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# Reconfigurable Solar Converter: A Single-Stage Power Conversion Pv-Battery System

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**ABSTRACT-** A new, hybrid integrated topology, fed by photovoltaic (PV) and fuel cell (FC) sources and suitable for distributed generation applications, is proposed. It works as an uninterruptible power source that is able to feed a certain amount of power into the grid under all conditions. PV is used as the primary source of power operating near maximum power point (MPP), with the FC section (block), acting as a current source, feeding only the deficit power. The unique "integrated" approach obviates the need for dedicated communication between the two sources for coordination and eliminates the use of a separate, conventional dc/dc boost converter stage required for PV power processing, resulting in a reduction of the number of devices, components, and sensors. Presence of the FCsource in parallel (with the PVsource) improves the quality of power fed into the grid by minimizing the voltage dips in the PVoutput. Another desirable feature is that even a small amount of PV power (e.g., during low insolation), can be fed into the grid. On the other hand, excess power is diverted for auxiliary functions like electrolysis, resulting in an optimal use of the energy sources. The other advantages of the proposed system include low cost, compact structure, and high reliability, which render the system suitable for modular assemblies and "plug-n-play" type applications. All the analytical, simulation, and experimental results of this research are presented.

## INTRODUCTION:

In the past, centralized power generation was promoted. The power generation units were generally built away from the populated areas but close to the sites where the fuel (i.e., fossil fuel) was available. This kept the transportation cost (of the fuel) to a minimum and eliminated the possibility of pollution in populated areas. Such schemes remained quite popular until recently despite drawbacks such as Ohmic ($i2R$) losses (due to transmission of electricity through cables over long distances), voltage regulation problems, power quality issues, and expansion limitations. With the power demand increasing consistently, a stage has come when these centralized power generation units can be stressed no further. As a result, the focus has shifted to generation (and consumption) of electric power "locally" leading to "distributed power generation systems" (DGS) [1]–[4]. At the same time, increased awareness about the importance of a clean environment and the quickly vanishing fossil fuels have given impetus to the idea of local power generation using nonconventional energy (NCE) sources (e.g., photovoltaic (PV)

cells, fuel cells (FC), wind energy, etc.), which may suit a particular region and provide power at various load centers along the main power grid. Most of these sources are pollution-free and abundant.

Unfortunately, they are not so reliable. For example, the PV source is not available during the nights or during cloudy conditions. Wind energy may or may not be available. Other sources, such as fuel cells may be more reliable, but have monetary issues associated with them. Because of this, two or more NCE sources are required to ensure a reliable and cost-effective power solution. Such integration of different types of energy sources into a DG system is called a hybrid distributed generation system (HDGS) [4]–[20]. A combination of PV and FC sources forms a good pair with promising features [6] for HDGS applications. Of course, the slow response of the FC needs to be compensated with an ultra capacitor or a battery (ultra capacitor is preferable due to its high energy density) [4], [11]. A brief survey of the literature dealing with HDGS systems is presented next. Among the earlier work, Tam and Rahman [5] have proposed an HDGS configuration shown in Fig. 1(a). It consists of two inverters, operating in parallel, whose outputs are tied to the grid through a single, multi winding, step-up transformer. The drawback with this otherwise elegant scheme is that it does not utilize the available sources efficiently as maximum power point tracking (MPPT) is not implemented. Later, Ro and Rahman [6] improved upon this system by introducing a two-loop controller with MPPT. Tao *et al.*, [12] have proposed a multi input, bidirectional dc–dc converter configuration involving a combination of dc-link and magnetic coupling. The configuration offers high boosting capability and galvanic isolation. However, it consists of multiple power processing stages with an additional dc/ac inverter stage for feeding ac loads. Thus, it requires a large number of device. Monai *et al.*, [13] have proposed another HDGS configuration involving PV, FC, and battery sources that can meet the fluctuating requirements at the load end. The authors have proposed a modified Euler-type moving average prediction model for proper sharing of load among the various sources. The proposed system is a good solution for high power standalone or utility applications. Agbossou *et al*. [14] have proposed a hybrid system in which the excess energy generated by the renewable sources is used for producing hydrogen. Rajashekara [15] proposes another useful system, with PV and FC sources, for space applications. This system uses the PV power optimally by diverting the excess power for production of hydrogen through electrolysis. Another HDGS system with wind, PV, and battery sources has been discussed by Valenciaga *et al*., [7], where they propose a control technique that not only maintains the load demand but also the state-of-charge of the battery. Blaabjerg *et al.*, [16] have given an elaborate review of the various control and grid synchronization techniques used in HDGS systems. Some other useful HDGS configurations, based on FC, PV, and wind sources, have also been reported [17]–[20]. Recently, a PV- and FC-fed hybrid topology has been proposed [4], which makes use of a dedicated boost type dc–dc converter for each of the two sources, with a common inverter stage [Fig. 1(b)] for grid connection. The dc–dc converter stages are meant for boosting the low PV and FC voltages. The PV side converter also takes care of MPPT. One of the problems with this system is that, at very low insolation levels, the PV side dc–dc converter must be cut off to prevent its inefficient operation [21].

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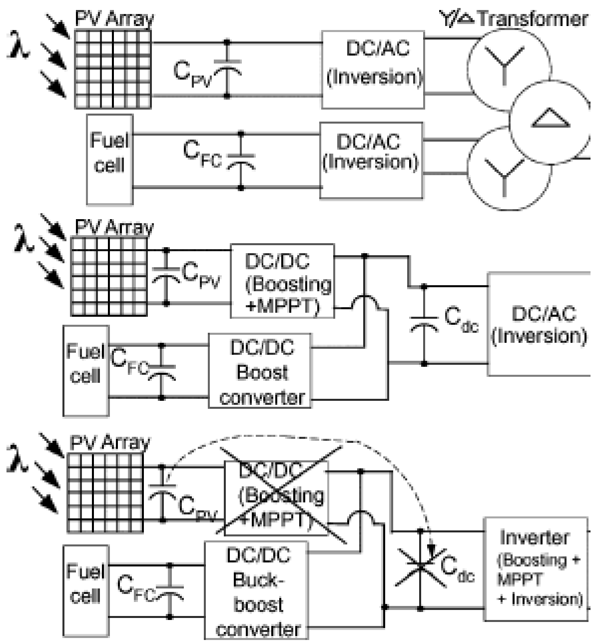


Thus, at small power levels, generation by the PV source remains unutilized. This may be acceptable for highpower applications, but could be a matter of concern for residential or medium-power installations [22]. If the function of the PV side dc–dc converter is merged with the inversion stage, as shown in Fig. 1(c), even a small fraction of power generated during low insolation can be utilized. Most HDGS configurations discussed earlier use an H-bridge inverter topology for interfacing with the grid, which either needs a line frequency bulky transformer at the output or high dc link voltage at the inverter input. This paper proposes an integrated solution for PV/FC-based HDGS using a new configuration depicted in Fig. 1(c). The proposed system uses an inverter with boosting capability, which eliminates the requirement of high dc voltage at the inverter input, thereby saving the cost of high-voltage buffer capacitor. Various other features, working principle, control strategy and simulation, and experimental results for the proposed configuration are described in the subsequent sections of this paper.

## PROBLEM STATEMENTS

DES technologies have very different issues compared with traditional centralized power sources. For example, they are applied to the mains or the loads with voltage of 480 volts or less; and require power converters and different strategies of control and dispatch. All of these energy technologies provide a DC output which requires power electronic interfaces with the distribution power networks and its loads. In most cases the conversion is performed by using a voltage source inverter (VSI) with a possibility of pulse width modulation (PWM) that provides fast regulation for voltage magnitude. Power electronic interfaces introduce new control issues,but at the same time, new possibilities. For example, a system which consists of micro-generators and storage devices could be designed to operate in both an autonomous mode and connected to the power grid. One large class of problems is related to the fact that the power sources such as microturbines and fuel cell have slow response and their inertia is much less. It must be remembered that the current power systems have storage in generators' inertia, and this may result in a slight reduction in system frequency. As these generators become more compact, the need to link them to lower network voltage is significantly increasing. However, without any medium voltage networks adaptation, this fast expansion can affect the quality of supply as well as the public and equipment safety because distribution networks have not been designed to connect a significant amount of generation. Therefore, a new voltage control system to facilitate the connection of distributed generation resources to distribution networks should be developed. In many cases there are also major technical barriers to operating independently in a standalone AC system, or to connecting small generation systems to the electrical distribution network with lower voltage, and the recent research issues includes:

1. Control strategy to facilitate the connection of distributed generation resources to distribution networks.
2. Efficient battery control.
3. Inverter control based on only local information.
4. Synchronization with the utility mains.
5. Compensation of the reactive power and higher harmonic components.
6. Power Factor Correction.
7. System protection.
8. Load sharing.
9. Reliability of communication.
10. Requirements of the customer.

DES offers significant research and engineering challenges in solving these problems. Moreover, the electrical and economic relationships between customers and the distribution utility and among customers may take forms quite distinct from those we know today. For example, rather than devices being individually interconnected in parallel with the grid, they may be grouped with loads in a semi-autonomous neighborhood that could be termed a microgrid is a cluster of small sources, storage systems, and loads which presents itself to the grid as a legitimate single entity. Hence, future research work will focus on solving the above issues so that DES with more advantages compared with tradition large power plants can thrive in electric power industry.

## PROBLEM DESCRIPTION

These new distributed generations interconnected to the low grid voltage or low load voltage cause new problems which require innovative approaches to managing and operating the distributed resources. In the fields of Power Electronics, the recent papers have focused on applications of a standby generation, a standalone AC system, a combined heat and power (cogeneration) system, and interconnection with the grid of distribution generations on the distribution network, and have suggested technical solutions which would permit to connect more generators on the network in good conditions and to perform a good voltage regulation. Depending on the load, generation level, and local connection conditions, each generator can cause the problems described in the previous chapter. The main goals which should be achieved will thus be: to increase the network connection capacity by allowing more consumers and producer customers connection without creating new reinforcement costs, to enhance the reliability of the systems by the protections, to improve the overall quality of supply with a best voltage control.

### A. Configurations for DES
### B.

**1) Case I**: A Power Converter connected in a Standalone AC System or in Parallel with the Utility Mains

Fig. show a distributed power system which is connected to directly load or in parallel with utility mains, according to its mode. This system consists of a generator, an input filter, an AC/AC power converter, an output filter, an isolation transformer, output sensor (V, I, P), and a DSP controller. In the Figures, a distributed generator may operate as one of three modes: a standby, a peak shaving, and a standalone power source. In a standby mode shown in Fig. a generator set serves as a UPS system operating during mains failures. It is used to increase the reliability of the energy supply and to enhance the overall performance of the system. The static switch SW 1 is closed in normal operation and SW 2 is open, while in case of mains failures or excessive voltage drop detection SW 1 is open and SW 2 is simultaneously closed. In this case, control techniques of DES are very similar to those of UPS. If a transient load increases, the output voltage has relatively large drops due to the internal impedance of the inverter and filter
stage, which frequently result in malfunction of sensitive load. Fig. can serves as a peak shaving or interconnection with the grid to feed power back to mains. In both modes, the generator is connected in parallel with the main grids. In a peak shaving mode, this generator is running as few as several hundred hours annually because the SW 1 is only closed during the limited periods. Meanwhile, in an

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interconnection with the grid, SW 1 is always closed and this system provides the grid with continuous electric power. In addition, the converter connected in parallel to the mains can serve also as a source of reactive power and higher harmonic current components.

In a standalone AC system shown in Fig. the generator is directly connected to the load lines without being connected to the mains and it will operate independently. In this case, the operations of this system are similar to a standby mode, and it serves continuously unlike a standby mode and a peak shaving mode.

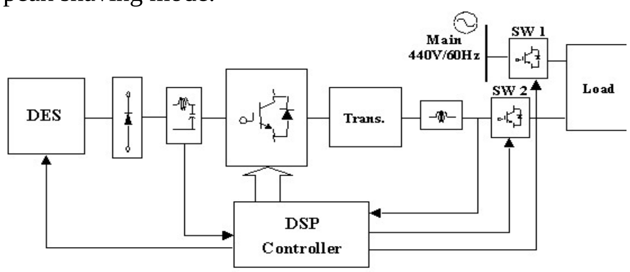


Fig. Block diagram of a standby mode

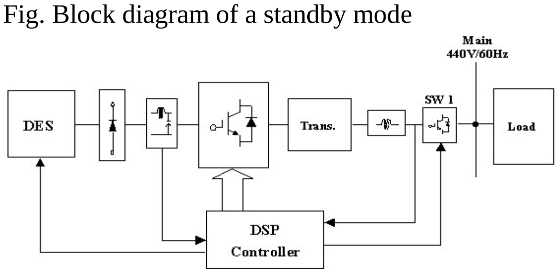


Fig. Block diagram of a peak shaving mode

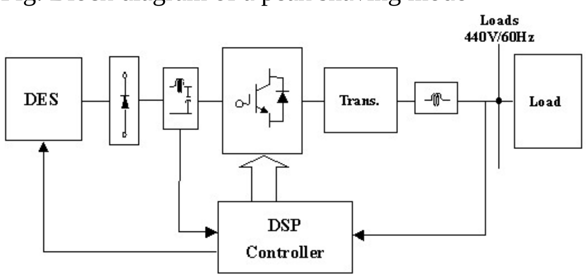


Fig. Block diagram of a standalone mode

As shown in Fig. the output voltage of the generator is fed to a DC/AC converter that converts a DC output of the generator to be fixed voltage and frequency for utility mains or loads. The DSP controller monitors multiple system variables on a real time basis and executes control routines to optimize the operation of the individual subsystems in response to measured variables. It also provides all necessary functions to sense output voltages, current, and power, to operate protections, and to give reference signals to regulators. The output power of the converter is controlled according to the reference signal of the control unit. As described above, in order to compensate for reactive power and higher harmonic components or to improve power factor, the active power (P) and reactive power (Q) should be controlled independently. Moreover, the above system needs over-dimensioning some parts of the power converter in order to produce reactive power by the converter at rated active power. Because a power converter dimensioned for rated current can supply reactive power only if the active component is less than rated. Therefore, a control strategy easy to implement is required to ensure closed loop control of the power factor and to provide a good power quality. In case that a generator is used for distributed generation systems, the recent research focuses are summarized as follows:

1. Control strategy which permits to connect more generators on the network
2. Compensation of the reactive power and higher harmonic components
3. An active power (P) and a reactive power control (Q) independently
4. Power factor correction
5. Synchronization with the utility mains
6. System protections

**2) Case II**: Power Converters supplying power in a standalone mode or feeding it back to the utility mainsFig.shows a block diagram of multiple power converters for a standalone AC system or feeding generated powers back to the utility mains. If all generators are directly connected to the loads, the systems operate as a standalone AC system. Meanwhile, if these are connected in parallel to the mains, these provide the utility grids with an electric power. Each system consists of a generator, an input filter, an AC/AC power converter, an output filter, an isolation transformer, a control unit (DSP), a static switch (SW 1) and output sensors (V, I, P). The function of the static switch (SW 1) is to disrupt the energy flow between the generator and mains or loads in the case of disturbances in the mains voltage. As shown in Fig., this configuration is very similar to parallel operation of multiple UPS systems except that the input sources of inverters are independent generation systems such as micro turbines, fuel cells, and photovoltaics, etc. instead of utility mains.

In case of parallel operation of UPS systems, a recent critical research issue is to share linear and nonlinear load properly by each unit. In general, the load sharing is mainly influenced by non uniformity of the units, component tolerance, and line impedance mismatches. Another issue is a proper control scheme without any control interconnection wires among inverters because these wires restrict the location of the inverter units as well as these can act as a source of the noise and failure. Moreover, in three-phase systems they could also cause unbalance and draw excessive neutral currents. Even if conventionally passive L-C filters were used to reduce harmonics and capacitors were employed to improve the power factor of the ac loads, passive filters have the demerits of fixed compensation, large size, and resonance. Therefore, the injected harmonic, reactive power burden, unbalance, and excessive neutral currents definitely cause low system efficiency and poor power factor. In particular, a power factor can be improved as AC/AC power converters function a complete active filter for better power quality and the above problems should be overcome by a good control technique to assure the DES to expand increasingly around the world.

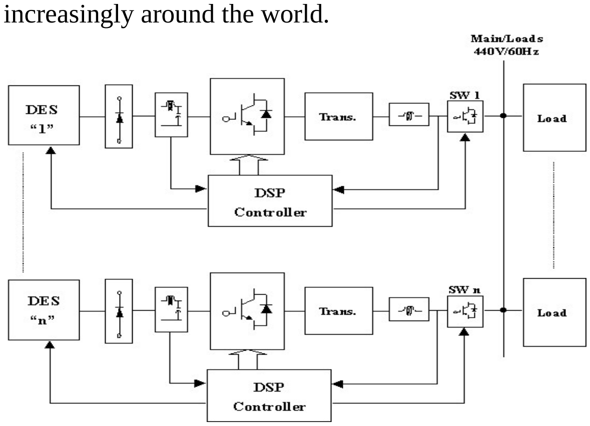


Fig. Block diagram of power converters connected in parallel

So the above issues can be applied to distributed power systems similarly, and the recent research focuses are summarized as follows:

1. Standardized DES modeling using the software tools
2. Equal load sharing such as the real and reactive power, the load harmonic current among the parallel connected inverters.
3. Connection capability of more DES to the utility mains in best conditions
4. Independent P, Q control of the inverters
5. Power factor correction
6. Reduction of Total Harmonic Distortion (THD).

## BASIC CONCEPT, OPERATING MODES, AND SALIENT FEATURES OF THE PROPOSED SYSTEM

The proposed topology is built around a buck-boost inverter topology capable of inversion (dc–ac), boosting and bucking the voltage and MPPT. The basic idea behind the proposed integrated configuration is shown in Fig. 2(a). A detailed view of Fig. 2(a) is shown in Fig. 2(b) along with an example (electrolysis) application. A combination of PV and FC sources feeds the configuration. While the PV source directly feeds the inverter through a buffer capacitor, CPV, the FC source is interfaced through a buck-boost type dc–dc converter, as shown in the figure. An extra block is added across CPV to divert the excess power generated by the PV source. The proposed system is designed to meet a certain minimum active power demand (Preq) from the grid side. PV is the main source, which is continuously made to track the MPP, while feeding the required amount of power into the grid. The FC source, with buck boost type dc–dc converter, acts as a current source in parallel with the PV source. It is only used to supplement the PV source during low or zero insolation. Thus, FC supplies only the deficit power into the grid. On the other hand, any "excess power" generated by the PV source is conditioned and diverted to an auxiliary application such as electrolysis, to produce hydrogen, which can be stored for later use by the FC source. This results in an optimal utilization of the available sources, rendering a highly economical system [14]. The aforesaid description leads to the following three modes

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in which the proposed system operates:

1) Mode-I: Only PV mode (only PV provides power).

2) Mode-II: Hybrid mode (both PV and FC provide power).

3) Mode-III: Only FC mode (only FC provides power).

These operating modes are summarized in Table I.

TABLE I
OPERATING MODES OF THE PROPOSED HDGS SYSTEM

| Operating Mode | Applicable Condition | Active Source(s) | Active Power Converter(s) |
|---|---|---|---|
| I | $P_{ex}=P_{PV}-P_{req} \geq 0$ | Only PV | Buck* (for $P_{ex} > 0$) |
| II | $P_{def}=P_{req}-P_{PV} > 0$ | PV and FC | Buck-boost |
| III | $P_{PV} \approx 0$ | Only FC | Buck-boost |

*Buck converter is optional. It depends upon the excess power application.

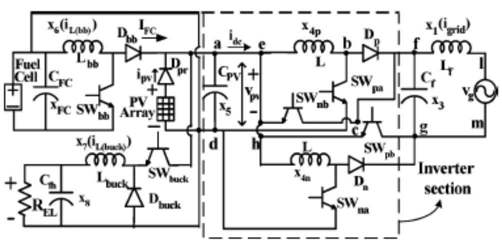


Fig. 3. Circuit schematic of the proposed integrated configuration for hybrid distributed generation system. xi denotes the corresponding state variable. Due to its unique hybrid integrated nature, the proposed configuration offers several desirable features as outlined next:

1) It obviates the requirement of a boost converter stage for conditioning the PV power, as shown in Fig. 1(c).

2) Out of the two capacitors Cdc and CPV [Fig. 1(a)], only one is required [Fig. 1(c)].

3) Presence of FC in parallel reduces the fluctuations in the PV voltage due to changing environmental conditions. This, in turn, reduces the fluctuations in the power fed into the grid. Consequently, the grid voltage profile improves [23].

4) Elimination of dips and surges in the PV voltage increases the speed of MPPT.

5) In two-stage systems [4], usually, both PV array and dc capacitor (Cdc) voltages are sensed for MPPT and power control, respectively. In the proposed system, Cdc (or CPV) appears right across the PV terminals due to elimination of the dedicated boost stage on the PVside [Fig. 1(b)].

Hence, only one sensor is adequate.

6) It eliminates the requirement of extra hardware for communication and coordination between various sources [24] to generate and use the available energy optimally.

7) The special configuration, in which the PV and FC sources are connected, ensures that the FC section works as a current source irrespective of the voltage magnitude at its output. This facilitates an appropriate adjustment of the PV voltage for PV's operation close to MPP.

8) Proposed configuration is a compact, low-cost, and reliable solution for HDG applications.

**DESIGN PROCEDURE**

Design of the proposed HDGS system involves the design of the three power converters described in the previous section. It includes the determination of the values of capacitors and

inductors, which is presented in this section, and the ratings of the various power devices used in the system, which is obtained with simulations in Section VI. Table III summarizes the design values of the various components.

A. Design of Inverter It involves the design of buck-boost inductor L, capacitor Cf and inductor Lf [25]. Design values of the parameters are

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$$L \leq (V_{PV}^2 \times T_s)/(4 \times P_{PV(\text{rated})}) \quad (11)$$

$$C_f = (P_{PV(\text{rated})} \times T_s)/(V_g \times \Delta V_g) \quad (12)$$

$$L_f = ((2 \times \pi \times f_c)^2 \times C_f)^{-1} \quad (13)$$

$$C_{PV} = \frac{2 \times P_{PV(\text{rated})}}{4 \times (2 \times \pi \times f_g) \times V_{PV} \times \Delta v_{PV}} \quad (14)$$

where ΔVg and ΔVPV are the allowed maximum ripple in the grid and PV voltage, respectively, PPV(rated) is the maximum rated power extracted from the PV array and fc is the lowest cutoff frequency determined by the circuit parameters of the inverter configuration. l can have any value satisfying (11), but is optimally chosen such that the converters operate in critical conduction mode at the peak of the grid voltage.

B. Design of FC Side dc-dc Converter

The FC side dc–dc converter is required to supply the deficit power to the grid. It acts as a voltage-fed controlled current source. Thus, a proper design of inductor Lbb is critical. As the FC supplies the deficit power under the control of a hysteresis controller, the design of Lbb should ensure that the converter operates in CCM. Let ΔI be the allowed ripple in the inductor current. Then, the values of inductor and capacitor are given by

TABLE III
DESIGN VALUES OF THE COMPONENTS AND RATINGS OF THE DEVICES USED IN THE SIMULATION MODEL

| Diodes and Switches | $SW_{pa}$(or $SW_{na}$) | | $SW_{pb}$(or $SW_{nb}$) | | $D_p$(or $D_n$) | | $SW_{buck}$ | | $D_{buck}$ | | $SW_{bb}$ | | $D_{bb}$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | FBV ≈340V | $I_{rms}$≈ 7.77A | FBV ≈230.3V | $I_{rms}$≈ 4.44A | RBV ≈230.3V | $I_{rms}$ ≈4.44A | FBV <120V | $I_{rms}$≈ 5.55A | RBV <120V | $I_{rms}$≈ 5.55A | FBV< 65V | $I_{rms}$≈ 7.7A | FBV< 120V | $I_{rms}$≈ 2.77A |
| Components | $C_{PV}$=6000μF | | L=0.2mH | | $L_f$=3.25mH | | $C_f$= 6.15μF | | $L_{buck}$=5.25mH | | $C_{fh}$=500μF | | $L_{bb}$=3mH | |

FBV ⇒ Forward blocking voltage (RMS value); RBV ⇒ Reverse blocking voltage (RMS value); $I_{rms}$ ⇒ RMS value of current

Where VFC and ΔVFC are the average value of and the allowed ripple in the fuel cell voltage, respectivelyC. Buck Converter Design Design value of the inductor used in the buck converter is given by

$$L_{buck} = [T_s \times (V_{PV} - V_{El}) \times V_{El}]/(V_{PV} \times \Delta I_{buck}) \quad (17)$$

where, VEl is the output voltage across the electrolysis load and ΔIbuck is the allowed ripple in the buck inductor current.

**CONCLUSION**

A compact topology, suitable for grid-connected applications has been proposed. Its working principle, analysis, and design procedure have been presented. The topology is fed by a hybrid combination of PV and FC sources. PV is the main source, while FC serves as an auxiliary source to compensate for the uncertainties of the PV source. The presence of FC source improves the quality of power (grid current THD, grid voltage profile, etc.) fed into the grid and decreases the time taken to reach theMPP. Table IV compares the system performance with and without the FC block in the system. A good feature of the proposed configuration is that the PV source is directly coupled with the inverter (and not through a dedicated dc–dc converter) and the FC block acts as a current source. Considering that the FC is not a stiff dc source, this facilitates PV operation at MPP over a wide range of solar insolation, leading to an optimal utilization of the energy sources. The efficiency of the proposed system in mode-1 is higher (around 85% to 90%) than mode 2 and 3 (around 80% to 85%). A laboratory prototype of the proposed system has shown encouraging results in terms of efficiency, complexity, reliability, EMI concerns, and other features. Table V compares the proposed system and some of the existing HDGS configurations with respect to various parameters and features.

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