuzzy information: A case study for

Turkey,'' J. Energy Storage, vol. 28, Apr. 2020, Art. no. 101211.
[30] L. Kong, J. Yu, and G. Cai, ''Modelling, control, and simulation of a photovoltaic/hydrogen/supercapacitor hybrid power generation system for grid-connected applications,'' Int. J. Hydrogen Energy, vol. 44, no. 46, pp. 25129–25144, Sep. 2019.
[31] R. Almirante, E. Cassone, E. Distaso, and P. Tambura, ''Overview on recent developments in energy storage: Mechanical, electrochemical and hydrogen technologies,'' Energy Convers. Manage., vol. 132, pp. 372–387, Jan. 2017.
[32] U. Akram and M. Khalid, ''A coordinated frequency regulation framework based on hybrid battery-ultracapacitor energy storage technologies,'' IEEE Access, vol. 6, pp. 7310–7320, 2017.
[33] Z. Wang, Y. Jia, C. Cai, Y. Chen, N. Li, M. Yang, and Q. Li, ''Study on the optimal configuration of a wind-solar-battery-fuel cell system based on a regional power supply,'' IEEE Access, vol. 9, pp. 47056–47068, 2021.
[34] K. A. Khan and M. Khalid, ''Hybrid energy storage system for voltage stability in a DC microgrid using a modified control strategy,'' in Proc. IEEE Innova. Smart Grid Technol. Asia (ISGT Asia), May 2019, pp. 2760–2765.
[35] T. Ma, H. Yang, and L. Lu, ''Development of hybrid battery–supercapacitor energy storage for remote area renewable energy systems,'' Appl. Energy, vol. 153, pp. 56–62, Sep. 2015.
[36] M. M. Gulzar, M. Iqbal, S. Shahzad, H. A. Muqeet, M. Shahzad, and M. M. Hussain, ''Load frequency control (LFC) strategies in renewable energy-based hybrid power systems: A review,'' Energies, vol. 15, no. 10, p. 3488, May 2022.
[37] L. Zhang, X. Hu, Z. Wang, F. Sun, and D. G. Dorrell, ''A review of super-capacitor modelling, estimation, and applications: A control/management perspective,'' Renew. Sustain. Energy Rev., vol. 81, no. 2, pp. 1868–1878, 2018.
[38] F. Meganathan, S. Danyal, S. H. Hosseini, M. Sabahi, and S. M. Nia pour, ''Modelling and control of a new three-input DC–DC boost converter for hybrid PV/FC/battery power system,'' IEEE Trans. Power Electron., vol. 27, no. 5, pp. 2309–2324, May 2012.
[39] Y.-M. Chen, C.-S. Cheng, and H.-C. Wu, ''Grid-connected hybrid PV/wind power generation system with improved DC bus voltage regulation strategy,'' in Proc. 21st Annu. IEEE Appl. Power Electron. Conf. Expo., Mar. 2006, p. 7.
[40] X. Li, D. Hui, and X. Lai, ''Battery energy storage station (BESS)-based smoothing control of photovoltaic (PV) and wind power generation fluctuations,'' IEEE Trans. Sustain. Energy, vol. 4, no. 2, pp. 464–473, Apr. 2013.
[41] S. S. Martin, A. Chevak, A. El Ouafi, and M. Mabrouk, ''Modelling and simulation of hybrid power system integrating wind, solar, biodiesel energies and storage battery,'' in Proc. Int. Renew. Sustain. Energy Conf. (IRSEC), Nov. 2016, pp. 457–463.
[42] R. Sebastián, ''Battery energy storage for increasing stability and reliability of an isolated wind diesel power system,'' IET Renew. Power Gener., vol. 11, no. 2, pp. 296–303, Feb. 2017.
[43] B. P. Hayes, A. Wilson, R. Webster, and S. Z. Djokic, ''Comparison of two energy

storage options for optimum balancing of wind farm power outputs,'' IET Gener., Transmits. Diatribe., vol. 10, no. 3, pp. 832–839, 2016.

[44] L. Qu and W. Qiao, ''Constant power control of DFIG wind turbines with supercapacitor energy storage,'' IEEE Trans. Ind. Appl., vol. 47, no. 1, pp. 359–367, Jan. 2011.

[45] G. Lei, H. Song, and D. Rodriguez, ''Power generation cost minimization of the grid-connected hybrid renewable energy system through optimal sizing using the modified seagull optimization technique,'' Energy Rep., vol. 6, pp. 3365–3376, Nov. 2020.

[46] M. B. Camara, B. Dayo, and H. Guillous, ''Polynomial control method of DC/DC converters for DC-bus voltage and currents management— Battery and supercapacitors,'' IEEE Trans. Power Electron., vol. 27, no. 3, pp. 1455–1467, Mar. 2012.

[47] S. Adhikari and F. Li, ''Coordinated V-f and P-Q control of solar photo-voltaic generators with MPPT and battery storage in microgrids,'' IEEE Trans. Smart Grid, vol. 5, no. 3, pp. 1270–1281, May 2014.

[48] S. Najafi-Shad, S. M. Barakat, and A. Yazdani, ''An effective hybrid wind-photovoltaic system including battery energy storage with reducing control loops and omitting PV converter,'' J. Energy Storage, vol. 27, Feb. 2020, Art. no. 101088.

[49] M. G. Villalva, J. R. Gozzoli, and E. R. Filho, ''Comprehensive approach to modelling and simulation of photovoltaic arrays,'' IEEE Trans. Power Electron., vol. 24, no. 5, pp. 1198–1208, May 2009.

[50] G. Abad, J. Lopez, M. Rodriguez, L. Arroyo, and G. Iwanski, Doubly Fed Induction Machine: Modelling and Control for Wind Energy Generation. Hoboken, NJ, USA: Wiley, 2011.

[51] Y. Xu and X. Shen, ''Optimal control-based energy management of multiple energy storage systems in a microgrid,'' IEEE Access, vol. 6, pp. 32925–32934, 2018.

[52] M. Aly, E. M. Ahmed, H. Rezk, and E. A. Mohamed, ''Marine predators algorithm optimized reduced sensor fuzzy-logic based maximum power point tracking of fuel cell-battery standalone applications,'' IEEE Access, vol. 9, pp. 27987–28000, 2021.

[53] M. S. Guney and Y. Tepe, ''Classification and assessment of energy storage systems,'' Renew. Sustain. Energy Rev., vol. 75, pp. 1187–1197, Aug. 2017.

[54] S. Bucaniid, A. Sciascope, M. Mozdzierz, and G. Brus, ''A novel approach to the optimization of a solid oxide fuel cell anode using evolutionary algorithms,'' IEEE Access, vol. 7, pp. 34361–34372, 2019.

[55] N. Benyahia, H. Denon, M. Zoaria, T. Residua, and N. Barouche, ''Power system simulation of fuel cell and supercapacitor based electric vehicle using an interleaving technique,'' Int. J. Hydrogen Energy, vol. 40, no. 45, pp. 15806–15814, Dec. 2015.

[56] M. Ceraolo, G. Lutze Berger, and D. Poli, ''State-of-charge evaluation of supercapacitors,'' J. Energy Storage, vol. 11, pp. 211–218, Jun. 2017.

A. M. Trzynadlowski, Introduction to Modern Power Electronics. Hoboken, NJ, USA: Wiley,2015.