Electrical Power and Energy Systems 79 (2016) 66–74

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Encompassing nine switch converter approach in wind-hydro hybrid power system feeding three phase three wire dynamic loads

Josephine Rathinadurai Louis [a,*], Suja Shanmugham [b], Jovitha Jerome [c]

[a] Electrical and Electronics Engineering, PSG Institute of Technology and Applied Research, Coimbatore 641062, Tamil Nadu, India
[b] Electrical and Electronics Engineering, Coimbatore Institute of Technology, Coimbatore 641014, Tamil Nadu, India
[c] Instrumentation and Control Engineering, PSG College of Technology, Coimbatore 641004, Tamil Nadu, India

ARTICLE INFO

Article history:
Received 19 February 2015
Received in revised form 6 December 2015
Accepted 2 January 2016

Keywords:
Squirrel cage induction generator
Nine switch converter
Ultra-capacitor
Hybrid power system

ABSTRACT

This paper proposes a novel nine switch converter based isolated wind hydro hybrid power system feeding three phase three wire dynamic loads. The proposed system comprises of three generating units and two storage units. In this work, hydro and wind turbine generation system is deployed through squirrel cage induction generator (SCIG) with 50 kW and 40 kW respectively. The main impact of this work is the integration of additional PV unit and two storage units namely battery and ultra-capacitor (UC) into the system through the proposed nine switch converter which was unfeasible through the conventional voltage source inverter. This proposed converter operates in bidirectional mode as either converter or inverter which overcomes the limitation of utilizing additional bidirectional converters. By this novel approach, power can be effectively stored and retrieved from the storage devices through the converter based on the load demand. Sudden increase in load and evaluation under minimal renewable energy support was also studied to evaluate the significance of the proposed system and results are obtained to prove the successful working of the proposed scheme.

Introduction

During the last few decades the costs of acquiring fossil prices has increased tremendously due to high demands and this caused many scientists and other researchers to focus on identifying and developing renewable energy sources. In studies related to renewable energy sources, SCIG has been employed for power generation by small micro hydro and wind systems. Further required reactive power is then provided by the capacitor bank which is located at the stator terminals. Also SCIG has several advantages which include its simple structure, maintenance free nature, tough and sturdy mechanical structure, brushless and much more paramount features in comparison with traditionally deployed synchronous generator that are employed for hydro applications [1–3].

Grid connected variable speed wind energy conversion system (WECS) based upon the use of SCIG was deployed using back to back connected power converters [4]. For these particular systems, SCIG was decoupled by the power converter which in turn decouples from the grid and enhances overall reliability. For grid connected systems that utilize renewable energy sources, total active power may be fed directly to the grid. However, in case of standalone systems that supply local loads, the extracted power exceeds local loads which include losses. If excess power is generated by the wind turbine then it has to be diverted either directly into a dump load or provisions has to be made for it to be stored into the battery bank. Furthermore, if extracted power is lower than consumer load, resulting deficit power, then storage element such as battery bank supplies the remaining power [5,6].

For standalone or autonomous systems, voltage and frequency control (VFC) issues are significant. Researcher's elucidated solutions for VFC related problems in the case of autonomous systems that employ SCIG [7–9]. Studies are also conducted in the area pertinent to stand alone WECS that employ doubly fed induction generator (DFIG). The battery based controller was suggested for VFC issues specifically with respect to isolated WECS [2]. In specific issues of VFC an electronic load controller was located at stator terminals and the controller transfers the power based on the requirement of loads. The proposed work was motivated by the conventional design of isolated wind hydro hybrid system using cage induction generators and battery storage [10]. In the conventional work, load side converter was used as bidirectional converter for storing the excess power to the battery with three different load conditions such as 30 kW, 60 kW and 110 kW. Similarly, the stored power can be retrieved through the same load side converter. But the conventional work may not be able to

* Corresponding author. Mobile: +91 97 50541213.
E-mail address: jessijolouis@gmail.com (J.R. Louis).

http://dx.doi.org/10.1016/j.ijepes.2016.01.010
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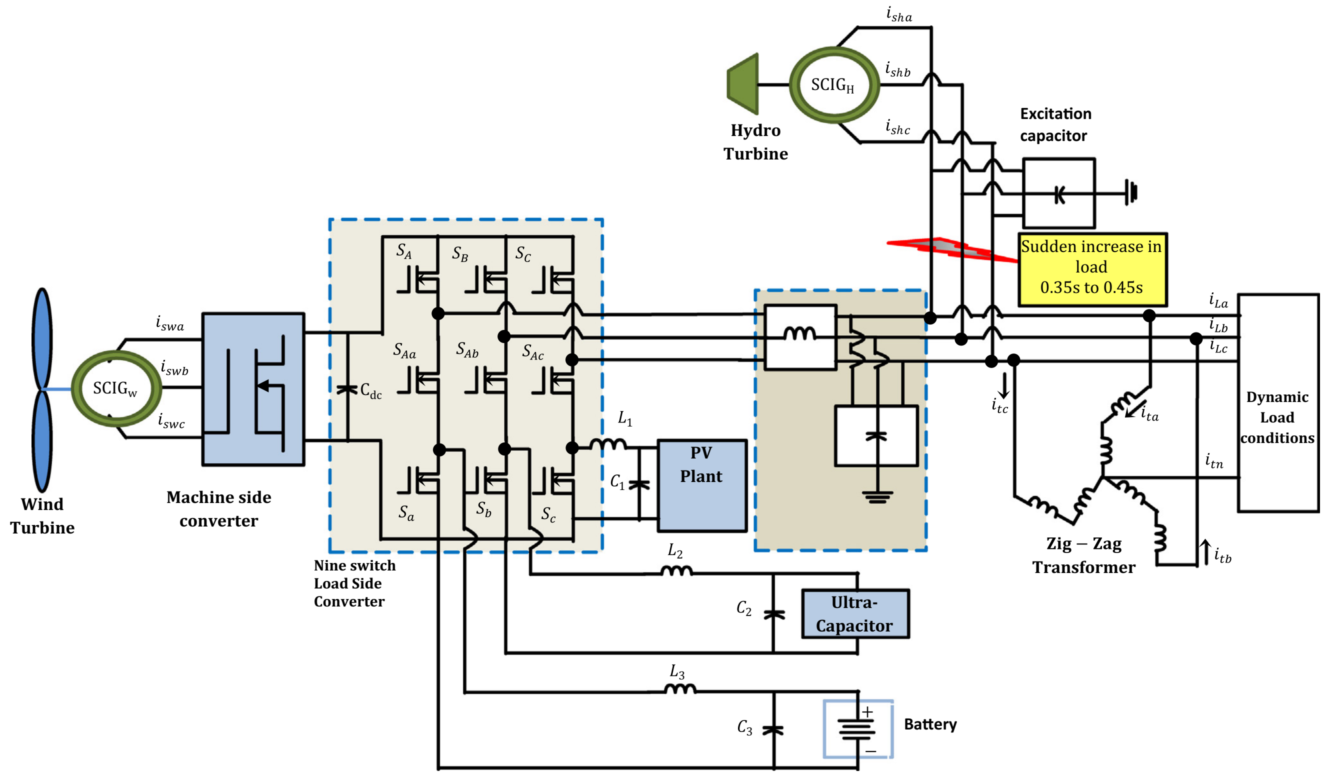

Fig. 1. Proposed nine switch architecture of novel nine switch converter based isolated wind hydro hybrid power system.

integrate other additional energy sources like photovoltaic (PV) panels or additional storage elements such as ultra-capacitors or fuel cells. Hence sudden increase in load may not be supported with the conventional system. As ultra-capacitors are not present in the system, the nonlinear or sudden change in load conditions may not be effectively supported by the battery alone [11]. Also the importance of ultra-capacitors and their advantages was studied and incorporated in the proposed work. The limitations specified in the conventional system may degrade the overall performance of the system during nonlinear load conditions. Hence the limitations may be overcome by incorporating ultra-capacitors into the hybrid system. Research integrating DC/DC bidirectional converter with super capacitors and battery was also considered. The number of switches required for the bidirectional DC/DC converter is observed to be higher which may result in higher circuit complexity [12]. Further the frequency analysis was carried out for permanent magnet synchronous generator (PMSG) type wind turbines [13]. In addition, modeling of wind turbine generator, validation of squirrel cage induction generator to the local grid, power compensation in wind park, variable speed controllers in wind power generators are also studied [14–20].

Factors considered with respect to converter topology and ultra-capacitor

With respect to the converter topologies, traditionally the grid side converter is connected to the grid in shunt configuration and this shunt configuration injects current into the grid. If the grid side converter is connected in series with the grid, the generator stator voltage is effectively the sum of the grid and converter voltages. In the event of a grid disturbance, the series converter voltage compensation for doubly fed induction generator wind turbine low voltage side through solution is also considered [21,22]. A unified converter topology was reported for unbalanced voltage dips and the system shows good tolerance to grid disturbances [23].

Few researchers have shown that the stator voltage need not be hundred percent compensated during the entire period of fault. This was demonstrated by using decaying injected voltage and with time constant less than the stator time constant while still keeping rotor currents within its limits [24,25]. Nowadays as an alternate to the traditional back to back voltage source converter, nine switch converters have been used. The nine switch converter has the advantage of reduced switch count compared to the conventional back to back voltage source converters. However it requires a higher rated DC bus capacitor to produce the same output voltages compared to two level voltage source converters [26–30]. This might overshadow the gains that come with its reduced component count as the switching devices may be unduly over stressed. The advantage in the nine switch converter lies in its auto complementary tuning of shunt and series converters under both normal and sag operating conditions. Under normal operating condition, the shunt converter is modulated to give its maximum output and complementary series converter output is kept almost zero. On the other hand, in voltage sag conditions, a larger output voltage is needed at the series converter output and therefore it can be modulated to give a higher output voltage and consequently a small complementary voltage appears at the shunt output.

With respect to the ultra-capacitor, they are double layer electrochemical capacitor that can store thousand times more energy than a typical capacitor. Ultra-capacitor also shares the characteristics of both batteries and conventional capacitors and has energy density of about 20% of a battery. Moreover, they have almost negligible losses and long life span. They can process a large number of charge (several thousand cycles) compared to normal batteries and only a few thousand cycles for lead acid batteries and can supply much higher currents than batteries. Assisting a hybrid power plant with a parallel ultra-capacitor bank makes economic sense when

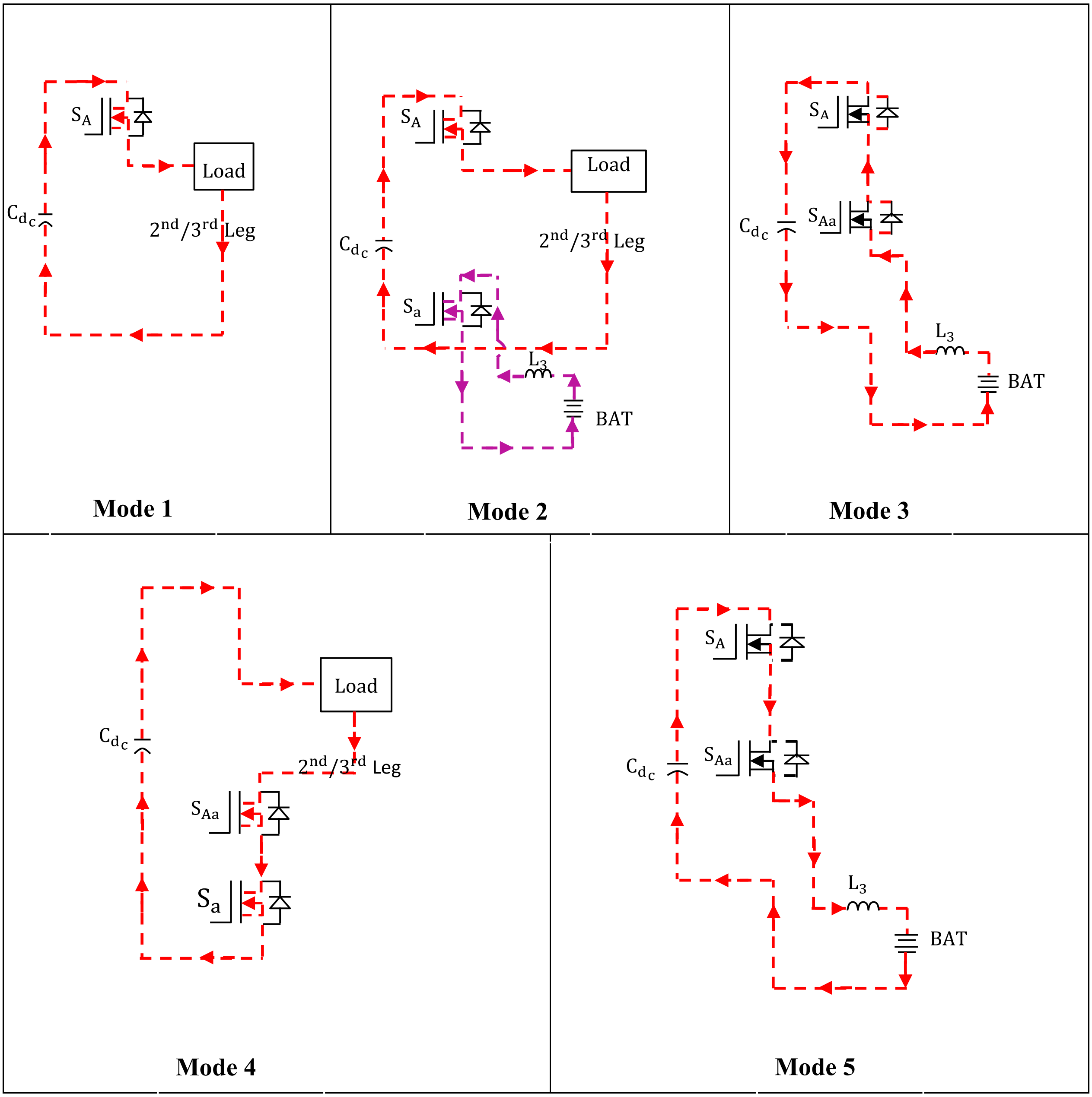

Fig. 2. Modes of operation of nine switch converter.

Table 1
Working principle for single leg nine switch converter.

S_A	S_{Aa}	S_a	Operation
1	0	0	$+V_0$ (Inverter)
1	0	1	$+V_0$ (Inverter), Inductor L_3 charged from Battery
0	0	0	C_{dc} charge from Inductor L_3
0	1	1	$-V_0$ (Inverter)
0	1	0 (Battery)	Battery charged from C_{dc} through L_3 (Battery and Ultra capacitor)
		0 (Ultra-capacitor)	
		1 (PV plant)	$-V_0$ (Inverter) (PV Plant)

satisfying the peak power demands or transient conditions since the ultra-capacitor bank supplies the extra power, thereby reducing the cost of the overall system. Further ultra-capacitor banks can be used for short term energy storage due to their high cycling efficiency, convenience for charging and discharging, additionally to meet the instantaneous load ripples [31–36].

Hence by considering the above factors the hybrid power system was designed to effectively supply the required load as per

Table 2
Switching sequence of load side converter.

S_A	S_{Aa}	S_a	S_B	S_{Bb}	S_b	S_C	S_{Cc}	S_c	Line to neutral voltage			Line to line voltage		
									V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}
0	1	X	0	1	X	0	1	X	0	0	0	0	0	0
1	0	X	0	1	X	0	1	X	2/3	−1/3	−1/3	1	0	−1
1	0	X	1	0	X	0	1	X	1/3	1/3	−2/3	0	1	−1
0	1	X	1	0	X	0	1	X	−1/3	2/3	−1/3	−1	1	0
0	1	X	1	0	X	1	0	X	−2/3	1/3	1/3	−1	0	1
0	1	X	0	1	X	1	0	X	−1/3	−1/3	2/3	0	−1	1
1	0	X	0	1	X	1	0	X	1/3	−2/3	1/3	1	−1	0

0 – OFF, 1 – ON, X – 0 (or) 1, X – converter mode, 1 – inverter mode.

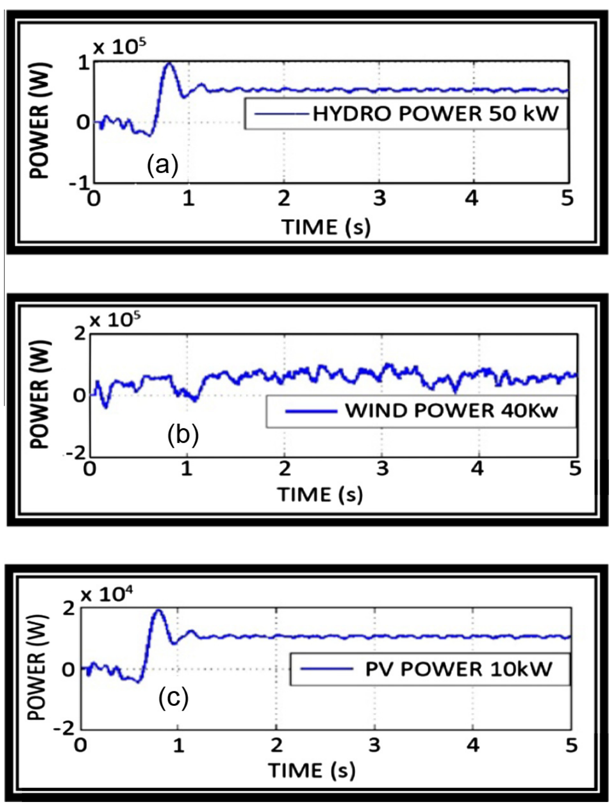

Fig. 3. (a) Hydro, (b) wind and (c) PV power under rated generation (waveform remains the same for 30 kW, 60 kW, 90 kW and 120 kW load demand).

the demand. Thus the main work aims to develop a novel nine switch converter based isolated wind hydro hybrid power system integrated with PV, battery and ultra-capacitor which overcomes the drawbacks of the conventional system.

Proposed model of the hybrid system

The proposed architecture of novel nine switch converter based isolated wind hydro hybrid power system is shown in Fig. 1. The proposed system consists of a machine side converter (MSC), nine switch load side converter (NSLSC), zig zag transformer, PV plant, battery and ultra-capacitor. In this system, generation of hydro turbine and wind turbine is based on squirrel cage induction generators $SCIG_H$ and $SCIG_W$ with a capacity of 50 kW and 40 kW respectively.

Similarly PV plant is designed to generate 10 kW. In the initial stage, the power generated from the hydro turbine is used to meet the load demand. If hydro power is insufficient to meet the load demand, then power generated from the renewable energy sources such as the wind and the PV plant is used. The generated renewable power is stored in the battery with the help of bidirectional converter and from the battery; the stored power is retrieved through bidirectional converter which is again used to meet the load demand. When there is sudden load variation which requires higher load demand, ultra-capacitor can be utilized to support the sudden increase in loads. Normally resonant controller is observed to give good results due to infinite gain at a selected resonant frequency which completely eliminates the steady state control at that frequency. But, the proposed approach focuses on analyzing the performance of the system under the dynamic load variation condition and therefore eliminating the steady state error that does not influence the performance of the system. So in this work, PI controller has been used due to its simplicity and effectiveness and ultra-capacitor are also used in simulation studies.

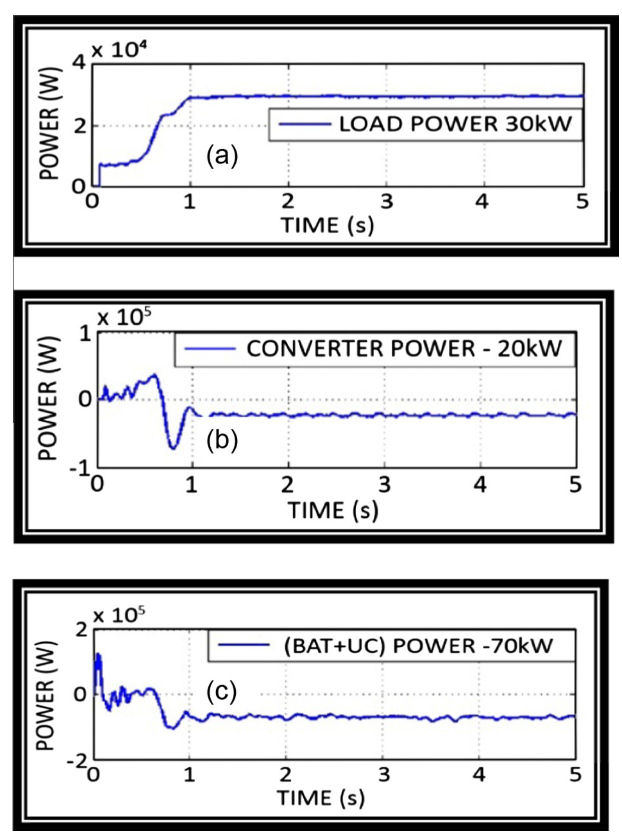

Fig. 4. Waveforms during 30 kW load condition ((a) load power, (b) power through converter, (c) battery with ultra-capacitor power).

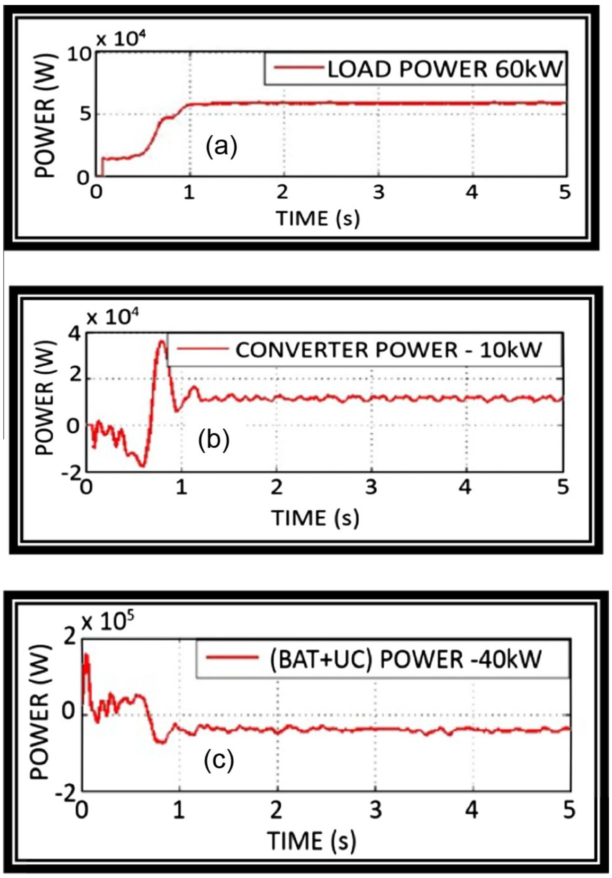

Fig. 5. Waveforms during 60 kW load condition ((a) load power, (b) power through converter, (c) battery with ultra-capacitor power).

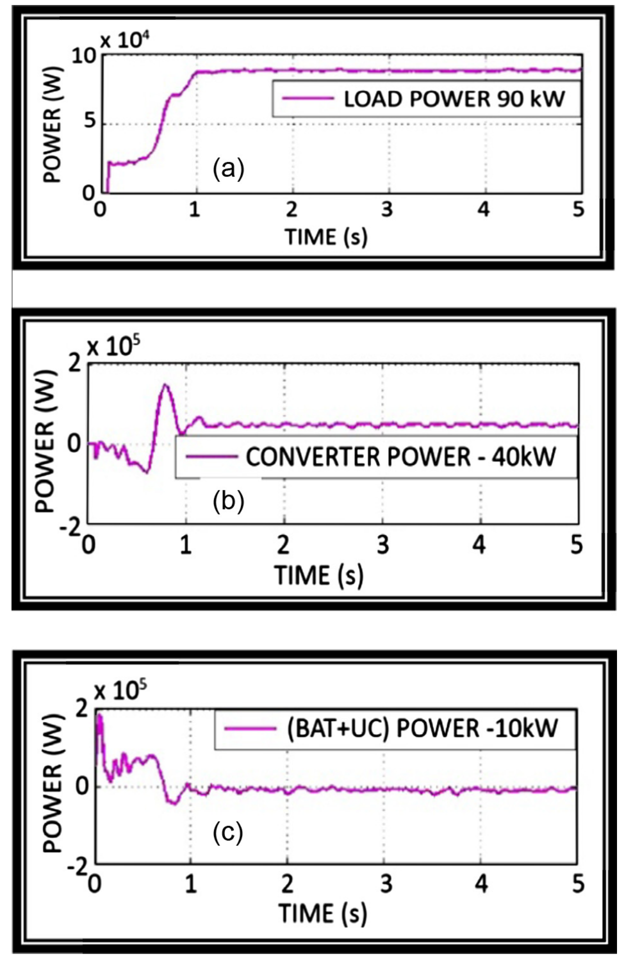

Fig. 6. Waveforms during 90 kW load condition ((a) load power, (b) power through converter, (c) battery with ultra-capacitor power).

Working principle of nine switch converter

The proposed nine switch converter comprises of upper leg switches S_A, S_B, S_C, middle leg switches S_{Aa}, S_{Bb}, S_{Cc} and lower leg switches S_a, S_b, S_c respectively. When the upper leg switches and middle leg switches form the conduction mode structure, it converts DC/AC. Similarly, when the middle leg switches and the lower level switches form the conduction mode structure, it acts as DC/DC converter. The working principle of the proposed nine switch converter is explained through single phase unit which comprises three switches namely S_A, S_B, S_C and explained in Fig. 2. In this working principle, the inverter operation, charging and discharging (battery) operation of the nine switch converter is clearly described through the modes of operation in Fig. 2. Similarly, the other two legs namely S_B, S_{Bb}, S_b and S_C, S_{Cc}, S_c works in the same principle. In the case of PV plant, only power can be supplied to meet the demand and it cannot store power like battery and hence discharging operation alone is applied for PV plant.

In mode 1, the current initiates from the capacitor C_{dc} and flows through the switch S_A to the load, and then attains the neutral point of either second or third leg based on the three phase inverter mode of operation (120° phase shift). In mode 2, besides the above mentioned cycle which gives $+V_0$ wherein the current flows through S_A, in which current initiates from the positive terminal of battery and flows through inductor L_3 to the switch S_a and then gets neutralized at the negative terminal of the battery. In mode 3, all the switches are in off condition. Now the stored current in L_3 at stage 2 is discharged through the antiparallel diode of the switches (S_{Aa}, S_a) to charge the capacitor C_{dc}.

In mode 4, current initiates from capacitor C_{dc} and flows through either second or third leg with 120° phase shift to the load and attains neutral via switches S_{Aa}, S_a at the negative of the capacitor C_{dc}. In mode 5, the current from C_{dc} flows through the drain source of the switches S_A and S_{Aa}, then charges the inductor L_3. Then the inductor L_3 in turn charges the battery which is again neutralized at the negative terminal of capacitor C_{dc}. The above mentioned working principle is same for ultra-capacitor but for PV panel, in mode 5, inverter operation takes place instead of charging operation. Table 1 clearly explains the working principle of the proposed nine switch converter. Table 2 shows the switching sequence of the load side converter.

Control of machine side converter ($SCIG_W$)

The main function of the machine side converter is to reach the maximum torque and to deliver the required magnetizing current to the wind turbine. The control method for the machine side converter is derived from the basic control algorithm [10]. In the intended algorithm the position of rotor of $SCIG_W$ and the wind speed are sensed. The speed of the rotor can be attained from the position of the rotor. The tip speed ratio λ_w is defined as

$$\lambda_w = (\omega\,\theta_{rw} r_w)/\eta_w v_w \tag{1}$$

where $\omega\,\theta_{rw}$ is the speed of the rotor, r_w is the radius of the wind turbine, η_w is the gear ratio, v_w is the wind speed.

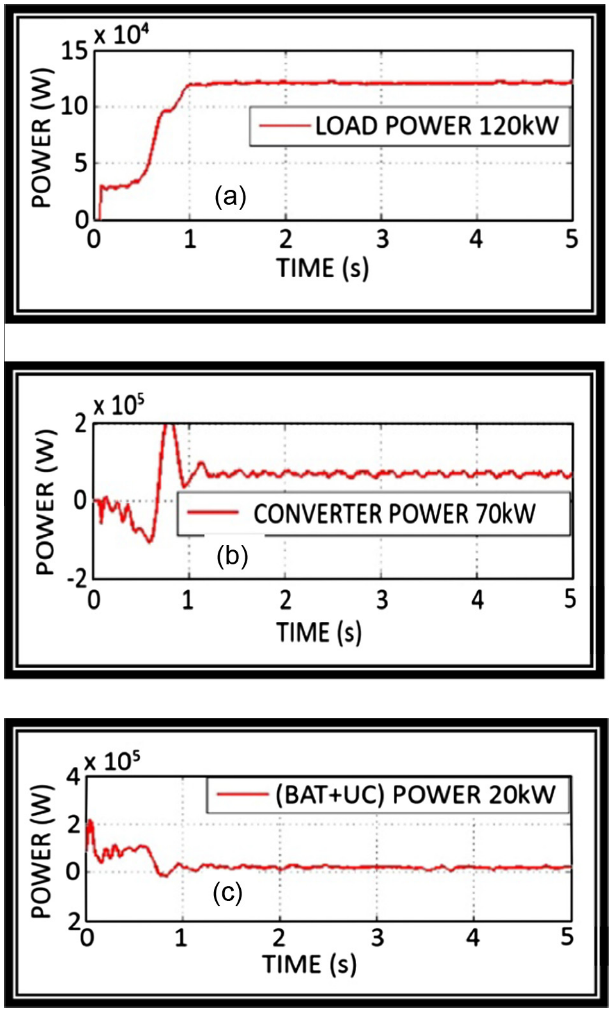

Fig. 7. Waveforms during 120 kW load condition ((a) load power, (b) power through converter, (c) battery with ultra-capacitor power).

The $SCIG_W$ operating speed should be at the maximum tip speed ratio (λ_w^*), for maximum power tracking in the wind turbine generator system. Using Eq. (1), the reference rotor speed (w_{rw}^*) can be generated as

$$w_{rw}^* = (\lambda_{rw}^* v_w \eta_w)/r_w \quad (2)$$

To calculate the rotor error at nth sampling, the reference speed of the rotor of $SCIG_W$ is compared with w_{rw} and calculated [10]. Reference d-axis $SCIG_W$ stator current generation and pulse width modulation signal generation for machine side converter are followed as per conventional arrangements.

Control of load side converter ($SCIG_H$)

Load side converter maintains the rated voltage and frequency irrespective of the connected load at the load terminals. Power balance is maintained by directing the power from the battery and ultra-capacitor, if there is a deficit in generated power and the load requirement. To maintain the balance in load voltage, the load side converter supplies the required reactive power. This proposed control loop block has nine switch converter which acts as a bidirectional converter. In addition to this, along with PV plant, battery and ultra-capacitor, the proposed control loop block regulates charging and discharging operation. Generation of reference three phase $SCIG_H$ currents are obtained as per the basic load side control integrating PI controller only. Also the DC link capacitor voltage selection formula, battery modeling, selection of switching devices in machine side converter and load side converter, selection of rating of filter on load side converter are all obtained from the conventional configuration [10].

Results and discussion

A simulation model is developed in Matlab using Simulink and Sim power system set toolboxes. The simulation is carried out on Matlab version 12 with ode 45 solver. The different loads are modeled using resistive and inductive elements and diode rectifier fed resistive loads combined with an LC filter. The unbalanced load is modeled using breakers in individual phases.

Also PI controller has been incorporated for simulation studies. The proposed approach focuses on analyzing the performance of the system under the dynamic load conditions such as 30 kW, 60 kW, 90 kW, 120 kW, sudden increase in load and evaluation during minimal renewable energy sources. The battery with ultra-capacitor together is designed for 110 kW at the maximum. Fig. 3 remains the same for different load demands as the hydro, wind, PV generates 50 kW, 40 kW, 10 kW respectively.

Evaluation during 30 kW load condition

During this load condition, the hydro turbine is sufficient to deliver 30 kW load demand. Hence the unused 20 kW flows through the bidirectional converter and the battery with ultra-capacitor stores power of 70 kW [20 kW (hydro) + 40 kW (wind) + 10 kW (PV)]. The corresponding waveforms during 30 kW load condition are shown in Fig. 4.

Evaluation during 60 kW load condition

During 60 kW load demand, the hydro power generated may not be sufficient to meet the requirements and the wind power has to supply the remaining power. Therefore wind power compensates additional 10 kW. Hence the power through the converter will be 10 kW (supplied by the wind turbine). Also the battery with ultra-capacitor stores 40 kW [30 kW (wind) + 10 kW (PV)]. The respective waveforms are shown in Fig. 5.

Evaluation during 90 kW load condition

Under this load condition, the load power is 90 kW. The generated hydro turbine power of 50 kW is not sufficiently to satisfy the load demand of 90 kW. Thus, required 40 kW power from the wind turbine flows through the converter to meet the load demand and thus the converter power becomes 40 kW.

So the entire generated 40 kW power from the wind turbine is utilized for load demand and there is no excess power from the wind turbine to be stored in the battery and ultra-capacitor. Thus the total power stored in the battery and ultra-capacitor in this condition would be only the PV power of 10 kW. The corresponding waveforms are shown in Fig. 6.

Evaluation during 120 kW load condition

The 120 kW load variation condition is shown in Fig. 7. Under this condition hydro turbine power of 50 kW is not sufficient to meet the load demand of 120 kW. Thus 40 kW power generated from the wind turbine flows through the converter to meet the load demand and there is no excess power from the wind turbine to be stored in the battery and ultra-capacitor. 10 kW generated from the PV power flows through the converter to meet the load

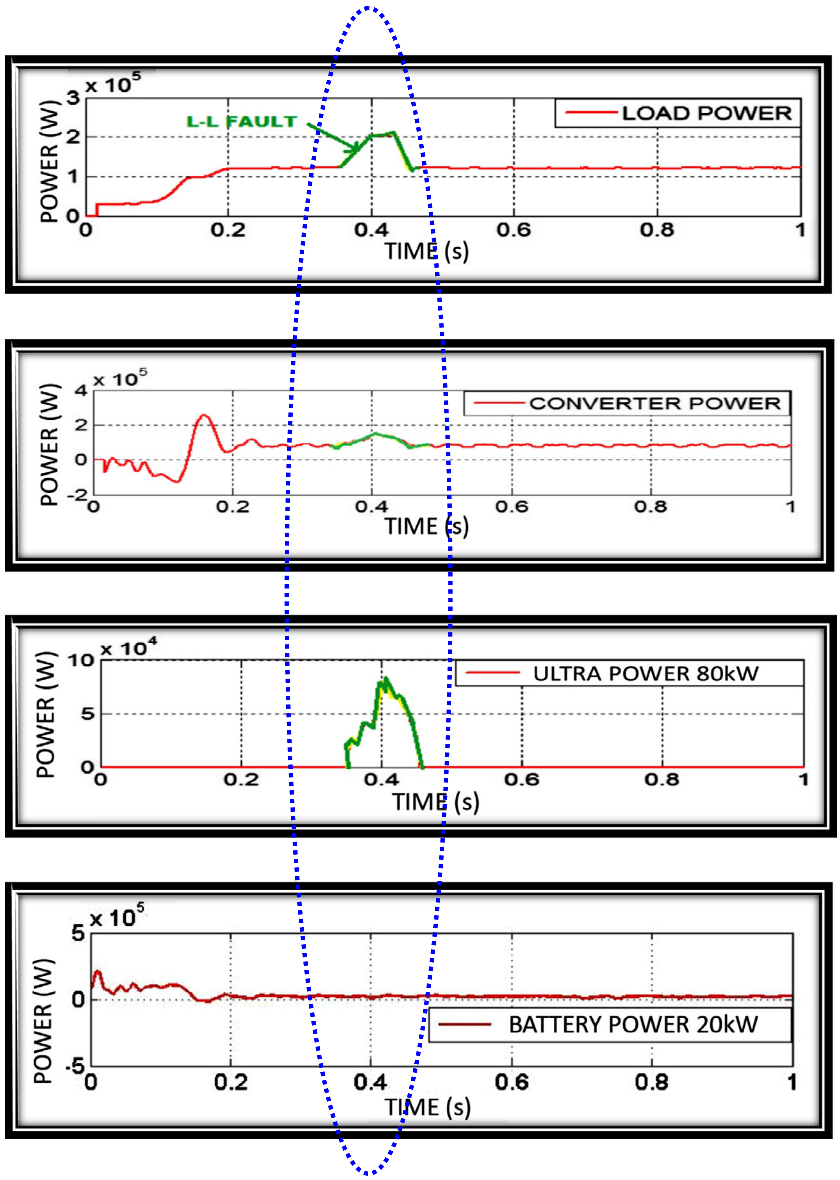

Fig. 8. Waveforms during sudden increase in load.

demand. Now the excess 20 kW power is discharged from the battery and flows through the converter. Now the overall converter power is +20 kW and the positive sign indicates the discharging of the battery power to the load.

Evaluation during sudden increase in load

Increase in load condition is considered for 120 kW load demand with sudden increase in load between 0.35 and 0.45 s. When there is sudden abrupt increase in load, additional 100 kW is required for a short duration of time and thus 120 kW of power requires may increase up to 200 kW of demand. In this condition, hydro, wind and PV together supports 100 kW. This sudden change in load cannot be supported by the battery alone. Under this condition, ultra-capacitor supports the sudden change with 80 kW load power and battery supports 20 kW and the corresponding waveforms are shown in Fig. 8 (battery and ultra-capacitor are shown separately for ease of understanding).

Evaluation of higher load demand under minimal renewable energy support

As discussed in the previous evaluations, the hydro power supplies 50 kW, wind power supplies 40 kW and PV power supplies 10 kW. During night time, PV power is zero. Under this condition, the hydro power, wind power and load demand are considered as 50 kW, 20 kW and 140 kW respectively as shown in Fig. 9. Now the excess 70 kW power is discharged from the battery and flows through the converter. Now the overall converter power becomes 90 kW. Here the battery power is +70 kW and positive sign indicates the discharging of the battery power to the load as mentioned in Fig. 9.

Conclusions

A novel nine switch converter isolated wind hydro hybrid power system under dynamic load condition was analyzed in this proposed work. The novel hybrid power system based on nine

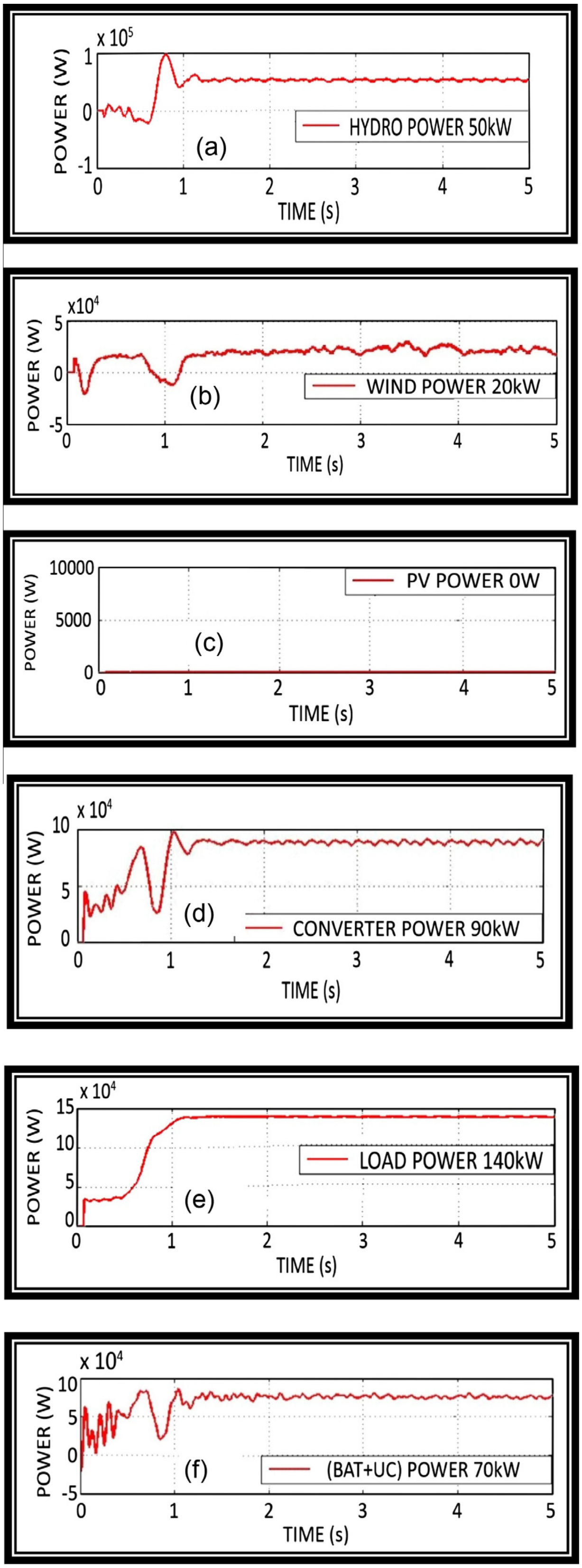

Fig. 9. Waveforms during evaluation under minimal renewable energy support ((a) Hydro power, (b) wind power, (c) PV power, (d) power through converter, (e) load power, (f) battery and ultra-capacitor power).

switch converter integrates PV generating unit and two storage units. The significance of the proposed nine switch converter was shown through the bidirectional (converter/inverter) operation. Majorly the work focused on the use of nine switch converter to enable the SCIG wind turbine to ride-through several balanced and severe unbalanced demand conditions. Further the nine switch three phase converters paramount due to its reduced device count and enhanced utilization when compared to the classical topology of two 2-level voltage source converters.

Ultra-capacitor bank in a hybrid power plant makes economic sense when satisfying the peak power demands or transient conditions as they supply extra power, thereby reducing the cost of the overall system. The performance of the system is evaluated under different dynamic load variation conditions such as 30 kW, 60 kW, 90 kW and 120 kW indicating the successful working of the proposed scheme. Evaluation under sudden change in load and evaluation under minimal renewable energy support was also studied. The sudden change in power is effectively compensated by the support of ultra-capacitor.

Acknowledgement

The authors wish to thank All India Council for Technical Education (AICTE), India for supporting this research and providing necessary facilities.

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