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Ultralow power energy harvester and battery charger

VFQFPN 3 x 3 x 1 mm 20L   **Die form**
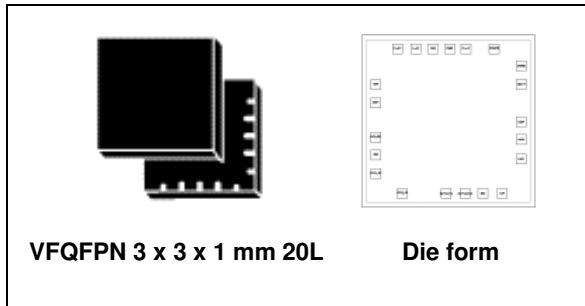
Features

- Transformerless thermoelectric generators and PV modules energy harvester

- High efficiency for any harvesting source

- Up to 70 mA maximum battery charging current

- Fully integrated buck-boost DC-DC converter

- Programmable MPPT by external resistors

- 2.6 V to 5.3 V trimmable battery charge voltage level (± 1% accuracy)

- 2.2 V to 3.6 V trimmable battery discharge voltage level (± 1% accuracy)

- Two fully independent LDOs (1.8 V and 3.3 V output)

- Enable/disable LDO control pins

- Battery disconnect function for battery protection

- Battery connected and ongoing charge logic open drain indication pins

Applications

- Charge any battery type, including lithium based, solid state thin film and super-capacitor.

- WSN, HVAC, building and home automation, industrial control, remote metering, lighting, security, surveillance.

- Wearable and biomedical sensors, fitness.

Description

The SPV1050 is an ultralow power and high-efficiency energy harvester and battery charger, which implements the MPPT function and integrates the switching elements of a buck-boost converter.

The SPV1050 device allows the charge of any battery, including the thin film batteries, by tightly monitoring the end-of-charge and the minimum battery voltage in order to avoid the overdischarge and to preserve the battery life.

The power manager is suitable for both PV cells and TEG harvesting sources, as it covers the input voltage range from 75 mV up to 18 V and guarantees high efficiency in both buck-boost and boost configuration.

Furthermore the SPV1050 device shows very high flexibility thanks also to the trimming capability of the end-of-charge and undervoltage protection voltages. In such way any source and battery is matched.

The MPPT is programmable by a resistor input divider and allows maximizing the source power under any temperature and irradiance condition.

An unregulated voltage output is available (e.g. to supply a microcontroller), while two fully independent LDOs are embedded for powering sensors and RF transceivers. Both LDOs (1.8 V and 3.3 V) can be independently enabled through two dedicated pins.

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VFQFPN 3 x 3 x 1 mm - 20L

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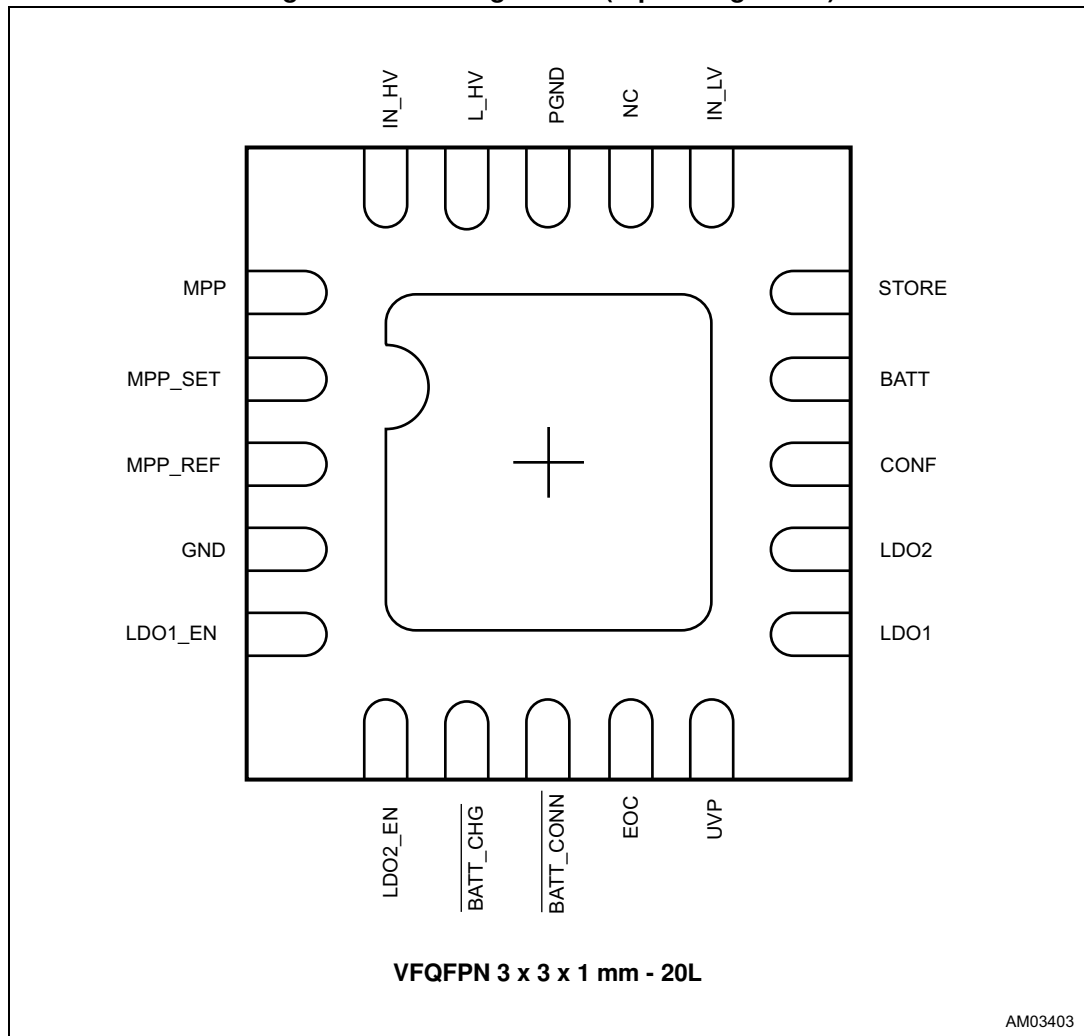
3 Pin description

Table 1. Pin description

Pin no.	Name	Type	Description
1	MPP	I	Max. power point tracking voltage sense pin. To be connected to the voltage source through a ladder resistor.
2	MPP-SET	I	Max. power point setting voltage pin. To be connected to the MPP pin through a ladder resistor. Connect to STORE if MPP function is not required.
3	MPP-REF	I	Max. power point reference voltage pin. To be connected to a 10 nF capacitor. Connect to an external voltage reference if MPP function is not required.
4	GND	GND	Signal ground pin.
5	LDO1_EN	I	If high, enables LDO1.
6	LDO2_EN	I	If high, enables LDO2.
7	$\overline{\text{BATT\_CHG}}$	O	Ongoing battery charge output flag pin (open drain). If low, it indicates that the battery is on charge. If high, it indicates that the battery is not on charge.
8	$\overline{\text{BATT\_CONN}}$	O	Battery status output flag pin (open drain). If high, it indicates that the pass transistor between the STORE and BATT pins is open (battery disconnected). If low, it indicates that the pass transistor between the STORE and BATT pins is closed (battery connected).
9	EOC	I	Battery end-of-charge pin. To be connected to the STORE pin through a resistor divider between EOC and GND.
10	UVP	I	Battery undervoltage protection pin. To be connected to the STORE pin through a resistor.
11	LDO1	O	1.8 V regulated output voltage pin.
12	LDO2	O	3.3 V regulated output voltage pin.
13	CONF	I	Configuration pin. Boost configuration: to be connected to the voltage supply source. Buck-boost configuration: to be connected to ground.
14	BATT	I/O	Battery connection pin.
15	STORE	I/O	Tank capacitor connection pin.
16	IN_LV	I	Low voltage input source. It has to be connected to the inductor for both boost and buck-boost configuration.
17	NC	-	Not connected.
18	PGND	PGND	Power ground pin.

Table 1. Pin description (continued)

Pin no.	Name	Type	Description
19	L_HV	I	Input pin for buck-boost configuration. Boost configuration: to be connected to ground. Buck-boost configuration: to be connected to the inductor.
20	IN_HV	I	High voltage input source. Boost configuration: to be connected to ground. Buck-boost configuration: to be connected to the voltage supply source.

4   Maximum ratings

Table 2. Thermal data

Symbol	Parameter	Value		Unit
		Min.	Max.	
$R_{th\ j\text{-}c}$	Max. thermal resistance, junction to case		7.5	°C/W
$R_{th\ j\text{-}a}$[1]	Max. thermal resistance, junction to ambient		49	°C/W
P_{TOT}	Maximum power dissipation at T_{amb} = 85 °C		1	W
T_j	Junction temperature range	-40 ÷ 125		°C
$T_{storage}$	Storage temperature	150		°C

1. Measured on 2-layer application board FR4, Cu thickness = 17 um with total exposed pad area = 16 mm^2

Table 3. Absolute maximum ratings

Symbol	Parameter	Value	Unit
IN_LV	Analog input	V_{STORE} + 0.3	V
IN_HV	Analog input	20	V
L_HV	Analog input	IN_HV + 0.3	V
CONF	Analog input	5.5	V
MPP	Analog input	5.5	V
MPP-SET	Analog input	5.5	V
MPP-REF	Analog input	5.5	V
BATT	Analog input/output	5.5	V
STORE	Analog input/output	5.5	V
UVP	Analog input	V_{STORE} + 0.3	V
EOC	Analog input	V_{STORE} + 0.3	V
$\overline{BATT\_CONN}$	Digital output	5.5	V
$\overline{BATT\_CHG}$	Digital output	5.5	V
LDO1_EN	Digital input	V_{STORE} + 0.3	V
LDO2_EN	Digital input	V_{STORE} + 0.3	V
LDO1	Analog output	V_{STORE} + 0.3	V
LDO2	Analog output	V_{STORE} + 0.3	V
PGND	Power ground	0	V
GND	Signal ground	-0.3 to 0.3	V

5 Electrical characteristics

V_{STORE} = 4 V, T_{amb} = - 40 to 85 °C, unless otherwise specified. Voltage with respect to GND unless otherwise specified.

Table 4. Electrical characteristics

Symbol	Parameter	Test condition		Min.	Typ.	Max.	Unit
Battery operating range							
I_{BATT}	Maximum battery charging current					70	mA
V_{BATT}	BATT pin voltage range			2.2		5.3	V
$V_{BATTACC}$	Battery voltage accuracy			-1		+1	%
R_{BATT}	Pass transistor resistance			6	7	8	Ω
Bandgap							
V_{BG}	Internal reference voltage				1.23		V
	Accuracy			-1		+1	%
UVP							
V_{UVP}	Undervoltage protection range	$(V_{UVP} + UVP_{HYS}) < (V_{EOC} - EOC_{HYS})$		2.2		3.6	V
EOC							
V_{EOC}	Battery end-of-charge voltage	$(V_{UVP} + UVP_{HYS}) < (V_{EOC} - EOC_{HYS})$		2.6		5.3	V
EOC_{HYS}	EOC hysteresis	V_{STORE} decreasing			-1		%
STORE							
V_{STORE}	STORE pin voltage operating range			V_{UVP}		V_{EOC}	V
Static current consumption							
I_{SD}	Shutdown current	Shut down mode: Before first startup or $\overline{BATT\_CONN}$ high T_{AMB} < 60 °C				1	nA
I_{SB}	Standby current	Standby mode: BATT_CONN low, BATT_CHG high, VSTORE = 5.3 V and LDO1,2_EN low T_{AMB} = 25 °C			0.8		µA
I_{OP}	Operating current in open load	Operating mode (LDOs in open load) $\overline{BATT\_CONN}$ low $\overline{BATT\_CHG}$ high T_{AMB} = 25 °C	LDO1_EN = 1 or LDO2_EN = 1		1.7		µA
			LDO1,2_EN = 1		2.6		

Table 4. Electrical characteristics (continued)

Symbol	Parameter	Test condition	Min.	Typ.	Max.	Unit
DC-DC converter						
V_{IN_LV}	Input voltage range	Boost configuration	0.15		V_{EOC}	V
V_{IN_HV}		Buck-boost configuration	0.15		18	
V_{IN-MIN}	Minimum input voltage at startup	Boost configuration $\overline{BATT\_CONN}$ high or at first startup		0.55	0.58	V
		Buck-boost configuration $\overline{BATT\_CONN}$ high or at first startup		2.6	2.8	
I_{B-SU}	Startup input current	Boost configuration		30		µA
I_{BB-SU}		Buck-boost configuration		5		µA
$R\text{-}ON_B$	Low-side MOS resistance	Boost configuration	0.5	1.0	1.5	Ω
$SR\text{-}ON_B$	Synchronous rectifier MOS resistance		0.5	1.0	1.5	
$R\text{-}ON_{BB}$	Low-side MOS resistance	Buck-boost configuration	1	1.5	2	Ω
$SR\text{-}ON_{BB}$	Synchronous rectifier MOS resistance		1	1.5	2	
f_{SW}	Maximum allowed switching frequency	Boost and buck-boost configurations			1	MHz
$UVLO_H$	Undervoltage lockout threshold (V_{STORE} increasing)	Boost and buck-boost configurations		2.6	2.8	V
$UVLO_L$	Undervoltage lockout threshold (V_{STORE} decreasing)		2	2.1		V
MPPT						
$T_{TRACKING}$	MPPT tracking period	$\overline{BATT\_CHG}$ low	12		20	s
T_{SAMPLE}	MPPT sampling time	$\overline{BATT\_CHG}$ high	0.3		0.5	s
V_{MPP}	MPP pin voltage range	Boost and buck-boost configurations	0.075		V_{UVP}	V
MPP_{ACC}	MPP tracking accuracy	Boost and buck-boost configurations	95			%
LDO						
$V_{LDO1,2}$	LDO1,2 adjusted output voltage	LDO1_EN = 1		1.8		V
		LDO2_EN = 1		3.3		
$\Delta V_{LDO1,2}$	LDO1 dropout	V_{UVP} + 200 mV < V_{BATT} ≤ 5.3 V I_{LDO1} = 100 mA			0.5	%
	LDO2 dropout	3.3 < V_{UVP} + 200 mV < V_{BATT} ≤ 5.3 V I_{LDO2} = 100 mA			0.5	
t_{LDO}	$LDO_{1,2}$ startup time	BATT_DIS low $C_{LDO1,2}$ = 100 nF			1	ms
I_{LDO1}[1]	I_{OUT} max from LDO1				200	mA

Table 4. Electrical characteristics (continued)

Symbol	Parameter	Test condition	Min.	Typ.	Max.	Unit
I_{LDO2}[1]	I_{OUT} max from LDO2				200	mA
$V_{LDO1,2\_EN\_H}$	LDO1,2 enable input HIGH		1			V
$V_{LDO1,2\_EN\_L}$	LDO1,2 enable input LOW				0.5	V
Digital output						
$V_{\overline{BATT\_CONN\_L}}$	V_{BATT_DIS} LOW	1 mA sink current	40	70	150	mV
$V_{\overline{BATT\_CHG\_L}}$	V_{XBATT_CHG} LOW	1 mA sink current	40	70	150	mV

1. Guaranteed by design, not tested in production.

6   Functional description

The SPV1050 is an ultralow power energy harvester with an embedded MPPT algorithm, a battery charger and power manager designed for applications up to about 400 mW.

The SPV1050 device integrates a DC-DC converter stage that can be configured as boost or buck-boost by tying the CONF pin to PV+/TEG+ or to ground respectively as shown in *Figure 4* and *Figure 12 on page 20*.

If the embedded MPPT algorithm is enabled, the device regulates the working point of the DC-DC converter in order to maximize the power extracted from the source by tracking its output voltage. See further details in *Section 6.2: Boost configuration on page 16* and *Section 6.3: Buck-boost configuration on page 20*.

The MPPT algorithm can be disabled by shorting the MPP-SET pin to the STORE pin, and by providing an external voltage to the MPP-REF pin.

In case of low impedance source (e.g. USB), the MPP-REF must be connected to GND. The IC will switch at the highest duty cycle possible until the V_{EOC} on the STORE pin is triggered.

In case of high impedance source with limited current capability (i.e. if the source is unable to sustain switching at the maximum duty cycle), the MPP-REF pin must be connected to a voltage reference selected such that $V_{MPP-REF} > V_{IN(MIN)}$. This voltage reference can be set through a resistor ladder connected to STORE or any other voltage reference available in the application.

If the MPP pin is connected to the source by a resistor ladder, then the same consideration must be extended to the MPP pin. Referring to *Figure 19* (where connections between MPP-SET to R2-R3 must be open and MPP-SET must be considered as connected to STORE):

–   If R1 = 0 Ω: then $V_{MPP-REF} = V_{IN(MIN)}$
–   Otherwise: $V_{MPP-REF} = V_{MPP(MIN)} = V_{IN(MIN)} * (R2+R3)/R1$

6.1   Battery charger

In order to guarantee the lifetime and safety of the battery, the SPV1050 device controls an integrated pass transistor between the STORE and BATT pins and implements both the undervoltage (UVP) and the end-of-charge (EOC) protection thresholds.

Figure 3. Battery management section
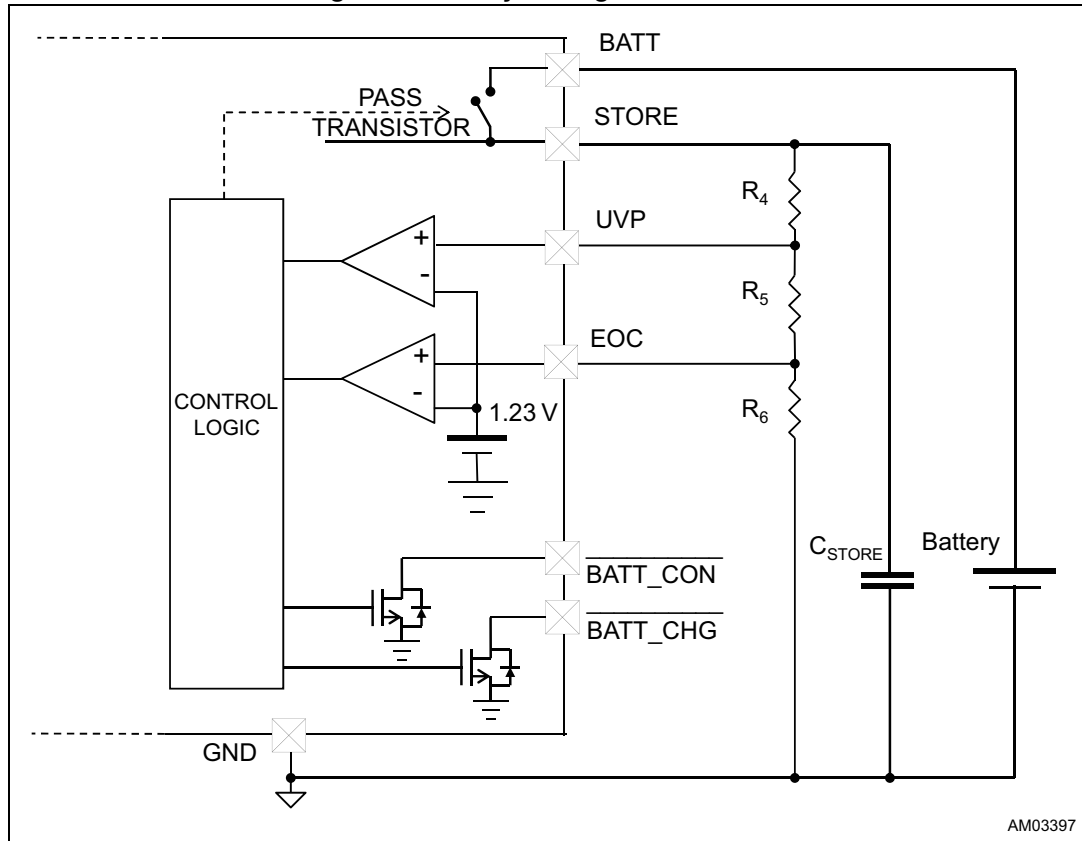
Before the first startup the pass transistor is open, so that the leakage from the battery is lower than 1 nA. The pass transistor will be closed once the voltage on the STORE pin will rise such that the EOC threshold V_{EOC} is triggered. If the battery is full, and until $V_{STORE} > V_{EOC} - EOC_{HYS}$, the DC-DC converter will stop switching to avoid battery overcharge.

On the contrary, in order to avoid the overdischarge of the battery, the pass transistor will be opened once the voltage on the STORE pin will decrease down to UVP threshold V_{UVP}.

These functions are simply implemented by the control of two voltage thresholds, V_{UVP} and V_{EOC}, which can be regulated by a resistor partitioning (R4, R5, R6) between STORE, UVP and EOC pins.

The scaled voltages on the UVP and EOC pins will be compared with the internal bandgap voltage reference V_{BG} set at 1.23 V.

The design rules to setup the R4, R5 and R6 are the following:

Equation 1

$$V_{BG} = V_{UVP} \cdot (R5 + R6) / (R4 + R5 + R6)$$

Equation 2

$$V_{BG} = V_{EOC} \cdot R6 / (R4 + R5 + R6)$$

In order to minimize the leakage due to the output resistor partitioning it has to be typically:

Equation 3

$$10 \text{ M}\Omega \le R4 + R5 + R6 \le 20 \text{ M}\Omega$$

Further, the SPV1050 device provides two open drain digital outputs to an external microcontroller:

- **$\overline{\text{BATT\_CONN}}$**
  This pin is pulled down when the pass transistor is closed. It will be released once the pass transistor will be opened (e.g. triggering of V_{UVP}). If used, this pin must be pulled-up to the STORE by a 10 MΩ (typical) resistor.

- **$\overline{\text{BATT\_CHG}}$**
  This pin is pulled down when the DC-DC converter is switching, while it's released when it is not switching, i.e. when the EOC threshold is triggered until the voltage on the STORE pin drops at V_{EOC} - EOC_{HYS} , when the UVLO threshold is triggered or during the T_{SAMPLE} of the MPPT algorithm. If used, this pin must be pulled-up to the STORE by a 10 MΩ (typical) resistor.

6.2 Boost configuration

*Figure 4* shows the boost application circuit.

Figure 4. Boost configuration
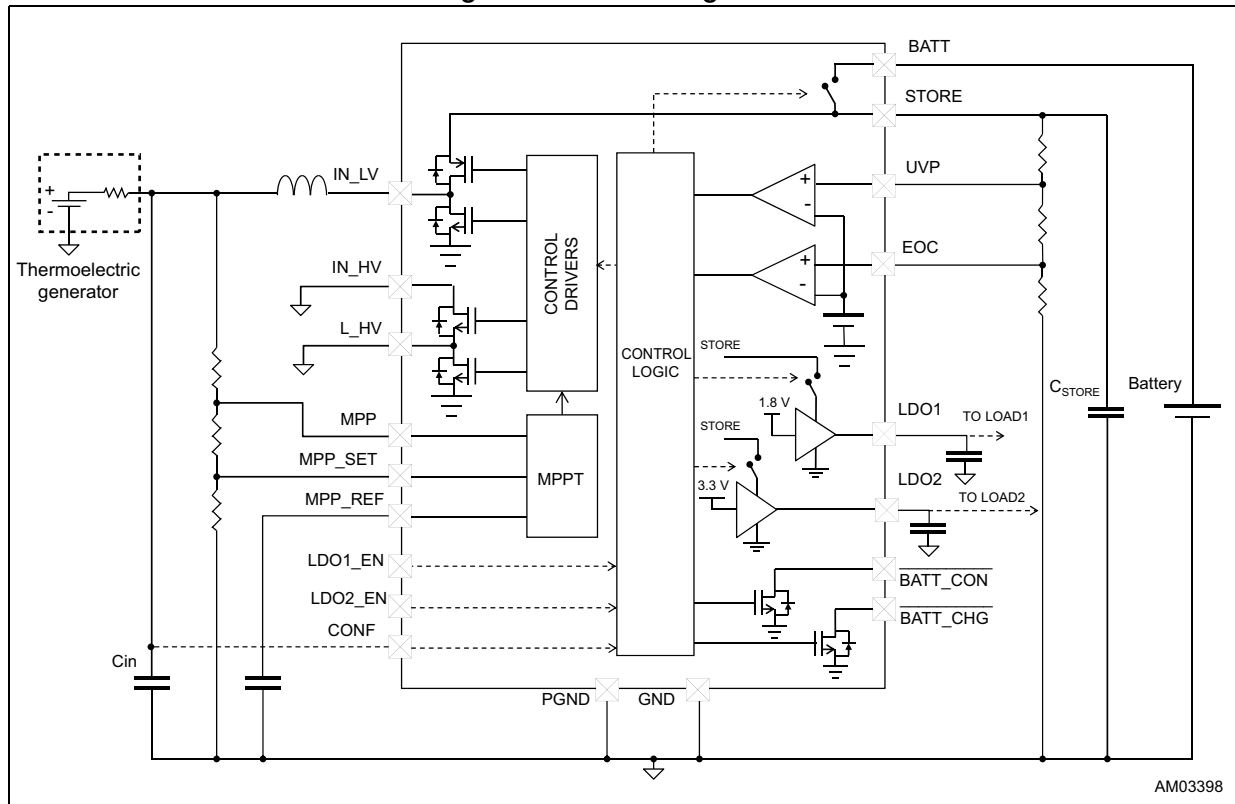
In case of boost configuration, once the harvested source is connected, the SPV1050 device will start boosting the voltage on the STORE pin. In the range of $0 \leq V_{STORE} < 2.6$ V the voltage boost is carried on by an integrated high-efficiency charge pump, while the DC-DC converter stage will remain OFF.

Figure 5 shows the behavior of input voltage V_{IN} and V_{STORE} at the startup.

Figure 5. Boost startup
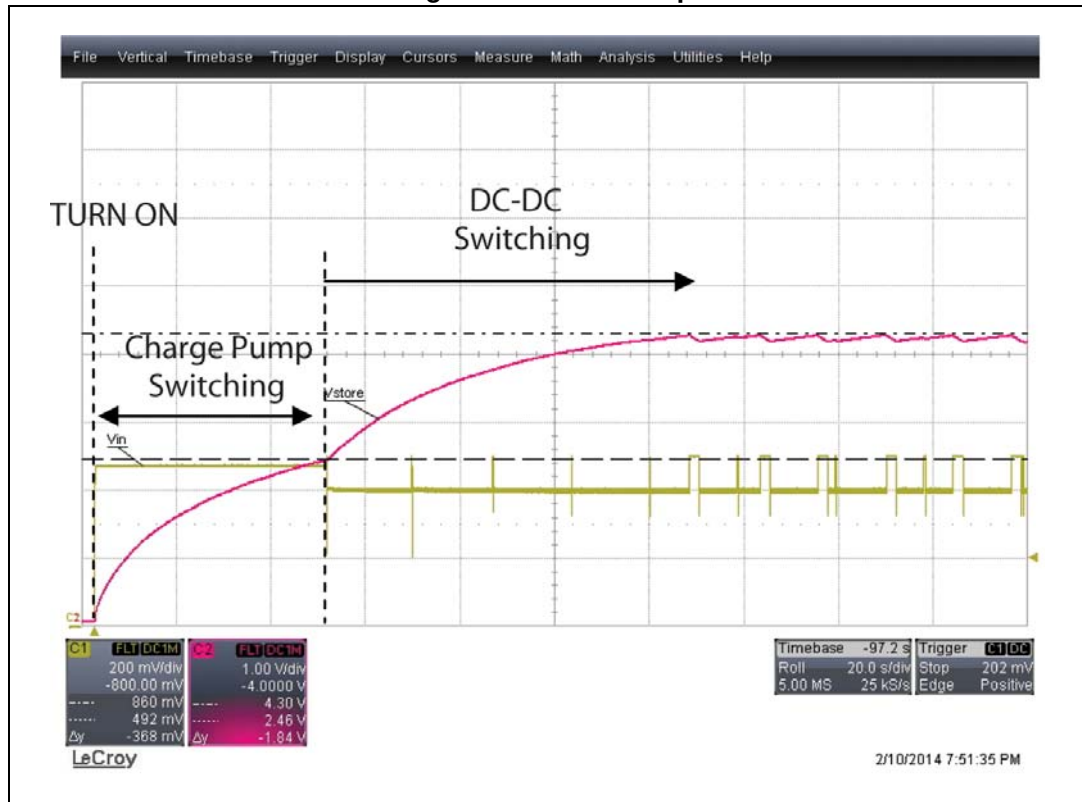
In the range $2.6\ V \leq V_{STORE} < V_{EOC}$ the voltage is boosted by the DC-DC converter. In this voltage range the SPV1050 device sets its internal impedance according to the integrated MPPT algorithm (the MPPT mode is active). The SPV1050 device will stop switching for 400 ms (T_{SAMPLE}) every 16 seconds ($T_{TRACKING}$). During the T_{SAMPLE}, the input open circuit voltage V_{OC} is sampled by charging the capacitor on the MPP-REF pin. Once the T_{SAMPLE} is elapsed, the DC-DC converter will start switching back by setting its own impedance such that V_{IN} stays as close as possible to V_{MPP} of the source. A resistor partitioning connected between the source and the pins MPP and MPP-SET has to be properly selected, in order to match the manufacturer's specs. Please refer to *Section 6.4: MPPT setting on page 24* for further details.

The periodic sampling of V_{OC} guarantees the best MPPT in case of source condition variations (e.g. irradiation/thermal gradient and/or temperature changes).
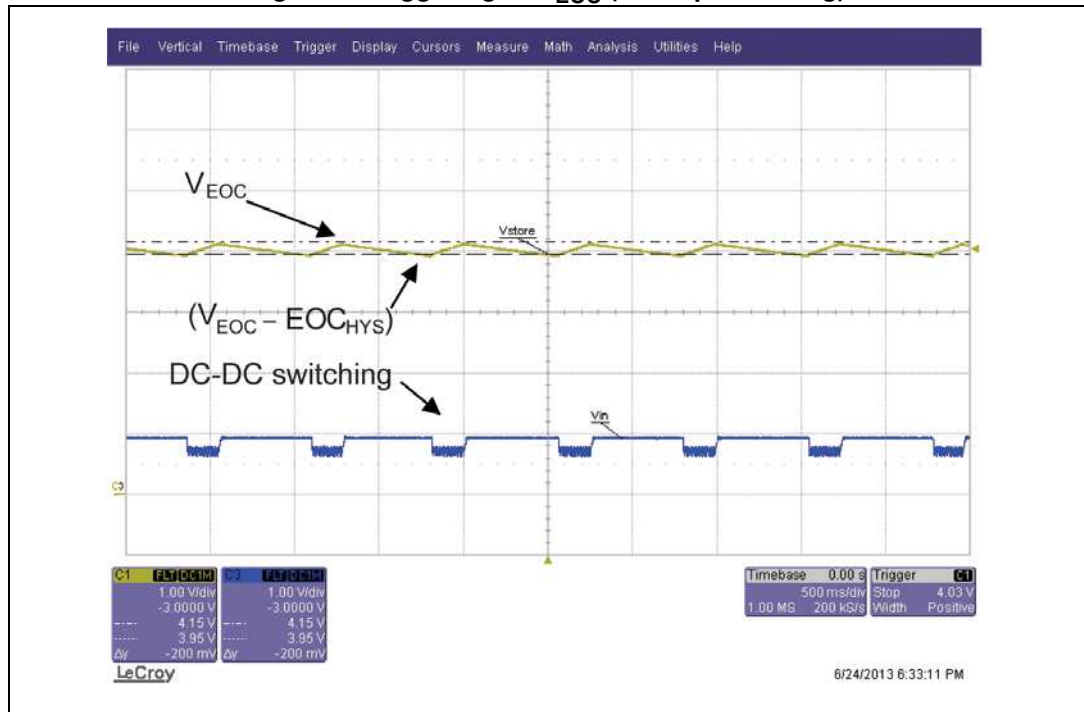
Figure 6 shows the input voltage waveform of a PV panel supplying V_{OC} = 1.25 V and V_{MPP} = 1.05 V.
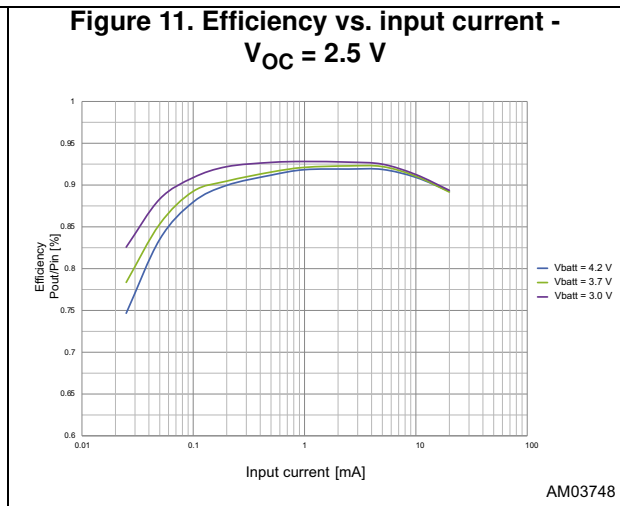
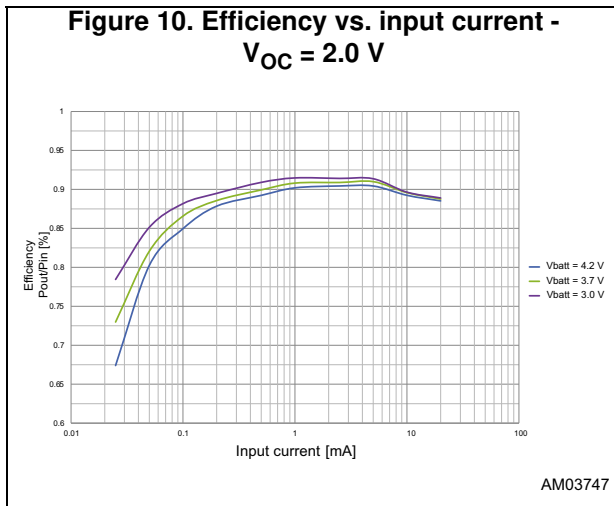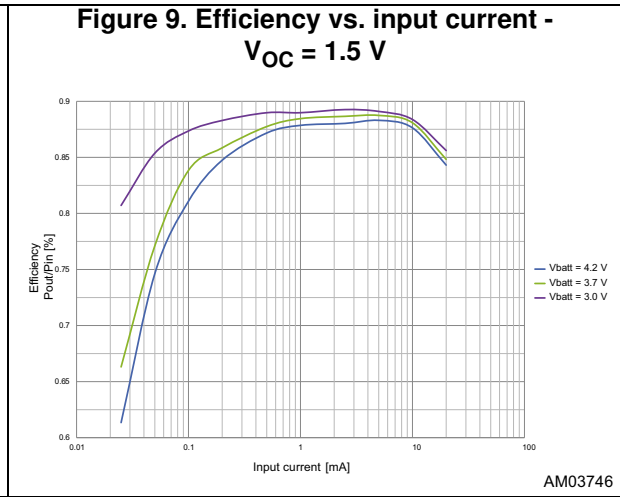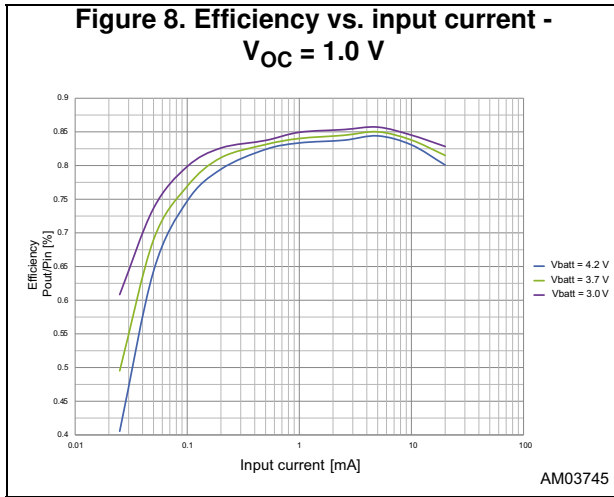**Figure 6. MPPT tracking**
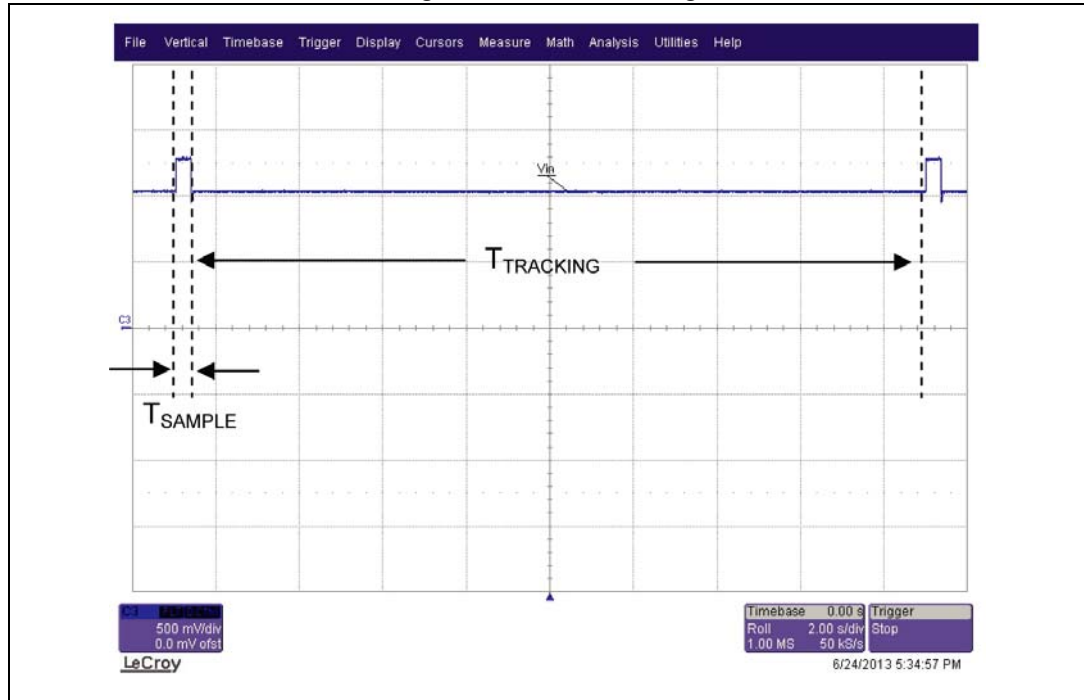
Once the V_{EOC} threshold is triggered, the switching of the DC-DC converter is stopped until V_{STORE} will decrease to V_{EOC} - EOC_{HYS}.

Figure 7. Triggering of V_{EOC} (BATT pin floating)

The following plots from *Figure 8* to *Figure 11* show the power efficiency of the DC-DC converter configured in boost mode at T_{amb} = 25 °C in some typical use cases at different open circuit voltages:

Figure 8. Efficiency vs. input current - V_{OC} = 1.0 V

AM03745

Figure 9. Efficiency vs. input current - V_{OC} = 1.5 V

AM03746

Figure 10. Efficiency vs. input current - V_{OC} = 2.0 V

AM03747

Figure 11. Efficiency vs. input current - V_{OC} = 2.5 V

AM03748

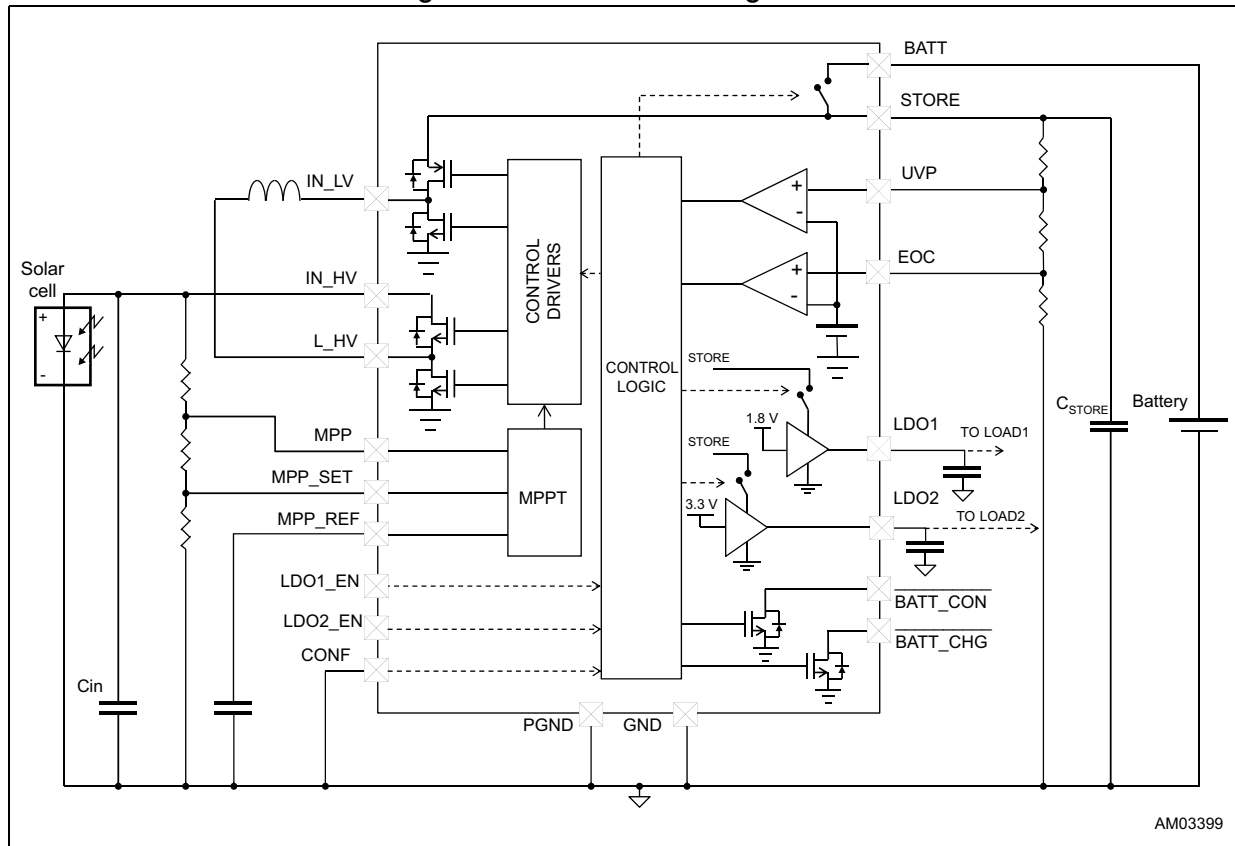## 6.3 Buck-boost configuration

Figure 12 shows the buck-boost application circuit.

Figure 12. Buck-boost configuration

In case of buck-boost configuration, once the harvested source is connected, the IN_HV and STORE pins will be internally shorted until V_{STORE} < 2.6 V. *Figure 13* shows the behavior of the input voltage V_{IN_HV} and V_{STORE} at the startup.

Figure 13. Buck-boost startup (I_{IN} = 5 µA)

In the range 2.6 V $\leq$ V_{STORE} < V_{EOC} the integrated DC-DC converter will start switching. In this operating range the SPV1050 input impedance is set by the embedded MPPT algorithm (the MPPT mode is active). The SPV1050 device will stop switching for 400ms (T_{SAMPLE}) every 16 seconds ($T_{TRACKING}$). During the T_{SAMPLE}, the input open circuit voltage V_{OC} is sampled by charging the capacitor on the MPP-REF pin. Once the T_{SAMPLE} is elapsed, the DC-DC converter will start switching back by setting its own impedance such that V_{IN} stays as close as possible to V_{MPP} of the source. A resistor partitioning connected between the source and the pins MPP and MPP-SET has to be properly selected in order to match the V_{MPP} given by the source manufacturer. Please refer to *Section 6.4: MPPT setting* for further details.
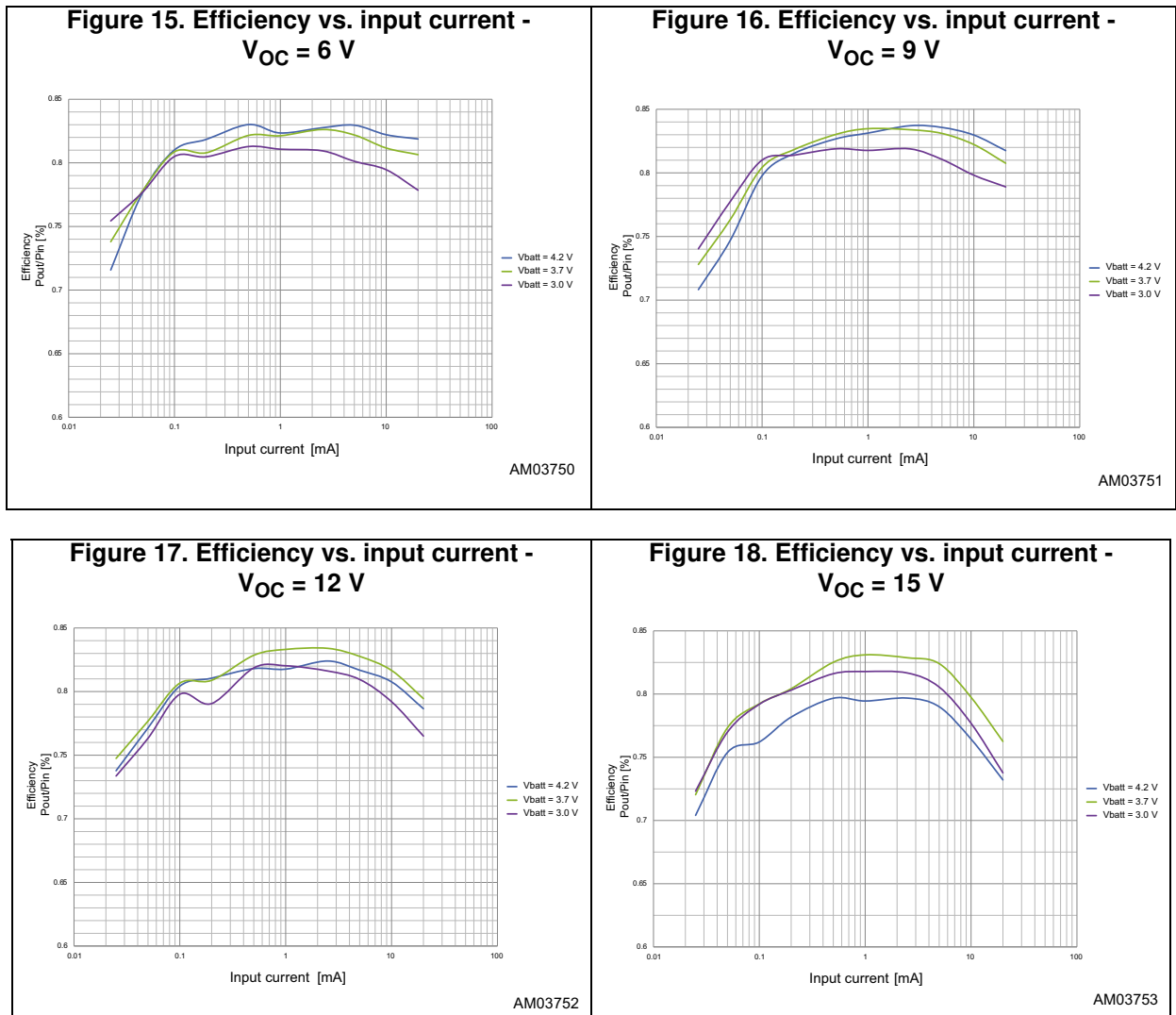
The periodic sampling of V_{OC} guarantees the best MPPT in case of source condition variations (e.g. irradiation and/or temperature changes).

Figure 14 shows the MPPT tracking form in case of V_{OC} = 9.9 V and V_{MPP} = 8.2 V.

Figure 14. MPPT tracking
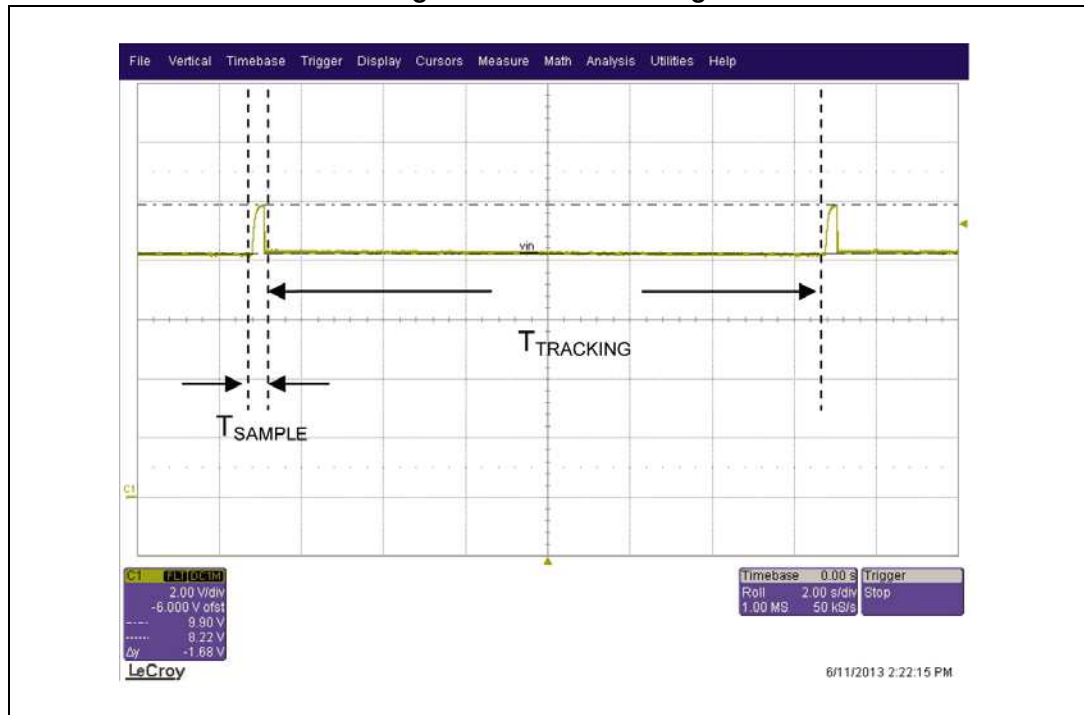
The following plots from *Figure 15* to *Figure 18* show the power efficiency of the DC-DC converter configured in buck-boost mode at T_{amb} = 25 °C in some typical use cases:

Figure 15. Efficiency vs. input current - V_{OC} = 6 V

Figure 16. Efficiency vs. input current - V_{OC} = 9 V

Figure 17. Efficiency vs. input current - V_{OC} = 12 V

Figure 18. Efficiency vs. input current - V_{OC} = 15 V

6.4 MPPT setting

When the MPPT feature is enabled, the SPV1050 device sets its working point such that V_{IN} = V_{MPP}. In fact, V_{MPP} is a fraction of the open circuit voltage V_{OC} of the harvesting source.

Figure 19. MPPT setup circuitry
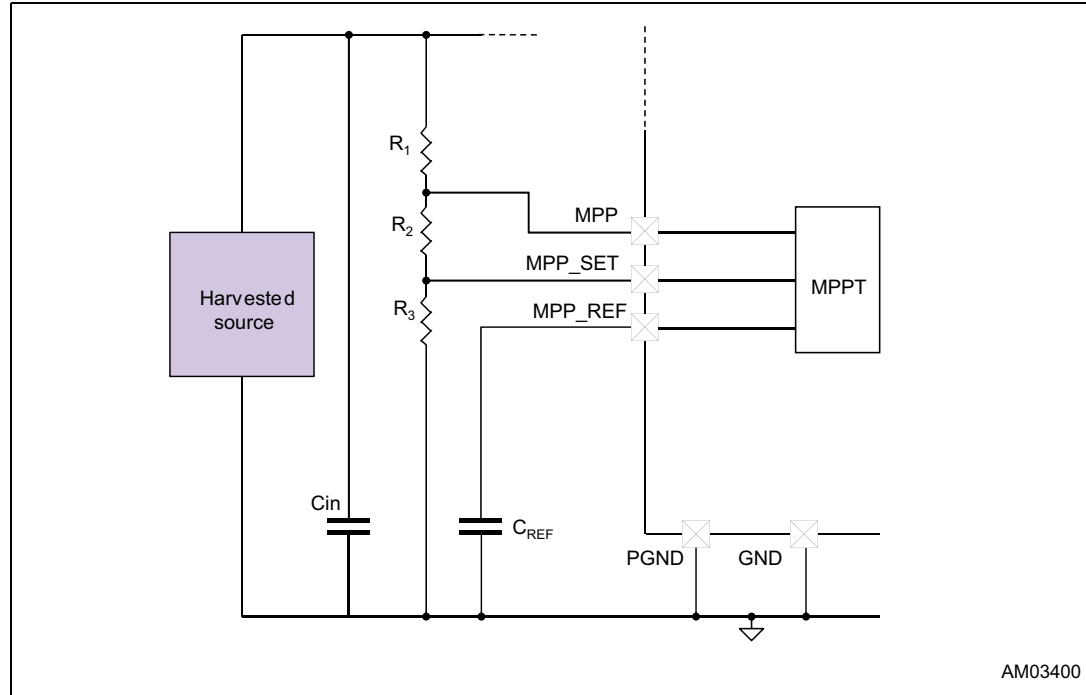
The maximum power point is set through the input resistor partitioning R1, R2 and R3.

First of all, set the total input resistance (R1 + R2 + R3) considering the maximum acceptable leakage current ($I_{LEAKAGE}$):

Equation 4

$$I_{LEAKAGE} = V_{OC} / (R1 + R2 + R3)$$

Typically, assuming 10 MΩ ≤ R1 + R2 + R3 ≤ 20 MΩ, the leakage on the input resistor partitioning can be considered as negligible.

Then set the R2 + R3 selecting the minimum between the results of equations *5* and *6* which consider that the voltage on the MPP pin must be lower than the minimum V_{UVP} ($V_{UVP(min)}$ = 2.2 V) and the energy balance on the inductor even at very low input power (see details in Appendix A, Application tips), respectively:

Equation 5

$$R2 + R3 \leq (R1 + R2 + R3) * V_{UVP(min)} / V_{OC}$$

Equation 6

$$R2 + R3 \leq 51 * (R1 + R2 + R3) * V_{MPP(min)} / V_{EOC}$$

Finally, set the R3 considering the MPP_{RATIO} (in case of PV panels MPP_{RATIO} = V_{MP} / V_{OC}):

Equation 7

$$MPP_{RATIO} = R3 / (R2 + R3)$$

In boost mode if the electrical characteristics of the selected source and battery are such that $V_{OC-MAX} \leq V_{UVP(min)}$, then the resistor R1 can be replaced by a short-circuit. Consequently, only R2 and R3 have to be selected for a proper setting of MPP_{RATIO}.

In a PV panel the V_{MPP} is typically within 70% ÷ 80% of V_{OC}.

In a TEG the V_{MPP} is typically about 50% of V_{OC}.

The MPPT accuracy can be strongly affected by an improper selection of the input capacitor. The input capacitance C_{IN} = 4.7 µF generally covers the most typical use cases.

The energy extracted from the harvested source, and stored in the input capacitance, is transferred to the load by the DC-DC converter through the inductor. The energy extracted by the inductor depends by the sink current: the higher input currents cause higher voltage drop on the input capacitance and this may result a problem for low voltage (< 1 V) and high energy (> 20 mA) sources. In such application cases the input capacitance has to be increased or, alternatively the L1 inductance has to be reduced.

During the T_{SAMPLE} time frame the input capacitor C_{IN} is charged up to V_{OC} by the source with a T1 time constant resulting from the capacitance and the equivalent resistance R_{EQ} of the source.

In case of the PV source, assuming I_{MPP} the minimum current at which the MPP must be guaranteed, the REQ can be calculated as following:

Equation 8

$$R_{EQ} = (V_{OC} - V_{MPP}) / I_{MPP} = V_{OC} \cdot (1 - MPP_{RATIO}) / I_{MPP}$$

Thus C_{IN} is calculated by the following formula:

Equation 9

$$C_{IN} \leq T1 / R_{EQ}$$

The following plots in *Figure 20* and *Figure 21* show the effect of different C_{IN} values on the time constant. If the capacitance is too high, the capacitor may not be charged within the T_{SAMPLE} = 400 ms time window, thus affecting the MPPT accuracy.

Figure 20. Energy harvester equivalent circuit	Figure 21. Voltage vs. time at different C values and fixed current