Cascade Dual Buck Inverter With Phase-Shift Control

Pengwei Sun, Student Member, IEEE, Chuang Liu, Student Member, IEEE, Jih-Sheng Lai, Fellow, IEEE, and Chien-Liang Chen, Member, IEEE

Abstract—This paper presents a new type of cascade inverter based on dual buck topology and phase-shift control scheme. The proposed cascade dual buck inverter with phase-shift control inherits all the merits of dual buck type inverters and overcomes some of their drawbacks. Compared to traditional cascade inverters, it has much enhanced system reliability thanks to no shoot-through problems and lower switching loss with the help of using power MOSFETs. With phase-shift control, it theoretically eliminates the inherent zero-crossing distortion of the single-unit dual buck type inverter. In addition, phase-shift control and cascade topology can greatly reduce the ripple current or cut down the size of passive components by increasing the equivalent switching frequency. A cascade dual buck inverter has been designed and tested to demonstrate the feasibility and advantages of the system by comparing single-unit dual buck inverter, 2-unit and 3-unit cascade dual buck inverters at the same 1 kW, 120 V ac output conditions.

Index Terms—Cascade inverter, dual buck inverter, phase-shift control.

I. INTRODUCTION

Among various multilevel voltage-source inverters, the most commonly used and commercially available ones are the neutral-point-clamped inverter, flying capacitor inverter, and cascade H-bridge inverter [1]–[4]. The cascade type inverters are capable of reaching higher output voltage level by using commercially standard lower voltage devices and components. They also feature a modular design concept which makes maintenance less burdensome [1]–[10]. The cascade inverters are well suited for utility interface of various renewable energy sources, such as photovoltaics, fuel cells, battery energy storage, and electric vehicle drives, where separate dc sources naturally exist [11]–[21]. However, because most current cascade inverters are based on a series connection of several single voltage source inverters (VSI) with two active devices in one leg, they suffer from shoot-through problems, the most dominating failure of VSI. In addition, for the hard-switched cascade inverters operating at higher dc bus voltage, they lose the benefit of using power MOSFETs as the active switching devices for efficiency improvement and fast switching speed when they are available at certain voltage and power level. For example, when the cell dc bus voltage goes up to 300 V to 600 V, high voltage power MOSFETs (600 V to 900 V level, like CoolMOS or MDmesh series) cannot be adopted to work at hard-switched situations like traditional cascade H-bridge inverters because of the reverse recovery issues of the body diode [34]–[38] unless soft-switching techniques are employed [39]–[41].

This paper proposes a new cascade dual buck inverter based on single dual buck inverter topology to better address the issues mentioned above. The dual buck type inverters are still VSI, but with the unique topology and operation, they do not have the shoot-through worries, which leads to greatly enhanced reliability [22]–[24]. Thanks to the lack of shoot-through worries of each building block, the cascade dual buck inverter features improved system reliability compared to other cascade inverters. In addition, the cascade dual buck inverter does not have the dead time related issues of conventional VSI-based cascade inverters, which can easily push the duty cycle to the theoretical limit and fully transfer the energy to load through total PWM. In addition, the cascade dual buck inverter can be hard-switched while utilizing the benefits of power MOSFETs at certain power levels.

Phase-shift control is widely used for cascade inverters because it is easy to implement with digital controllers and it equivalently increases the switching frequency by the number of cascade units, which reduces the output voltage and current ripple [25]–[27]. For the cascade dual buck inverter, phase-shift control is adopted as well. Besides the common benefits, it solves another problem for this unique cascade topology. One of the inherent drawbacks of single dual buck inverters is the current zero-crossing distortion, which will be explained in detail in Section III. Fortunately, with the help of phase-shift control, cascade dual buck inverter theoretically eliminates the zero-crossing distortion from zero to full load conditions.

The paper first shows different topologies of the proposed cascade dual buck inverters and their operation principles. This paper takes single-phase cascade dual buck half-buck inverter as the analytical and design subject to demonstrate the feasibility and advantages of cascade dual buck inverters. The phase-shift control scheme is analyzed by comparing single-unit dual buck inverter and 2-unit cascade dual buck inverter. The closed-loop control for cascade dual buck inverter has been designed and implemented. A 1 kW, 120 V ac output cascade dual buck inverter system has been built to validate the proposed topology and control by comparing the experimental test results of single-unit dual buck inverter, 2-unit and 3-unit cascade dual buck inverters.

II. TOPOLOGY AND OPERATION PRINCIPLE

The single-unit dual buck inverter has two basic forms, dual buck half-buck inverter [22], [24] and dual buck full-bridge inverter [23]. The proposed cascade dual buck inverter has
two types accordingly: cascade dual buck half-bridge inverter, shown in Fig. 1, and cascade dual buck full-bridge inverter, shown in Fig. 3. This paper will focus on the analysis, design, and testing of the cascade dual buck half-bridge inverter to demonstrate the feasibility and advantages of cascade dual buck inverters.

In [24], the control strategy for two dual buck half-bridge inverters in series output to obtain higher voltage was proposed. However, the two dual buck inverters shared the same dc power supply, had two sets of filter inductor and capacitor, and the connection was only effective for two units. The proposed inverter in this paper features a different series connection concept, the cascading, which has separate dc power supplies for each cell, and is extended to $N$ unit connection, and shares the same filter components.

Fig. 1 shows the topology of the proposed cascade dual buck half-bridge inverter. It consists of $N$ units of single dual buck half-bridge inverter. Each unit is composed of two power MOSFETs and two fast recovery diodes. Each unit has two output ports, $i_P$ and $i_N$ ($i = 1, 2, \ldots, N$). To realize the cascade topology, the $iN$ port of the $i$th unit is connected with the $(i + 1)P$ port of the $(i + 1)$th unit, and port $1P$ and $NN$ are used as the output ports.

$S_{ip}$ and $D_{ip}$ are a working pair, and operate at the positive half-cycle of output current $i$. $S_{in}$ and $D_{in}$ are another working pair, and operate at the negative half-cycle of output current $i$. The single unit operation modes are shown in Fig. 2 [22], [24]. For the cascade dual buck inverter, if phase-shift control is not adopted, we can switch all the units exactly the same way as single-unit inverter. This means the PWMs for $S_{ip}$ and $S_{in}$ are the same. However, this will bring the zero-crossing distortion problem of single-unit dual buck inverters into the cascade topology. In addition, without phase-shift control, the cascade topology loses the benefits of increased equivalent switching frequency and reduced output current ripple. Therefore, the proposed cascade dual buck inverter utilizes the phase-shift control technique to eliminate the zero-crossing distortion problem of single unit dual buck inverter and at the same time achieve higher equivalent switching frequency thus cutting down output current ripple. The detailed analysis of phase-shift control of cascade dual buck inverter will be presented in Section III.

Fig. 3(a) shows the topology of single-unit full-bridge dual buck inverter [23]. For the cascade dual buck full-bridge inverter shown in Fig. 3(b), we can put $N$ units of this single full-bridge dual buck inverter in series just like cascade dual buck half-bridge inverter in Fig. 1. The operation principle of cascade dual buck full-bridge inverter with phase-shift control will be similar to cascade dual buck half-bridge inverter, and will not be discussed in this paper.

### III. Phase-Shift Control Analysis

One of the significant characteristics of a single-unit dual buck type inverter is that the switch is selectively working based on the direction of output current. From the operation modes of single-unit half-bridge dual buck inverter in Fig. 2, we can clearly see that when $i_1$ is positive, $S_{1p}$ and $D_{1p}$ are the working pair, and when $i_1$ is negative, $S_{1n}$ and $D_{1n}$ are the working pair. However, this distinctive operation leads to its inherent drawback, current zero-crossing distortion, which will be explained in detail below. This issue can be passively mitigated by turning
Fig. 3. Single-unit dual buck full-bridge inverter serving as one cell for cascade dual buck full-bridge inverter. (a) Single-unit dual buck full-bridge inverter. (b) Cascade dual buck full-bridge inverter.

Fig. 4. Equivalent circuit of single-unit half-bridge dual buck inverter when \( S_{1p} \) is ON.

on both \( S_{1p} \) and \( S_{1n} \) near zero-crossing period. However, this remedy is against the operating principle and the best feature of the dual buck type inverter, which is high reliability by avoiding turning on both active switches at the same time. In addition, this passive measure results in higher switching losses because at zero-crossing period two switches are switching while the original goal of dual buck inverter is to have only one switch operating at any given time.

Thankfully, cascade topology solves the issue of zero crossing distortion by using phase-shift control scheme. With phase-shifted PWM fed to different cascade units, current zero-crossing distortion is theoretically eliminated. In addition, the phase-shift control greatly increases the equivalent switching frequency by \( N \) times that of single-unit inverter, which leads to significantly lower current ripple or smaller passive filter components.

In order to illustrate the phase-shift control, single-unit half-bridge dual buck inverter and 2-unit cascade half-bridge dual buck inverter are analyzed. Fig. 4 shows the equivalent circuit of single-unit half-bridge dual buck inverter when \( S_{1p} \) is ON. Fig. 5 shows the gate signal of \( S_{1p} \) and the current through output inductor \( i_1 \). The shaded area of Fig. 5 corresponds to the operation mode shown by Fig. 4.

The current ripple of \( i_1 \) can be derived from Fig. 4 and Fig. 5 as follows:

\[
\Delta i_1 = \frac{(0.5V_{dc} - v_o)D_s T_s}{L_{1p} + L_f} \tag{1}
\]

where \( D_s \) is the duty cycle of the switch \( S_{1p} \), \( 0.5 \leq D_s \leq 1 \) (Bipolar SPWM), and \( T_s = \frac{1}{f_s} \) and \( f_s \) is the switching frequency of \( S_{1p} \).

At zero-crossing period, \( D_s \) is approaching 0.5. Therefore, the current ripple of \( i_1 \) at zero-crossing region is not zero. The same analysis applies to the negative half-cycle current. After the two half-cycle currents with switching frequency component are filtered by output capacitor \( C_f \), the current \( i_{o1} \) gets its average component. It connects the averages of positive half-cycle current and negative half-cycle current at zero-crossing period. Because both half-cycle current averages at zero crossing are not zero, there is a jump from the negative average to the positive average, which is the current zero-crossing distortion. Since the load is resistive, the output voltage \( v_o \) has the same shape as \( i_{o1} \), and thus has the distortion. In light load condition, the resistance is much larger, so the zero-crossing distortion of the output voltage is amplified by the multiplication of the distorted current and the load resistance.

Fig. 6 shows the experimental result of output current \( i_1 \) and output voltage \( v_o \) across the load at zero-crossing period of single-unit dual buck inverter.
Fig. 7. Equivalent circuit of 2-unit cascade half-bridge dual buck inverter when $S_{1p}$ and $S_{2p}$ are both ON.

Fig. 8. Gate signals of $S_{1p}$, $S_{2p}$, and current $i_2$ through output inductor of 2-unit cascade half-bridge dual buck inverter.

Fig. 9. Experimental result of 2-unit cascade half-bridge dual buck inverter at zero crossing period.

Table I: Current Ripple Derivation for 3, 4, and 5-Unit Cascade Dual Buck Inverters

<table>
<thead>
<tr>
<th>Current Ripple</th>
<th>$\Delta i_j$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>$\Delta i_1 = \frac{2}{3} V_{dc} - v_o (D_s - 1/3) T_s}{3L_{np} + L_f}$</td>
</tr>
<tr>
<td>4</td>
<td>$\Delta i_2 = \frac{2}{3} V_{dc} - v_o (D_s - 2/4) T_s}{4L_{np} + L_f}$</td>
</tr>
<tr>
<td>5</td>
<td>$\Delta i_3 = \frac{2}{3} V_{dc} - v_o (D_s - 2/5) T_s}{5L_{np} + L_f}$</td>
</tr>
</tbody>
</table>

where $\lceil x \rceil$ is the ceiling function, and is defined as the smallest integer not less than $x$

$$\lceil x \rceil = \min \{ m \in \mathbb{Z} | m \geq x \}$$

where $x$ is a real number, $m$ is an integer, and $\mathbb{Z}$ is the set of integers.

As can be seen from (4), at zero-crossing period, $D_s$ is very close to 0.5, and thus the current ripple at zero-crossing region is greatly reduced compared to single-unit inverter. Theoretically, when $n$ is the even number, there is no current distortion at zero-crossing point because $\lceil (n - 1)/2 \rceil / n$ is equal to 0.5. It is obvious with the increase of the number of cascade units, the current ripple becomes smaller and smaller.

Fig. 9 shows the experimental result of output current $i_2$ and output voltage $v_o$ across the load at zero-crossing period of 2-unit dual buck inverter with phase-shift control. There is practically no current distortion.

From Figs. 6 and 9, we can see that the equivalent switching frequency of 2-unit cascade inverter with phase-shift control is doubled, which leads to current ripple cut-down. From (1) and
et al. ·

... to ensure a higher +

\[ v(8) \]

d \text{ approaches 1, the maximum ratio is only 25\%.} 

d \text{ can be different from each other. However, to maintain the}

power balance of each cascade unit, it is desirable to have equal

d_j. So if \( d_1 = d_2 = \cdots = d_n = d \), (9) can be rewritten as

\[
(d_1 + d_2 + \cdots + d_n) \cdot \frac{V_{dc}}{2} = d \cdot \frac{NV_{dc}}{2}.
\]

From (10) and Fig. 11, it is easy to derive the equivalent

average model of N-unit cascade dual buck inverter shown in

Fig. 12, where \( \Sigma L_j = L_1 + L_2 + \cdots + L_n \).

Define \( L = \Sigma L_j + L_f \), and we have the following equation

from Fig. 12:

\[
d(t) \cdot \frac{NV_{dc}}{2} - v_o(t) = L \frac{di(t)}{dt}.
\]

Transform (11) to \( s \) domain, we have

\[
i(s) = \frac{1}{sL} (d(s) \cdot \frac{NV_{dc}}{2} - v_o(s)).
\]

So the transfer functions from duty cycle \( d \) to current \( i \) and

voltage \( v_o \) to current \( i \) are as follows:

\[
G_{id}(s) = \frac{i(s)}{d(s)} = \frac{NV_{dc}}{sL}
\]

\[
G_{iv}(s) = \frac{i(s)}{v_o(s)} = \frac{1}{sL}
\]

where \( G_{id}(s) \) is the control-to-output transfer function and

\( G_{iv}(s) \) is an uncontrolled feed-forward term. By introducing an

admittance compensation controller \( G_{AC}(s) \), shown in Fig. 13, the

undesirable term can be cancelled out, which brings in smoother

zero-current start-up and reduced current steady-state error [31], [32].

Fig. 13 shows the control block diagram of N-unit cascade half-bridge dual buck inverter operating at standalone mode. The

closed-loop design adopts dual-loop design, the inner current

loop with a simple proportional controller \( G_P(s) \) to achieve fast

dynamic response with enough stability margin and the outer

voltage loop with a PR controller \( G_{PR}(s) \) to ensure a higher loop gain at fundamental frequency reducing the steady-state voltage error [28]–[30]. For this 1 kW, 120 V ac output cascade inverter system, the controllers are designed as follows.

For the PR controller in (15), \( k_p \) is the proportional gain, \( k_i \) is the resonant gain, and \( \omega_r \) is the equivalent bandwidth of the resonant controller. In principle, the bandwidth \( \omega_r \) needs to be as small as possible to obtain a highly selective bandwidth, but for digital implementation, it is quite difficult to realize

\[
\text{IV. CLOSED-LOOP SYSTEM CONTROL DESIGN}
\]

In order to demonstrate the feasibility and advantages of cascade dual buck inverter, the closed-loop control is derived and designed below for a 1 kW, 120 V ac standalone system shown in Fig. 1.

Fig. 11 shows the average model of N-unit cascade half-bridge dual buck inverter. \( d_j \) (\( j = 1, \ldots, n \)) is the duty cycle of each corresponding unit and \( L_j \) (\( j = 1, \ldots, n \)) is the output inductor of each unit

\[
L_j = L_{jp} \quad i > 0
\]

\[
L_j = L_{jn} \quad i < 0.
\]
Fig. 13. Control block diagram of N-unit cascade half-bridge dual buck inverter operating at standalone mode.

A current loop in a dual-loop system is designed to have a high loop bandwidth with enough stability margin rather than to reduce the current steady-state error by providing a high gain at fundamental frequency [42]. In this design, a simple proportional controller will meet the requirement

\[ G_P(s) = 0.05. \]  

(16)

In [32], the equivalent dc bus voltage is \( V_{dc} \) for single unit inverter system, and thus the outcome of admittance compensation term is the reciprocal of \( V_{dc} \). From Fig. 13, we can clearly see that the equivalent dc bus voltage for the cascade dual-buck inverter is \( NV_{dc}/2 \). Therefore, the admittance compensation transfer function is obtained as follows:

\[ G_{AC}(s) = \frac{1}{NV_{dc}/2} \]  

(17)

In order to close the outer voltage loop, shown in Fig. 13, \( G_{vi}(s) \) is derived below based on the model in Fig. 12

\[ G_{vi}(s) = \frac{1}{sC_f + 1/R}. \]  

(18)

\( G_{LPF}(s) \) is second-order low pass filter with cut-off frequency 5 kHz and a damping ratio 0.7.

With the designed controllers above, the Bode plot of both compensated inner current loop gain and compensated outer voltage loop gain is shown in Fig. 14. As can be seen, the current loop has the cross-over frequency 1.2 kHz with gain margin 15.3 dB and phase margin 70.7°. The voltage loop has the cross-over frequency 209 Hz with phase margin 87.2°, and at 60 Hz fundamental frequency it has a gain of 35.5 dB to reject the steady state error.

Fig. 15 shows the PWM generation flow chart based on the current reference signal from Fig. 13. Fig. 16 shows the experimental results for PWM generation based on the sequence from Fig. 15. It can be seen that the PWMs for \( S_{ip} \) and \( S_{in} \) never overlap, which means this cascade dual buck inverter is shoot-through free. The phase-shifted PWMs are simple to implement by digital controller by just adding an incremental angle to the adjacent cascade unit.

V. COMPARATIVE EXPERIMENTAL RESULTS

To prove the viability and merits of the proposed cascade dual buck inverter with phase-shift control, a 1 kW, 120 V ac output cascade dual buck half-bridge inverter system in standalone operation was designed and tested. The system structure of the experiment is the same as in Fig. 1, and the control scheme applied is shown in Figs. 13 and 15. The system controller and PWM generation are conducted by TI floating point.
Fig. 15. PWM generation for all switches of N-unit cascade half-bridge dual buck inverter with phase-shift control.

Fig. 16. Experimental results of PWM generation for N-unit cascade half-bridge dual buck inverter with phase-shift control. (a) PWM generation for $S_{1p}$ and $S_{1n}$ based on $i_{ref}$ direction. (b) PWM phase-shift of $S_{1p}$ and $S_{2p}$ for 2-unit cascade dual buck inverter. (c) PWM phase-shift of $S_{1p}$, $S_{2p}$, and $S_{3p}$ for 3-unit cascade dual buck inverter.

Fig. 17. Output current $i_o$, ac and dc voltage waveforms for single-unit, 2-unit cascade, and 3-unit cascade inverter system at 1 kW. (a) Single-unit inverter. (b) 2-unit cascade inverter. (c) 3-unit cascade inverter.

DSP TMS320F28335. The switching frequency of the devices is set to be 20 kHz. Because the cascade dual buck inverter adopts phase-shifted PWM control, the equivalent switching frequency of the inverter is 40 kHz for 2-unit and 60 kHz for 3-unit cascade inverters, respectively. The MOSFET is selected as STY80NM60 N with on-resistance 35 mΩ, and the diode is RURG3060 with reverse recovery time 55 ns. The passive components are selected as follows: $L_{jp} = L_{jn} = 250 \mu$H, $L_f = 1$ mH, $C_f = 2.4 \mu$F, and $C_d = 1.2$ mF. The system has the ability of serving as single-unit, 2-unit, and 3-unit systems. For comparison, tests were conducted with single-unit, 2-unit, as well as 3-unit systems. All the output power of three tests is 1 kW, and output ac voltage is 120 V RMS. For single-unit system, $V_{dc}$ is 360 V, and for 2-unit cascade system, $V_{dc}$ is 180 V, and for 3-unit cascade system, $V_{dc}$ is 120 V.
Fig. 18. Output current $i_o$, ac and dc voltage waveforms for single-unit, 2-unit cascade inverter system at 300 W. (a) Single-unit inverter. (b) 2-unit cascade inverter.

Table II

| THD Measurement for Both Single-Unit and Cascade Dual Buck Inverters |
|---------------------------------|---|---|---|---|
|                                | 1kW |   | 300W |   |
| 1-unit                          | 2.6% | 2.4% | 10.3% | 10.0% |
| 2-unit                          | 0.9% | 0.8% | 1.7%  | 1.5%  |
| 3-unit                          | 0.9% | 0.8% | 1.5%  | 1.2%  |

Fig. 17 shows the output current $i_o$ through load and voltage waveforms of single-unit dual buck inverter, 2-unit cascade dual buck inverter, and 3-unit cascade dual buck inverter at 1 kW output. It is clear that with phase-shift control for 2-unit system and 3-unit system, the current zero-crossing distortion was almost eliminated. However, the single-unit zero-crossing is severe.

The distortion problem is more obvious in light load conditions for single-unit inverter. Fig. 18 shows the comparison between single-unit inverter and 2-unit cascade inverter at 300 W output. The aggravated current and voltage distortion with very high THD will be intolerable and impose a risk for the load operation. In contrast, the cascade dual buck inverter with phase-shift control does not have this distortion at light load either. The THD is measured for both single-unit inverter and cascade dual buck inverter under full load and light load conditions. The result is shown in Table II. As can be seen, the THD at 300 W for single-unit inverter is 10% while for cascade dual buck inverter it is only around 1%.

Fig. 19. Voltage waveforms across split capacitors for 3-unit cascade dual buck half-bridge inverter system at 1 kW.

Fig. 20. Output positive half-cycle current $i_P$, ac and dc voltage waveforms for single-unit, 2-unit cascade, and 3-unit cascade inverter system at 1 kW. (a) Single-unit inverter. (b) 2-unit cascade inverter. (c) 3-unit cascade inverter.
Fig. 19 shows the voltage $v_{cd1}$ and $v_{cd2}$ across the split capacitors from one cell of 3-unit cascade dual buck half-bridge inverter. For the cascade dual buck half-bridge inverter, the split capacitors are needed for each cascade unit. It can be seen that the voltage of the capacitors is naturally balanced. In some cases, if the voltage across the capacitors is unbalanced, due to use of different types of capacitors, different ESR or other factors, a voltage balance compensator might be considered [33] to solve the issue. The cascade dual buck full-bridge inverter is a better alternative to save two split capacitors and totally avoid the issue.

Fig. 20 shows the positive half cycle output current $i_p$ through inductor and voltage waveforms of single-unit dual buck inverter, 2-unit cascade dual buck inverter and 3-unit cascade dual buck inverter. $d_p$ is the duty cycle for current positive half-cycle. This shows the unique operating feature of single-unit dual buck inverter is inherited by cascade dual buck inverter. Every dual buck unit in the cascade system maintains the no-shoot-through characteristic, and thus leads to a more robust and reliable cascade inverter system than traditional voltage source based cascade inverter.

Fig. 21 shows the output current and voltage waveforms of single-unit inverter and 3-unit cascade dual buck inverter under load step conditions. Load step-up and step-down tests were done to show the fast dynamics and good stability of the designed control system for cascade dual buck inverter. Even though single-unit system can withstand load change, its inherent zero-crossing distortion will affect the control system and be harmful to the load.

Fig. 22 shows the measured efficiency curve under different power output conditions for cascade dual buck half-bridge inverter.

VI. CONCLUSION

A new series of cascade dual buck inverters has been proposed based on single-unit dual buck inverters. The cascade dual buck inverter has all the merits of traditional cascade inverters, and improves on its reliability by eliminating shoot-through worries and dead-time concerns. With the adoption of phase-shift control, the cascade dual buck inverter solves the inherent current zero-crossing distortion problem of single-unit dual buck inverter.

To prove the effectiveness of the proposed topology and control scheme, a cascade dual buck half-bridge inverter system operating at standalone mode with 1 kW, 120 V ac output capability has been designed and tested. By comparison of experimental results of single-unit dual buck inverter with 2-unit and
3-unit cascade dual buck inverters, the viability and advantages of the cascade dual buck inverter are validated.

REFERENCES

Pengwei Sun (S’07) received the B.S. and M.S. degrees in electrical engineering, in 2004 and 2007, respectively, from North China Electric Power University (NCEPU), Beijing, China. Since 2007, he has been a Graduate Research Assistant and Ph.D. student in Future Energy Electronics Center (FEEC), Virginia Tech, Blacksburg, VA. His research interests include design and control of high-efficiency single-phase and three-phase inverters, as well as multi-level and cascade inverters for renewable energy applications, including electric vehicle, solar and wind power systems.

Chuang Liu (S’11) received the M.S. degree in electrical engineering, in 2009, from Northeast Dianli University, Jilin, China. Since 2009, he has been a Ph.D. student of electrical engineering at Harbin Institute of Technology, Harbin, Heilongjiang, China. Since September 2011, he has been with Future Energy Electronics Center (FEEC), Virginia Tech, Blacksburg, VA, as a Visiting Student, supported by the Chinese Scholarship Council. His research interests include intelligent universal transformer (IUT) for renewable energy systems, as well as future dc-based renewable energy nanogrid, PHEV/PEV smart parking lot/building, and battery energy storage systems.

Jih-Sheng Lai (S’85–M’89–SM’93–F’07) received the M.S. and Ph.D. degrees in electrical engineering from the University of Tennessee, Knoxville, TN, in 1985 and 1989, respectively. From 1980 to 1983, he was the Head of the Electrical Engineering Department of the Ming-Chi Institute of Technology, Taipei, Taiwan, where he initiated a power electronics program and received a grant from his college and a fellowship from the National Science Council to study abroad. In 1986, he became a Staff Member at the University of Tennessee where he taught control systems and energy conversion courses. In 1989, he joined the Electric Power Research Institute (EPRI) Power Electronics Applications Center (PEAC), where he managed EPRI-sponsored power electronics research projects. From 1993, he worked with the Oak Ridge National Laboratory as the Power Electronics Lead Scientist, where he initiated a high power electronics program and developed several novel high power converters including multilevel converters and soft-switching inverters. In 1996, he joined Virginia Polytechnic Institute and State University. He is currently a Professor and the Director of the Future Energy Electronics Center, Blacksburg, VA. His main research areas are in high efficiency power electronics conversions for high power and energy applications. He has published more than 200 technical papers and two books and received 18 U.S. patents.


Chien-Liang Chen (M’11) received the B.S. degree from National Taiwan University of Science and Technology, Taipei, the M.S. degree from National Tsing-Hua University, Hsinchu City, Taiwan, and the Ph.D. degree from the Virginia Polytechnic Institute and State University, Blacksburg, VA, in 2002, 2004, and 2011, respectively, and all in electrical engineering. He is currently doing postdoctoral research at the Future Energy Electronics Center (FEEC), Virginia Tech., Blacksburg, VA. His research interests include grid-tie inverters, parallel inverters, microgrid applications, and soft-switching techniques.