Boost Type Multi-Input Independent Generation System With Multi-Winding Simultaneous Power Supply

YANHUI QIU\textsuperscript{1}, DAOLIAN CHEN\textsuperscript{2}, (Senior Member, IEEE), AND JIAWEI ZHAO\textsuperscript{2}
\textsuperscript{1}College of Automation, Qingdao University, Qingdao 266071, China
\textsuperscript{2}College of Electrical Engineering, Qingdao University, Qingdao 266071, China

Corresponding author: Daolian Chen (chendaolian@hotmail.com)

This work was supported in part by the Key Project of Natural Science Foundation of China under Grant 51537001, and in part by the Mount Tai Scholars’ Climbing Plan of Shandong Province, China.

\textbf{ABSTRACT} The Boost type multi-input independent generation system (IGS) with multi-winding simultaneous power supply is proposed and deeply investigated, the important conclusions are obtained. Its circuit structure is composed of a single-stage multi-winding Boost type multi-input inverter with high-frequency-link and a single-stage isolated battery charging/discharging converter connected together at the output end, its circuit topological family includes 4 types of circuit such as full-bridge etc, the maximum power energy management control strategy (EMCS) with output voltage single-loop and three-state one-cycle phase-shift modulation is adopted, and the magnetic saturation of the energy storage inductor and the distortion of output voltage of the IGS are effectively suppressed. By comparing the load power and the total input sources power, the proposed EMCS achieves smooth transition among different power supply modes. The designed and developed 2.5kVA experimental prototype has shown that the proposed IGS has advantages such as single-stage conversion, high frequency galvanic isolation among load, multi-input sources and battery, simultaneous power supply in a high-frequency switching cycle, wide regulating range of duty cycle, small size and light weight, and strong load adaptability, etc.

\textbf{INDEX TERMS} Independent generation system, multi-input inverter, multi-winding boost, three-state one-cycle phase-shift modulation, simultaneous power supply.

\section{I. INTRODUCTION}
Due to the rapid depletion of traditional fossil energy and increasingly serious environmental pollution, new energy such as photovoltaic (PV) cells, wind power is getting more and more attention. The independent generation system (IGS) is widely used in remote areas, islands, communication base stations, street lights and other areas without electricity or unstable power grids [1]–[4]. The single new energy source is usually unstable and intermittent, the IGS with single new energy source can’t provide stable and continuous power supply. In order to improve the stability and flexibility of the IGS, the IGS with multiple new energy sources can be adopted [5]–[8].

Traditional two-stage multiple single-input DC-DC converter type IGS in [9]–[11] contains several independent single-input DC-DC converters and a Buck SPWM inverter. The outputs of the multiple single-input DC-DC converters are connected in series or parallel to the DC bus. It has features such as complex circuit structure, bulky size and high cost, which limits its practicability.

To simplify the circuit structure and reduce the cost, the two-stage multi-input DC-DC converter type IGS is proposed by using a multi-input DC-DC converter replacing multiple single-input DC-DC converters [12]–[20]. The Buck and Boost type two-stage multi-input IGS with parallel time-sharing power supply are presented in [12]–[14], where the PV, wind turbine adopt maximum power point tracking (MPPT) algorithm and the DC bus voltage is maintained by the battery or fuel cell. The multiple input sources are connected in parallel through unidirectional selective power switches. It has features as time-sharing power supply in a high-frequency switching cycles, narrow regulating range of duty ratio, low converter efficiency, no isolation among...
multiple input sources and weak voltage matching ability, etc. The multi-mode, Buck-Boost, Boost type two-stage multi-input IGS with serial simultaneous power supply are proposed in [15]–[17] respectively, the multiple input sources are connected in series through selective power switches and bypass diodes. It has the features such as simultaneous power supply in a high-frequency switching period, wide regulating range of duty ratio, non-isolation among the inputs and weak voltage matching ability, etc. A Boost/dual half-bridge integrated DC-DC converter type two-stage multi-input IGS is proposed in [18], where the power switches of the Boost converter and the power switches of the dual half-bridge converter’s primary side are shared. It is a single-stage power conversion when the battery is charged, but it is a three-stage power conversion when the battery discharges energy to the load. Besides, this structure is difficult to expand to n channels, and there is no electrical isolation among the multiple inputs. A dual forward units integrated DC-DC converter type two-stage multi-input IGS is proposed in [19], it is isolated among multiple input sources and between input and output through multiple high frequency transformers, the volume is relatively large. A three active bridges integrated DC-DC converter type two-stage multi-input IGS is proposed in [20], where the three active bridges are connected with a three-winding high frequency transformer and the power flow is controlled by the phase-shift angle between the active bridges. It achieves the isolation among multiple input sources and between input and output, but the control strategy is complicated and it exists circulating current among the inputs.

Compared with traditional two-stage multiple single-input DC-DC converter type IGS, the two-stage multi-input DC-DC converter type IGS simplifies the circuit structure and reduces the cost. However, it still has a two-stage circuit structure, thus the conversion efficiency and power density are not satisfactory. Besides, when a battery charging/discharging converter is connected with the DC bus, it is two-stage power conversion whether the battery is charged or discharges to the AC load.

Compared with the Buck type inverter, the Boost type inverter has the advantages of single-stage voltage boosting, direct control of the output current and easy realizing MPPT of the PV cell, long life of the energy storage inductors’ components, timely protection with over current and high system reliability, etc [21]. In recent years, with the emergence of new type devices such as bidirectional blocking insulated-gate bipolar transistor (IGBT) and the development of superconducting technology, Boost type inverter will have a more important application value.

In order to further simplify the circuit structure, reduce power conversion stage, and demonstrate the superiority of the Boost type inverter, it is necessary to seek a Boost type multi-input inverter with a single-stage circuit structure. This paper proposes Boost type multi-input IGS with multi-winding simultaneous power supply, the main contributions of this paper can be summarized as follows:

1. We propose Boost type multi-input IGS with multi-winding simultaneous power supply, the system has advantages such as simultaneous power supply, isolation among load, multi-input sources and battery, single-stage voltage boosting, wide regulating range of duty cycle, strong load adaptability, etc.

2. We propose the maximum power EMCS with the three-state one-cycle phase-shift modulation, the magnetic saturation of the energy storage inductor and the distortion of the grid-connected current are effectively suppressed. By comparing the load power and the total input sources power, the proposed EMCS achieves smooth transition among different PSMs.

3. By introducing the concept of the equivalent switching cycle, the steady principle and design criteria of the main circuit elements are derived. Designed 2.5kVA experimental prototype verifies the feasibility and advancement of the proposed circuit structure, topological family and EMCS.

In the text, the circuit structure, topological family and EMCS of a Boost type multi-input IGS with multi-winding simultaneous power supply is presented firstly, then the steady-state operation principle and design criteria of the main circuit parameters are deeply investigated. At last, the experimental results are given. The main variables used in the paper are detailed in Table 1.

II. CIRCUIT STRUCTURE AND TOPOLOGICAL FAMILY
The circuit structure and topological family of the Boost type multi-input IGS with multi-winding simultaneous power supply is shown in Fig. 1. The circuit structure is composed of a single-stage Boost type multi-input high-frequency-link inverter and a single-stage isolated battery charging/discharging converter, with their outputs connected in parallel on the AC side. The multi-input inverter combines multiple isolated single-input single-output high frequency inverting circuits with an output cycloconverter and filter circuit through a multi-input single-output high frequency transformer $T_1$, where the high frequency inverting circuit is cascaded by the input filter capacitor $C_{i1} \sim C_{in}$, energy storage inductor $L_1 \sim L_n$ with bypass switch $S_{01} \sim S_{0n}$, active clamped circuit and high frequency inverting bridge. The single-stage isolated battery charging/discharging converter is a single-stage high-frequency-link Buck type SPWM inverter or Boost type SPWM rectifier with a $L_C$ series resonance circuit.

“Simultaneous power supply” means that multiple input sources can simultaneously deliver energy to the load at a time during the high frequency switching period $T_{s1}$.

The topological family contains four circuits, where the push-pull, push-pull forward and half-bridge circuits are suitable for multiple input sources with the same duty cycle, and the full-bridge circuit can be used for multiple input sources with the same duty cycle or different duty cycle.

The energy storage inductor currents $i_{11}, i_{12}, \ldots, i_{1n}$ are converted into high-frequency bipolar tri-state pulse currents $i_{N11}, i_{N12}, \ldots, i_{N1n}$ through the high frequency inverting circuit, and then transmitted to multilevel bipolar tri-state
FIGURE 1. Circuit structure and topological family of the proposed boost type multi-input IGS with multi-winding simultaneous power supply. (a) Circuit configuration. (b) Push-pull. (c) Push-Pull Forward. (d) Half-bridge. (e) Full bridge.
TABLE 1. The main variables used in the paper ($j = 1, 2$).

| Symbol      | Variable                                      |
|-------------|-----------------------------------------------|
| $U_{i1}, U_{i2}$ | first, second input voltage                   |
| $I_{i1}, I_{i2}$ | first, second input current                  |
| $U_{b}, I_{b}$ | battery voltage, current                      |
| $U_{oa}, I_{oa}$ | output voltage, current                       |
| $f_{s1}, f_{s2}$ | switching frequency of multi-input inverter, battery |
| $I_{i1}, I_{i2}$ | first, second energy storage inductor current |
| $i_{i1}, i_{i2}$ | first, second energy storage inductor current reference |
| $U_{cl1}, U_{cl2}$ | clamp capacitor voltage, current              |
| $T_{s1}, N_{i1}, N_{2}$ | multi-winding transformer, winding turns       |
| $T_{s2}, N_{i2}, N_{2}$ | high frequency transformer, winding turns      |
| $U_{in1}, U_{in2}$ | voltage, current of $T_1$ primary winding      |
| $I_{in1}, I_{in2}$ | voltage, current of $T_1$ secondary winding    |
| $i_{m}$ | modulation current of multi-input inverter    |
| $i_{m1ref}, i_{m2ref}$ | equivalent modulation current reference       |
| $i_{cl}$ | filter inductor current of battery converter  |
| $d_{i1}$ | equivalent energy storage duty cycle of $i_{th}$ input |
| $d_{i2}$ | equivalent bypass duty cycle of $i_{th}$ input |
| $d_{r}$ | equivalent release duty cycle of $i_{th}$ input |
| $R_{n}$ | equivalent resistor of the energy storage inductor |
| $I_{oa1}, I_{oa2}$ | total, first, second output current amplitude |
| $\theta$ | phase difference                              |
| $C_{cl1}, C_{cl2}$ | clamp capacitor                               |
| $I_{i1}, I_{i2}$ | first, second energy storage inductor         |
| $C_{i1}, C_{i2}$ | input filter capacitor of multi-input inverter |
| $L_{o}, C_{l}$ | output filter inductor, capacitor             |
| $T_{es}$ | equivalent switching cycle                    |
| $U_{s11}, U_{s12}, i_{s11}$ | drive signal, voltage, current of $S_{11}$ |
| $R_{L}$ | load resistance                               |

Pulse current $i_{N2}$ through $T_1$, lastly $i_{N2}$ is converted into the desired sinusoidal voltage $u_{oa}$ via the cycloconverter and output filter. When $|u_{oa}| \leq U_{in}N_2/N_{i1}$, $L_n$ is magnetized in the full switching period $T_{s1}$ and the energy storage current $i_{L_n}$ keeps rising in this interval. To suppress the undesired rise of $i_{L_n}$, the bypass switch $S_{b}$ is turned on during this interval to allow $i_{L_n}$ flow through $S_{b}$. When the Boost type multi-input inverter is used for the active power condition, the energy storage inductor currents of Boost inverter will rise sharply and make the inverter broken. Therefore, the Boost type multi-input inverter is not suitable for active power conditions, an isolated battery charging/discharging converter is necessary to provide the required active power, which greatly enhances the load adaptability of the system.

III. ENERGY MANAGEMENT CONTROL STRATEGY
A. MAXIMUM POWER EMCS
Taking the full-bridge circuit (shown in Fig. 1(e)) as an example, the EMCS of the proposed Boost type IGS is shown in Fig. 2. The single-stage Boost type multi-input inverter adopts maximum power EMCS with the three-state one-cycle phase-shift modulation, which achieves the phase-shift control of multiple inverting circuit, the MPPT of multiple input sources, as well as suppress the saturation of the energy storage inductor and the distortion of the output voltage. The single-stage isolated battery charging/discharging converter adopts unipolar phase-shift SPWM control strategy with output voltage closed-loop, which achieves stability of the output voltage and provides the reactive power required by the load.
As shown in Fig. 2(a), multiplying the output signals of the MPP voltage loop \( i_{\text{out}} \), \( i_{\text{in1}} \), \( i_{\text{in2}} \) by the absolute value of the unit sine reference \( |\sin(\omega t)| \), the equivalent modulation current reference \( i_{\text{m1ref}} \) and \( i_{\text{m2ref}} \) are obtained. Then the equivalent energy release duty ratio of the first and second input \( d_1 \), \( d_2 \) are obtained through the one-cycle controller [22], where \( d_1 = i_{\text{m1ref}}N_2/(I_{\text{ref}}N_{11}) \) and \( d_2 = i_{\text{m2ref}}N_2/(I_{\text{ref}}N_{12}) \) in the steady state. The one-cycle controller in the paper integrates the equivalent modulation current \( i_{\text{m1}}, i_{\text{m2}} \) until their integrated value in a high-frequency switching cycle is equal to the integrated value of \( i_{\text{m1ref}}, i_{\text{m2ref}} \), where \( i_{\text{m1}}, i_{\text{m2}} \) can be regarded as \( i_{\text{m1}}N_{11}/N_2, i_{\text{m2}}N_{12}/N_2 \) during the energy release period. According to how \( i_{\text{Lm}} \) changes, the multi-input inverter can be divided into three operating states in a high frequency cycle: 1) energy storage state, 2) energy release state, 3) bypass state. When the reference value \( i_{\text{Lref}}>i_{\text{Lm}} \), the inverter works in energy storage and energy release state, where the bypass switch does not work and \( i_{\text{Lm}} \) rises; When \( i_{\text{Lref}}<i_{\text{Lm}} \), the inverter works in bypass and energy release state, where the bypass switch works and \( i_{\text{Lm}} \) may rise \((|u_o| > U_{\text{in}2}N_2/N_{11})\) or fall \((|u_o| < U_{\text{in}2}N_2/N_{11})\). By calculating the ratio of the energy storage time and bypass time of several high-frequency switching cycles, the equivalent energy storage-duty cycle \( d_i \) and the equivalent bypass duty cycle \( d_s \) are obtained, and it is satisfied that \( d_i + d_s = 1 - d_f \). Lastly, the drive signal of the cycle converter is obtained by comparing sine reference with a zero comparator.

The MPP voltage outer-loop is designed with a slow response to reduce the impact on the inner-loop [23], while the three-state one-cycle phase-shift control inner-loop has a fast response to suppress the disturbance of the input. Besides, the output voltage loop of the battery charging/discharging converter is designed with a fast response to stabilize the output voltage and provide the required reactive power.

### B. THREE PSMS

Comparing the load power \( P_o \) and the sum of maximum input power \( P_{\text{max}} \), the proposed IGS has three kinds of PSMSs, as shown in Fig. 3. Mode I: \( P_{\text{max}} + P_{\text{2max}} > P_o \), the PV and wind turbines provide the required load power and charge the battery, as shown in Fig. 3(a). Mode II: \( P_{\text{max}} + P_{\text{2max}} < P_o \), the maximum power of PV and wind power cannot meet the load, and the battery works in discharge state to provide insufficient load power, as shown in Fig. 3(b). Mode III: \( P_{\text{max}} + P_{\text{2max}} = P_o \), the battery works in empty load state and does not provide active power, as shown in Fig. 3(c). The grid-connected condition of the single-stage Boost type multi-input high-frequency-link inverter belongs to mode III.

The proposed control method can realize the smooth transition of different PSMSs by controlling the phase difference \( \theta \) between the filter inductor current \( i_{\text{Lf}} \) and the output voltage \( u_o \), the waveforms of \( u_o, i_{\text{Lf}}, i_m \), and the modulation current \( i_m \) are shown in Fig. 4. The fundamental component of \( i_m \) is in phase with output voltage \( u_o \) to provide the active power, the phase difference \( \theta \) differs according to the power flow amplitude and direction of the battery charging/discharging converter. 1) When \( P_o = P_{\text{1max}} + P_{\text{2max}}, |\theta| = 90^\circ \), the active power output of the battery is zero and only reactive power is provided. 2) When \( P_o > P_{\text{1max}} + P_{\text{2max}}, 0 < |\theta| < 90^\circ \), the battery discharges energy to the load. 3) When \( P_o = P_{\text{1max}} + P_{\text{2max}}, 90^\circ < |\theta| < 180^\circ \), the battery is charged and absorbs the excess active power. Consequently, by adjusting \( \theta \) according to the load power and the total input power, the proposed EMCS achieves real-time control of battery converter’s power flow and the system’s smooth transition among different PSMSs.
IV. HIGH FREQUENCY SWITCHING ANALYSIS AND EXTERNAL CHARACTERISTICS

A. ANALYSIS OF HIGH FREQUENCY SWITCHING PROCESS

The single-stage Boost type multi-input high-frequency-link inverter and the single-stage isolated battery converter work independently, and only the high-frequency switching process of the former converter is analyzed. In a high-frequency switching period \( T_{S1} \), the single-stage Boost type multi-input high-frequency link inverter has two working conditions: energy storage & energy release condition and bypass & energy release condition.

The high frequency switching waveform and equivalent circuits under \( u_0 > 0 \) and energy storage & energy release condition are shown in Fig. 5. In this condition, the cyclo-converter power switches \( S_3(S_3') \) and \( S_7(S_7') \) are always on, \( S_6(S_6') \) and \( S_8(S_8') \) are alternately on in the high frequency cycle. Interval \( t_0-t_1 \) is the commutation overlap period of the two inverting circuits, as is shown in Fig. 5(b). Interval \( t_1-t_3 \) is the energy storage period of the two inverting circuits, as is shown in Fig. 5(c). Interval \( t_3-t_5 \) is the energy storage period of the first inverting circuit and the energy release period of the second inverting circuit, as is shown in Fig. 5(d). Interval \( t_5-t_7 \) is the energy release period of the two inverting circuits, as is shown in Fig. 5(e). Interval \( t_7-t_{16} \) is similar to interval \( t_5-t_8 \). For the bypass & energy release condition, the energy storage period is replaced by the bypass period, where the bypass switch \( S_{0n} \) is on and the lagged bridge arm switches \( S_{n3}, S_{n4} \) are off.

B. ANALYSIS OF EXTERNAL CHARACTERISTICS

When \( |u_0| > U_{ij}N_2/N_{ij} \), the inverter has three operating states: energy storage, energy release and bypass. The energy storage inductor current waveform under the three operating states: energy storage, energy release and bypass. The energy storage period is replaced by the bypass period, \( u_0 \) increases as \( d_{s1} \) increases; (2) For a constant \( d_{s1} \) get from the one-cycle controller, \( u_0 \) increases as \( d_{s1} \) decreases.

V. ANALYSIS ON KEY ISSUES

A. REFERENCE OF ENERGY STORAGE INDUCTOR CURRENT \( i_{l,ref} \)

When \( |u_0| > U_{ij}N_2/N_{ij} \), according to the instantaneous power balance, there is

\[
U_{ij}i_{ij} (d_{s1} + d_{s2}) = u_0i_{ej} \sin(o\tau)
\]

where \( i_{ej} \) and \( i_{ej} \) are the instantaneous value, amplitude value of the \( j \)th equivalent output current.

Then the reference of the energy storage inductor current \( i_{l,ref} \) is given as

\[
i_{l,ref} = \frac{u_0i_{ej} \sin(o\tau)}{(d_{s1} + d_{s2}) U_{ij}} = \frac{kU_{ij}}{} (7)
\]

where the coefficient \( k = d_{s1} + d_{s2} \) \( k \leq 1 \), based on the previous analysis of external characteristics, \( k \) is designed as 0.85.

B. ENERGY STORAGE INDUCTOR \( L_j \)

The value of the energy storage inductor determines the amount of the high-frequency current ripple, the relationship between the energy storage inductor value and the inductor current ripple can be expressed as

\[
L_j = \frac{1 - d_{s2}}{\Delta I_{l,ref}} = \frac{1 - 0.85N_2U_{ij}/(N_{ij}u_0)}{\Delta I_{l,ref}} (8)
\]

where \( \Delta I_{l,j} \) is the inductor current ripple, and \( \Delta I_{l,j} \) is designed by \( \Delta I_{l,j} = 10%I_{l,imax} \) when \( u_0 \) gets the peak value of the output voltage.

Under the interval \( |u_0| < U_{ij}N_2/N_{ij} \), the inverter works in the bypass & energy release condition, but the energy storage inductor current keeps increasing. \( U_{l,meanb}, I_{l,meanb}, L_{l,meanb} \) are the average values of \( u_0, i_0, i_{l,ref} \) in this interval respectively, \( I_{L_{p,b}} \) and \( I_{L_{0,b}} \) are the peak and initial value of \( i_{l,ref} \) respectively, \( T_b \) is the duration time of this interval, it can be obtained that

\[
I_{L_{p,b}} \approx I_{L_{0,b}} + \frac{(U_{ij} - U_{l,meanb})N_2I_{l,meanb}}{L_jN_1I_{l,meanb}} * T_b \approx I_{L_{0,b}} + \frac{2(U_{ij} - U_{l,meanb})N_2I_{l,meanb}}{L_jN_1(I_{p,b} + I_{l,0,b})} * T_b (9)
\]

The value of \( L_j \) can be calculated with \( I_{L_{p,b}} < 70%I_{L_{p}} \), and finally \( L_j \) takes the larger value in (8) and (9).
FIGURE 5. High frequency switching waveform and equivalent circuit of the multi-input inverter (a) High frequency switching waveforms (b) Interval $t_0$-$t_1$, (c) Interval $t_1$-$t_3$, (d) Interval $t_3$-$t_5$, (e) Interval $t_5$-$t_8$. 
FIGURE 6. The Inductor current waveform and external characteristics curve of the proposed multi-input inverter. (a) Inductor current waveform (b) External characteristics curve.

C. TURN RATIO OF THE TRANSFORMER

According to (5), the turn ratio of the transformer is expressed as

\[ \frac{N_2}{N_{ij}} = \frac{u_o d_{ij}}{U_{ij}(d_{pj} + d_{ij})} = \frac{u_{op} d_{ij}}{U_{in min}(d_{pj} + d_{ij})} \]  

where \( d_{ijp} \) and \( d_{ijr} \) are the equivalent energy storage duty cycle and the equivalent energy release duty cycle at the lowest input voltage and peak output voltage respectively. Besides, \( d_{ijp} \) and \( d_{ijr} \) are designed as 0.6 and 0.3 in this paper respectively.

D. VOLTAGE STRESS OF POWER SWITCHES

The voltage stress of the inverting switch is \( 2\sqrt{2}U_o N_{ij}/N_2 \) in pull-pull, push-pull forward and half bridge circuit, and is \( \sqrt{2}U_o N_{ij}/N_2 \) in full-bridge circuit; The voltage stress of the cycloconverter switch is \( \sqrt{2}U_o \); The voltage stress of the active clamp switch is \( \sqrt{2}U_o N_{ij}/N_2 \) in the push-pull, push-pull forward and full bridge circuits, and is \( \sqrt{2}U_o N_{ij}/N_2 + U_{ij}/2 \) in the half-bridge circuit.

VI. EXPERIMENT VERIFICATIONS

Taking the full-bridge topology shown in Fig. 1(e) as an example to verify the effectiveness of the proposed IGS and EMCS, the key parameters of the proposed IGS are listed in Table 2. The PV and wind power in the experiment are both simulated by programmable DC power supply Chroma 62150H-200S with the setting MMP(96V, 1500W), The MPPT method of combining open-circuit voltage with disturbance observation is adopted, the control chip DSP28377D is used.

The experiment results for the proposed IGS under rated resistive load and mode III is shown in Fig. 7. It should be noted that the battery charging/discharging converter is simulated by programmable AC power supply Chroma61845 in the experiment. The experiment results show that 1) The PV and wind turbines work at the MPPs(96V, 15.6A, 1500W), and the load power is equal to the sum of the maximum power of the two input sources, the system operates in mode III. The inverter has three operating states: energy storage, energy release, and bypass, the EMCS effectively suppresses the magnetic saturation of the energy storage inductor, \( T_1 \) is symmetrical magnetized.
The experiment results of the mode transition under resistive load, inductive load ($\cos\phi = 0.75$) and capacitive load ($\cos\phi = 0.75$) are shown in Fig. 8. The values of different parameters during all the three modes of operation are shown in Table 3. It can be seen that when $P_{1\text{max}} + P_{2\text{max}} = 1500W$ and the load power changes from 2.5kVA to 1.5kVA, the system changes from Mode I to Mode II smoothly. The proposed EMCS achieves real-time control of charging/discharging converter’s power flow and the system’s smooth transition among different PSMs under different loads. The system has strong load capacity and all the reactive power is provided by programmable AC supply.

The conversion efficiency curve of the proposed Boost type multi-input inverter under $U_{i1} = U_{i2} = 96V$ and $P_1 = P_2$ is shown in Fig. 9. The maximum conversion efficiency is 90.7%, and the conversion efficiency at rated power is 87.3%. The inherent loss of the multi-input inverter dominates under light load, which includes the iron loss of the magnetic components and the switching loss of the power switches, and the conversion efficiency is low; As the load increases, the conversion efficiency increases; the conduction loss of power switches and blocking diode, the copper loss of the magnetic components dominates under heavy load, and the conversion efficiency becomes lower because of the conduction loss proportional to the square of the RMS current. The maximum conversion efficiency is obtained for the output power of 1250W, since the design allowance of the multi-input inverter is small. With the development and application of the bidirectional blocking power device such as the reverse-blocking IGBT, the proposed inverter will be not necessary to connect in series with the reverse blocking diode, and the conversion efficiency will be greatly improved.

The conversion efficiency of Buck-Boost multi-input DC-DC converter with serial simultaneous power supply in [16] under $U_{i1}/U_{i2} = 48V/36V$, $U_{dc} = 400V$, and $P_o = 200W$ is 80%, the conversion efficiency of the dual forward units integrated DC-DC multi-input converter in [19] under $U_{i1}/U_{i2} = 120V/80V$, $U_{dc} = 400V$, and $P_o = 200W$ is 91%, while the converters proposed in [12]–[15], [17], [18], and [20] do not provide the conversion efficiency. Compared with the two-stage multi-input inverters in [16] and [19], the proposed multi-input inverter has higher or similar conversion efficiency, simpler circuit structure, smaller volume and weight; Compared with the two-stage multi-input inverters in [12]–[15], [17], [18], and [20], the proposed multi-input inverter has advantages such as isolation among load, multi-input sources and battery, single-stage voltage boosting, wide regulating range of duty cycle ($0\sim0.7$), strong load adaptability, smaller size and weight.
TABLE 3. The values of different parameters during all the three modes of operation.

| Load               | P_{max}−P_{min} | P_{n}     | P_{d} | Mode | Figure |
|--------------------|-----------------|-----------|-------|------|--------|
| resistive load     | 2500W           | 2.5kVA/(R_c=19.4Ω) | 0     | Mode III | Figure 7 |
| resistive load     | 1500W           | 1kVA/(R_c=48.4Ω)   | -     | Mode II  | Figure 8a |
| capacitive load    | 1500W           | 2.5kVA/(R_c=14.5Ω, L_c=250mH) | +     | Mode I   | Figure 8b |
| capacitive load    | 1500W           | 1.5kVA/(R_c=24.2Ω, L_c=150mH) | -     | Mode II  | Figure 8b |
| inductive load     | 1500W           | 2.5kVA/(R_c=14.5Ω, L_c=40mH)  | +     | Mode I   | Figure 8c |
| inductive load     | 1500W           | 1.5kVA/(R_c=24.2Ω, L_c=68mH)  | -     | Mode II  | Figure 8c |

VII. CONCLUSION

1) The proposed multi-input IGS circuit structure is composed of a single-stage Boost type multi-input high-frequency-link inverter and a single-stage isolated battery charging/discharging converter connected in parallel on the AC output. It includes push-pull, pull-pull forward, half-bridge and full bridge 4 types of circuit. The system has advantages such as simultaneous power supply, isolation among load, multi-input sources and battery, single-stage voltage boosting, wide regulating range of duty cycle, strong load adaptability, direct control of the output current and easy realizing the MPPT of the PV cell etc.

2) The single-stage Boost type multi-input high-frequency-link inverter adopts maximum power EMCS with the three-state one-cycle phase-shift modulation, the single-stage isolated battery charging/discharging converter adopts the unipolar phase-shift SPWM control strategy with output voltage closed-loop. By comparing the load power and the total input sources power, the proposed EMCS achieves real-time control of charging/discharging converter’s power flow and the system’s smooth transition among different PSMs.

3) The external characteristic curve of the multi-input inverter is obtained, and the design criteria of key circuit parameters are derived. Designed 2.5kVA experimental prototype verifies the feasibility and advancement of the proposed circuit structure, topological family and EMCS.

REFERENCES

[1] J. Hong, J. Yin, Y. Liu, I. Peng, and H. Jiang, “Energy management and control strategy of photovoltaic/battery hybrid distributed power generation systems with an integrated three-port power converter,” IEEE Access, vol. 7, pp. 82838–82847, 2019.

[2] E. J. Agnoletto, D. S. De Castro, P. V. A. Neves, P. Q. Machado, and V. V. Oliveira, “An optimal energy management technique using the ε-constraint method for grid-tied and stand-alone battery-based microgrids,” IEEE Access, vol. 7, pp. 165928–165942, 2019.

[3] S. U. Jeon, J. Noh, S. Kang, and J.-W. Park, “Practical power management of PV/ESS integrated system,” IEEE Access, vol. 8, pp. 189775–189785, 2020.

[4] Z. Zhou, C. Wang, and L. Ge, “Operation of stand-alone microgrids considering the load following of biomass power plants and the power curtailment control optimization of wind turbines,” IEEE Access, vol. 7, pp. 186115–186125, 2019.

[5] R. M. Elavarasan, G. Shefaliullah, S. Padmanaban, N. M. Kumar, A. Annam, A. M. Vetrivelvan, L. Mihet-Popa, and J. B. Holm-Nielsen, “A comprehensive review on renewable energy development, challenges, and policies of leading Indian states with an international perspective,” IEEE Access, vol. 8, pp. 74432–74457, 2020.

[6] Z. Y. Zhou, F. Xiong, B. Huang, C. Xu, R. Jiao, B. Liao, Z. Yin, and J. Li, “Game-theoretical energy management for energy internet with big data-based renewable power forecasting,” IEEE Access, vol. 5, pp. 5731–5746, Feb. 2017.

[7] W. Yi, Y. Zhang, Z. Zhao, and Y. Huang, “Multitasking robust scheduling for smart distribution grids: Considering renewable energy and demand response uncertainty,” IEEE Access, vol. 6, pp. 45715–45724, 2018.

[8] Y. An, Z. Zhao, S. Wang, Q. Huang, and X. Xie, “Coordinative optimization of hydro-photovoltaic-wind-battery complementary power stations,” CSEE J. Power Energy Syst., vol. 6, no. 2, pp. 410–418, Jun. 2020.

[9] S. Pradhan, B. Singh, B. K. Panigrahi, and S. Murshid, “A composite sliding mode controller for wind power extraction in remotely located solar PV-wind hybrid system,” IEEE Trans. Ind. Electron., vol. 66, no. 7, pp. 5322–5331, Jul. 2019.

[10] P. S. Kumar, R. P. S. Chandrasena, V. Ramu, G. N. Srinivas, and K. V. S. M. Babu, “Energy management system for small scale hybrid wind solar battery based microgrid,” IEEE Access, vol. 8, pp. 8336–8345, 2020.

[11] Y. E. Majeed, I. Ahmad, and D. Habibi, “A multi-input cascaded DC–DC converter for very small wind turbines,” IEEE Trans. Ind. Electron., vol. 66, no. 6, pp. 4414–4423, Jun. 2019.

[12] B. Wang, X. Zheng, J. Ye, and H. B. Gooi, “Deadbeat control for a single-inductor multiple-input multiple-output DC–DC converter,” IEEE Trans. Power Electron., vol. 34, no. 2, pp. 1914–1924, Feb. 2019.

[13] O. Lopez-Lapena, “Time-division multiplexing control of multi-input converters for low-power solar energy harvesters,” IEEE Trans. Ind. Electron., vol. 65, no. 12, pp. 9668–9676, Dec. 2018.

[14] B. Wang, L. Xian, U. Manandhar, J. Ye, A. Ukil, and H. B. Gooi, “A stand-alone hybrid PV/fuel cell power system using single-inductor dual-input single-output boost converter with model predictive control,” in Proc. IEEE Energy, Power Transp. Electrify., Singapore, Oct. 2017, pp. 1–5.

[15] X. Li, Z. Dong, C. K. Tse, and D. D.-C. Lu, “Single-inductor multi-input multi-output DC–DC converter with high flexibility and simple control,” IEEE Trans. Power Electron., vol. 35, no. 12, pp. 13104–13114, Sep. 2020.

[16] S. Athikakal, G. G. Kumar, K. Sundaramoorthy, and A. Sankar, “A non-isolated bridge-type DC–DC converter for hybrid energy source integration,” IEEE Trans. Ind. Appl., vol. 55, no. 4, pp. 4033–4043, Jul. 2019.

[17] A. H. Chander, L. K. Sahu, and M. Jalhotra, “Dual input converter fed transformerless multilevel inverter for standalone PV application,” in Proc. IEEE Comput., Power Commun. Technol., New Delhi, India, Sep. 2019, pp. 487–491.

[18] B. Mangu, S. Akshatha, D. Suryanarayana, and B. G. Fernandes, “Grid-connected PV-wind-battery-based multi-input-transformer-coupled bidirectional DC-DC converter for household applications,” IEEE J. Emerg. Sel. Topics Power Electron., vol. 6, no. 3, pp. 1086–1095, Sep. 2016.

[19] C.-L. Shen and S.-W. Wang, “A novel dual-input power converter for renewable-energy generation system,” in Proc. Int. Conf. Adv. Robot. Intell. Syst. (ARIS), May 2015, pp. 1–6.

[20] M. Jafari, Z. Malekmashidi, G. Lei, T. Wang, G. Platt, and J. Zhu, “Design and implementation of an amorphous high-frequency transformer coupling multiple converters in a smart microgrid,” IEEE Trans. Ind. Electron., vol. 64, no. 2, pp. 1028–1037, Feb. 2017.

[21] D. Chen, J. Jiang, Y. Qiu, J. Zhang, and F. Huang, “Single-stage three-phase current-source photovoltaic grid-connected inverter high voltage transmission ratio,” IEEE Trans. Power Electron., vol. 32, no. 10, pp. 7591–7601, Oct. 2017.

[22] N. Vamanan and V. John, “Dual-comparison one-cycle control for single-phase bidirectional power converters,” IEEE Trans. Ind. Appl., vol. 54, no. 5, pp. 4621–4631, Sep. 2018.

[23] Y. Jia and R. Wu, “Voltage source grid-connected PV inverters based on MPPT and droop control,” in Proc. IEEE 2nd Annu. Southern Power Electron. Conf. (SPEC), Dec. 2016, pp. 1–6.
YANHUI QIU was born in Fujian, China, in 1988. He received the B.S. and Ph.D. degrees in electrical engineering from Fuzhou University, Fuzhou, China, in 2011 and 2017, respectively. He holds a postdoctoral position with the College of Automation, Qingdao University. His current research interests include power electronics conversion, renewable energy source generating, and digital control.

DAOLIAN CHEN (Senior Member, IEEE) was born in Fujian, China, in 1964. He received the B.S., M.S., Ph.D. degrees and Postdoctoral Certification from the Department of Electrical Engineering, Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, China, in 1986, 1989, 1998, and 2001, respectively. He was a Teaching Assistant, a Lecturer, an Associate Professor, and a Professor with the Department of Electrical Engineering, NUAA, in 1989, 1991, 1996, and 2002, respectively. He was a Professor with the College of Electrical Engineering, Fuzhou University, Fuzhou, China, in 2005. Since 2014, he has been a Delta Scholar and the National Outstanding Professional and Technical Personnel. He has been a Millions of Leading Engineering Talents in National Ten Thousand Talent Program, China, since 2016. He has been a Chief Professor with the College of Electrical Engineering, Qingdao University, Qingdao, China, since 2017, and a Mount Tai Scholars’ Climbing Plan Expert in Shandong, since 2020. He has been the Dean of the College of Electrical Engineering, Qingdao University, since 2018. He has published three works and more than 100 technical articles. He holds more than 30 invention patents. His research interests include power electronics conversion, new energy source generating, and aviation electrical power supply systems.

Dr. Chen received one national and three province class reward productions of science and technology.

JIAWEI ZHAO was born in Shandong, China, in 1997. He received the B.S. degree in electrical engineering and automation from Shandong University, Jinan, China, in 2019. He is currently pursuing the M.S. degree in power electronics and drives with Qingdao University, Qingdao, China. He is currently studying and analyzing the topology of power electronic converters, especially high voltage gain dc–dc converters.