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A Hybrid Photovoltaic-Fuel Cell for Grid Integration With Jaya-Based Maximum Power Point Tracking: Experimental Performance Evaluation

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ABSTRACT This paper deals the grid integration of photovoltaic (PV), fuel cell, and ultra-capacitor with maximum power point tracking (MPPT). The voltage oriented control for the grid-integrated inverter is proposed to regulate dc link voltage. Here, the fuel cell is employed as the main renewable energy source and PV as an auxiliary source with ultra-capacitor, which compensates power variation. An integrated CUK converter is proposed for peak power extraction from PV modules. The Jaya-based MPPT method is employed to achieve fast PV tracking ability with zero deviation around maximum power point (MPP) and has accelerated searched performance in equated with particle swarm optimization (PSO) and artificial bee colony (ABC) techniques. The hybrid PV-fuel cell with ultra-capacitor as energy storage works effectively under varying operating conditions. Compared to other energy storing devices, ultra-capacitor provides a fast dynamic response by absorbing/delivering power fluctuations. The hybrid PV-fuel storage control methodologies are experimentally validated using dSPACE (DS1104) board that provides optimal power extraction with stable power affirmation for a standalone/grid-connected system.

INDEX TERMS Fuel cell, maximum power point tracking, photovoltaic, ultra capacitor, utility grid.

NOMENCLATURE

I_{out}	PV cell current output
I_{Photon}	Photon current
I_{Diode}	Current through diode
$I_{Parallel}$	Current through parallel resistor
I_{sat}	Diode saturating current
V_{Diode}	Voltage across diode
V_{TH}	Thermal voltage
V_{Fuel}	Fuel cell output voltage
N_{cell}	Number of cells
V_{SFC}	Single fuel cell voltage
E_{Nernst}	Nernst voltage
$V_{activation}$	Activation losses
V_{ohmic}	Ohmic losses
V_{conc}	Concentration losses
I_{Lt} is	Limiting current
C_{O2}	Dissolved oxygen concentration
$t_{m.t}$	Thickness of the membrane
R_{PE}	Parallel equivalent resistance
$V(T)$	Capacitor voltage after t=T
$P(D_{duty})$	Momentary power at D_{duty}
$D^T_{duty_{m,n}}$	Amount of m^{th} variable for n^{th} aspirants in the interim of T^{th} iteration
$D^T_{duty_{m,worst}}$	Amount of m^{th} variable for the worst aspirants in the interim of T^{th} iteration
n	Number of aspirants ($n = 1, 2, 3, \ldots P$);
$R_{m,1}$ and $R_{m,2}$	Random variables ε [0], [1]
V_{RD}, V_{RQ}	d-q components of the inverter
m_D	Diode factor
K_B	Boltzmann constant

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V_{out}	Output voltage
R_{series}	Series resistance
T_{Abs}	Absolute temperature
$Q_{electron}$	Charge on electron
$R_{Parallel}$	Resistance in parallel
T_{abs}	Absolute temperature (K
P_{H_2}, P_{O_2}	Partial pressures of hydrogen and oxygen (atm)
I_{Fuel}	Fuel cell current
R_{ohmic}	Ohmic resistance
n is	Number of liberated electrons
F	Faraday's constant
A_C	Active cell area
$r_{r.m}$	Resistivity of membranes
R_{SE}	Series equivalent resistance,
RC	Time constant which evaluates charging/ discharging of starting capacitor voltage
$V_{initial}$	Initial voltage of the capacitor.
D_{duty}	Duty ratio and $0 < D_{duty} < 1$
$D^T_{duty_{m,best}}$	Amount of m^{th} variable for the best aspirants in the interim of T^{th} iteration
M	Total variables
P	Maximum number of aspirants
ΔV_D, ΔV_Q	PI controllers output
I_D, I_Q	d-q components of grid current

I. INTRODUCTION

Because of fossil fuel conventional sources depreciation, the renewable energy sources are in great imposition remarkably. Among entire renewable sources, the photovoltaic (PV) received enormous diligence as it has environment-friendly nature, safe, clean, portable behavior and free availability [1], [2]. However, installation and fabrication outlay is formidable presently which will depreciate bit by bit with exploration and substantial scale application. The extracted power from the PV module depends on environmental factors which observe power variations under fluctuating operating conditions. Therefore, there is an urgency to incorporate with auxiliary power supply viz. battery, diesel generator, and fuel cell. The battery and diesel generators are unable to provide all load demand and particular duration backup respectively. As PV power generation depends on solar irradiance level and has more fluctuation power with changing atmospheric conditions [3]. The fuel cell is controlled supply which delivers supplementary power requirement and meets inadequate PV-power integration with high efficiency, extensible and fuel adjustable as major benefits [4].

As the non-linear behavior of PV modules, Maximum Power Point Tracking (MPPT) methodology is an essential component to obtain a Maximum Power Point (MPP) [5]. Numerous MPPT techniques have been examined in the literature viz. Perturb & Observe (P&O) [6], Hill Climbing (HC) [7], and Incremental Conductance (INC) [8], as conventional algorithms. However, these techniques are ruined under fluctuating atmospheric conditions. The intelligent MPPT algorithms like fuzzy logic and neural networks have been employed for peak power extraction from renewable energy sources [9], [10]. Due to complex fuzzy inference rule and large trained data demand, these techniques have not been moved successfully under varying solar irradiance and partial shading situations. Numerous evolutionary algorithms viz. Particle Swarm Optimization (PSO), Firefly Algorithm (FA), Artificial Bee Colony (ABC), Flower Pollination Algorithm (FPA), Gray Wolf Optimization (GWO) [11]–[16] etc have been reviewed in the literature. The major disadvantages associated with PSO are that large number of iteration required for convergence, the divergence of high-speed particle and slow convergence computational period. Nevertheless, the above-mentioned algorithms are not competent to a rapid search of MPP with high convergence velocity, lesser computational load, and minimum execution expense microcontroller. However, the Jaya based MPPT has fast tracking ability of MPP with zero deviation around this point and has accelerated searched performance in equated with PSO and ABC technique [17], [18].

Numerous dc-dc converters are recently proposed for renewable energy applications [20]–[24]. In contrast to distinct dc-dc converters, the CUK converter has minimum switched losses; superior voltage moderation and better efficiency to execute MPPT action. However, classical CUK converters are failed to deliver sharp speed up/down voltage prescribed to distinct utilization. Therefore, in this research work, an integrated CUK converter is considered with high gain which operates continuous conducting states as steep voltage booster [25]. Various inverter controller have been inspected viz. predictive controller [26], Hysteresis Current Control (HCC) [27], Sine Pulse Width Modulation (SPWM) [28]–[30], Space Vector Pulse Width Modulation (SVPWM) [31]–[33] etc. to assure steady PV power injection to the utility grid with proper synchronized inked to accomplish switched pulses to the inverter. Segregated to traditional inverter controllers, the Voltage Oriented Control (VOC) strategy has been recommended to achieve unity power factor by regulating DC-link voltage under varying operating conditions with augmented controlled power to comprehensive tracked grid integration.

In [19], Fuel-ultra capacitor-based hybrid system has been modeled for reduction of fuel cell utilization which provides better efficiency and discussed for a standalone system. However, PV-Fuel-ultra capacitor-based hybrid system using recent MPPT algorithms under different loading conditions has not been discussed experimentally. In [34], a control system for the reduction of low-frequency oscillations as well as improvement of maximum power extraction from fuel cell stack has been discussed. In this work, classical P&O based MPPT algorithm and double stage inverter control method been employed which results in an increment in fuel cell life period, elimination of low-frequency oscillations and prevention of needless reactant consumption.

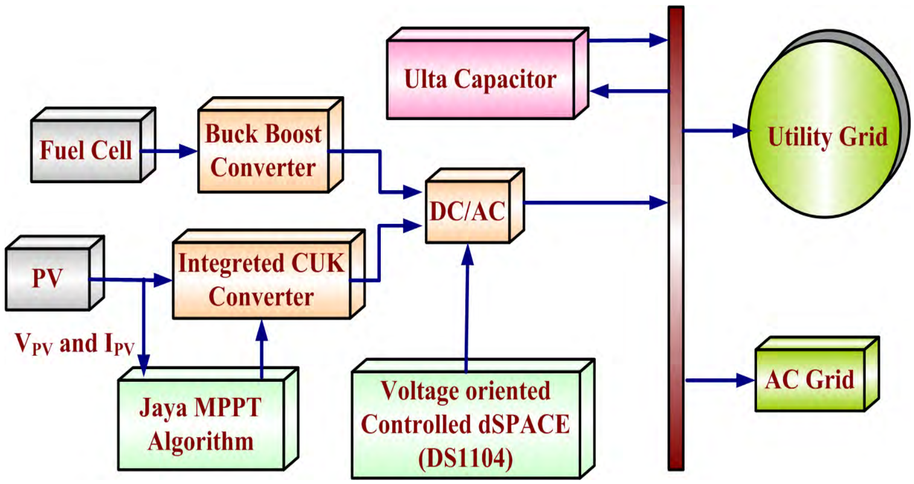

FIGURE 1. Overall PV-Fuel cell schematic with grid integration.

However, hybrid power system discussion with recent MPPT algorithm is missing in this paper which explains optimal power extraction with stable power affirmation. In [35], genetic and fuzzy based fuel-super capacitor hybrid system applicable for hybrid electric vehicle has proposed which provides smoothness in fuel cell output, improves fuel cell life period and responsible for the decrement of consumption of hydrogen. However, the practical justification of Genetic Algorithm (GA) based optimization of the fuzzy membership function is difficult as authors have presented only simulation results to validate this hybrid energy management system. In [36], hybrid Fuel-PV and battery based DC microgrid system have been proposed in which PV system, Fuel-cell and battery system operates in MPPT, power control modes of operation, respectively and validated only through only simulation platform for the analysis of required active power using DC link voltage regulation. In [18], Jaya DE MPPT algorithm has been implemented for PV system under varying operating situations. This evolutionary algorithm provides quick convergence speed, accurate MPP response and high PV tracking power in every type of changing weather situations. However, employment of Jaya DE algorithm with hybrid PV-Fuel-cell system is missing in this research work. In [37], a Jaya based MPPT algorithm for the PV system has been proposed in which swarm intelligent technique provides iteration based updated solutions compared to recent PSO and FA algorithms. However, application of Jaya based MPPT method has been discussed in this research paper.

The main contribution of this research work is the experimental realization of Hybrid PV-Fuel cell with Jaya MPPT technique for grid integration has neither been discussed nor validated formerly by the author's prime survey. The voltage oriented inverter controller provides unity power factor with better DC-link utilization and validated using dSPACE (DS 1104) obtained practical responses.

II. OVERALL PV-FUEL CELL SCHEMATIC WITH GRID INTEGRATION

Fig. 1 presents the overall hybrid PV-Fuel system with ultra-capacitor responsible for compensation of dynamic power from renewable energy sources. The solar energy delivers power as per atmospheric situations and rest insufficient power is fed by the fuel cell for proper power management of hybrid PV-Fuel cell system. An integrated CUK converter is employed for MPPT action which is connected using common DC-link. A Jaya MPPT algorithm is employed to obtain the utmost PV power tracking. Voltage oriented control method is implemented for the 3-phase inverter. The standalone/ grid integrated mode of hybrid PV-Fuel based power system is analyzed and power management responses have been discussed.

A. PV GENERATOR MATHEMATICAL MODELLING

Fig. 2(a) depicts the equivalent PV cell made by P-N junction. Several series and shunt interconnection of PV cells are arranged to make PV module with considered solar irradiance and ambient temperature. The mathematical relationship describing the PV cell model is expressed as:

$$\left.\begin{aligned} & I_{out} = I_{Photon} - I_{Diode} - I_{Parallel} \\ & \Rightarrow where, I_{Diode} = I_{sat}\left[e^{\left(\frac{V_{Diode}}{m_D V_{TH}}\right)} - 1\right] \end{aligned}\right\} \quad (1)$$

$$\left.\begin{aligned} & V_{Diode} = V_{out} + I_{out}R_{series} \\ & V_{TH} = \frac{K_B T_{Abs}}{Q_{electron}}, I_{Parallel} = \frac{V_{Diode}}{R_{Parallel}} \end{aligned}\right\} \quad (2)$$

where, I_{out} is PV cell current output; I_{Photon} is photon current; I_{Diode} is current through diode; $I_{Parallel}$ is current through parallel resistor; I_{sat} is diode saturating current; V_{Diode} is voltage across diode; V_{TH} is thermal voltage; m_D is diode factor; K_B is Boltzmann constant; V_{out} is output voltage; R_{series} is

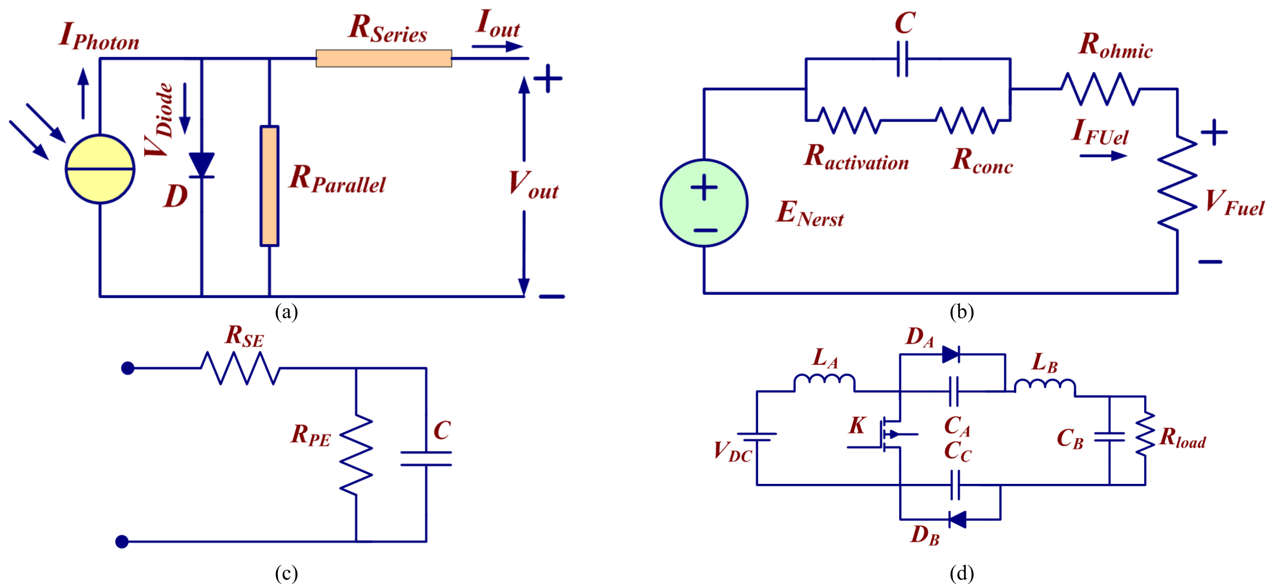

FIGURE 2. Modelling and equivalent circuit (a) Equivalent PV cell schematic, (b) PEMFC Equivalent model, (c) simple equivalent circuit of ultra-capacitor, and (d) integrated CUK converter.

series resistance; T_{Abs} is absolute temperature; $Q_{electron}$ is charge on electron; and $R_{Parallel}$ is resistance in parallel.

B. PEMFC MATHEMATICAL MODELLING

PEMFC mathematical model has been considered with the help of its equivalent model depicted in Fig. 2(b). Fuel cell acts as an electrochemical appliance which transforms hydrogen fuel to electrical energy. Air/Fuel as inputs is transfigured to water and electrical energy using electrochemical regeneration [38]. The fuel cell comprises anode and cathode as electrodes with electrolytes which isolates hydrogen cell liberated charged ions. PEMFC output voltage is expressed mathematically as:

$$\left.\begin{aligned} V_{Fuel} &= N_{cell}.V_{SFC} \\ V_{Fuel} &== N_{cell}\begin{bmatrix} E_{Nernst} - V_{activation} \\ -V_{ohmic} - V_{conc} \end{bmatrix} \end{aligned}\right\} \tag{3}$$

where, V_{Fuel} is fuel cell output voltage; N_{cell} is number of cells; V_{SFC} is single fuel cell voltage; E_{Nernst} is nernst voltage; $V_{activation}$ is activation losses; V_{ohmic} is ohmic losses; and V_{conc} is concentration losses.

$$E_{Nernst} = \left[\begin{matrix} 1.229 - 8.5 * 10^{-4}\left(T_{abs} - 298.15\right) \\ +4.308 \times 10^{-5} T\left(\ln P_{H_2} + \ln P_{O_2}\right) \end{matrix}\right]\Bigg\} \tag{4}$$

where, T_{abs} is absolute temperature (K); P_{H_2} and P_{O_2} is partial pressures of hydrogen and oxygen (atm).

$$V_{activation} = \left(\begin{matrix} K_1 + K_2 T_{Abs} + \\ K_3 T_{Abs} \ln Co_2 + K_4 T_{Abs} \ln I_{Fuel} \end{matrix}\right) \tag{5}$$

where, K_1, K_2, K_3, K_4 is semi-empirical coefficient, K_1 is -0.95, K_2 is 3.55×10^{-4}, K_3 is 0.8×10^{-7}, K_4 is 0.197×10^{-3}, and I_{Fuel} is fuel cell current.

$$\left.\begin{aligned} V_{Ohmic} &= -I_{ohmic} R_{ohmic} \\ V_{conc} &= \frac{R T_{Abs}}{nF} \ln\left[1 - \frac{I_{Fuel}}{I_{Lt} A_c}\right] \end{aligned}\right\} \tag{6}$$

where, R_{ohmic} is ohmic resistance; n is number of liberated electrons; F is Faraday's constant; I_{Lt} is limiting current; A_C is active cell area; and R is 8314.47Ω.

$$\left.\begin{aligned} Co_2 &= \frac{P_{O_2}}{5.18 \times 10^{-6} \times e^{-498/T_{Abs}}} \\ R_{ohmic} &= \frac{r_{r.m} \times t_{m.t}}{A_c} \end{aligned}\right\} \tag{7}$$

where, C_{O2} is dissolved oxygen concentration, $r_{r.m}$ is resistivity of membranes, and $t_{m.t}$ is thickness of the membrane.

C. MATHEMATICAL MODELLING OF ULTRA-CAPACITOR

Fig. 2(c) illustrates the simple equivalent circuit of ultra-capacitor which comprises a capacitor, equivalent series and a parallel resistor which is responsible for charging/discharging and subjective to discharge deficiency. Ultra-capacitors are effectual storage apparatus which consume/deliver power at DC-link and provides steady voltage level beyond unspecified variation. R_{SE} is a series equivalent resistance, and R_{PE} is parallel equivalent resistance. The ultra-capacitor charged output voltage can be mathematically described as:

$$V(T) = V_{initial} \times e^{-T/RC} \tag{8}$$

where, RC is time constant which evaluates charging/discharging of starting capacitor voltage; $V(T)$ is capacitor voltage after $t = T$; $V_{initial}$ is the initial voltage of

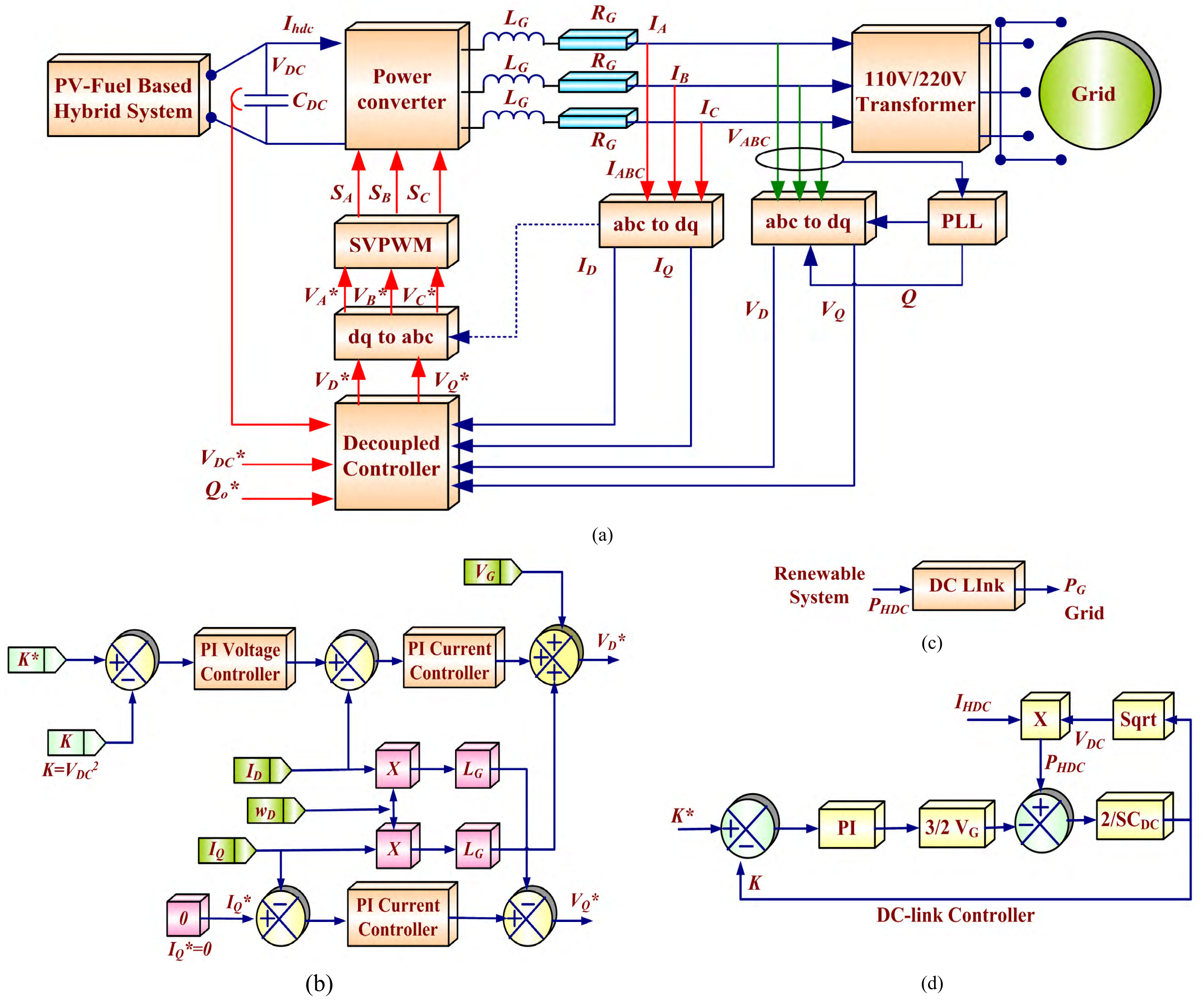

FIGURE 3. Block diagram of control logic (a) voltage oriented control strategy for grid integrated inverter, (b) dc-link decoupled structure, (c) renewable system to utility grid power transmission, and (d) dc-link voltage regulation.

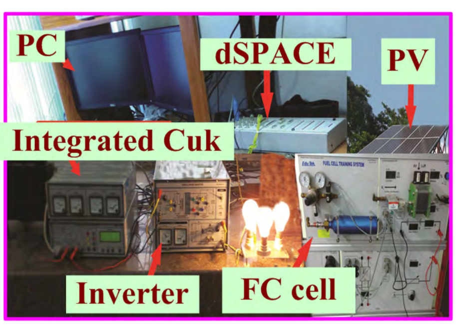

FIGURE 4. Standalone hybrid PV-Fuel cell hardware setup.

the capacitor. Also, energy harassed from ultra-capacitor is mathematically expressed as:

$$E_{ultra-capacitor} = 0.5 \times C \times (V_{initial}^2 - V_{final}^2) \quad (9)$$

D. INTEGRATED CUK CONVERTER

Conventional CUK converter combines the characteristics of buck and boost converters. In equated with buck-boost converter, CUK converter comprises opposite feature with good dynamic responses and provides capacitive segregation contrary to switch failing. The major disadvantages of classical CUK converters are unable to deliver sharp speed up/down voltage required to different utilization. Moreover, a swift comparator circuitry is needed to generate high duty ratio for large voltage transformation. However, due to high switched frequency, the control circuitry is collapsed because of less period pre-eminence of the diode. Therefore, this research work proposed integrated CUK converter depicted in Fig. 2(d) comprises diodes (D_A and D_B) and input capacitors (C_A and C_C) which deliver sharp outcomes. Table 1 shows the employed specifications of integrated

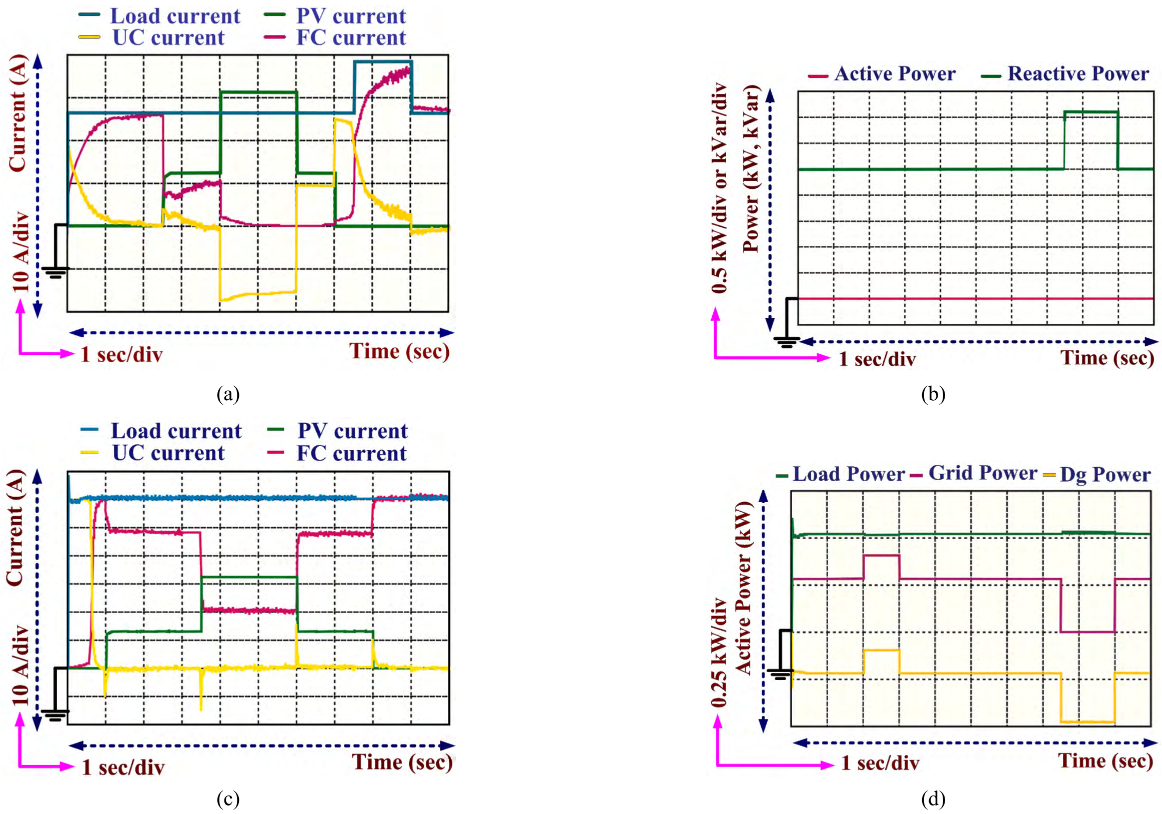

FIGURE 5. Experimental results- loading and power waveforms (a) current contributed from PV, fuel cell, ultra-capacitor and load, (b) active/reactive power distributed by distributor generators to the load, (c) grid connected mode hybrid PV-Fuel cell performance at different loading and sun irradiance level, and (d) active/reactive power distributed by distributor generators to the load and grid.

TABLE 1. Integrated CUK converter specifications.

Parameters	Values
Inductors (L_A & L_B)	4mH, 4mH
Capacitors (C_A, C_B & C_C)	4 μF, 2.5 μF, 4 μF
Load resistor	24 Ω

CUK converter. In mode 1 operation (Switch K is ON) L_A inductor gets charged through V_{DC} and capacitors (C_A and C_C) gets discharged and vice versa. Mathematically state-space equations are expressed as:

$$\left.\begin{aligned} \frac{dI_{L_A}}{dt} &= -\frac{(1-d)}{L_A}V_{C_C} + \frac{dV_{DC}}{L_A} \\ \frac{dI_{L_B}}{dt} &= \frac{dV_{C_A}}{L_B} + \frac{dV_{C_C}}{L_B} - \frac{dV_{C_B}}{L_B}, \; \frac{dV_{C_A}}{dt} = -\frac{d}{C_A} \times I_{L_B} \end{aligned}\right\} \tag{10}$$

$$\left.\begin{aligned} \frac{dV_{C_B}}{dt} &= \frac{1}{C_B}I_{L_B} - \frac{1}{R_{Load}C_C}V_{C_B} \\ \frac{dV_{C_C}}{dt} &= -\frac{d}{C_C}I_{L_B} \end{aligned}\right\} \tag{11}$$

E. JAYA BASED MPPT ALGORITHM

In this research work, the Jaya based recent meta-heuristics methodology is employed which provides less iteration and prominent power rating compared to PSO, ACO and ABC algorithm under highly fluctuating atmospheric conditions. Jaya algorithm was pioneered by Rao in 2015 which comes from Sanskrit word and has context 'Conquest'. This optimized technique is planted on the achievement of triumph by withdrawing defeat. The searched particle approaches the best location by overthrow unfavorable locations which result particle position gets updated. First of all the worst solution is evaluated and further, in every iteration worst solution is updated (Searching better solution) by withdrawing from worst. Hence, the adjacent solution is found superior to the precedent worst result. Where, $P(D_{duty})$ is momentary power at D_{duty} (duty ratio) and $0 < D_{duty} < 1$. The updated position can be evaluated mathematically by considering the preceding best and worst result as:

$$D^{T+1}_{duty_{m,n}} = \left\{ \begin{pmatrix} D^{T}_{duty_{m,n}} + R_{m,1}\begin{bmatrix} D^{T}_{duty_{m,best}} \\ -\left|D^{T}_{duty_{m,n}}\right| \end{bmatrix} \\ -R_{m,2}\left[D^{T}_{duty_{m,worst}} - \left|D^{T}_{duty_{m,n}}\right|\right] \end{pmatrix} \right\} \tag{12}$$

where, $D^{T}_{duty_{m,n}}$ is the amount of m^{th} variable for n^{th} aspirants in the interim of T^{th} iteration. $D^{T}_{duty_{m,best}}$ is the amount of m^{th} variable for the best aspirants in the interim of T^{th} iteration. $D^{T}_{duty_{m,worst}}$ is the amount of m^{th} variable for the worst aspirants in the interim of T^{th} iteration. T is number of iteration

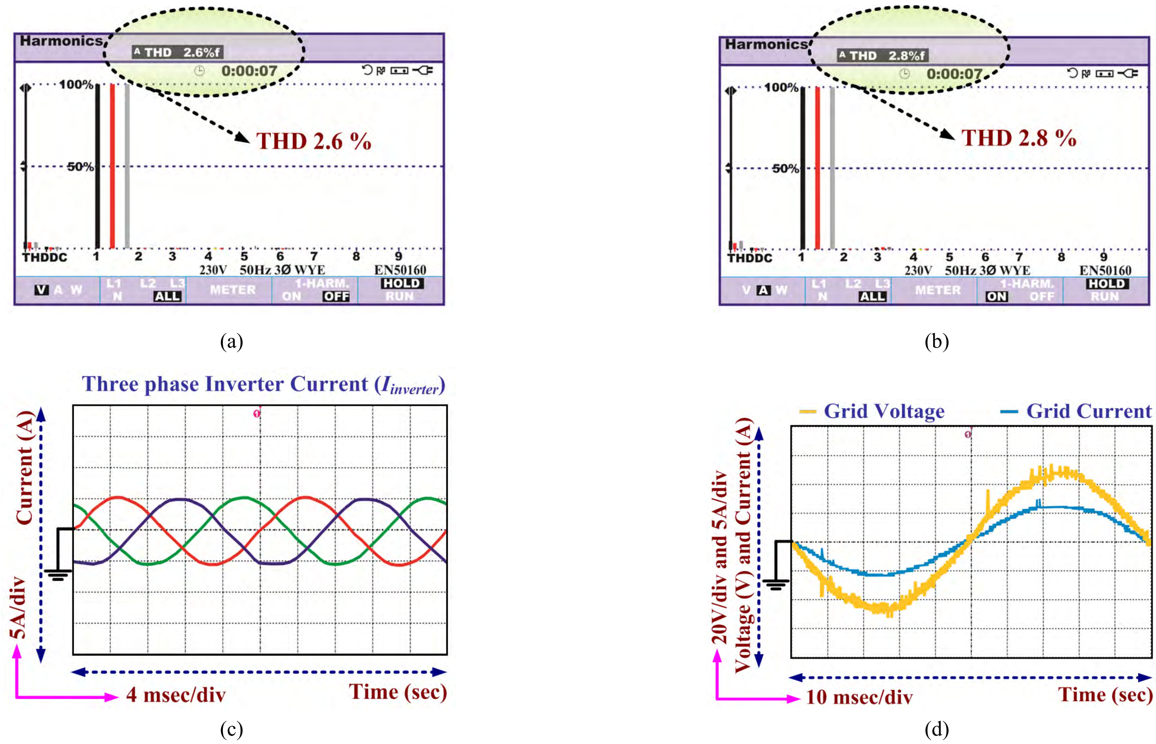

FIGURE 6. Experimental results- THD, grid voltage, grid current, and inverter current waveform. (a) THD spectrum of inverter voltage, (b) THD spectrum of inverter current, (c) steady state 3-ph inverter current, and (d) grid voltage and grid current.

($t = 1, 2, 3, \ldots N$); N is Maximum number of iteration; m is number of variables ($m = 1, 2, 3, \ldots M$); M is total variables; n is number of aspirants ($n = 1, 2, 3, \ldots P$); P is the maximum number of aspirants; $R_{m,1}$ and $R_{m,2}$ is random variables $\varepsilon[0,1]$.

The ultimate selection progression is described mathematically as:

$$\left.\begin{array}{l} iff \left(D^{T}_{duty_{m,n}}\right) < f\left(D^{T+1}_{duty_{m,n}}\right) \\ then, D^{T+1}_{duty_{m,n}} = D^{T}_{duty_{m,n}} \\ = D^{T+1}_{duty_{m,n}}, otherwise \end{array}\right\} \tag{13}$$

The Jaya based MPPT tracking algorithm is employed with the real-time process by considering sun irradiance (G) and temperature (T) constant

$$P_{G,T} = F(V), \quad 0 < V < V_{open} \tag{14}$$

where, V_{open} is open circuit voltage, P_{GT} is conditional power output. Suppose $P = F(V)$ as objective function has been considered for PV generation maximization, where F denotes the real operation of photovoltaic power system with V and P represents voltage setting and power generation. Jaya based MPPT provides achievement of MPP tracking within fewer periods and has minimum searching parameters. This algorithm has no requirement of method based parameters and has simpler implementation without proper tuning. In this method, N PV modules with N local maximum of PV characteristics are employed. The fitness function has been considered as power generation and larger power generations can be obtained with better voltage setting.

Moreover, maxima have achieved at 0.8 V_{open} and mathematically particle has located initially as with boundaries $0.1V_{open}$ and 0.9 V_{open}

$$V_{0,i} = 0.8iV_{open\_STC} \quad for\ i = 1, 2, \ldots, N \tag{15}$$

where, $V_{0,i}$ is the initial solution ($i$particle).

F. VOLTAGE ORIENTED CONTROL STRATEGY FOR GRID INTEGRATED INVERTER

The voltage oriented control strategy for grid-integrated inverter proposed in this research work to achieve unity power factor by regulating DC-link voltage (V_{DC}) followed by reference DC link (V_{DCRef}). The output of inverter current becomes pure sine wave by regulating current of the enclosed circuit. Fig. 3(a) depicts the facilitated model of transformer represented by the connecting resistor (R_G) and inductor (L_G) to the circuit. As grid voltage and d-axis components are oriented to each other the V_{Gq} becomes zero. Mathematical relation describing V_{Gd} and V_{Gq} is represented as:

$$\left.\begin{array}{l} V_{Gd} = R_G I_D + L_G \dfrac{dI_D}{dt} + V_{RD} - \omega L_G I_Q = V_G \\ V_{Gq} = R_G I_Q + L_G \dfrac{dI_Q}{dt} + V_{RQ} + \omega_f L_G I_Q = 0 \end{array}\right\} \tag{16}$$

where, V_{RD}, V_{RQ} is d-q components of the inverter; I_D, I_Q is d-q components of grid current.

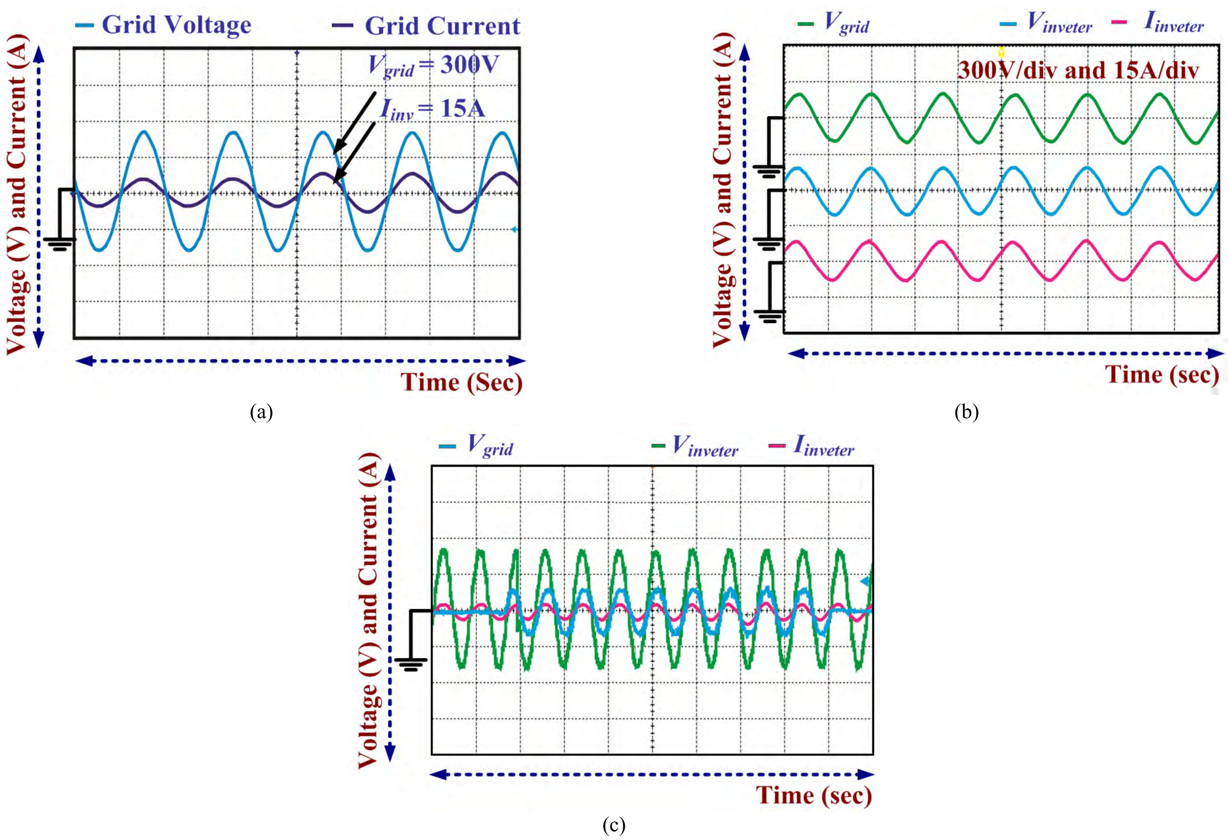

FIGURE 7. Experimental waveforms (a) Grid voltage in phase agreement with Inverter current, (b) inverter voltage, grid voltage, and inverter current, and (c) grid and inverter under dynamic operating conditions.

Assuming insubstantial filter resistance $R_G \approx 0$, the decoupled structure describes mathematically as:

$$\left.\begin{array}{l} V_{RD} = V_G + \omega_f L_G I_Q + \Delta V_D \\ V_{RQ} = \Delta V_Q - \omega_f L_G I_D \end{array}\right\} \tag{17}$$

where, ΔV_D, ΔV_Q is PI controllers output; DC link voltage controlled is modeled in Fig. 3(b) and stored energy is expressed as:

$$E_{Capacitors} = 0.5 \times C_{DC} \times V_{DC}^2 \tag{18}$$

Non-linear expression governing hybrid, grid and capacitor stored energy is presented in Fig. 3(c) described mathematically as:

$$\left.\begin{array}{l} 0.5C_{DC}\dfrac{dV_{DC}^2}{dt} = P_{HDC} - P_G \\ \Rightarrow K = V_{DC}^2, 0.5C_{DC}\dfrac{dK}{dt} = P_{HDC} - P_G \\ \Rightarrow P_G = {}^3\!/_2 \times V_G \times I_D, P_{HDC} = V_{DC} \times I_{HDC} \end{array}\right\} \tag{19}$$

Combining these equations, the DC-link voltage regulator is designed using Fig. 3(d). The generated PV power (P) depends on controllable factor V and non-controlled factor G (Sun insolation level) and T_{amb} (ambient temperature) be mathematically described as $P = (V, G, T_{amb})$ and MPPT objective function is mathematically expressed as $F\left(D_{duty}\right) = P^{\max}(D_{duty})$.

III. EXPERIMENT RESULTS AND INVESTIGATIONS

A practical justification of Jaya based MPPT has been carried out with dSPACE real-time platform for 200W grid tied PV-fuel system. The voltage reference control has been produced by sampling PV parameters using ADC component and employed through PI controller. The proper duty ratio has been maintained by minimizing the error between V_{PV} and V_{REF} using PI-controller. Hall sensors (LA-SSP and LV-25) are employed to sense V_{PV} and I_{PV} of PV module. The sensor's output has been fed to ADC unit with dSPACE board and PWM pulses for power converter has been produced to perform MPPT functioning. The practical performance of hybrid PV-Fuel cell for grid integration carried out using a dSPACE platform at *25°C* ambient temperature. Fig. 4 depicts the standalone hybrid PV-Fuel cell (Rated power *25 kW*) performance (hardware setup) at different loading and sun irradiance level. The current contributed from PV, Fuel cell, ultra-capacitor and load have been demonstrated using obtained practical responses in Fig. 5(a). Active/Reactive power distributed by distributor generators to the load is illustrated using Fig. 5(b). At the start the fuel cell and ultra-capacitor contribute power with zero PV power. Ultra-capacitor is responsible to compensate sluggish reaction of the fuel cell system. At $t = 2.5$ *sec*, the solar insolation level is increased to *500 W/m*^{2} which result decrement in fuel cell power contribution and

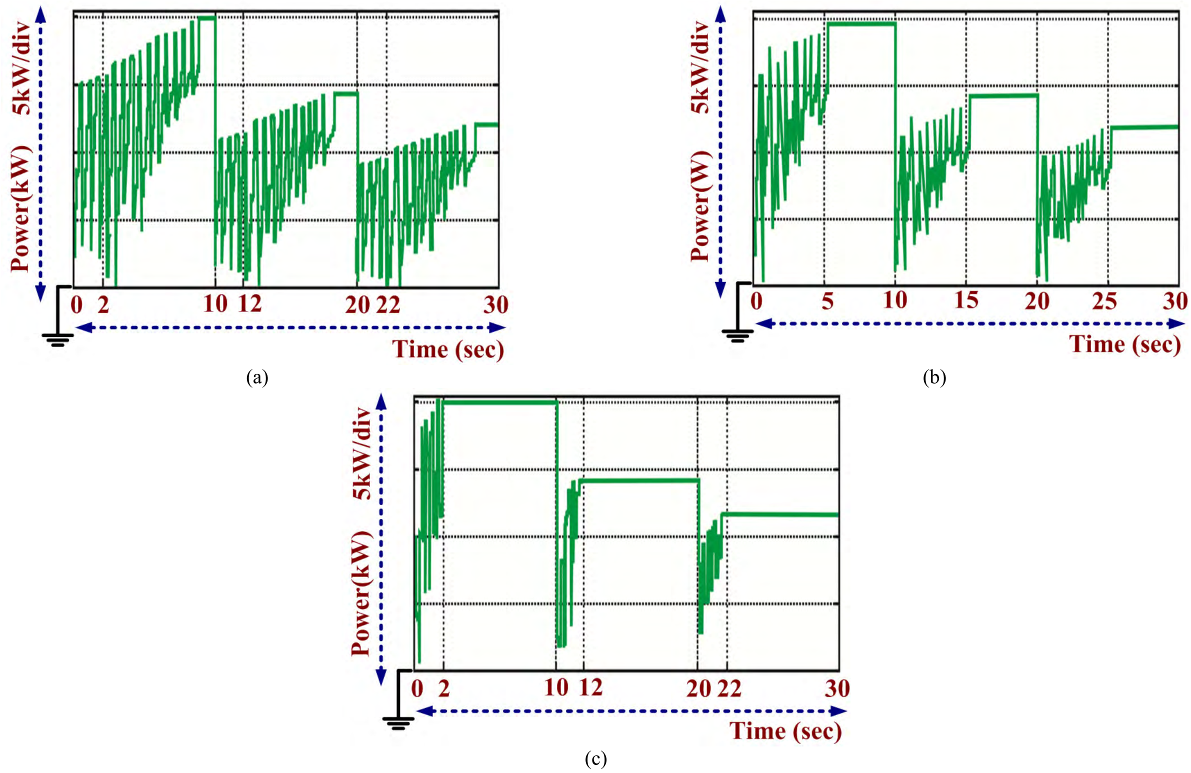

FIGURE 8. Experimental waveform- power tracking performance, (a) PSO, (b) ABC, and (c) Jaya algorithm.

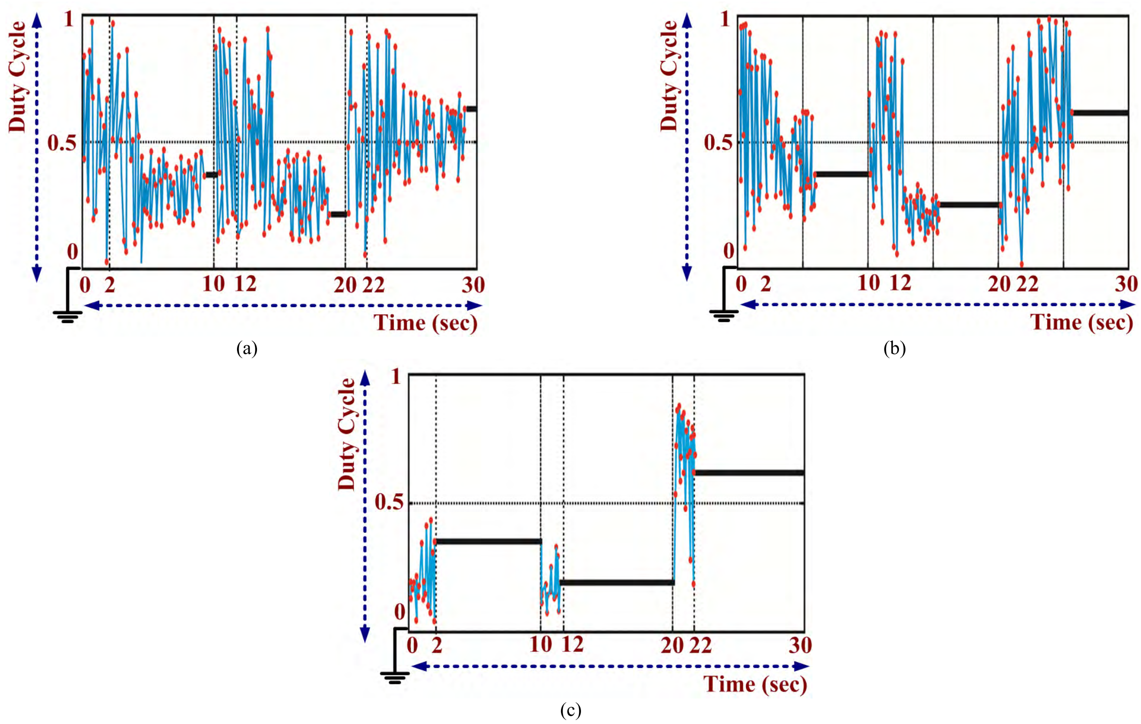

FIGURE 9. Experimental waveform- tracked trajectory of duty cycle of integrated CUK converter, (a) PSO, (b) ABC, and (c) Jaya Algorithm.

ultra-capacitor is responsible to consume transitory fuel cell generated power. At $t = 4$ *sec*, the solar insolation level reached to *1000W/m*^{2} and PV generated power is sufficient to drive the load. Additionally, ultra-capacitor is charging with zero contribution from fuel power cell. Moreover, at $t = 6$ *sec*, the solar irradiance level decreased to *500W/m*^{2}

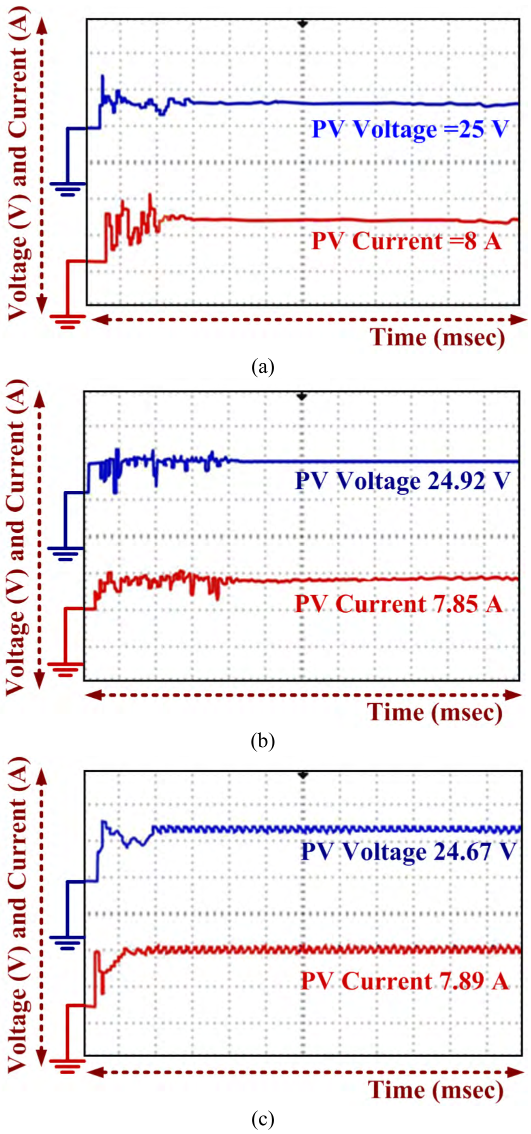

FIGURE 10. Performance of the PV power system under partial shading conditions using algorithms (a) Jaya, (b) ABC, and (c) PSO.

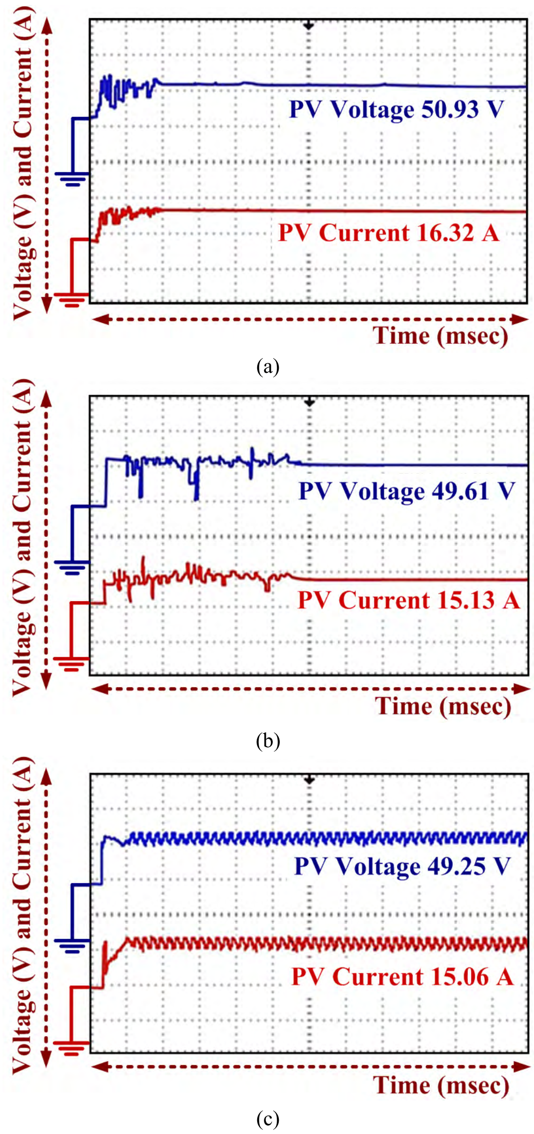

FIGURE 11. Performance of the PV power system under no partial shading conditions using algorithms (a) Jaya, (b) ABC, and (c) PSO.

and ultra-capacitor is responsible to deliver load required power and fuel cell contributes with sleepy respond. In case of grid-integrated mode with *50 kW* power rating is considered and surplus power is delivered to the utility grid, subsequently utilized by the local load. Fig. 5(c) portrays the grid-connected mode hybrid PV-fuel cell performance at different loading and sun irradiance level. At the start, the fuel cell and ultra-capacitor contribute power. At $t = 1$ *sec*, solar irradiance level is raised to $500W/m^2$. Fuel cell generated power is lowered and ultra-capacitor consumes transitory power. At $t = 2$ *sec*, utility grid power is lowered by *10 kW* when there is a *30%* increment in local load. Solar irradiance level reaches to $500W/m^2$ at $t = 6$ *sec* and becomes zero at $t = 8$ *sec* respectively which is explained with Fig. 5 (d). Fuel cell delivers the power to the local load with zero shared PV output. Ultra-capacitor consumes and delivers power as per requirement. At $t = 7.5$ *sec*, the distributed generated fed power to the utility grid when entire local loads are eliminated. Fig. 6(a) and 6(b) depict the THD spectrum of inverter voltage and inverter current with 2.6% and 2.8 % THD respectively which are quite satisfactory and found lower than 5% as per IEEE 519 standard. Fig. 6(c) illustrates the experimentally obtained steady state inverter current which is purely sinusoidal and satisfies IEEE 929-2000 standard. Grid voltage and grid current are the good agreement in the unity power factor with each other and has a quite satisfactory performance with THD less than 5% is depicted with Fig. 6(d).

Fig. 7(a) demonstrates the practically found grid voltage in phase agreement with inverter current and has less THD than 5% which satisfy IEEE 519 standard. The synchronized inverter voltage and inverter current are practically obtained illustrated in using Fig. 7(b). Fig. 7(c) demonstrates the synchronized waveform of grid and inverter under dynamic operating conditions. The performance of PSO, ABC, Jaya algorithms compared under fluctuating solar irradiance level and partial shade situations. It found that average tracked period to reach MPP for PSO, ABC and Jaya algorithm are 9sec, 5.6 sec, and 1.8 sec respectively. The Jaya algorithm provides improved and fast-tracked performance, less power loss, better PV power tracking efficiency compared to PSO and ABC technique depicted in Fig. 8. The proposed Jaya algorithm delivers rapid convergence speed, converges in less iteration compared to PSO and ABC algorithms with same population size have considered. Moreover, the tracked trajectory of the duty cycle of integrated CUK converter using PSO, ABC, and Jaya algorithms illustrated using Fig. 9. Noted that the duty ratio of integrated CUK converter has more divergence in PSO and ABC algorithm based MPPT.

To verify the effectiveness of the proposed Jaya controller as a MPPT tracker, the series connected PV stings with no shading, and 50 % shading situations have been considered. The PV responses are realized under 50% partial shading conditions and presented in Fig 10. Fig 11 denotes the PV responses under no partial shading effect in which high PV tracking power is obtained using the proposed Jaya method compared to others MPPT methods.

The performance of Jaya based MPPT method has been equated with PSO and ABC based algorithms under partial shade situations. Practical result shown in Fig. 10 interprets that the MPP tracking using Jaya based MPPT method has rapid progression and other algorithms such as PSO and ABC struggles to track PV power from PV modules. The PV power extraction using proposed Jaya based MPPT has less convergence period as well as negligible oscillation near to MPP area under partial shading condition.

IV. CONCLUSION

The hybrid PV- Fuel cell- Ultra-capacitor based grid-connected system is experimentally realized in standalone/ grid connected mode under changing operating conditions. An integrated CUK converter has been implemented which acts as power balancer between renewable energy source and inverter with Jaya MPPT technique. The performance of Jaya algorithm is equated practically with PSO and ABC algorithm. Compared to PSO and ABC methods, the proposed Jaya based MPPT provides better PV power point tracking, precise responses and least power oscillation near to MPP region. Experimental results also reveal that, proposed Jaya MPPT technique has 5 times rapid PV tracking convergence velocity than PSO method. The voltage oriented control as a grid inverter control is employed and unity power factor is achieved under different operating situations with DC-link voltage regulation. The hybrid PV-Fuel cell-Ultra-capacitor is experimentally validated and reliable power-sharing is realized effectively under different loading and ambient situations using dSPACE (DS 1104) board.

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