A High Performance Online Uninterruptible Power Supply UPS System Based on Multitask Decomposition

Lin, Qiongbin; Cai, Fenghuang; Wang, Wu; Chen, Sixiong; Zhang, Zhe; You, Shi

Published in:
IEEETransactions on Industry Applications

Link to article, DOI:
10.1109/TIA.2019.2935929

Publication date:
2020

Document Version
Peer reviewed version

Link back to DTU Orbit

Citation (APA):

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.
A High-Performance Online Uninterruptible Power Supply (UPS) System Based on Multi-task Decomposition

Qiongbin Lin, Member, IEEE, Fenghuang Cai, Wu Wang, Sixiong Chen, Zhe Zhang, Senior Member, IEEE, Shi You, Member, IEEE,

Abstract—High quality online uninterruptible power supplies (UPS) are widely used in applications e.g. precision medical equipment with critical loads. This paper proposes a low-cost and high performance online UPS system. Firstly, the performance improvement of a bidirectional switch based bridgeless power factor (PFC) converter, which is regulated by a hybrid control strategy with load current feedforward is studied. Secondly, the proposed closed-loop controller integrates improved predictive current control with predictive voltage control and applies to the second-stage neutral-point-clamped (NPC) three-level inverter for low output voltage harmonics. Moreover, a push-pull dc-dc converter interfaces and boosts voltage of a 24V battery bank as the backup energy source. Considering complexity of the UPS system as well as cost reduction, we implement a multi-task decomposition method for control on a monolithic low-cost digital signal processor (DSP) embedded with Control Law Accelerator (CLA). Finally, the experimental results from a 1kVA prototype can effectively verify validly of the theoretical analysis and design.

Index Terms—Online UPS, bidirectional switch bridgeless PFC, multi-task decomposition, three-level inverter, digital control, low cost.

I. INTRODUCTION

Online uninterruptible power supplies (UPS) provide stable, reliable and high quality power to critical loads such as communication systems, data centers, medical equipment, etc. [1], [2]. Moreover, UPS has also become an effective solution to improve energy efficiency in smart buildings [3], [4]. Generally, an UPS needs to achieve high efficiency, high power density and low cost design, and at the same time to ensure power factor correction (PFC), fast fault response and high quality output voltage. Due to the adopted line-frequency transformers, the traditional online UPS system is bulky and expensive. Therefore, using high-frequency transformers (>20 kHz) is able to reduce the volume of online UPS [5], [6], however, in such systems there are more semiconductor switches operating at high switching frequency, which decreases the overall conversion efficiency. Then the soft-switching topologies are the choices to reduce the switch losses [7]. On the other hand, non-isolated online UPS systems have no transformers meaning fewer of high-frequency switches used and therefore can solve the problems in terms of volume and efficiency associated with online UPS [8]-[14].

For efficiency improvement, volume reduction and low number of switches, various non-isolated UPS topologies have been proposed and reported [8]-[14]. A phase locked loop (PLL) based passive power filter was proposed in [8] to reduce harmonic distortion, implement PFC, and improve system efficiency. However, the passive filter is bulky and heavy. To reduce the volume of power filters, the parallel active power filter structure has been used in [9]-[10], but this structure is complicated and costly. The Z-source inverter is adopted in [11], which effectively ensures the quality of output inverter voltage when the battery voltage sags. Nevertheless, this structure increases the overall system volume due to the added Z-source network and battery bank to provide 360V dc voltage. A transformerless online UPS system consisting of a four-leg rectifier, a battery charger/discharger, and an inverter, was studied in [12]; it reduces the size, weight and cost of the system, but the needed battery voltage of 192V is still high and complicates the battery management system. Another transformerless line-interactive UPS with low ground leakage current was reported in [13], but battery bank is high and up to 180V. Thus, in [14], the battery bank voltage of 24V is used. The front-stage is a bridgeless dual Boost PFC converter, which improves efficiency of the rectifier but increases the number of power devices. The inverter is traditional single-phase full-bridge circuit, in which the employed IGBTs have high losses and
give high output voltage distortion because of the non-linearity introduced by their saturation voltage.

Besides UPS topologies, control algorithms of an entire UPS system need to be improved and even optimized in terms of both steady state and dynamic performance. Therefore, in order to minimize output voltage distortion in particular under nonlinear load, a multi-loop control architecture was proposed in [15], which can realize low output harmonic with repetitive control delay to improve inverters' dynamic and static performance. Additionally, the repetitive control is able to eliminate effects on periodic signals, and thereby the method of shortening the repetitive control delay to improve inverters’ dynamic and static performance has been used in [17]-[18]. In [19]-[20], some modified repetitive control schemes were used to improve the control performance and simplify calculation. However, most of the aforementioned control strategies are implemented for every part of UPS with a serial software architecture. Then using complex control strategy or mathematical calculation in the UPS overall system will impose a high processing burden on the master controlling chip and may cause UPS system instability. In order to overcome such issues, a distributed UPS system using distributed multiprocessor control boards has been discussed in [25], but this method is complicated and costly. On the other hand, the traditional methods use single high performance digital signal processor (DSP) or multi DSPs to implement these complex system control and mathematical logic operations, resulting in a simple structure but high cost.

In order to improve power density and efficiency of an online UPS system, this paper proposes a novel single-phase online UPS topology. The rectifier in this topology is a single-phase bridgeless PFC with bidirectional switches, as shown in Fig. 1. In comparison to traditional diode rectifier bridge PFC, VIENNA rectifier [26] and bridge-less dual Boost PFC [27], it has several advantages such as only one driving circuit needed, less devices, simple control, and high efficiency. The dc-dc converter, interfacing the battery bank and dc bus, adopts push-pull boost circuit and uses 24V battery bank. The single-phase neutral point clamped (NPC) inverter has three-level output voltage, which not only improves output waveform quality but efficiency [28]. In order to implement complex control strategies in a low-cost, low-speed DSP with control law accelerator (CLA), a control method for multi-task decomposition is proposed and therefore the tasks can process in parallel.

This paper is organized as follows. After this introduction, Section II introduces the proposed topology as well as its operation principles; Section III presents the control method for the whole UPS system; Section IV provides experimental results to verify the theoretical analysis; finally, Section V gives the conclusion.
II. TOPOLOGY AND ITS OPERATION PRINCIPLES

A. The proposed topology

Fig.1 shows the proposed online UPS topology, which is non-isolated in the grid-connected mode and galvanic isolated in battery mode. Under the grid-connected mode, the bridgeless rectifier with switches \( G_1 \) and \( G_2 \) achieves power factor correction and at the same time provides a stable dc bus voltage up to \( \pm 360V \), and then deliver high quality power to the load through the NPC inverter. When the power grid fails, the battery supports the dc bus voltage through isolated push-pull dc-dc converter. Fig.2 shows the operating modes of the various circuit sections of proposed online UPS system.

B. Bridgeless PFC with bidirectional switch

Assuming that the inductor \( L_1 \) operates in continuous conduction mode (CCM), as shown in Fig. 2(a), Rectification Mode 1 and 2 are the operating modes of the circuit during the positive half cycle of the grid. Due to symmetry, the operation principles are the same in the negative half cycle.

Rectification Mode 1: The circuit works in boost inductor charging mode. \( G_1 \) conducts high frequency operation with conduction duty cycle of \( d_{g1} \). IGBT \( G_2 \) anti-parallel diode conducts. The grid voltage \( v_b \) applies to inductor \( L_1 \), and the inductor \( L_1 \) starts to charge. The inductor current ripple is calculated by

\[
\Delta i_1 = \frac{v_b}{L_1} d_{g1} T_1
\]

where \( T_1 \) is the switching period of PFC converter.

Rectification Mode 2: The circuit works in boost inductor discharging mode. IGBT \( G_1 \) is open and diode \( D_1 \) conducts the freewheeling current. The difference between \( v_b \) and output dc voltage \( V_f = V_{bus}/2 \) is inversely applied to inductor \( L_1 \) and the current of inductor \( i_1 \) decreases linearly. Then,

\[
\Delta i_1 = \frac{v_b - v_2}{L_1} (1 - d_{g1}) T_1
\]

Equalizing (1) and (2) obtains

\[
V_d = \frac{v_b}{1 - d_{g1}}
\]

In the negative half cycle similarly we get

\[
V_d = \frac{v_b}{1 - d_{g2}}
\]

where \( d_{g2} \) is the duty cycle of IGBT \( G_2 \).

Apparently, the achieved voltage gain is the same as that in the conventional Boost PFC.

C. Isolated push-pull dc-dc converter

When there is a grid power failure and the PFC rectifier stops working, the battery provides dc bus voltage up to \( \pm 360V \) through the push-pull dc-dc converter with a high frequency transformer. As illustrated in Fig.2 (b), during dc Mode 1, MOSFET \( G_1 \) is on and \( G_3 \) is off, and the rectifier diodes \( D_{b1} \) and \( D_{b3} \) turn on, the output voltage is stable through \( L_1 \), \( L_2 \) and \( C_1 \) and \( C_2 \).

Assuming that the conduction duty cycle of the switch \( G_3 \) is \( d_{g3} \), then, \( d_{g3} = \frac{V_{bus}}{2V_b} \). The battery bank voltage is \( V_b \), the center tap transformer is vertically symmetrical and the turns ratio is 1. Assuming turns ratio is \( N_1:N_2 \), Where \( N_1 \) is the number of turns in primary winding and \( N_2 \) is the number of turns in secondary winding. The output voltage is

\[
2V_d = \frac{N_2}{N_1} d_{g3} V_b
\]

D. Single-phase NPC inverter

The most critical part of the online UPS is the inverter that supplies the voltage to the load. The working principle of the NPC inverter is shown in Fig. 2(c). When the inverter is in the positive half cycle, \( S_1 \) operates at a high frequency, \( S_2 \) turns on, and \( S_1, S_2 \) do not participate in the operation. When the inverter is in the negative half cycle, the action of switches is reversed. Here, only the operation principle in the positive half-cycle is analyzed since the NPC inverter works symmetrically in the negative half-cycle.

Inverter Mode 1: \( S_1 \) and \( S_2 \) turn on, the inverter energy is provided by the positive bus capacitor \( C_1 \), and the inductor current rises linearly under the combined action of positive bus voltage and output voltage.

\[
\Delta i_{12} = \frac{v_{inv}}{L_2} (1 - d_{i1}) T_2
\]

where \( v_{inv} \) is the inverter output voltage, \( i_{12} \) is the inverter inductor current, and \( d_{i1} \) is the duty cycle of the switch \( S_i \).

Inverter Mode 2: \( S_1 \) turns off, \( S_2 \) turns on, and the inverter voltage to the load is supplied by the energy store at output filter. The inductor current drops linearly under the action of output voltage

\[
\Delta i_{12} = \frac{V_d}{L_2} d_{i1} T_2
\]

The relationship between the duty cycle and the bus voltage and the inverter voltage can be obtained from (6) and (7).

\[
v_{inv} = d_{i1} V_d
\]

III. SYSTEM CONTROL TECHNOLOGY

A. Multi-task decomposition

According to the relationship between the input-output voltage and the duty ratio, the PWM driving signal required by each controller can be obtained. Prior to this, the DSP needs to be decomposed modularly to make it suitable for collaborative control between the various parts of the online UPS system. The decomposition of each module is shown in Fig. 3.

Where the CLA is responsible for the subroutines of the PFC converter and the push-pull converter, and both of the converters have switching frequency of 40 kHz. In addition to executing the 20kHz switching frequency for the NPC
inverter, the main core also needs to capture, sampling and interrupt the procedures, etc. This design is difficult to achieve if the main frequency of single-core microcontroller is only 60MHz. Therefore, this design uses the "pseudo-dual core" task-parallel architecture to achieve the CLA "multiplier" effect. The CLA triggering mechanism of the PFC and dc-dc converter in Fig. 3 is triggered periodically by PWM1 and PWM2, respectively. The grid-connected state and the battery mode in the UPS work independently, so the two subroutines in CLA had no interruption of nesting.

Fig. 4 shows the block diagram of specific control strategy of each module. Where the rectified PFC converter is controlled by combining the proportional integral (PI) voltage outer loop and deadbeat mixed conduction mode (MCM) current inner loop. At the same time, the load current feed forward control is added to improve the dynamic and static performance of the PFC. The push-pull dc-dc converter uses traditional voltage and current double loop PI control, so the detailed controller design is no given here. In order to improve the dynamic and static performance of the inverter as well as reduce the waveform distortion with nonlinear load, the current inner loop adopts predictive control based on the voltage PI outer loop to improve the dynamic response speed of the system through the inductor current prediction.

B. PFC control

The outer voltage loop of the bridgeless PFC is realized by PI control, and for the inner current loop, deadbeat control is used. In CCM, we have

\[
\begin{align*}
L_1 \frac{di_{L1}}{dt} &= v_g(n) - V_d (t_n < t < t_n + T_s d_{PFCn}) \\
L_1 \frac{di_{L1}}{dt} &= v_g(n) - V_d (t_n + T_s d_{PFCn} < t < t_{n+1})
\end{align*}
\]  

(9)

where \( n \) is the \( n \)th switch period of a power frequency cycle and \( v_g(n) \) is the corresponding voltage of power grid. \( T_s \) and \( d_{PFC} \) are the switching period and duty cycle of the PFC converter, respectively.

Given that the grid voltage as a constant value during a single switching cycle, the duty cycle expression of CCM is

\[
d_{PFC}[n] \approx \frac{(i_{L1}[n+1]-i_{L1}[n])L_1}{T_s V_d} + \frac{V_d-v_g[n]}{V_d} = d_i + d_{ccm}
\]

(10)

where,

\[
d_{ccm} = \frac{V_d-v_g[n]}{V_d}
\]

(11)

\[
d_i = \frac{(i_{L1}[n+1]-i_{L1}[n])L_1}{T_s V_d}
\]

(12)

\( d_{ccm} \) is a voltage-dependent steady-state open-loop term, and \( d_i \) is a current-dependent sinusoidal correction term. The conventional PI controller controls the duty cycle \( d_i \) to make the output sinusoidal.

Due to the sinusoidal ac output current, there will be discontinuous current mode (DCM) or the mixed current mode (MCM) i.e. CCM and DCM coexisting, depending on the load. Therefore, continuous current mode operation no longer holds and the traditional control method deteriorates the performance of the prototype. Therefore, further analysis of PFC control under DCM and MCM is required. The duty cycle of the steady-state open-loop term can be obtained as follows

\[
d_{ccm} = \sqrt{2L_s f_s f_i d_{ccm}}
\]

(13)
where \( d_{\text{dcm}} \) is the duty ratio of PFC inductor in DCM, \( d_{\text{ccm}} \) is the duty ratio in CCM, \( g_e = \frac{P_{\text{m}}}{V_g} \), and the input power \( P_{\text{m}} = g_e \cdot v_g^2 \) when the PFC current completely tracks the input voltage. Analyze the steady-state open-loop duty cycle operating in critical mode to select a suitable steady-state open-loop term. Using the CCM steady-state open-loop term \( d_i \) in (11) and DCM steady-state open-loop term \( d_{\text{dcm}} \) in (13), the duty ratio \( d_{\text{ccm}} \) of the steady-state open-loop term of the critical mode can be obtained as

\[
d_{\text{ccm}} = 2L_1 f_s V_g \tag{14}\]

According to (11), the minimum value of \( d_i \) at the peak grid voltage is

\[
d_{\text{ccmin}} = 1 - \frac{\sqrt{2} v_g^*}{V_g} \tag{15}\]

where \( V_g \) is the root meaning square value of the grid voltage.

When \( d_{\text{ccmin}} \) is larger than (15), the PFC works in CCM, otherwise it works in DCM. Combining (14), (15) and \( g_e = \frac{P_{\text{m}}}{V_g} \), \( g_e \) needs to satisfy (16) when the system is completely discontinuous or completely continuous.

\[
\begin{align*}
g_e &< \frac{1}{2L_1 f_s} - \frac{\sqrt{2} V_g^*}{2L_1 f_s V_g} & \text{DCM} \\
g_e &\geq \frac{1}{2L_1 f_s} & \text{CCM}
\end{align*}
\tag{16}
\]

The MCM control mode of the PFC converter determines the duty cycle steady-state open-loop term to select \( d_{\text{dcm}} \) or \( d_{\text{ccm}} \) according to \( g_e \). In the PFC circuit of the online UPS, there is a double-line-frequency ripple, 100Hz or 120Hz, in the dc bus voltage during the grid-connected mode. The bandwidth of the voltage loop is usually set low to attenuate such low frequency ripple; however, the PFC dynamic performance suffers. Therefore, load current feed forward is introduced in the current dead-beat MCM controller to the PFC. Applying Kirchoff’s Current Law (KCL), the inverter load current \( i_o \) is the difference between the diode output current \( i_d \) and the filter capacitor output current \( i_c \). We get

\[
i_o = i_d - i_c = (1 - D) i_{L2} - C_\alpha \frac{dv}{dt} \tag{17}\]

After discretizing (17), the instantaneous value expression of the output current of the dc bus with load can be obtained as

\[
i_o(k) = (1 - d_{\text{PFC}}[k - 1]) i_{L2}(k) - C_\alpha \frac{v_o[k] - v_o[k - 1]}{T_s} \tag{18}\]

The PFC controller in Fig. 4 can be obtained by putting the above load current as a feed forward term into the PFC current deadbeat MCM control.

C. Three level inverter control

The inverter adopts PI control and repetitive control in the voltage outer loop; improved predictive control is used in the inner current loop, and the predictive control directly gives the duty cycle of the next switching cycle according to the inductor current reference so that improve the dynamic performance of the inverter.

When the inverter is operating at steady state, the changes of the bridge arm point A and \( v_{L2} \) of the filter inductor \( L_2 \) during the the switching period of \([k, k+1]\) are

\[
v_{L2}[k] = v_{\text{in}}[k] + (i_{L2}[k + 1] - i_{L2}[k]) \frac{L_2}{T_s} \]

where \( v_{\text{in}} \) is inverter voltage, \( L_2 \) is inverter filter inductance, \( i_{L2} \) is inductor current, and \( d_{\text{inv}} \) is inverter duty cycle. The inner loop control target is the value of the inductor current at \([k+1]\), which is the value of the sampled value \( i_{L2}[k + 1] \) tracking reference current value \( i_{\text{ref}}[k + 1] \).

The output duty cycle of the inner loop controller is expressed as

\[
d[k] = \frac{v_{\text{in}}[k] + (i_{\text{ref}}[k + 1] - i_{L2}[k]) \frac{L_2}{T_s} \times d_{\text{inv}}[k]}{V_d[k]} \tag{19}\]

The input-to-output transfer function of the current loop can be derived by combining (20) and LC type filters

\[
i_{L2}(z) = \frac{1}{L_2 \frac{T_s}{z} + k_p (z - 1) + 1} \tag{21}\]

The inverter circuit parameters of \( T_{L2} \) and inductor \( L_2 \) are selected as 50 μs and 1.8 mH respectively without considering the system delay. Fig. 5(a) and Fig. 5(b) are graphs showing the variation of the zero-pole of (21) with the coefficient \( k_p \). The necessary and sufficient condition for the system to be stable in the Z domain is that its poles are distributed in the unit circle of the Z domain. In Fig.5 (a), when the proportional coefficient \( k_p < \frac{L_2}{T_{L2}} \), the system with
the pole in the right half of the real axis will have low-pass output characteristic. When \( L_2/Tz_2 < k_p < 2L_2/Tz_2 \), the system with the pole in the left half of the real axis will have high-pass output characteristic. Thus, the proportional coefficient \( k_p \) of the predictive controller must be less than \( L_2/Tz_2 \).

Since the actual on-line UPS system has control delay, the duty cycle \( d[k] \) in (20) needs to add a delay zero-order keeper \( Z^1 \) before outputting. After adding the zero-order keeper in (21), we get

\[
i_{L2}(z) = \frac{1}{L_2 Tz^2 k_p} z(z-1) + 1
\]  

Fig. 5(c) shows the variation of the zero-pole point of (22) with \( k_p \). Since the system will not be stable when \( k_p > L_2/Tz_2 \), thus, in order to satisfy both the stability and low-pass output characteristics of the system, the proportional coefficient must be satisfied \( k_p < L_2/Tz_2 \), and its stability margin is \( L_2/Tz_2 \). The purpose of predictive control is to make the error be zero in the next cycle. Too small stability margin will result in insufficient stability margin and poor dynamic performance of the online UPS system. However, it is difficult to reduce the control error to zero due to the parameter uncertainty of system in practical use.

In order to overcome this problem, an improved predictive current control strategy that can automatically convert the current error into zero is proposed combined with [29], which doubles the stability margin of the system. The improved design of the predictive current inner loop is given by

\[
v_{\text{in},[k]} + (v_{\text{ref},[k+1]} - i_{L2}[k] - 0.5e_i[k]) \frac{k_p L_2}{Tz^2} d[k] = v_{d_0}[k] \]  

where \( e_i[k] \) is the current error.

Fig. 4 shows the control structure of the improved inverter current loop, and Fig. 5(d) shows the corresponding closed-loop root locus. The predictive current can give a control duty cycle \( d[k] \) in (23) needs to add a delay zero-order keeper \( Z^1 \) before outputting. After adding the zero-order keeper in (21), we get

\[
i_{L2}(z) = \frac{1}{L_2 Tz^2 k_p} z(z-1) + 1
\]  

The pole in the right half of the real axis will have low-pass output characteristic. When \( L_2/Tz_2 < k_p < 2L_2/Tz_2 \), the system with the pole in the left half of the real axis will have high-pass output characteristic. Thus, the proportional coefficient \( k_p \) of the predictive controller must be less than \( L_2/Tz_2 \).

Since the actual on-line UPS system has control delay, the duty cycle \( d[k] \) in (20) needs to add a delay zero-order keeper \( Z^1 \) before outputting. After adding the zero-order keeper in (21), we get

\[
i_{L2}(z) = \frac{1}{L_2 Tz^2 k_p} z(z-1) + 1
\]  

Fig. 5(c) shows the variation of the zero-pole point of (22) with \( k_p \). Since the system will not be stable when \( k_p > L_2/Tz_2 \), thus, in order to satisfy both the stability and low-pass output characteristics of the system, the proportional coefficient must be satisfied \( k_p < L_2/Tz_2 \), and its stability margin is \( L_2/Tz_2 \). The purpose of predictive control is to make the error be zero in the next cycle. Too small stability margin will result in insufficient stability margin and poor dynamic performance of the online UPS system. However, it is difficult to reduce the control error to zero due to the parameter uncertainty of system in practical use.

In order to overcome this problem, an improved predictive current control strategy that can automatically convert the current error into zero is proposed combined with [29], which doubles the stability margin of the system. The improved design of the predictive current inner loop is given by

\[
v_{\text{in},[k]} + (v_{\text{ref},[k+1]} - i_{L2}[k] - 0.5e_i[k]) \frac{k_p L_2}{Tz^2} d[k] = v_{d_0}[k] \]  

where \( e_i[k] \) is the current error.

Fig. 4 shows the control structure of the improved inverter current loop, and Fig. 5(d) shows the corresponding closed-loop root locus. The predictive current can give a control duty cycle \( d[k] \) in (23) needs to add a delay zero-order keeper \( Z^1 \) before outputting. After adding the zero-order keeper in (21), we get

\[
i_{L2}(z) = \frac{1}{L_2 Tz^2 k_p} z(z-1) + 1
\]  

Fig. 5(c) shows the variation of the zero-pole point of (22) with \( k_p \). Since the system will not be stable when \( k_p > L_2/Tz_2 \), thus, in order to satisfy both the stability and low-pass output characteristics of the system, the proportional coefficient must be satisfied \( k_p < L_2/Tz_2 \), and its stability margin is \( L_2/Tz_2 \). The purpose of predictive control is to make the error be zero in the next cycle. Too small stability margin will result in insufficient stability margin and poor dynamic performance of the online UPS system. However, it is difficult to reduce the control error to zero due to the parameter uncertainty of system in practical use.

In order to overcome this problem, an improved predictive current control strategy that can automatically convert the current error into zero is proposed combined with [29], which doubles the stability margin of the system. The improved design of the predictive current inner loop is given by

\[
v_{\text{in},[k]} + (v_{\text{ref},[k+1]} - i_{L2}[k] - 0.5e_i[k]) \frac{k_p L_2}{Tz^2} d[k] = v_{d_0}[k] \]  

where \( e_i[k] \) is the current error.

IV. EXPERIMENTAL RESULTS

To verify the performance of the proposed UPS system, a laboratory prototype with an output power of 1kVA has been implemented with the specifications shown in Table I. The parameters of this prototype are given in Table II. And the DSP in the prototype uses TMS320F28035.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>1kVA</td>
<td>PFC switching frequency</td>
</tr>
<tr>
<td>Rated Efficiency</td>
<td>Grid mode: &gt;90%</td>
<td>DC-DC switching frequency</td>
</tr>
<tr>
<td></td>
<td>50Hz/60Hz</td>
<td>Inverter switching frequency</td>
</tr>
<tr>
<td></td>
<td>220V ±1V</td>
<td>Grid input voltage</td>
</tr>
<tr>
<td></td>
<td>±160V</td>
<td>DC bus voltage</td>
</tr>
<tr>
<td></td>
<td>220V in, 240V out</td>
<td>Inverter output voltage</td>
</tr>
<tr>
<td></td>
<td>1000VDC</td>
<td>Inverter output power</td>
</tr>
<tr>
<td></td>
<td>1.2mH</td>
<td>PFC boost inductor</td>
</tr>
<tr>
<td></td>
<td>3.8mH</td>
<td>Inverter filter inductor</td>
</tr>
<tr>
<td></td>
<td>700μF</td>
<td>DC bus capacitor</td>
</tr>
<tr>
<td></td>
<td>4.7μF</td>
<td>Inverter filter capacitor</td>
</tr>
<tr>
<td></td>
<td>STGW15N120H1</td>
<td>PFC switch IGBT</td>
</tr>
<tr>
<td></td>
<td>R1RP8120</td>
<td>PFC freewheeling Diode</td>
</tr>
<tr>
<td></td>
<td>STG14N60KD</td>
<td>Inverter switch IGBT</td>
</tr>
<tr>
<td></td>
<td>MUR1560</td>
<td>NPC freewheeling Diode</td>
</tr>
</tbody>
</table>

![Experimental setup](Fig. 6. Experimental setup.)

The constructed prototype of proposed UPS and its experiment test platform are shown in Fig. 6. It is worth to mention that it will have a very high voltage spikes across the devices \( G_1 \) and \( G_2 \) in the push-pull dc-de converter shown in Fig. 2(b) due to the leakage inductance of the center tapped transformer windings, if there is no any absorb/snubber circuit. Therefore, \( RC \) absorb circuits are used in this experimental
hardware. Then, the following experimental tests are carried out.

A. Grid-connected mode

Fig. 7 shows measured waveforms from the PFC converter and the cascaded NPC inverter with the resistive load. Where $v_d$ is the variation waveform of driving voltage duty cycle, $v_g$ and $i_g$ are the grid voltage and current, respectively. Fig. 7(a) and Fig. 7(b) show the PFC waveform at 25% of full load and rated load 1kw when the grid input voltage is 220Vrms; Fig. 7(c) shows that sudden load causes the dc bus voltage to drop of approximately 9.5% when no load current feed forward. The experimental waveform after adding the load current feed forward control as shown in Fig. 7(d), and the bus voltage drops only 3.9%.

B. Battery mode

The experimental waveform of the battery to maintain the stability of dc bus voltage is shown in Fig. 8. Where $V_{ds}$ is the drain to source voltage of the switch $G_3$, $V_{pwm}$ is the driving signal of $G_3$, and it is inverse phase with the gate voltage of $V_{G3}$ due to the isolated driving circuit with optocouplers. $i_b$ is the battery output current, and $V_{db}$ is the voltage of the secondary side rectifier diode $D_{b2}$. The voltage and current waveforms of each key point when the push-pull output power is 100W as shown in Fig. 8(a), and the waveform corresponding to the output power at 700 W as shown in Fig. 8(b).

When the power supply is normal, the experimental waveforms of the dc bus voltage, which is supplied by the PFC rectifier and loaded by the inverter, is as shown in Fig. 9. Where $V_{GS4}$ is the driving voltage of the switch $S_4$, $V_A$ is the voltage of the midpoint of the bridge arm to the negative bus,
the inverter voltage is $v_{inv}$, and the load current is $i_o$.

Under light load condition, the experimental waveform of inverter output voltage, the waveforms of the corresponding driving signal and the bridge point A is as shown in Fig. 9(a). Fig. 9(b) and Fig. 9(c) show the output voltage and current at light load and full load, respectively. The distortion of the inverter voltage waveform when the voltage PI loop with nonlinear load as shown in Fig. 9(d). The inverter voltage waveform when the repetitive control voltage loop is combined with the predictive current inner loop under a nonlinear load as shown in Fig. 9(e).

C. Transition from grid-connected mode to battery mode

When there is a power failure, the online UPS needs to be powered by the battery bank to ensure safe and reliable operation of the equipment. Fig. 10 shows the experimental waveform of the power supply from the battery mode when the power failure occurs and the PFC rectifier does not work. In Fig. 10 (a), it can be seen that when there is no power from the utility grid, the battery provides the dc bus voltage to ensure the stability of the UPS output inverter voltage. The corresponding experimental waveforms of the inverter voltage and battery current in this mode are shown in Fig. 10(b).

The measured efficiencies and total harmonic distortion (THD) are presented in Fig. 11. The efficiency test of the invert output with resistive load is shown in Fig. 11(a). The peak value of the two-stage conversion efficiency of the grid-connected state and the battery mode is 92% and 90.8%, respectively. As can be seen from Fig. 11(b), the commercial grid side PFC grid-connected current THDi is 3.4% at full load, and the invert output voltage THDu with resistive load is 1.7% at the full load.
Fig. 10. Experiments of grid-connected mode and battery mode.

Table III shows the performance comparison of different UPS structures to compare the performance of the proposed UPS prototype. Online UPS develops towards high frequency and power density, traditional methods use multi-chip DSP to work together or single-chip high-performance DSP to realize the high frequency of the UPS. In the proposed experimental prototype, if the semiconductor devices with low conduction and switching loss are used for instance wide bandgap devices, the efficiency of the whole system can be further improved.

<table>
<thead>
<tr>
<th>Types of UPS</th>
<th>Efficiency</th>
<th>Power Ratings</th>
<th>Battery bank</th>
<th>Size</th>
<th>Master chip</th>
<th>Switching frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z-source inverter based UPS[battery mode][12]</td>
<td>95%</td>
<td>3kVA</td>
<td>360V</td>
<td>medium</td>
<td>Only one DSP in battery mode</td>
<td>10kHz</td>
</tr>
<tr>
<td>Little battery bank online UPS[14]</td>
<td>92%</td>
<td>1kVA</td>
<td>24V</td>
<td>small</td>
<td>TMS320F28335 (150MHz)</td>
<td>AC-DC 30kHz DC-DC 30kHz DC-AC 20kHz</td>
</tr>
<tr>
<td>UPS proposed in this paper</td>
<td>92%</td>
<td>1kVA</td>
<td>24V</td>
<td>small</td>
<td>TMS320F28303 (60MHz)</td>
<td>AC-DC 40kHz DC-DC 40kHz DC-AC 20kHz</td>
</tr>
</tbody>
</table>

V. CONCLUSION

A low-cost single-phase online UPS topology is proposed and researched in this paper. A novel single-phase bridgeless boost PFC circuit with a bidirectional switch has been used, and the dynamic and the static performance of the PFC has also been improved by the MCM current deadbeat control with the load current feed forward. By the voltage loop PI + repetitive control combined with the predictive current control strategy, THDu of ac output voltage is lower than 2% over the entire load range. A multi-task decomposition method for implementation of "multiplier", which is completed by the way of task parallelism, and overall control of the online UPS system on a monolithic low cost DSP embedded with CLA. This provides an effective solution for designing low cost, the high frequency, high
power density and high complex power electronic systems. It is worth to mention that the bidirectional switch rectifier containing two IGBTs can be replaced by one GaN bidirectional switch with lower power loss, when the price of high voltage GaN device decline in future. Based on the proposed online UPS and its control strategy with multi-task decomposition, the system efficiency will be higher by using SiC diodes and SiC MOSFETs in inverter.

REFERENCES


Qiongbin Lin (M’18) was born in Fujian, China. He received the B.Sc. degree in industrial automation, and the B.Sc. degree in business administration, and the M.Sc. degree in control theory and control engineering, and the Ph.D. degree in electrical engineering from Fuzhou University, Fuzhou, China, in 2000, 2002, 2003, and 2010, respectively. He is currently an Associate Professor at College of Electrical Engineering and Automation, Fuzhou University, Fuzhou, China. He was a Postdoctoral Research Fellow with the College of Electrical Engineering, Zhejiang University, Hangzhou, China, from 2013 to 2015. From 2018 to 2019, he was a Visiting Scholar with the Technical University of Denmark, Denmark. Dr. Lin’s main research interests include power converter modeling and control, model-based and data-driven fault diagnosis, renewable energy and multi-energy systems, networked control systems and fuzzy nonlinear systems.
Fenghuang Cai was born in Fujian, China in 1976. He received his B.S in Industrial Automation, M.S in Control Theory and Engineering, Ph.D. in Electrical Engineering from the Fuzhou University, PR China, in 1998, 2002 and 2007, respectively. He joined Fuzhou University in 1998. Since 2010, he has been an Assistant Professor in Control Engineering. His current research interests include power electronics and control, which include modeling and optimization of power electronic system, digital-signal-processing-based control applications, distributed generation, and renewable energy.

Wu Wang was born in Fujian, China, in 1973. He received his B.S. degree in Mechanical Design and Manufacturing, and M.S. degree in Agricultural Mechanization Engineering from Fujian Agriculture and Forestry University, PR China, in 1996 and 1999, respectively. He received his Ph.D. degree in Electrical Engineering from the Fuzhou University, PR China, in 2004. He joined Fuzhou University in 2004, where he is currently a Professor in Control Engineering. His research interests include the modeling and control of power electronic systems, H-infinity control and filtering, and networked control.

Sixiong Chen was born in Fujian, China. He received the B.Sc. degree in Nuclear Physics from University of Science and Technology of China, Hefei, China, in 1992, and the M.Sc. degree in executive mater of business administration from Tsinghua University, Beijing, China, in 2014. He is currently a Professor-level Senior Engineer, Chief engineer of R&D Center, and the vice president of the company of Kehua Hengsheng Co., Ltd. He is the holder of 16 Chinese patents. His research interests include uninterruptable power supplies (UPS), renewable energy systems (RES) and energy storage systems (ESS).

Mr. Chen has received several awards and honors including the Special Allowance Expert of the State Council Award, Fujian Science and Technology Innovation Leading Talents Award, The first prize of the Ministry of education's Technology Invention Award, and the first prize for Scientific and Technological Progress in Fujian Province. He is the Vice-Chairman of Information System Power Supply Technology Committee of China Power Supply Society.

Zhe Zhang (M’11-SM’16) received the B.Sc. and M.Sc. degrees in power electronics from Yanshan University, Qinhuangdao, China, in 2002 and 2005, respectively, and the Ph.D degree from the Technical University of Denmark, Kgs. Lyngby, Denmark, in 2010. He is currently an Associate Professor in the Department of Electrical Engineering, at the Technical University of Denmark (DTU). Since Jan. 2018, he has been Head of Studies in charge of Electrical Engineering MSc Programme at DTU. From 2005 to 2007, he was an Assistant Professor at Yanshan University. From June 2010 to August 2010, he was with the University of California, Irvine, CA, USA, as a visiting scholar. He was an Assistant Professor at the Technical University of Denmark during 2011 and 2014. He has authored or co-authored more than 150 transactions and international conference papers and filed 8 patent applications. He has supervised over 10 Ph.D students since 2013. Dr. Zhang’s current research interests include wide bandgap devices and their applications, high frequency dc-de converters, multiple-input dc-dc converters, soft-switching power converters and multi-level dc-ac inverters for renewable energy systems (RES), hybrid electric vehicles (HEV) and uninterruptable power supplies (UPS); piezoelectric-actuator and piezoelectric-transformer based power conversion systems.

Dr. Zhang has received several awards and honors including Best Paper Award in IEEE ECCE, Best Paper Award in IEEE IGBSG, Best Teacher of the Semester, Chinese Government Award for Outstanding Students Abroad, etc. He is also a guest associate editor in IEEE Transactions on Industrial Electronics and Guest Editor in IEEE Journal of Emerging and Selected Topics in Power Electronics.

Shi You received the M.Sc. degree in electrical engineering from the Chalmers Institute of Technology, Gothenburg, Sweden, in 2007, and the Ph.D degree in electrical engineering from the Technical University of Denmark (DTU), Kongens Lyngby, Denmark, in 2011. He is currently a Senior Researcher with the Center for Electric Power and Energy, Department of Electrical Engineering, DTU. His research interests include optimal design, planning, operation and control of active distribution networks, and integrated multicarrier energy systems.