HOW2POWER TODAY
Your Power Design Newsletter

Exclusive Technology Feature

ISSUE: November 2009

Drive Multiple LED Strings with SEPIC Converters

by L.K. Wong and T.K. Man, National Semiconductor, Santa Clara, Calif.

With the emergence of LED lighting as one of the most promising business areas in recent years, the driving of high-brightness LEDs has become a hot topic. For applications with more than one LED, the LEDs can be connected in series to form an LED string. If the number of LEDs further increases, multiple LED strings can be used. A common method to drive multiple LED strings is to make use of a power converter together with linear current regulators.

Based on the input voltage and the output voltage, which is related to the number of LEDs in a string, a buck or boost topology will normally be used in the power converter. However, if the input voltage is closed to the output voltage, the above topologies are not suitable. This article explains why a SEPIC topology offers the best solution to this problem and presents a design example to illustrate the implementation of a SEPIC-based LED driver circuit.

Basic LED drivers

The primary function of an LED driver is to control the current of LEDs to a constant, say I_{LED}. The value of I_{LED} is related to the color of the LED and is LED dependent. If dimming is required, PWM control will commonly be employed, meaning that the driver should control the LED current to either I_{LED} or zero with a dimming frequency, which normally ranges from 200 Hz to more than 1 kHz.

Fig. 1 shows a block diagram of an LED driver with *k* strings of LEDs. The LED driver consists of a power converter and *k* linear current regulators. The input voltage and output voltage of the power converter are represented by V_{IN} and V_{OUT}. Each LED string has *n* LEDs. The voltage drop at each LED string is V_{LEDi}, where *i* is from 1 to *k*. V_{LEDi} is the sum of the forward voltage (V_{Fij}) of each LED, where *j* is from 1 to *n*. Therefore, we have

$$V_{LEDi} = V_{Fi1} + V_{Fi2} + \ldots + V_{Fin}$$

Each LED string is connected between the output of the power converter and a linear current regulator, which is used to control the LED current. The voltage drop in each linear current regulator is represented by V_{CSi}.

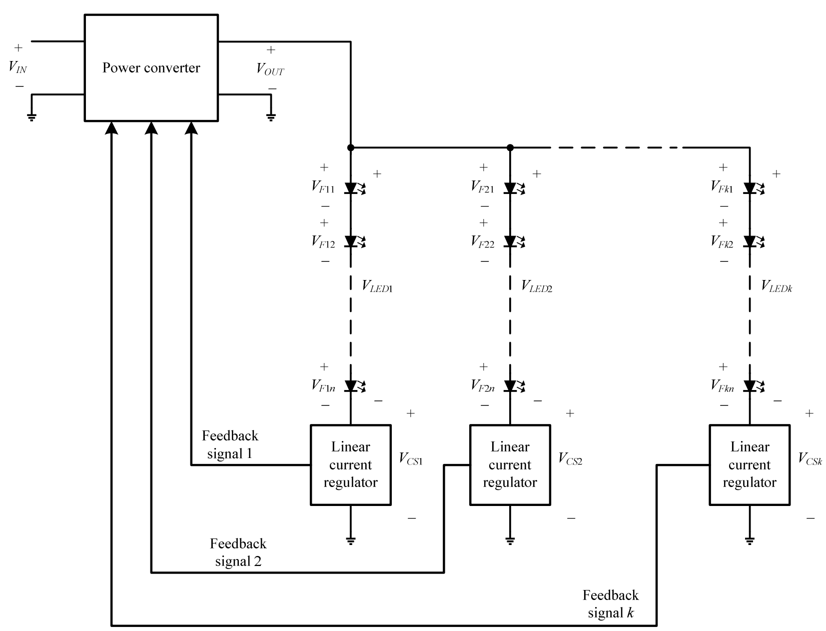

Fig.1. An LED driver for multiple LED strings

Selection Of A Power Converter Topology

The input voltage and the output voltage govern the topology chosen for the power converter. The output voltage is required to be higher than the maximum voltage drop of the LED string plus the voltage drop in the linear current regulator, i.e.

$$V_{OUT} > \max\{ V_{LEDi} + V_{CSi} \} \text{ for } 1 < i < k$$

First, V_{LEDi} is a function of V_{Fij}, the forward voltage of a single LED. The forward voltage of each LED has a tolerance. It is also temperature dependent. For example, V_{Fij} normally decreases when the temperature of an LED rises. Temperature rise is countable when LEDs are turned on. For an LED with I_{LED} of 0.35 A, typical values of V_{Fij} and the tolerance would be 3.2 V and ±10%.

Second, V_{CSi} is related to the power of the feedback signal. It should be large enough to maintain a good signal-to-noise ratio for the feedback signal. The linear current regulator also requires a minimum voltage for proper biasing. However, to optimize the efficiency, V_{CSi} should be minimized because the power loss of the i^{th} linear current regulator is $V_{CSi} \times I_{LED}$, which is a considerable amount of power. Since I_{LED} is fixed, the power loss is mainly determined by V_{CSi}, which is related to V_{OUT}, i.e.

$$V_{CSi} = V_{OUT} - V_{LEDi}$$

Let us consider an example of driving three LED strings with four LEDs in each string. The nominal V_{LEDi} is 12.8 V, and I_{LED} is 0.35 A for each string. A typical design of V_{OUT} is 15 V, which has already considered the tolerance of V_{LEDi}, and the minimum voltage drop required by V_{CSi}.

If a common rechargeable battery with a nominal voltage of 12 V is used, the battery voltage can vary from 10 V (almost fully discharged) to 14 V (fully charged), which will be close to V_{OUT}. Assume that a boost converter is used to obtain a V_{OUT} of 15 V, it requires a very small duty ratio if V_{IN} is near the upper limit (duty ratio is 6.7% if V_{IN} is 14 V). A small duty ratio may not be achievable in practice because most controllers possess lower limits on duty ratio or on-time. In this case, V_{OUT} has to be set higher, and consequently increases the power loss of linear current regulators so as to reduce the overall efficiency. Another possible method is to reduce the switching frequency in order to get rid of the lower limit of on-time. However, a low switching frequency will increase inductor current ripple. As a result, a larger and more expensive inductor is required.

The best power converter topology for the above application is SEPIC. It is because the input voltage of a SEPIC converter can be higher or lower than the output voltage. Other advantages of a SEPIC converter include the use of a low-side switch (which makes the switch driver easy to implement) and its noninverted output voltage.

LED Driver With SEPIC

Fig. 2 shows a schematic of an LED driver consisting of a power converter employing the SEPIC topology, linear current regulators, and a controller IC (LM3431). The linear current regulators are not standalone devices, but rather consist of controllers integrated in the controller IC working together with external pass transistors (Q2, Q3, Q4) and current-sense resistors (R10, R11, R12). The major components of a SEPIC converter include two inductors (L_1, L_2), two capacitors (C_S, C_8), a MOSFET Q_1, and a diode D_1.

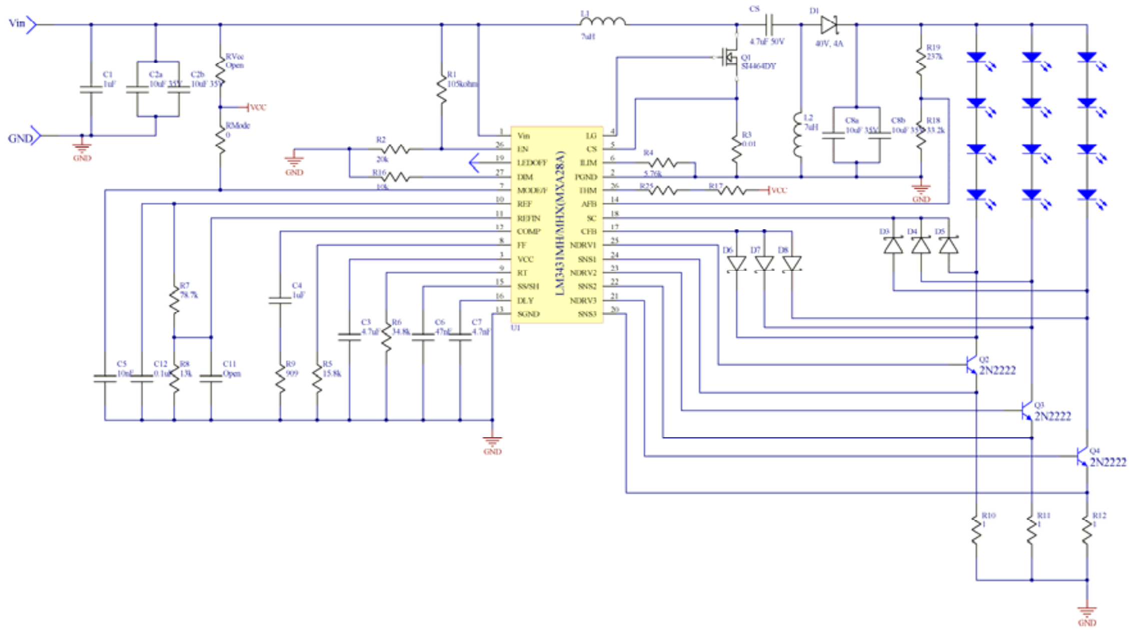

Fig. 2. This LED driver employs a SEPIC topology to drive three LEDs strings.

When Q_1 is turned on, L_1 and L_2 are charged up by V_{IN} and V_{CS} (the voltage across C_S) respectively, while C_S and C_8 are discharged by I_{L2} (inductor current of L_2) and the output current (the overall LED current). When Q_1 is turned off, L_1 and L_2 are discharged, and C_S and C_8 are charged up. Some basic formulas at steady state are shown as follows.

The input current equals I_{L1}, the inductor current of L_1. Since there are three LED strings, the output current is $3I_{LED}$. Then, I_{L1} and I_{L2} can be calculated as follows:

$$I_{L1} = \frac{3V_{OUT} I_{LED}}{V_{IN}}$$

$$I_{L2} = 3I_{LED}$$

Let D be the duty cycle, T_{SW} be the switching period, t_{on} be the on-time of Q_1, $I_{L1,ripple}$ and $I_{L2,ripple}$ be the inductor current ripple of L_1 and L_2,

$$D = \frac{V_{OUT}}{V_{IN} + V_{OUT}}$$

$$t_{on} = DT_{SW}$$

$$I_{L1,ripple} = \frac{V_{IN} t_{on}}{L_1}$$

$$I_{L2,ripple} = \frac{V_{CS} t_{on}}{L_2}$$

At steady state,

$$V_{IN} = V_{CS}$$

the inductor current ripple of L_2 can be formulated as

$$I_{L2,ripple} = \frac{V_{IN} t_{on}}{L_2}$$

To maintain continuous conduction mode (CCM) operation, L_1 and L_2 should be large enough to ensure that the inductor current is larger than half of the inductor current ripple, even at the highest V_{IN}.

In our example, the switching frequency is 700 kHz, so the switching period is 1.43 µs. Since V_{OUT} and I_{LED} are 15 V and 0.35 A, at the highest V_{IN} of 14 V,

D = 0.52

t_{on} = 739ns

I_{L1} = 1.125A

I_{L2} = 1.05A

In order to maintain the CCM operation, the maximum $I_{L1,ripple}$ and $I_{L2,ripple}$ should be 2.25 A (I_{L1}×2) and 2.1 A (I_{L2}×2). The minimum value of L_1 and L_2 are 4.6 µH and 4.9 µH. Since the tolerance of inductors can be up to 30%, L_1 and L_2 are selected to be 7 µH (4.9 µH ÷ 0.7).

Let the peak current of Q_1 and D_1 be $I_{Q1,peak}$ and $I_{D1,peak}$,

$$I_{Q1,peak} = I_{L1} + I_{L2} + \frac{I_{L1,ripple} + I_{L2,ripple}}{2}$$

$$I_{D1,peak} = I_{L1} + I_{L2} + \frac{I_{L1,ripple} + I_{L2,ripple}}{2}$$

The components Q_1 and D_1 should be capable of handling the peak current. The maximum value of the peak currents occurs with the lowest V_{IN}. In the example, since L_1 and L_2 are both 7 µH, when V_{IN} is 10 V,

D = 0.60

t_{on} = 857 ns

I_{L1} = 1.575 A

I_{L2} = 1.05 A

$I_{L1,ripple}$ = 1.22 A

$I_{L2,ripple}$ = 1.22 A

$I_{Q1,peak}$ = 3.85 A

$I_{D1,peak}$ = 3.85 A

A linear current regulator consists of a current sense resistor, a power transistor, and an amplifier (embedded in the controller IC). The amplifier output controls the base of the power transistor (2N2222) to control the current of an LED string to 0.35 A, which is sensed by a 1-Ω resistor. This sensed signal is fed back to the input of the amplifier to compare with a reference voltage of 0.35 V, which is divided down from a 2.5-V internal reference voltage by a resistor divider circuit formed by R7 and R8.

Furthermore, V_{OUT} of the converter can be adaptively adjusted during operation by means of a dynamic headroom control (DHC) method embedded in the LM3431. If the voltage of the LED strings decrease, which is normal owing to the temperature rise under operation, the DHC can reduce V_{OUT} slowly so that the power loss in the linear current regulators can be minimal. This can further improve the efficiency of the overall system.

Hardware Results

Fig. 3 shows the waveforms of the system under steady-state operation. Figs. 4 to 6 show the responses under dimming signal at 10%, 50% and 90% dimming duty ratio, with a dimming frequency of 380 Hz. In addition, a start up response is shown in Figure 7 and the efficiency of the system is listed in Table 1. The data was taken after 20 minutes of operation at full load to allow the temperature of LEDs to stabilize.

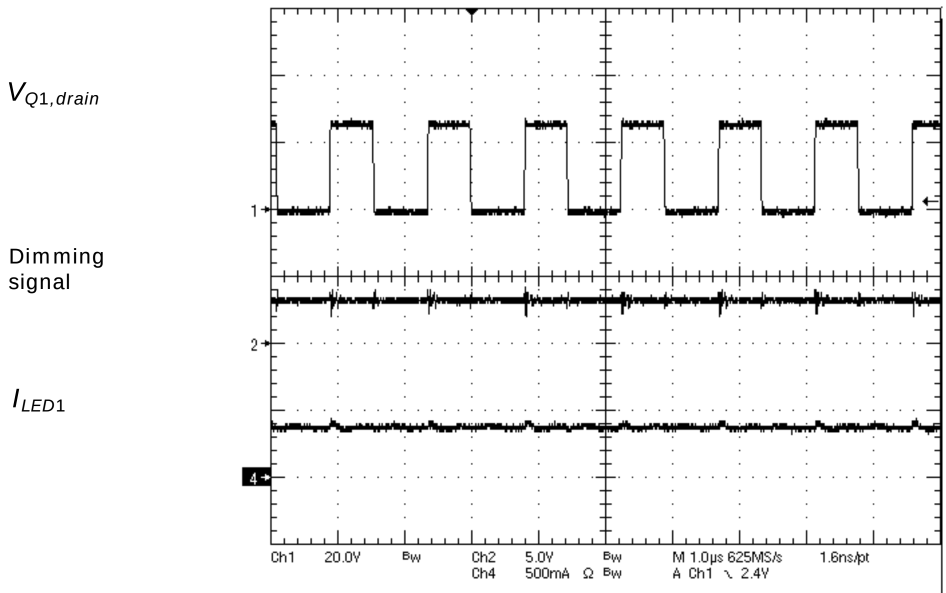

Figure 3. Steady-state waveforms for LED driver.

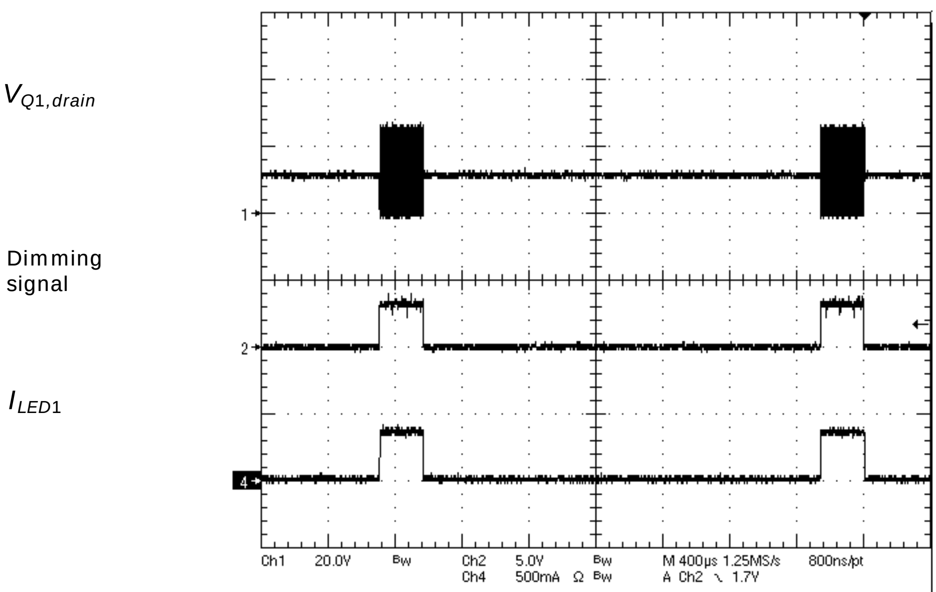

Figure 4. Waveforms under 10% dimming.

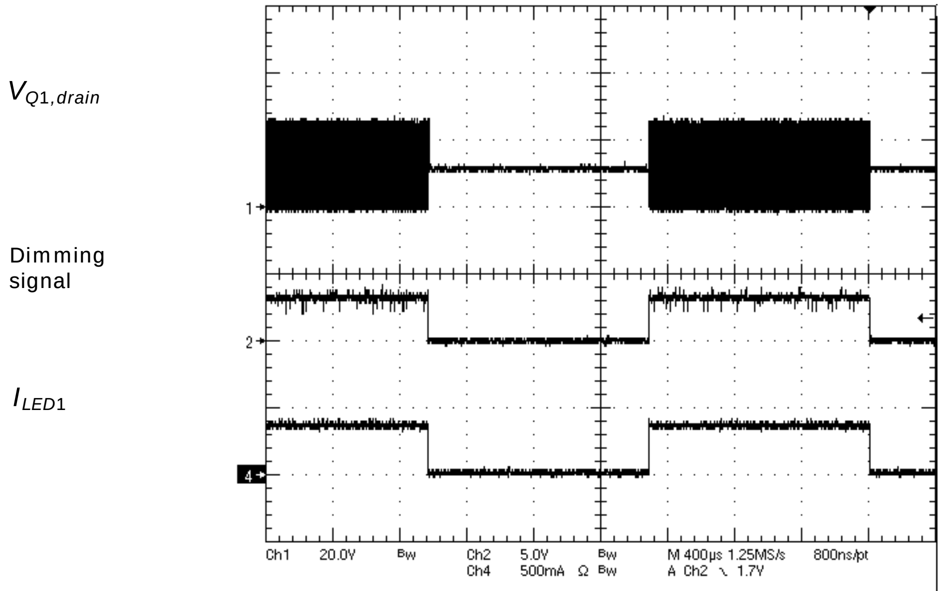

Figure 5. Waveforms under 50% dimming.

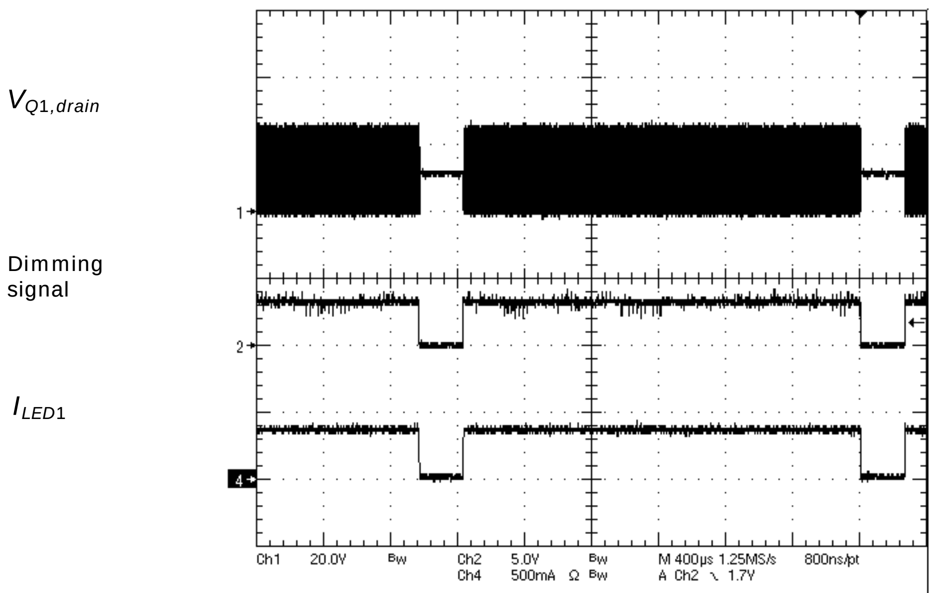

Figure 6. Waveforms under 90% dimming.

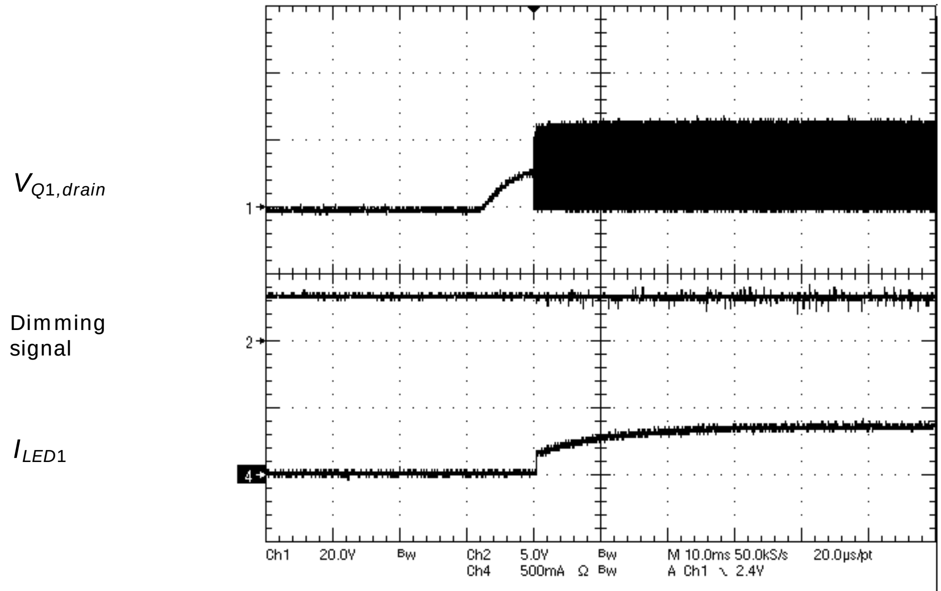

Figure 7. Start-up response.

V_{IN} (V)	10	12	14
I_{IN} (A)	1.641	1.368	1.180
V_{OUT} (V)	13.976	13.878	13.859
V_{LED1} (V)	12.461	12.458	12.468
V_{LED2} (V)	12.546	12.543	12.559
V_{LED3} (V)	12.549	12.547	12.558
I_{LED1} (A)	0.3495	0.3499	0.3500
I_{LED2} (A)	0.3485	0.3487	0.3488
I_{LED3} (A)	0.3464	0.3468	0.3470
P_{IN} (W)	16.410	16.416	16.520
P_{OUT} (W)	14.597	14.508	14.494
P_{LED} (W)	13.074	13.084	13.102
P_{OUT}/P_{IN}	88.9%	88.3%	87.7%
P_{LED}/P_{IN}	79.7%	79.7%	79.3%

Table 1. Measurement data from hardware.

From these measurements, it can be seen that the voltage drop on each LED string is around 12.5 V. This means that the forward voltage of each LED is less than the nominal value of 3.2 V owing to temperature rise. In this case, the DHC decreases V_{OUT} to less than 14 V, and as a result the power loss in the linear current regulators is reduced. The overall efficiency is almost 80% for the whole input-voltage range.

About the Authors

L. K. Wong received his Ph.D. degree at the Hong Kong Polytechnic University in 1999. Wong joined National Semiconductor as a senior product application engineer in 2006, working in the area of power electronics including modeling, control, and dc-dc power converter design. Currently, he is focusing on high-efficiency, high-performance LED driver design for general illumination and backlight applications. He is a member of the IEEE.

T. K. Man received the BSc (Hon) degree at Manchester Polytechnic in 1984, MSc degree in engineering at Hong Kong Polytechnic University in 1999 and MSc degree in IC Design Engineering at Hong Kong Science and Technology University in 2007. Man has 22 years experience in power supply design, both linear and switching. He joined National Semiconductor in 2004 as a product application manager in Hong Kong. Prior to National, Man worked at Motorola and ON Semiconductor. His research interests include control modeling of SMPS, LED lighting systems and energy harvest technology. He is a senior member of IEEE.