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Review of Power Conversion and Energy Management for Low-power, Low-Voltage Energy Harvesting Powered Wireless Sensors

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***Abstract*—In this paper, state-of-art power electronics and energy management solutions utilised in low-power (less than 5mW), low-voltage (less than 3 V) energy harvesting powered wireless sensors for Internet of Things (IoT) related applications are detailed. All aspects of an energy harvesting powered sensor system are examined including the challenges of low-power energy harvesting sources, energy management circuits including power converters and energy storage elements, as well as the impact of wireless sensor pulsed power profiles. In particular the paper focuses on existing voltage step-up energy management techniques, including the issues of cold-start and maximum power point tracking (MPPT), as well as energy storage which is necessary for wireless sensor operation. Both academic and commercially available energy harvesting powered systems are examined to provide a comprehensive analysis of existing solutions. Issues limiting current system performance are identified to help define future developments needed to enable efficient and effective energy harvesting powered wireless sensor operation.**

***Index Terms*— Energy harvesting, DC-DC power conversion, Energy management, Energy storage**

I. Introduction

Wireless sensors play an essential role in the development of automated buildings and homes towards creating fully autonomous smart structures. For the case of smart homes, wireless sensors can be utilised for a wide range of applications aimed at improving occupant comfort such as remotely or autonomously operated temperature control, household appliances, security systems, etc., while also facilitating increased building energy efficiency [1]. Similarly, wireless sensors can be used in industrial building settings to enable autonomous control of important operating conditions such as temperature, CO_2 and humidity, or to optimise overall building efficiency [2]. However, the main issue with wireless sensors for any application is the need for a separate and reliable power source for each of the individual sensors, where for example, a machine diagnostic application may require up to 300 sensor nodes over an industrial production area of 25 m^2 [2]. Future predictions for wireless sensors to enable the Internet of Things show an increase of two-fold between 2018 and 2023 which will result in a significantly higher demand for power sources for an estimated 50 billion wireless sensors [3].

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The Energy harvesters can be utilised as autonomous power sources for wireless sensor nodes for a wide range of applications in different environments, with the benefits of energy harvesting being well recognised for both commercial and residential settings [1]. In particular small form factor sources provide a suitable solution due to their comparable size with existing battery powered solutions as well as being suitably sized for smart homes and wearable sensors, the most commonly discussed/searched IoT applications [4]. They reduce the maintenance and disposal costs associated with battery powered systems and the infrastructural cost of implementing AC mains powered sensors. However by opting for an energy harvesting (EH) source, additional circuitry and energy management techniques are required when compared with AC and battery powered solutions. This is due to the low-power, low-voltage nature of small form factor EH sources and the significant power profile mismatch between the source and sensor. For this reason a DC-DC converter, energy management (EM) circuitry and energy storage are required between the EH source and a wireless sensor load, as shown in Figure 1.

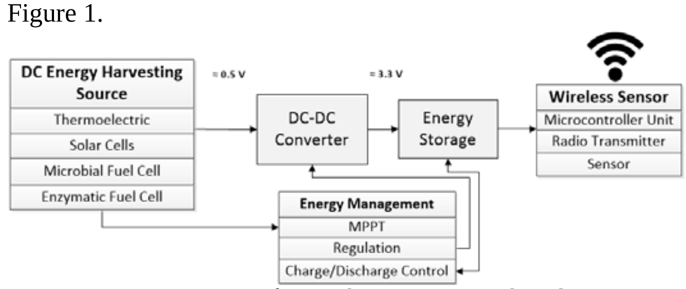

Fig. 1. System overview of energy harvesting powered wireless sensor.

Suitable small form factor DC EHs gather energy from ambient sunlight and indoor light sources by utilising photovoltaic (PV) [5], and dye-sensitised solar cells (DSSCs) [6], [7]. For a cell size of 22 cm^2, the voltage produced is as low as 0.4 V, with 0.24 mW power generation for 700 lux [8]. Thermoelectricity [9], also provides a viable energy source for wireless sensors, whether it be from human [10], or industrial sources [11], but again voltage and power levels are often limited to less than 1 V and as low as 0.15 mW, respectively for a small sized generator of 1.8 cm^3 [12]. Based on these sources EH powered sensors can be fitted to a wide range of locations; however due to the low voltage and power levels generated, the energy must be carefully managed. The issues may be better appreciated when it is considered that generated voltages are lower than the threshold voltage of a typical semiconductor switch, while power levels are of the same

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order of magnitude of the quiescent power in standard power electronics circuits.

This paper reviews existing DC-DC converters and energy management systems designed for low-power, low-voltage energy harvesting powered wireless sensors. It includes an introduction to the power/energy requirements of different sensor applications with particular focus on the energy management required to enable the wireless sensor to operate reliably, efficiently and autonomously. Other authors have performed a qualitative review of step-up DC-DC converters for low-power energy harvesting sources, including charge pumps, inductive based topologies and hybrid (capacitive and inductive) solutions, where the main focus is on the converters' principles of operation [13]. This paper provides a *quantitative* review of a wider range of solutions, comparing the circuits based on their performance of efficiency versus input voltage and voltage step-up ratio, etc., and detailing the additional components required to create a complete energy harvesting powered system; i.e. energy storage, MPPT and cold-start. Limitations of existing systems are identified to provide direction for future research to address them, thereby enabling the forecasted increase in wireless sensor deployments.

The structure of the paper is as follows: Section 2 introduces low-power wireless sensor loads whereby the operation and power requirements are detailed for a range of sensors, as well as the challenges to be overcome when using an energy harvester as the sole power source. Section 3 reviews existing suitable step-up converter circuits used for low-power, energy harvesting powered wireless sensors, including inductor, switched capacitor and transformer based converters. The performance of the converters is compared based on power delivery, input voltage and voltage step-up ratio, enabling identification of solutions that are suitable for different application conditions. Section 4 reviews the additional components required to work with the power conversion stage to create a completely autonomous energy harvesting powered wireless sensor. These include maximum power point tracking (MPPT), energy storage and cold-start circuitry. A range of different existing MPPT techniques suitable for low-power energy harvesting sources are detailed based on technique and power consumption. Storage elements are compared based on energy and power density, lifetime issues including leakage, as well as charge/discharge efficiency. Finally Section 5 presents and compares complete demonstrator system configurations that have been developed for different application environments. These illustrate the range of suitable solutions for various combinations of energy harvesting sources and wireless sensor load conditions. A discussion of methods to increase demonstrator performance is detailed and applied to identify future research opportunities.

II. Wireless Sensor Requirements

Prior to reviewing existing energy management solutions, the load requirements of wireless sensors are detailed to determine the requirements of the step-up converters in terms of voltage and power levels. As shown in Figure 1, the different components required for a wireless sensor system are a microcontroller unit (MCU), the sensor itself (e.g. temperature, humidity) and a wireless data transmitter. Depending on the overall system parameters, a range of different wireless sensor solutions can be utilised, with many documented in [14]. This literature review is focused on wireless sensors using ultra-low/low-power components (< 5 mW) for a typical IoT application (e.g. smart building or wearable sensor).

Figure 2 (a) shows the pulsed power required by a wireless sensor versus the continuous power being generated by a typical low-power, low-voltage EH source over several sense operations. Due to the power mismatch between source (less than 5 mW) and sensor (up to 100 mW, see Figure 2 (b)) there are limitations on the range of functionalities and data transfer rates that can be provided by an EH powered wireless sensor [15]. However low-power sensors operate in a pulsed manner thereby enabling EH systems to storage sufficient energy to ensure sensor operation while maintaining sufficiently accurate sensor readings.

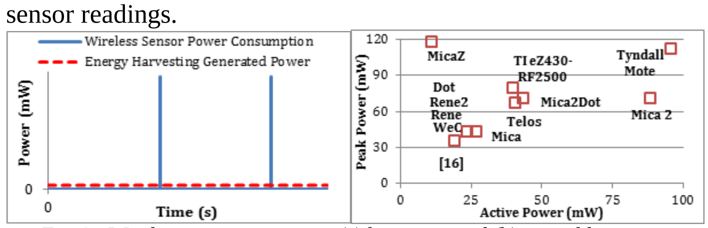

Fig. 2. Wireless sensor operation, (a) long-term and (b) typical low-power wireless sensor peak current versus active power requirements.

Figure 2 (b) shows the peak power of a range of different wireless sensors versus active power, where active power is the average power required by a sensor to perform a sensor reading and a wireless transmission when active. Taking the TI eZ430-RF2500 temperature sensor [16] as an example, Figure 3 shows the detailed profile of the sensor power consumption during a sense and transmission operation, which shows instantaneous power consumption levels of up to 80 mW.

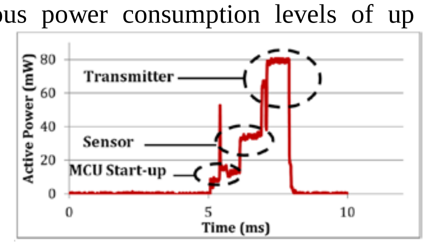

Fig. 3. Measured power profile of a low-power wireless temperature sensor.

This profile translates into an active power of 40 mW over ~3 ms. As well as the power, the sensor's energy demand is important; however due to energy requirements being dependent on the exact sensor timing and implementation method, which are often not reported, it is difficult to compare sensors in terms of energy consumption. For illustration, Table 1 shows the energy, power and timing values for three of the sensors featured in Figure 2 (b).

Comparing these wireless sensor requirements with the continuous low power profile produced by energy harvesting sources, the step-up converter, energy management circuitry and energy storage must be carefully selected to ensure correct wireless sensor operation. For these reasons a thorough review of existing converters and energy management techniques is merited.

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TABLE I
ENERGY AND POWER DEMANDS OF A SAMPLING OF SENSORS IN FIGURE 2 (B)

Sensor	Energy per Operation (mJ)	Sleep (μW)	Operation Time (s)	Sleep Time	Overall Average Power (mW)
Tyndall Mote	3.75	54.1	0.039	60	0.117
eZ430-RF2500	0.114	0.416	0.0029	1	0.118
MicaZ	7.49	62	0.905	59	0.186

III. DC-DC CONVERTERS

This section reviews existing DC-DC conversion techniques and converters suitable for small form factor low-power, low-voltage DC energy harvesting sources which produce power levels less than 5 mW at less than 3 V. The DC-DC converters ensure power is supplied at the correct voltage to power the sensor, therefore overcoming the voltage mismatch between source and load. The three step-up topologies commonly utilised for low-voltage energy harvesting powered applications include inductor based converters (boost converters in particular), switched capacitors (including charge pump) and transformer based converters.

Initially the operation of the three converter topologies is described to provide an understanding of the commonly used techniques for low-power, low-voltage DC-DC converters. From here the converters' performance in an energy harvesting system is compared based on efficiency versus output power, voltage conversion ratio and input voltage.

A. Boost Converters

Inductor based boost converters provide voltage step-up functionality. However, due to the low-power nature of suitable energy harvesting sources for IoT applications, power saving techniques are required to ensure sufficient power delivery to a sensor, with many documented in [8]. These include pulsed frequency modulation (PFM) [17], [18] (in place of pulsed width modulation (PWM)), burst mode operation and discontinuous conduction mode (DCM) operation. PFM operates by varying the frequency to reduce the switching related losses of the boost converter as the power reduces, while burst mode operates the converter in pulses rather than continuously which further reduces losses.

Burst mode operation is implemented by applying the EH source to store energy in the input capacitor (C_{In}) during T_{Charge}, when the boost converter is disabled. Power continues to be supplied to the output through an output capacitor (see Figure 4(a)). Once a predetermined voltage on C_{In} has been reached, the boost converter is enabled and the capacitor discharges periodically through the inductor to the output during T_{Boost}. The cycle repeats once the input capacitor voltage reduces below a certain threshold. Maximum source power may be extracted by ensuring that this capacitor voltage (V_{In}) is centred on the MPPT voltage.

During the boost operating time (T_{boost}), the circuit operates in DCM rather than continuous conduction mode (CCM) by ensuring the inductor current is zero during switching to further reduce the circuit losses. However the inductor current ripple and output voltage ripple are increased and this can have a detrimental effect on circuit components (i.e. MOSFETs, inductor and storage components) if not managed correctly. Figure 4 (a) shows the circuit schematic and (b) key operating waveforms of a commercial boost converter with burst mode, PFM and DCM operation [19]. The efficiency of this and other existing suitable boost converter circuits are detailed and compared with other step-up converter solutions in Section 3.4

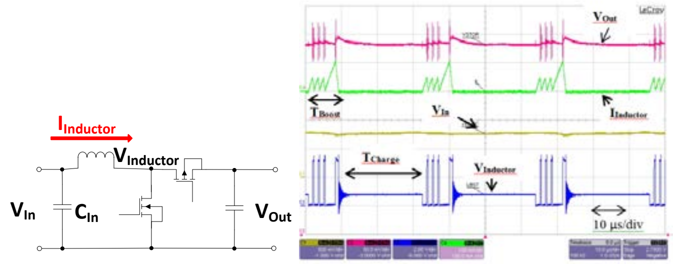

Fig. 4. (a) Boost converter and (b) circuit operating waveforms taken from [20].

B. Switched Capacitor Circuits

The next examined step-up converter is the switched capacitor (SC) circuit which, for the case of this work includes charge pumps. Switched capacitor circuits are an established technology [20], where the Dickson charge pump [21] was the precursor to many of the modern SC circuits. The operation of a switched capacitor circuit is to increase voltage by connecting capacitors in a series/parallel manner or by creating a clock signal to increment the voltage on successive capacitors. A major benefit of this circuit is the ability to start at lower input voltages when compared with other DC-DC converters, particularly inductor based converters. This advantage is exploited particularly during cold-start which is detailed in Section 4.3.

A significant disadvantage of the Dickson charge pump for energy harvesting sources is the voltage drop across the diodes required for voltage step-up. A commonly used method to negate this issue is to use MOSFETs instead of diodes as illustrated in Figure 5 (a). However, this requires that the MOSFETs are driven from sufficiently high voltage levels which are provided from an oscillator circuit [22], and this consumes additional energy.

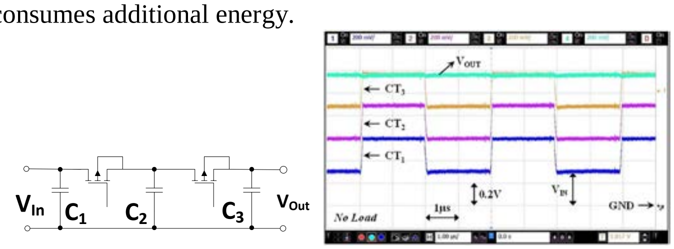

Fig. 5(a) Switched capacitor and (b) circuit operating waveforms from [23].

The operating waveforms of an example 3-stage switched capacitor circuit taken from [23] are shown in Figure 5 (b). The voltage per capacitor can be seen increasing by the magnitude of the input voltage with the output voltage connected to the 3rd stage. Other possible switched capacitor solutions, e.g. series/parallel, provide similar functionality with operating waveforms varying depending on topology.

It is worth noting that many of the existing switched capacitor circuits, [23], [24], [25], [26], are very focused on size. This is a key factor when selecting this type of converter as due to the lack of an inductor or coupled inductors the implementation can be very small, and easily integrated onto a system level PCB board or indeed on silicon at low cost. For example [25] focusses on an extremely small footprint, 1.0 mm^2, which is beneficial for wearable sensors as well as other biomedical related applications. However, the output power level is limited as a result and there is a corresponding trade-off in efficiency which is detailed in Section 3.4

C. Transformer Based Converters

Transformer based converters include coupled inductors with a high primary: secondary turns ratio which allows a low input DC voltage to be increased at the secondary winding, with turns ratios of up to 1 : 100 reported [27]. Figure 6 illustrates (a) the circuit topology and (b) the key steady-state waveforms of a transformer circuit taken from [28].

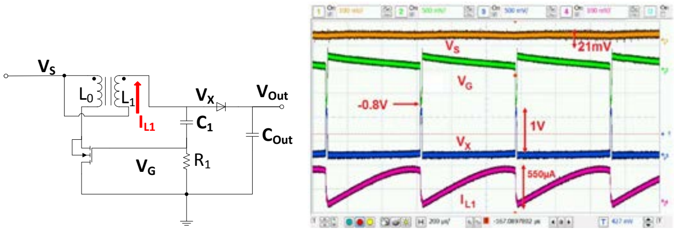

Fig. 6. (a) Transformer circuit and (b) circuit operating waveforms from [28].

The circuit operates using positive feedback oscillation by resonating between the transformer winding inductance (L_1) and a capacitor (C_1) which in turn operates the switch between L_0 and ground [29]. A disadvantage of the circuit is that its efficiency reduces when input voltage increases, 40% @ V_{in} = 0.06 V and 15% @ V_{in} = 0.5 V for a V_{out} of 4.5 V [27]. This is caused by the secondary coil suffering from high voltage stress for higher input voltage due to the circuit operation depending only on positive feedback oscillation [29]. The transformers proposed in [29], [30] address this issue by altering the circuit configuration to operate it as a boost converter at higher input voltages (e.g. > 0.1 V). This is achieved by disabling the switch at L_0 which results in the secondary winding (L_1) operating as an inductor in a boost converter configuration. The increase in efficiency of [28], [31] is due to a change in the operation modes with a Meat Grinder [32] and flyback utilised respectively.

D. Converter Comparison

In this section, the converters are compared based on their steady-state circuit performance under typical conditions encountered in energy harvesting applications. For the following graphs the step-up converters are divided into topologies: inductor based boost converters (blue), switched capacitors (green) and transformer based converters (red). Switched capacitors feature both charge pump and switched capacitor based circuits. For the case of transformer based converters, circuits which operate in a boost configuration during steady-state are shown in hollow red squares with the remaining transformer-only solution highlighted in a solid red square. The efficiencies of the circuits are taken as the maximum reported efficiency, and the associated output power, voltage step-up ratio and input voltage are recorded at this point. The efficiencies include the losses associated with energy management (which is detailed in Section 4) in particular controller and MPPT losses. Solutions that are applied only during cold start are not included in this analysis.

Initially all the converter topologies are compared based on efficiency versus output power as shown in Figure 7. Most of the existing circuits for IoT related applications are focused between 0.1 and 1 mW, the typical power levels of small form factor low-power energy harvesting sources. Many of the switched capacitor circuits are at the lower output power level with many delivering less than 0.1 mW. This is due to the main focus of SCs being on small form factor which results in a reduced power capacity of the circuit.

The efficiency varies significantly depending on output power and topology. For example the switched capacitor efficiency increases with an increase in output power, however this is the opposite for transformer based converters, while for the case of inductor based converters, the efficiency shows no obvious trend with power level. The inductor circuits are limited to relatively high power levels due to the implementation of discrete inductors, however some work has been focused on lower power (544 pW – 4 nW), by featuring a boost converter combined with a voltage doubler [33]. Inductors on silicon [34] also provide an opportunity to reduce the power level of inductor and transformer based solutions, as well as the overall form factor.

Based on the output power a future research possibility would be to examine the performance of SC circuits for power levels between 1 and 5 mW. The next circuit parameter to consider is the voltage step-up ratio (output voltage versus input voltage) versus the converter efficiency as shown in Figure 7 (b).

Initially examining the switched capacitor circuits, many have been focused at lower voltage step-up ratios, between a ratio of 1.5 and 4. Again this is in part due to the focus on small circuit form factor, whereby increasing the step-up ratio requires additional components and results in a larger circuit footprint. Inductor based converters have a wide range of voltage step-up ratios ranging from 1.5 to 50, with the majority centred on a conversion ratio of 10. This wide range is achievable because the duty cycle of the circuit varies the step-

TABLE II
CHARACTERISTICS OF A RANGE OF SUITABLE SUPERCAPACITORS FOR PULSED POWER DELIVERY FOR WIRELESS SENSORS

Topology	Advantages	Disadvantages	Limitations
Inductor Based Converter	- High efficiency across a range of input and load conditions - Wide input range - Wide range of output power capabilities	- Additional cold-start circuitry - Relatively large footprint due to inductor	- Existing solutions are limited to relatively high output power (see Figure 7)
Switched Capacitor	- Small footprint - Operates with low input voltage without additional cold-start circuitry	- Targeted at lower conversion ratio due to additional components required for larger conversion ratio - Relatively low output power capability, based on existing solutions	- Output voltage limited due to implementation of circuit requiring an integer number of stages
Transformer Based Converter	- Operates with low input voltages without additional cold-start circuitry - High efficiency when operating in boost mode during steady-state - High output power capability	- Relatively large footprint due to coupled inductors - Efficiency for existing solutions is relatively low, especially when compared to boost converters	- Same limitation as inductor based converters - Efficiency can be limited due to coupled inductors (see Section 3.3.)

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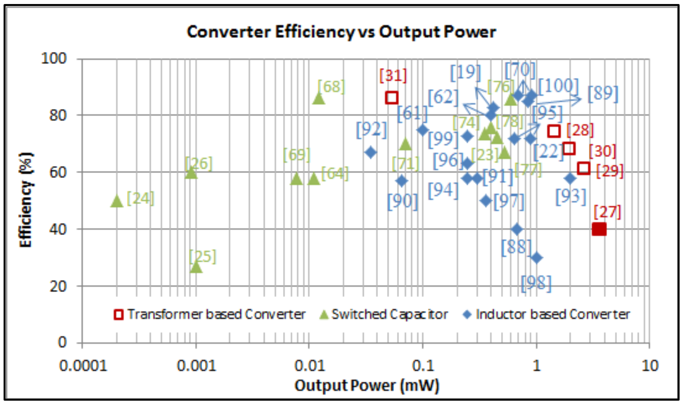
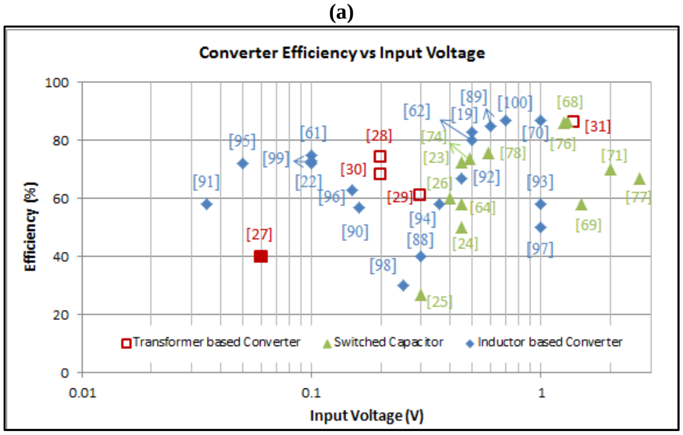
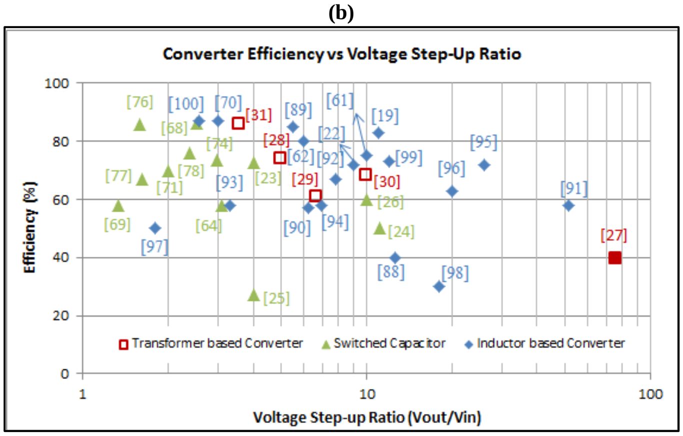
up ratio.



(a)



(b)



(c)

Fig. 7. Shows the existing DC-DC converter efficiency versus (a) output power, (b) voltage step-up ratio and (c) input voltage.

Finally transformer based solutions can have a very high step-up ratio as shown by [27], however as mentioned, the transformer is often used for cold-start and the circuit operates as a boost converter during steady-state. This is the case for all transformer based converters considered, excluding [27]. The overall efficiency trend for all examined converters shows higher efficiency for low voltage step-up ratio. This is explained by a reduced number of switching circuit stages or reduced duty cycle.

As it is not evident in the results of voltage step-up ratio in Figure 7 (b), the dependence of converter efficiency on input voltage is shown in Figure 7 (c). The input voltage ranges from 35 mV up to 2.7 V with the majority of results centred on the 0.3 – 0.6 V range. Much of the work on switched capacitors is focused at input voltages of 0.4 V or higher because, as mentioned above, the number of stages to produce a useable output voltage is limited by size, cost and efficiency. Inductor based solutions have a wide range of input voltages from 35 mV up to 2.4 V. The transformer based converters can operate at extremely low input voltages, however as discussed, maximum efficiencies relate to the circuits operating in a boost converter topology. Despite this the efficiency is somewhat limited due to the coupled inductor losses, e.g. leakage inductance. For all the converters, efficiency generally increases with an increased input voltage and this is explained by the relatively smaller effect of voltage drops across switching devices. Table 1 shows a comparative summary of the conversion topologies in terms of their relative advantages and disadvantages as identified from trends in Figures 7-9 above.

TABLE III
MPPT METHODS USED FOR LOW-POWER ENERGY HARVESTING

Ref	Method	Power Consumption	Ref	Method	Power Consumption
[40]	P&O	0.1 μW	[69], [70], [71]	Hill Climbing	2.1 μW
[72]	FOCV	≈ 0.15 μW	[73]	FOCV	≈ 3 μW
[74]	Hill Climbing	0.25–0.74 μW	[75]	Hill Climbing	3.8 μW (including controller losses)
[63]	FOCV	0.3 μW (including controller losses)	[5]	Hill Climbing	4.6 μW
[76]	Hill Climbing	0.45-0.85 μW	[77]	Hill Climbing	≈ 6 μW
[78]	Hill Climbing	0.46-0.93 μW	[45]	FOCV	150-700 μW

By combining the data from Figure 7-9 and the details in Table 1, suitable converters can be chosen for a range of input and output conditions. For example, clustering of data points in Figure 7 shows that inductor and transformer based solutions are more suitable for relatively high power, while switched capacitors are more suitable for lower power. Meanwhile, Figure 7 (b) shows that switched capacitor solutions are limited in the voltage step-up range that can be supplied. This limitation is due to switched capacitor solutions requiring a whole number of stages, e.g. 3, while the output voltage of the inductor and transformer based circuits can be varied depending on duty cycle.

In general a system featuring higher output power, a lower voltage step-up ratio and a relatively high input voltage results in a converter with high efficiency. However for many wireless sensors, the input and output parameters are often limited based on application sensor requirements and available footprint/volume. In general inductor based converters have a higher efficiency when compared to switched capacitor and transformer based converters, but have a larger footprint and require additional circuitry for cold-start.

IV. Energy Management

This section reviews the additional components accompanying DC-DC stages required to create a truly autonomous energy harvesting powered wireless sensor. These include maximum power point tracking, energy storage and cold-start stages. The existing MPPT techniques are detailed in Section 4.1 with particular focus on low-power, low-voltage

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EH sources. Energy storage is required to overcome the power mismatch between source and load, see Figure 2 (a), as well as supplying the load during times when the source isn't harvesting energy. Existing energy storage components are examined and compared based on their suitability for application in energy harvesting systems in Section 4.2. Finally Section 4.3 details cold-start techniques required to allow autonomous circuit operation, in particular after long periods of no operation.

A. Maximum Power Point Tracking

For the case of low-power, low-voltage sources, obtaining the maximum energy is paramount to enabling a system to become autonomous as well as possibly increasing the wireless sensing accuracy and functionality, due to the additional energy. MPPT is utilised for energy harvesting sources to ensure the maximum available energy is extracted, however there a wide range of methods to obtain the maximum power [35]. Figure 8 shows the typical current, voltage and power delivery for a range of different energy harvesting sources, where the IV and PV curves are the current/voltage and power/voltage curves respectively. It is clear to see that there is a point around which the maximum power is delivered for the different sources.

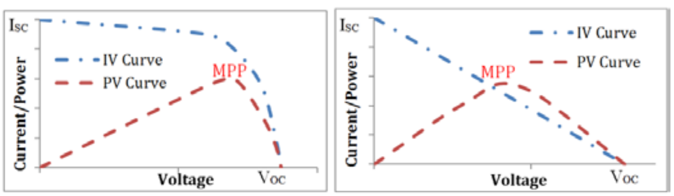

Fig. 8. Typical IV and PV curve for (a) solar cells and (b) thermoelectric, MFC, piezoelectric and RF harvesters.

Much work has been focused on highly sophisticated MPPT systems for large scale energy harvesting. These systems are often implemented digitally and therefore require a controller or signal processing system. For many low-power energy harvesting systems, including an MCU is not possible due to the additional power consumption as well as the financial cost. Some low-power MPPT systems have been implemented on dedicated controllers [36] which have been shown to consume from 1 mA to as low as 50 µA, [37] and [38] respectively. However for the case of this work, the reviewed MPPT literature are specific to low-power energy harvesting sources and are aimed at consuming ultra-low power (in the order of µW or less). Table 2 compares different reported MPPT methods in the literature in terms of their reported power consumption, where most methods are based on either the Perturb and Observe (P&O) or Fractional open-circuit voltage (FOCV) method.

Figure 9(a) shows a flowchart for P&O/hill climbing [39], which is an established MPPT method and is used significantly in high power solar systems. Much research has been performed to allow this MPPT method to operate at low-power levels. As seen in Table 2 the lowest power consumption achieved is P&O with a consumption 0.1 µW [40]. This method operates by reading the energy harvester voltage and power value and determining if the maximum power point has been reached. The circuitry required to implement this method can vary significantly which results in high accuracy, low-power consumption or financially cheaper systems depending on the circuit requirements. In general this method is more accurate than the FOCV, but is often more complex.

The FOCV [41], and fractional short-circuit current (FSCC) [42] methods represent a simple MPPT method used in low-power, low-voltage systems. For FOCV, the method operates by taking the maximum power point voltage as being a fixed percentage of the open-circuit voltage [43]

$$V_{MPP} \approx kV_{OC} \quad . \tag{1}$$

For the case of solar cells the maximum power is achieved at roughly 70 – 80% of the open-circuit voltage, see Figure 8 (a). For piezoelectric, thermoelectric and MFC the maximum power point occurs at approximately 50% [44] of the open-circuit voltage, see Fig. 8(b). The FOCV method is sufficiently accurate but requires minimal implementation complexity (see Fig. 9(b)).

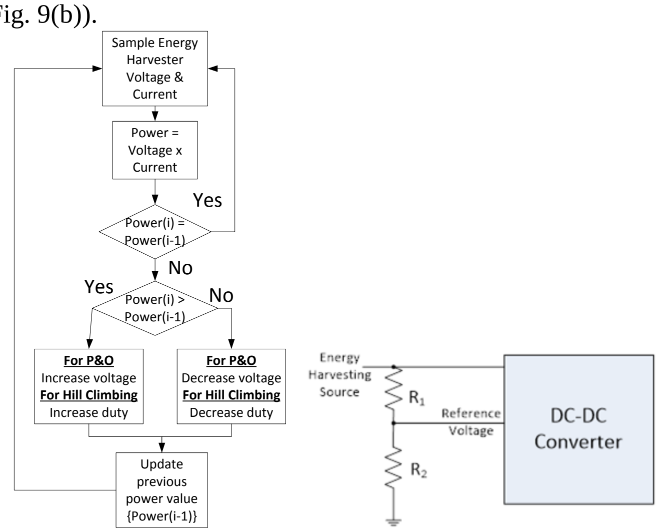

Fig. 9. Flowchart of (a) perturb and observe/hill climbing [80] and (b) fractional open-circuit voltage operation.

To implement the MPPT, as shown in Figure 9 (b), large resistance values are selected to ensure that minimal current is lost through the resistor divider ratio. The main disadvantage of this method is the possible inaccuracy, as the maximum power point might be a few percent above or below the resistor divider ratio. However the low conduction losses for low-power sources, relative ease of implementation and the overall low cost makes the method suitable solution for low-power energy harvesting powered systems.

B. Energy Storage

Energy harvesting powered wireless sensors, in particular small form factor low-power, low-voltage sources, require energy storage due to the low-power nature of the sources and the pulsed nature of the sensors, as shown in Figure 2 (a). Storage elements enable the wireless sensors to become autonomous by overcoming the significant voltage and current mismatch between source and sensor as well as enabling operation during periods when the EH source isn't supplying energy. For example solar cells will only produce energy during hours of sunlight if placed in a location with ambient sunlight or when fluorescent light sources are operating. In this case a storage element is required to power the sensor during periods of no light, e.g. night time. This holds true for many energy harvesting sources as their operation is dependent on external parameters. For these reasons energy harvesting

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powered wireless sensors for low power levels feature energy storage components, however the type, location and usage of the components can vary significantly depending on the application. This section details the electrical characteristics of existing storage elements and their best potential application within energy harvesting systems.

The three commonly used storage elements are batteries, electrolytic capacitors and supercapacitors (also known as ultracapacitors or double layer electrolytic capacitors) or different combinations of them. Each storage element has advantages and disadvantages to utilising them in an energy harvesting system. The storage elements are compared in Table 4 which shows key characteristics such as energy density (watt hours per kilogram) and power density (watts per kilograms), as well as other important characteristics.

Electrolytic capacitors have a high power density which allows the delivery of high power pulses for short time periods, however they are rarely used as the sole storage element due to their low energy density and relatively high leakage current. Instead for the case of energy harvesting powered wireless sensors, electrolytic capacitors are used in parallel with other storage elements to aid with high current discharging.

Supercapacitors have a very desirable combination of energy and power density for energy harvesting powered wireless sensors, as well as having higher charge/discharge efficiency when compared to batteries. They can store sufficient energy to supply a complete sensor operation, including the high power pulse typically required for data transmission, but suffer from leakage which limits their long-term storage capability. A supercapacitor can suffer from leakage of up to 25% of initial energy in 25 hours for a 33 F supercapacitor [45], but supercapacitor leakage is very specific to each supercapacitor even for different components from the same manufacturer.

Much of the current battery research is focussed on lithium based batteries [46]–[52], which are shown to have the highest energy and power density combination of the common battery topologies [53]. As outlined in Table 4, when considering a battery as the storage element for a system, factors such as cycle life and charge/discharge efficiency, as well as energy and power density must be considered. To overcome the power density issue faced by the battery, a battery with a parallel capacitor or supercapacitor is utilised in existing literature, [54] and [55] respectively. Batteries also suffer from leakage however it is significantly less than electrolytic and supercapacitor leakage.

TABLE IV
BATTERY, SUPERCAPACITOR AND ELECTROLYTIC CAPACITOR PERFORMANCE, ADAPTED FROM [85]

Topology	Electrolytic Capacitor	Supercapacitor	Lithium based Battery
Energy Density	0.01-0.3	1-10	30– 200
Power Density	> 100,000	< 10,000	< 1,000
Cycle life	Unlimited	> 500,000	1,000
Charge/Discharge Efficiency	99%	85-98%	80-90%
Fast Charge Time (s)	<0.1	0.3-30	1-5 hours
Discharge Time (s)	<0.1	0.3-30	0.3-3 hours
Leakage	I_L<(0.03*V*C) [79] {e.g. 0.1F I_L = 1.2 mA}	3µA after 72 hours [80]	1-2% per month (lithium-ion) 10-15% per month (Nickel-based) [81]
Examples	[82]	[83]–[85]	Lithium-ion battery [86] used in [67]

Electrolytic capacitors have the largest power density of the three. This indicates that they are very efficient at receiving and delivering pulses of power, but due to their low energy density, can’t retain energy for long periods. Therefore they are best used in combination with batteries or supercapacitors to enable the delivery of the very high power component of wireless sensor load pulses. Supercapacitors provide intermediate energy and power densities, whereby power can be delivered and received effectively, and also stored for relatively long periods. Therefore, in energy harvesting systems where there is a continuous energy source, they can be applied as the sole energy storage component, or they can be combined with either batteries or capacitors for very long term storage or very high pulsed power, respectively.

Aside from energy and power densities, another key factor to consider is the charge/discharge efficiency, which quantifies the ability of the storage element to deliver and receive energy efficiently. Examining Table 3 it is clear to see that electrolytic capacitors have the highest efficiency whilst batteries and supercapacitors can be as low as 80% and 85% respectively. This inefficiency is generally caused by a large equivalent series resistance (ESR) within the storage element and several researchers are targeting methods for reducing it, [56] and [57].

Finally lifetime issues play a major role in the storage element selection. Most IoT related applications required deploy and forget systems which may be located in harsh environments. Taking an outdoor sensor as an example and an operating temperature of 60°C the lifetime of the storage elements is greatly affected. A sample electrolytic capacitor’s lifetime is approximately 7.5 years [58] while supercapacitors lifetime can be limited to 3 years [59] (depending on voltage utilisation). For a sample battery the overall capacity is reduced by 20 % after 200 days of 60°C operation which results in limited lifetime [60].

C. Cold-Start

Cold-start occurs when the circuit is starting with a discontinuous source and no energy stored within the system, either in the energy management circuit or storage element. As many of the DC-DC converters feature switches and/or diodes, a gate-drive voltage larger than the energy harvesting source voltage is usually required to allow the circuit to operate correctly. Methods used to overcome cold-start include featuring an unregulated charge pump prior to the boost converter [61], [62], [63], an oscillator prior to a switched capacitor circuit, [23], [24], [64], and high turns ratio transformer based solutions [27], [29], whereby the source voltage is stepped-up and applied to store sufficient energy to supply gate-drive circuitry in more efficient DC-DC solutions. The cold-start circuitry for the boost and switched capacitor circuits operates in a similar fashion to that detailed in Section 3.2. For the transformer circuits, cold-start is achieved by resonance between the inductor and capacitor, as detailed in Section 3.3. Based on these methods, energy harvesting powered systems can be completely autonomous and not rely on external power sources. Cold-start is an

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inefficient process and is often excluded from published efficiency values due to the event rarely occurring, possibly as little as once over the lifetime of the system.

V. Demonstrator Energy Harvesting Systems

Up to this point, the individual components required to manage the energy for an energy harvesting powered wireless sensor have been detailed. However the methods in which the energy management is implemented varies depending on system conditions, e.g. input source voltage/power levels and output sensor power profiles, and this is illustrated through example demonstrator systems in this section.

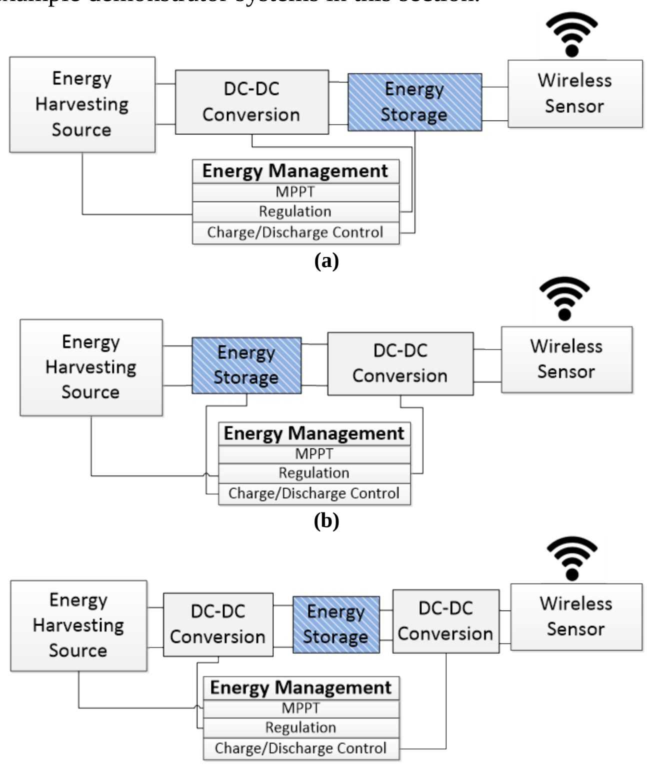

Fig. 10. Various energy storage configurations for energy harvesting powered wireless sensors.

As detailed each DC-DC step-up converter and the associated energy management techniques have benefits, e.g. switched capacitor circuits tend to be focused in small footprint applications, while inductor based solutions have higher efficiency but require separate cold-start circuitry as well as storage elements. Overall system configuration varies depending on system constraints and requirements. Figure 10 shows the various different system configurations for energy harvesting powered sensors implemented in the literature.

Figure 10 (a) shows the most common system configuration used where the EH input is connected to the DC-DC conversion circuitry which in turn is connected to an energy storage element in parallel with the load, see Figure 1. Many of the circuits documented in Section 3 and 4 utilise this system configuration. The benefit of using this method is that sufficient energy is stored in the storage element prior to a wireless sensor operation.

However by featuring the power conversion circuitry between the source and storage element, losses associated with the power converter are always encountered when the EH source is harvesting. Another issue faced by this system is due to the output voltage not being regulated which can result in sensor failure caused by voltage variance. Careful selection of the storage element is required to overcome this issue with particular focus on sufficient power density.

An alternative configuration is a system featuring the energy storage prior to the energy management circuit [65], [66] as shown in Figure 10 (b). This method can only be applied in cases where the energy source and storage elements have compatible voltages and therefore the voltage step-up ratio is usually quite low. It negates some of the issues associated with the system in Figure 10 (a) whereby the power conversion circuitry operation reduced to only operate when the wireless sensor operates. This method requires greater system integration to ensure that sufficient energy is available when the wireless sensor is operating. Also the charge/discharge efficiency of the storage element needs to be factored in as this will contribute when both the source and/or load are operational.

Finally a system featuring power conversion prior to and after energy storage is shown in Figure 10 (c) [67]. This solution encounters losses for both management circuits however the additional energy management circuit is featured to regulate the output voltage. This system configuration is desirable for sensitive load applications whereby a fixed, reliable and tightly regulated output voltage is required.

Table 5 shows examples of complete energy harvesting powered systems whereby the source, sensor, converter and storage are detailed as well as the system configuration as detailed in Figure 10. Overall system efficiency isn't included as it isn't reported for many systems. Within the source column, *continuous* or *intermittent* is included to indicate

TABLE V
CHARACTERISTICS OF A RANGE OF SUITABLE SUPERCAPACITORS FOR PULSED POWER DELIVERY FOR WIRELESS SENSORS

Ref	Source	Sensor	DC-DC Topology & (Efficiency)	Storage	MPPT	System Topology (see Figure 10)
[68]	PV (25 cm^2 @ 17 μW) *Continuous*	ZigBee Temperature Sensor	3-Stage Switched Capacitor (85%)	33 mF Supercapacitor	Hill Climbing	(a)
[25]	PV (1.6 mm^2 @ ≈ 40 μW) *Intermittent*	RF Temperature Sensor	4-Stage Switched Capacitor (27%)	0.6 μAh thin-film Cymbet Battery	FOCV	(a)
[31]	MFC (0.7 litre reactor @ 1.7 μW) *Continuous*	Wired Temperature Sensor	Transformer (86%)	Small External Battery	FOCV	(a)
[65]	PV Cell (6.75 cm^2 @ ≈ 0.15 mW) *Intermittent*	ZigBee Humidity Temperature, Sensor	Boost Converter (TPS63012, 55%)	10 F Supercapacitor	FOCV	(b)
[87]	PV + TEG (16 cm^2 @ ≈ 25 mW) *Intermittent*	Humidity, Lux, Temperature, Sensor	Transformer (LTC3108 up to 40%)	1.65 F Supercapacitor	FOCV	(c)
[88]	PV (20 cm^2 @ ≈ 20 mW) *Intermittent*	Temperature Sensor	Boost Converter (TPS61200, 40%)	120 mF Supercapacitor or 12 μAh Cymbet Battery	FOCV	(c)
[67]	PV (27.8 cm^2 @ ≈ 0.5 mW) *Intermittent*	ZigBee Humidity, Lux, Temperature	Boost Converter (TPS61221, 79%)	2.5 F Supercapacitor	FOCV	(c)

whether the source is delivering energy continuously or in pulses. This indicates the demonstrators' ability to operate in a real-world environment when performance can be intermittent due to the harvester operation being dependent on external parameters. It is clear to see that many of the existing demonstrator systems utilise commercially available DC-DC converters. These converters often have a wide input and output range which allows them to be used in many applications but not optimised for a specific system. The systems featuring customised DC-DC conversion show higher conversion efficiency, [68] and [31] with 85 and 86% respectively. This shows the increased performance of an optimised system, based on input and output specifications. It is worth noting that as detailed in Section 4.2 supercapacitors provide a desirable storage solution due to their suitable energy and power densities and as a result many existing systems feature a supercapacitor. The existing demonstrators show the need for careful system integration whereby the most suitable DC-DC converter is chosen for a particular combination of input and output conditions with suitable storage.

VI. Discussion/Conclusions

This review paper shows the volume of work focused at low-power, low-voltage energy management circuitry for energy harvesting powered wireless sensors, which illustrates the push to find alternative cost effective, reliable power sources for battery powered sensors with the growth of IoT systems. In particular the difficulties with utilising energy harvesting and the methods used to overcome them have been documented.

The paper reviews all components required to create a complete energy harvesting powered sensor system. These include DC-DC step-up converters, MPPT, energy storage and cold-start circuitry. An in-depth analysis of the circuit performance of suitable converters is detailed in Section 3, along with a summary of their advantages and disadvantages. The highest efficiency topology for a range of voltage and power levels was found to be the boost converter (e.g. 0.5 V the voltage of a solar cell) while the switched capacitor circuits have an extremely small form factor and the transformer solutions are focused at ultra-low voltages. MPPT techniques used for EH sources are compared based on their power consumption as well as accuracy in Section 4, along with a comparison of the characteristics of a range of suitable storage elements, which show the capability of existing solutions to satisfy different system requirements. The suitability of storage elements based on energy and power density as well as life cycles and charge/discharge efficiency for both short- and long-term has been detailed, with supercapacitors providing a robust solution to many applications.

The paper shows the case for the optimisation of energy harvesting powered systems by selecting an optimised DC-DC converter with the associated energy management techniques. Existing works show the benefit of different converters based on input voltage, voltage step-up and power delivery, however there is a need for the further development of converters. This includes the designing of inductor based converters for lower power levels by possibly implementing inductors on silicon, or by designing switched capacitor circuits for higher output power levels. This may result in higher performing systems which will increase the harvested energy and overall help enable the increase in number of sensors deployed to enable a power autonomous IoT.

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