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A conceptual implementation of a buck converter for an off-grid hybrid system consisting of solar and wind turbine sources

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Abstract: A hybrid renewable power generation system is proposed through parallel connection between two potential energy resources: photovoltaic (PV) and wind turbines. The method consists of incorporating a buck converter connected by a wind turbine to provide adjustment according to PV potential. Unlike the conventional buck-boost converter topology that is normally used, this research tries to emphasize the use of a buck converter as part of the system configuration. Design schemes were carefully performed and the postdesign system was tested through system simulation with MATLAB/Simulink software. The simulated system offers promising and significant results, thus making it suitable for hardware implementation.

Key words: Buck converter, MATLAB/Simulink, hybrid controller, photovoltaic, wind turbine

1. Introduction

The term 'hybrid' refers to a system with two or more components combined for the purpose of efficient utilization of resources [1]. Within the implemented research context, a hybrid system regulates and controls power production, including battery protection from extreme conditions. Power resources may consist of various arrangements between either fossil fuel or renewable energy devices: e.g., diesel-electric generator, gas turbine, hydro-wind photovoltaic (PV)-based systems, and wind PV-based installation [1–7]. A common hybrid system configuration consists of a switching regulator placed between batteries, load, and sources to achieve power balance [8–11]. The configuration ensures that each component is actively controlled but increases the complexity level.

Accurate selection of these system components requires control methods that can handle instability caused by variation between input energy and load [4,12]. Other factors such as efficiency, cost-effectiveness, and system reliability require the realization of coordination control between the systems, thus providing optimal charges for storage purposes [5]. Several approaches providing control strategies for hybrid systems involve a state-based strategy, sensing parameters, and programmed algorithms [10,11,13–17].

Few studies have been identified that practice hybrid control strategies to overcome limitations such as power fluctuations, hydrogen production system inefficiency, and poor system performance and deal with capacitor-based hybrid power systems [18–20]. Conventional control methods [16,18–21] may evolve into complex and advanced control methods through an intelligent controller [4,22,23]. A previous control method employed analog circuitry [24] by using a power controller consisting of a switching regulator (LTC 1435IS) and a current

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sensor (LTC 1621IGN). The design was proven to be low-cost, light, efficient, and compact. However, analog systems are heavily influenced by surrounding disturbances such as noise, temperature, and aging [11].

The trend of incorporating renewable energy resources as part of a hybrid power system is very evident in the literature [5–9,13,19,25–27], with wind and solar energy constituting the largest proportion [21]. However, climate and geographical conditions tend to cause power fluctuations in the system [20] and therefore some studies propose using a diesel generator as a backup for these hybrid power systems [4,21,28,29]. The idea has proven unsuitable for providing cleaner power generation systems, however [9].

The need for an energy management strategy for a hybrid system motivated the present research's design strategies. Design schemes included integrating a wind energy source into the existing PV source. A buck converter was employed to match wind turbine energy with PV energy, thus optimizing load power requirement. Results obtained with MATLAB/Simulink software validated the design concept, thus making it suitable for the postdesign process.

Section 2 describes the proposed system configuration. MATLAB/Simulink integration and buck topology are explained in Section 3. Section 4 presents the simulation results and Section 5 concludes.

2. System overview

The proposed hybrid system was constructed from the combination of wind energy and PV energy connected to a buck converter. The system block diagram is shown in Figure 1. The system consists of a combination of wind energy and solar panel energy. When both sources are in action, a discrepancy arises because of environmental conditions. The solar panel produces energy depending on irradiance and temperature and the wind turbine depends on wind characteristics. Any variation causes an error at the summing point, whereby it is converted to a logic signal and subsequently fed to the buck converter. The buck converter adjusts (lowers) the wind turbine energy depending on the solar panel energy before merging it with the load. Instead of buck-boost/boost topology, which remains the conventional approach [6,25,30–32], the buck converter offers easier troubleshooting, simplicity in hardware implementation, and cost-effectiveness [33].

The system was developed and tested by utilizing MATLAB/Simulink preexisting blocks. The models covered in this study consist of the "Wind generator" model from the "Simpower Appplication" library and PV from the "Simscape" library. These two models are covered in Section 3.

3. MATLAB/Simulink model

The MATLAB/Simulink model for solar cells is presented in Figure 2 and its settings are tabulated in Table 1. The specifications refer to a local solar panel (SPM010-P) from Solar Power Mart.

Table 1. Solar cell parameters.

Description	Rating
Weight	1.5 kg
Max power, P_{max}	10 Wp
Max power voltage, V_{mp}	18.00 V
Max power current, I_{mp}	0.56 A
Open-circuit voltage, V_{OC}	22.81 V
Short-circuit current, I_{SC}	0.59 A

Note: Values at standard test conditions (AM 1.5, 1000 W/m^2, 25 $^\circ$C).

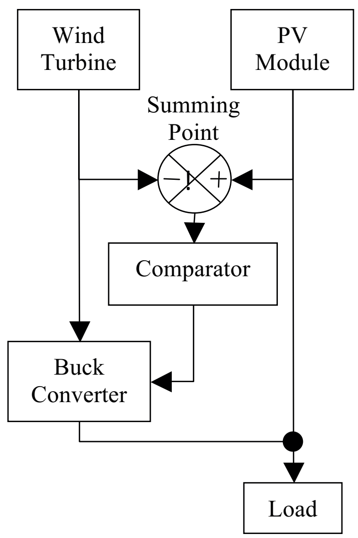

Figure 1. Proposed hybrid system block diagram.

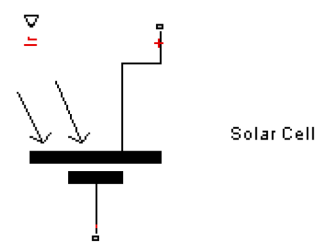

Figure 2. MATLAB/Simulink model representation of solar cell.

The system for the wind turbine was designed and developed for simulation purposes through MATLAB/Simulink. The wind turbine system is based on the integration of the "Wind Turbine" model and the DC machine, as shown in Figure 3.

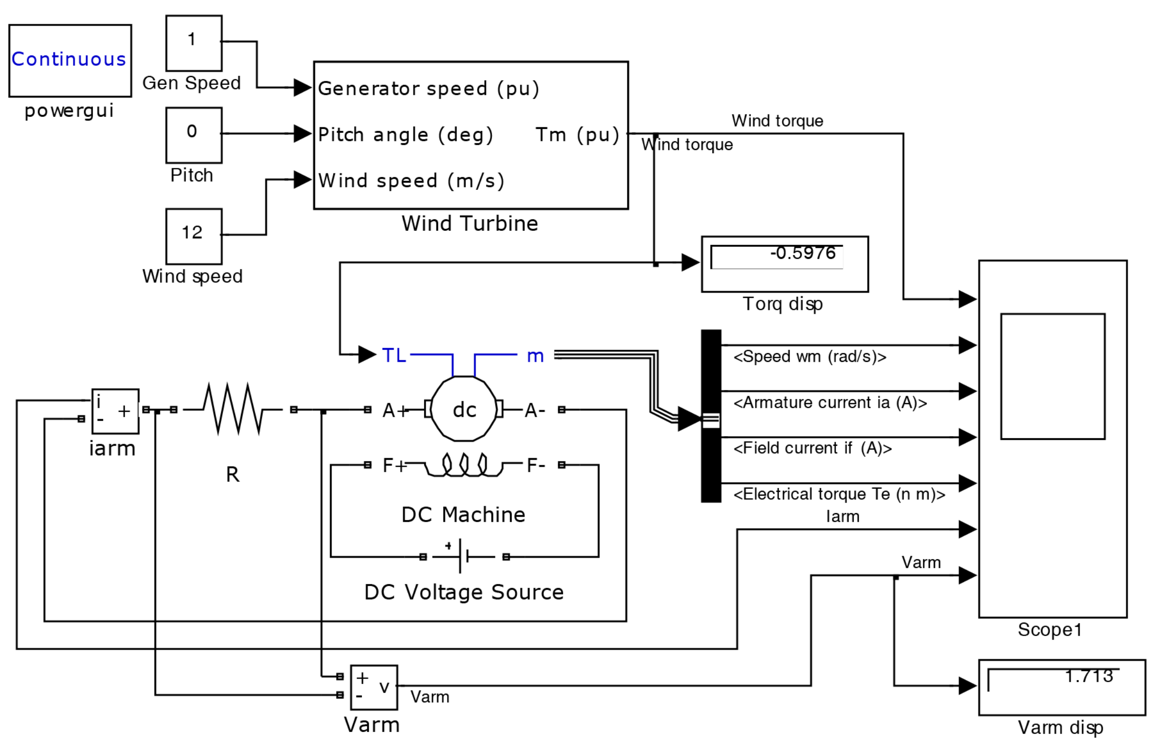

Figure 3. MATLAB/Simulink wind turbine integration with DC machine.

The buck converter model in Figure 4 consists of a switching device (normally MOSFET [32,34,35]), an inductor, a capacitor, a diode, a resistor (load), and a feedback element. A voltage mode-controlled feedback buck converter [32,36] is derived by comparing the voltage output with a reference value. Through a cyclic switching approach [34], any transition between feedback and set point causes a periodic pulse signal with duty cycle (D) ranging from 0%–100%, which can be described by two sets of differential equations in Eq. (1) [36].

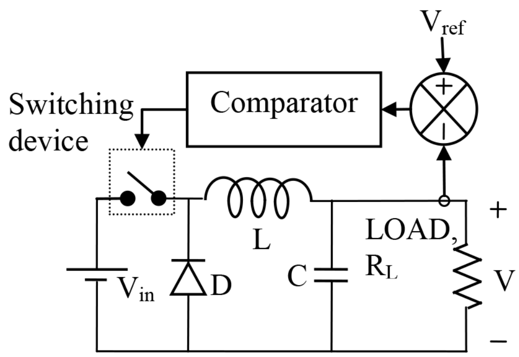

Figure 4. Buck converter model.

$$\frac{dv(t)}{dt} = \begin{cases} \frac{V_{in} - V(t)}{L}, \text{ switch OFF;} \\ \frac{V(t)}{L}, \text{ switch ON} \end{cases} \tag{1}$$
$$\frac{dv(t)}{dt} = \frac{((i(t)) - (v(t)/R))}{C}$$

By means of the buck converter parameters in [34], a MATLAB/Simulink-based buck converter system was constructed to provide necessary adjustment in terms of lowering the input potential to the desired PV level. The final design of the buck converter is shown in Figure 5.

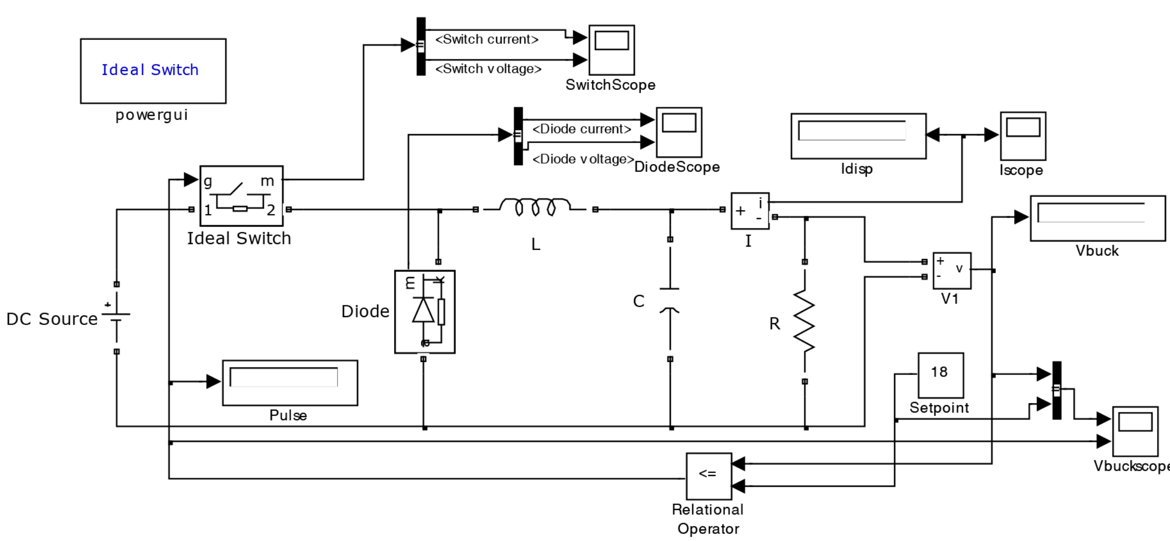

Figure 5. MATLAB/Simulink complete buck converter system.

4. Simulation results

The system for the hybrid sources and buck converter was assembled, carefully tuned, and configured for optimum performance. Figure 6 shows the overall subsystems incorporated into a single complete system consisting of a wind turbine connected to a buck converter and connected in parallel to a PV module. The MATLAB/Simulink model settings and characteristics for the wind turbine [37] and buck converter are tabulated in Tables 2 and 3, respectively.

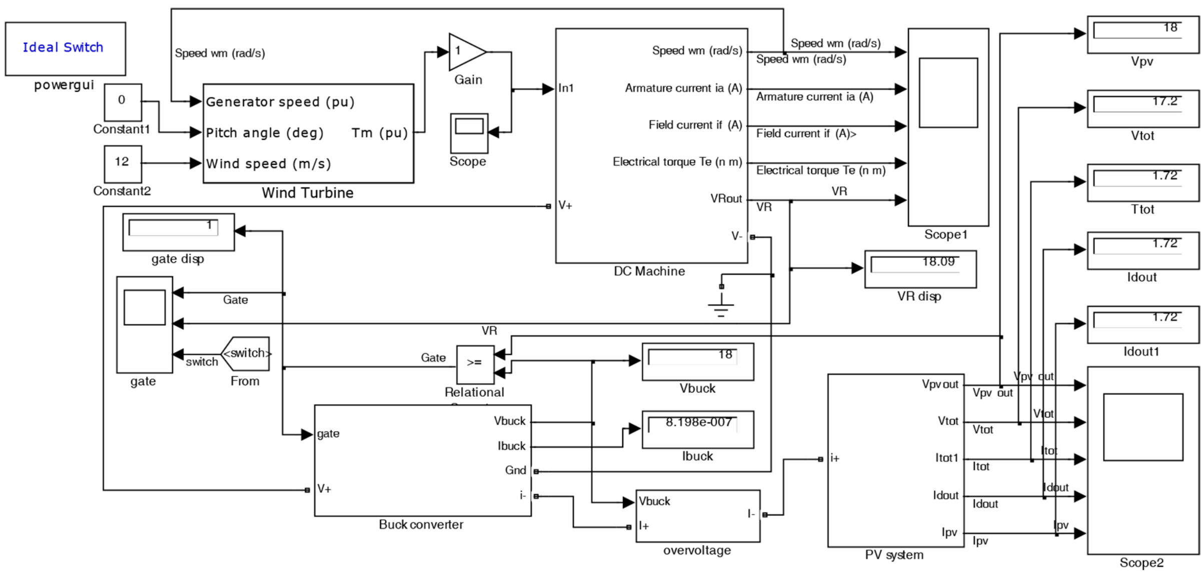

Figure 6. MATLAB/Simulink hybrid system.

Table 2. Wind turbine parameters.

Description	Rating
Generator speed	1.0
Pitch angle	0°
Wind speed	12 m/s
Field current	100 V

Table 3. Buck converter parameters.

Description	Rating
DC source	50 V
Set point	18 V

A switch was placed between the buck converter and the PV system (the "overvoltage" subsystem) to provide protection against overvoltage coming from the buck converter. System validation through MATLAB/Simulink was implemented to test the effectiveness of the proposed system, which lasted for 50 ms.

Figure 7a contains output waveform, called the "gate" signal, taken from the gate scope output. The gate signal resulted from the comparator resulting from the PV voltage (Vpv) and buck converter voltage (Vbuck). The gate signal became active during the last period of the rise region after 32 ms and exhibited a stable continuous pulse signal at 100 kHz until the end of the simulation, as shown in Figure 7b.

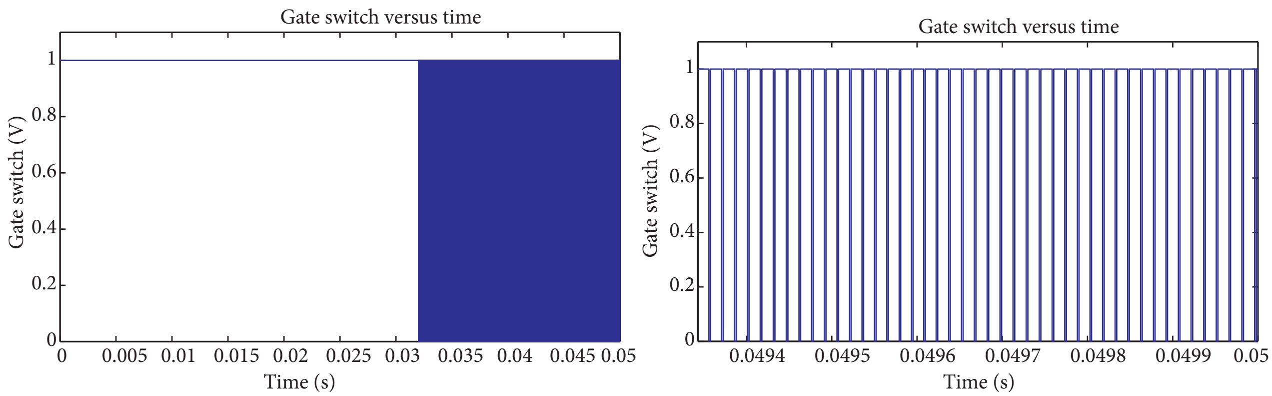

Figure 7. a. Simulated switching pattern for gate versus time. b. Simulated switching pattern for gate versus time (zoomed).

Figure 8a contains output waveform, labeled the "Vbuck" signal, taken from the buck converter output. The Vbuck signal resulted from the buck converter subsystem triggered by the comparator. The Vbuck output waveform became stable after 32 ms; when zoomed (Figure 8b), the output fluctuates within a ± 0.083% boundary.

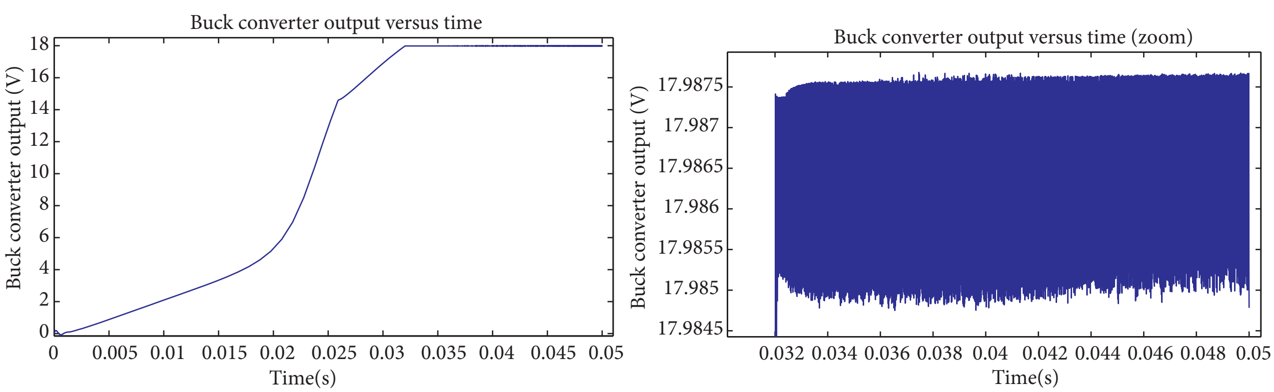

Figure 8. a. Simulated switching buck converter output versus time. b. Simulated switching buck converter output versus time (zoomed).

Power measurement was conducted across the buck converter, solar panel, and hybrid power. Figure 9 consists of the three power curves merged together in a single graph for comparison. The responses start to increase after 25 ms from start-up for the three power curves. PV power was initially at 30.04 W and increased to 30.96 W when subjected to a resistive load at 25.8 Ω. The buck converter power initially produced 0 W during the first 25 ms and jumped to 15.48 W when combined with PV power. The hybrid power rose from 28.39 W to 44.37 W when both sources were merged. A slight power variation existed between both sources and hybrid power because of internal potential from the diode placed at each output of both sources. It is clearly shown that the hybrid power produced was always a combination of the two sources.

A slight variation in wind turbine input was simulated through step input by varying input from 12 m/s to 25 m/s within a 40 ms period. The result obtained is depicted in Figure 10; the hybrid controller maintained a constant response with a similar power rating to the previous result. From the power curves of the sources, it is clearly shown that the hybrid power remains constant at power load demand in spite of sudden changes in the wind turbine.

A similar test with a different load setting at 35 Ω was conducted on the system with an identical step input source. Results show (Figure 11) that PV power was reduced to 29.58 W while buck converter power decreased to 14.79 W, thus making the hybrid power loss 5.79% of its original power. A comparison graph was constructed with respect to load and source variation (Figure 12). Any perturbation in the load strongly affected the source current, thus establishing the effectiveness of the hybrid system.

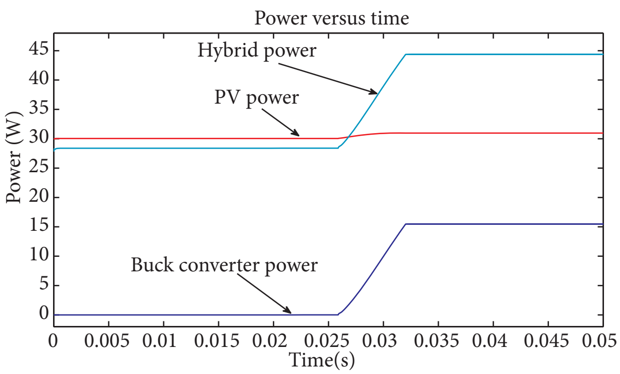

Figure 9. Simulated power curves output versus time.

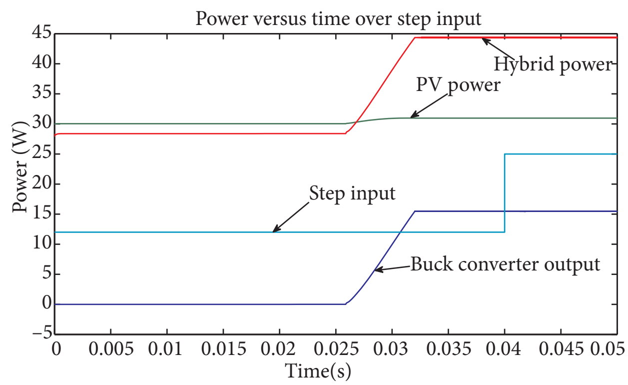

Figure 10. Simulated power curves output versus time over step input.

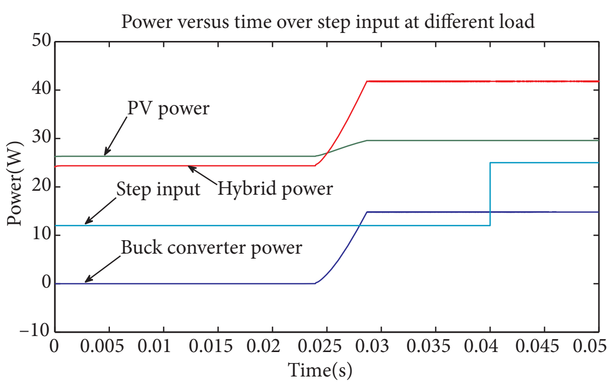

Figure 11. Simulated power curves output versus time at RL = 35 Ω.

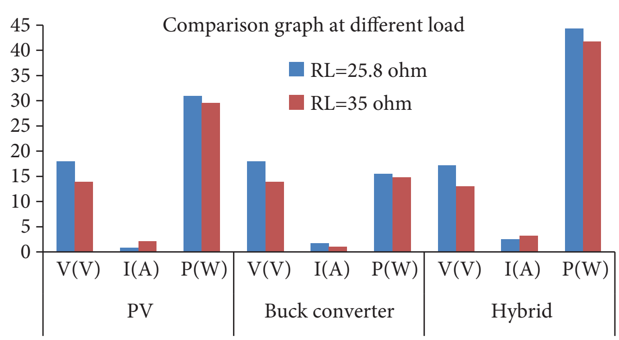

Figure 12. Comparison graph at different loads.

The simulation results obtained show that hybrid power is capable of supplying high-quality power to the load even when sudden changes occur in the source.

A comparative study was conducted between the proposed system and references [38–40]. Figure 13 shows the comparison levels of efficiency [40] of the hybrid power system at maximum efficiency. At 95.54%, the proposed hybrid system is higher than reference [38] and reference [39]. However, the proposed hybrid system lags behind reference [40] due to internal potential from the diode placed at each output of both sources.

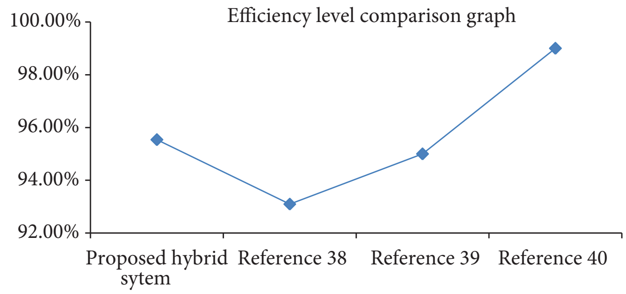

Figure 13. Efficiency level between proposed hybrid system and references [3840].

5. Conclusions

A hybrid system with renewable energy sources was presented; the different load settings simulated affected the system's performance. However, the system was designed for energy storage topology such as battery or fuel cell arrangement. The proposed system was simulated with MATLAB/Simulink software in various settings. The results obtained agree with design theory that corresponds with the dynamic of hybrid controllers for parallel connection and could optimize power transfer.

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