On Measuring Power Efficiency in DC-DC Converters at Light Load Currents

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Abstract—This paper tackles the problematic issue of measuring the efficiency at DC-DC converters operating in PFM mode, which are used for light loads such as sensor nodes. Such converters present a pulsed input current, which hinders a correct estimation of the average input power. For estimating it, two instruments were used (a power analyzer and a current waveform analyzer) as well as two methods respectively based on the following calculations: 1) exact from the voltage and current samples and 2) approximate from the average values of voltage and current. Tests were performed on a commercial boost converter (TPS61020). With both instruments, the first method provided correct values for the efficiency whereas the second, which is the most commonly used, underestimated the efficiency by a 3 % and 1.5 % for load currents of 10 mA and 70 mA, respectively. Just adding an input capacitor of 100 μ F solved that problem. The use of this capacitor was also beneficial for the first method when using the power analyzer since it reduced the instrument uncertainty.

Keywords—power efficiency, PFM mode, light loads, DC-DC converters, sensor nodes

I. INTRODUCTION

Wireless sensor networks and more broadly the internet of things are opening new applications and will play a very important role in the coming years [1]–[7]. Wireless sensor nodes are an essential part of this ecosystem. As they are autonomously powered by batteries or energy harvesters they remain most of the time asleep in order to save power. Thus, the power processing circuit, which mainly relies on a DC-DC converter, needs to be very power efficient at light loads.

Under light-load conditions, special fixed and variable frequency control techniques are used to improve the efficiency [8]. Fixed frequency control must be used whenever strict electromagnetic compatibility requirements must be complied. On the other hand, variable frequency techniques, which can be further classified as pulse-frequency modulation (PFM) [9]–[11] and burst mode (BM) [12]–[14], generally lead to poor output voltage regulation and electromagnetic interference but provide a high efficiency under light loads. Furthermore, in order to maintain a high efficiency over a wide-load current range, some converters use a hybrid control, operating on a fixed-frequency pulse-width modulation (PWM) mode at high currents and in PFM mode or BM at low currents. Sensor nodes can, in general, assume the weaknesses of variable frequency control techniques used in DC-DC converters and take advantage of their high efficiency under light loads.

For the power efficiency characterization, input and output powers must be measured. This can be done with two pairs of

voltage and current meters, such as briefly described in [11]. Other papers propose the use of more specific instruments such as a power analyzer (PA) and source/measure unit (SMU) [12], [13]. But in general, papers dealing with the design of PFM or Burst converters and their implementation, usually as integrated circuits, do not describe the efficiency test setup [8]–[10], [14]. One reason can be that authors consider this issue trivial and take the configuration used in [11] for granted. However, as stated in an application report [15], efficiency estimation in that type of converters can be inaccurate if an improper test setup is used. Even so, the topic seems overlooked and, to the best knowledge of the authors, no scientific paper deals with it.

This paper tackles this important but unnoticed issue. The input and output power of a synchronous boost converter operating in PFM mode are measured and then the efficiency estimated. The input power is measured using two instruments: a PA and a current waveform analyzer (CWA); both are able to simultaneously sample current and voltage. In addition, two measurement procedures are used to estimate input power: 1) voltage and current samples are multiplied and then the average value is obtained (exact calculation), 2) averages values of voltage and current are obtained and then multiplied (approximate calculation). Then, the efficiency obtained is compared using both procedures and conclusion are drawn.

II. POWER AND EFFICIENCY ESTIMATION

A. Average Power

Power is defined as the product of voltage (v) by current (i). Thus, for time-varying signals, the instantaneous power is given by

$$p(t) = v(t)i(t) \quad (1)$$

where t is time. As power is also time-varying, for periodic signals the average power is the parameter of interest, that is

$$P_{\text{avg}} = \frac{1}{T} \int v(t)i(t)dt \quad (2)$$

where the integral is performed during a single period T or for an integer number of periods of the signals. Whenever any of the signals is constant, e.g. the current, (2) is given by

$$P_{\text{avg}} = I_{\text{DC}} \frac{1}{T} \int v(t)dt = I_{\text{DC}} V_{\text{avg}} \quad (3)$$

This work was supported by the Spanish Ministry of Economy and Competitiveness and the European Regional Development Fund under project TEC2016-76991-P.

where I_{DC} is the constant current and V_{avg} is the average value of voltage. On the other hand, if no one is constant but nearly, (2) can be approximated by

$$P_{avg} \approx V_{avg} I_{avg} \quad (4)$$

where I_{avg} is the average value of current.

B. Efficiency Estimation

Fig. 1 shows a generic test setup to measure input voltage (v_i) and current (i_i) as well as output voltage (v_o) and current (i_o) of a DC-DC converter, where the V and A circles represent voltage and current meters, respectively. Then, the average input (P_i) and output (P_o) powers can be obtained via (2) through (4). To implement (2), a PA or the like should be used, whereas for the use of (3) or (4) multimeters are appropriate but still a PA or a CWA can be used. A PA has at least two channels that simultaneously sample voltage and current. On the other hand, bench-top multimeters measure either voltage or current, but not simultaneously. Multimeters are, in general, cheaper than PAs or CWAs and more available in laboratories. Whatever the power measurement method, power efficiency is given by

$$\eta = P_o / P_i \quad (5)$$

C. Signal Waveforms in PFM mode

Let us assume a DC-DC converter operating in PFM mode, where the switching period (T) increases with a decreasing load current (i_o), thus reducing switching losses. Fig. 2 qualitatively illustrates the PFM operation of a boost converter with i_L being the inductor current of the converter. First, the converter is off and the output capacitor (C_o , Fig. 1) supplies i_o , thereby decreasing v_o . Whenever v_o crosses a lower threshold, the converter is activated and transfers charge from the input capacitor (C_i , Fig. 1) to C_o through a burst of current pulses (i_L), which rapidly increases v_o . On the other hand, C_i and the internal resistance of the input ammeter (R_i) act as a low pass filter for i_i . This current originates a voltage drop at R_i than leads to a voltage drop at v_i . When v_o crosses a higher threshold, the converter switches off and the process repeats again. Voltage v_o decreases more slowly with a decreasing i_o and so T increases.

Since i_i is pulsating and v_i is not constant during the charge transfer, using (4) to estimate P_i can lead to inaccurate results and (2) should better be applied. However, adding a large input capacitor, as suggested in [15], can help since it smooths the input current. But the analysis is qualitative and no value for the input capacitor is provided. On the other hand, large input (and output) capacitors are used in [12], [13]. However, the authors do not justify the chosen capacitor values. In the rest of the paper, we obtain experimental results using both (2) and (4) for the input power with and without a large input capacitor.

Fig. 1. Generic test setup for the measurement of power efficiency.

Fig. 2. Waveforms of interest of a boost DC-DC converters operating in PFM mode.

III. MATERIALS AND METHOD

A commercial synchronous boost DC-DC converter (TPS61020, Texas Instruments) was employed to validate the different methods to estimate the efficiency. This converter operates in PFM mode, referred as power save mode (PSM) in the datasheet, at light load currents. For the tests, we used the evaluation module provided by the manufacturer, where v_o is fixed to 3.3 V, C_i is a ceramic capacitor of 10 μ F and C_o is a tantalum capacitor of 47 μ F in parallel with a ceramic capacitor of 2.2 μ F. From the datasheet, a small ripple at v_o (~ 20 mV) is expected.

The output of the converter was connected to an SMU (B2901, Keysight). An SMU forces a voltage or current and simultaneously measures voltage and current. Here, the SMU was set as a current sink with the following values of I_o (average value of i_o): 100 μ A, 1 mA, 10 mA, and 70 mA. The upper limit was chosen in order to always have the converter operating in PFM mode. The SMU directly provides the average power (P_o) by performing the product of voltage by current, which is equivalent to (3). For the measurements, an integration time of 100 PLC (power line cycles) was used.

The input of the converter was connected to a power supply (E3631A, Keysight) with the voltage adjusted to have an average value for v_i of 2.4 V (measured with the power measuring instruments). For measuring the input power (P_i), we used two different instruments: a PA (WT310, Yokogawa) and a CWA (CX3320, Keysight), with R_i equal to 500 m Ω and 410 m Ω , respectively. For both, P_i was estimated using (2) and (4). Both instruments simultaneously sample voltage and current for a pre-set acquisition time. For the PA, we used an acquisition time (selectable from 0.1 s to 5 s) of 2 s with a sample rate of 100 kSa/s (fixed, not selectable). For the CWA, acquisition time was adjusted in function of the load current. As T decreases with an increasing I_o , so does the required acquisition time to sample a given number of periods. Furthermore, due to the limited value of sample points used (16 M), sample rate was accordingly reduced for higher acquisition times. Table I shows the parameters used for the different load currents. In addition, the CWA was also used to monitor some of the waveforms of Fig. 2, in particular v_i , i_i , and v_o , and, hence, to verify the correct performance of the DC-DC converter and its input filter formed by C_i and R_i . No test point was available at the evaluation board to monitor i_L .

TABLE I. PARAMETERS USED AT THE CWA FOR MEASURING THE INPUT POWER

I_o (mA)	Acquisition time (s)	Sample rate (MSa/s)
0.1	2	5
1	1	10
10	0.1	100
70	0.02	500

The PA directly provides the results of (2) and (4). Contrariwise, the CWA needs some processing. First, power data were generated from voltage and current samples. Then, all of them were averaged within the acquisition times given in Table I. To have a higher repeatability, the resulting average values were further averaged using 20 data. Finally, (2) was obtained from the final power average, whereas (4) was calculated multiplying the final current average value by 2.4 V. Then, efficiency was obtained in all cases using (5). Tests were also performed adding a ceramic capacitor of 100 μ F ($C_{i,add}$) in parallel with C_i .

IV. EXPERIMENTAL RESULTS

A. Signal Waveforms

Fig. 3 to Fig. 6 show CWA screenshots corresponding to the signals of Fig. 2. Fig. 3 shows the case for $I_o = 100 \mu$ A. As can be seen, i_i increased up to 200 mA, whereas v_i presented a voltage drop higher than 100 mV. Period T (not inferred from Fig. 3) was about 7 ms. In Fig. 4, I_o was increased to 10 mA which led to a large decrease of T , whose value was about 90 μ s, as can be seen. The same case is presented in Fig. 5 but now v_o is shown (AC coupled) instead v_i . The converter switches on (i_i starts increasing) whenever v_o crosses a lower threshold, being the ripple of about 20 mV (excluding the short peaks). Finally, Fig. 6 shows the case when adding an input capacitor of 100 μ F for $I_o = 100 \mu$ A. Here, the effect of the input filter increases, thus reducing the input current peak to less than 40 mA and the voltage drop at v_i .

The period T decreased from about 7 ms for $I_o = 100 \mu$ A to about 20 μ s for $I_o = 70$ mA, which justifies the acquisition times used at the CWA (Table I) in order to have a high

number of periods and thus reduce the variability of the data values.

B. Results with the PA

The PA was configured with a crest factor of 3 both for voltage and current, which means that the maximum permitted value for the signals is 3 times the range value. For voltage, the minimum range value of 15 V was selected. On the other hand, the current range was adjusted to the minimum one that permitted the peak value. Then, the power scale is obtained as the product of the voltage and current ranges. Accuracy depends on frequency and is specified for sinusoidal signals, which is not the case. For the sake of simplicity, a unique representative value of $\pm(0.2\% \text{ reading} + 0.2\% \text{ range})$ was chosen for the uncertainty.

Table II shows the results for I_o from 100 μ A to 70 mA. P_o was directly provided by the SMU and its uncertainty is estimated from the manufacturer specifications of voltage and current. It is similar in all cases and lower than 0.27 %. The parameter I_i corresponds to the average value of i_i provided by the PA. As a boost converter was tested, values of I_i are higher than I_o . The values of P_i provided by the PA and corresponding to (2) and (4) are termed $P_{i,2}$ and $P_{i,4}$, respectively. I/P range refers to the automatic ranges used by the PA for the input current/power. Finally, relative uncertainty of $P_{i,2}$ is shown. Uncertainties for $P_{i,4}$ are not presented but are equal or slightly lower. As can be seen, even for the lowest values of I_i , the current range was high (100 mA), in order to accommodate the large peak of i_i (200 mA, Figs. 3 to 5), and correspondingly the power range (15 V $\times$ 100 mA = 1.5 W). This leads to unacceptable uncertainties for the cases of I_o equal to 100 μ A and 1 mA. For the ensuing calculus of η only the cases with uncertainties for $P_{i,2}$ lower than 10 % are considered. So, in Table II only the cases of I_o equal to 10 mA and 70 mA are useful.

Table III shows the results when $C_{i,add} = 100 \mu$ F, presenting only the cases whose uncertainty (for $P_{i,2}$) is smaller than 10 %. Now the current ranges were smaller than the corresponding cases in Table II since the peak current was also smaller (see Fig. 6), which leads to a significant reduction of the uncertainties. This also allows to include the case of $I_o = 1$ mA.

Fig. 3. Signals v_i (blue) and i_i (pink) when $I_o = 100 \mu$ A.

Fig. 4. Signals v_i (blue) and i_i (pink) when $I_o = 10$ mA.

Fig. 5. Signals v_o (blue, AC coupled) and i_i (pink) when $I_o = 10$ mA.

Fig. 6. Signals v_i (blue) and i_i (pink) when $I_o = 100$ μ A and a capacitor of 100 μ F is added to C_i .

TABLE II. RESULTS WITH THE PA WITHOUT ADDING AN INPUT CAPACITOR

I_o (mA)	P_o (mW)	I_i (mA)	$P_{i,2}$ (mW)	$P_{i,4}$ (mW)	I/P range (mA/W)	Uncertainty $P_{i,2}$ (% reading)
0.1	0.3285	0.2	0.4	0.5	100/1.5	750
1	3.285	1.6	3.6	3.8	100/1.5	83
10	32.87	15.2	35.2	36.4	100/1.5	8.7
70	230.2	103.7	245.1	248.8	200/3	2.7

TABLE III. RESULTS WITH THE PA ADDING AN INPUT CAPACITOR

I_o (mA)	P_o (mW)	I_i (mA)	$P_{i,2}$ (mW)	$P_{i,4}$ (mW)	I/P range (mA/W)	Uncertainty $P_{i,2}$ (% reading)
1	3.285	1.515	3.62	3.64	10/0.15	8.5
10	32.87	14.67	35.17	35.22	20/0.3	1.9
70	230.2	102.26	245.5	245.6	100/1.5	1.4

Table IV shows the calculated efficiency from (5) using the power values of Tables II and III, where $P_{i,2}$ has been used for η_2 and $P_{i,4}$ for η_4 . For $I_o = 1$ mA, results are only given for the case with $C_{i,add}$. For $I_o = 10$ mA, η_4 without $C_{i,add}$ is significantly lower than in the other cases, around 3 %. This indicates that input power is overestimated using (4) and thus power efficiency underestimated unless we add $C_{i,add}$, which agrees with [15]. However, there the author concludes that this is due to the inaccurate measurement of the current, which is doubtful, and probably is more related with using (4), as pointed out previously. On the other hand, using (2) leads to better estimations of the power efficiency independently of using $C_{i,add}$. But the use of $C_{i,add}$ is still beneficial since it leads to a lower uncertainty on the results, as inferred from Tables II and III. Finally, for $I_o = 70$ mA the use of (4) without $C_{i,add}$ stills underestimated efficiency but to a lesser degree (around 1.5 %). Fig. 7 shows the results graphically, where can clearly be seen that efficiency is underestimated when using (4) to estimate P_i and no input capacitor is added.

C. Results with the CWA

The CWA was configured with a voltage range of 2 V, being the uncertainty $\pm(1.2\% \text{ reading} + 0.6\% \text{ range})$. For $v_i = 2.4$ V this results in a relative uncertainty of 1.7 %. As for the current, a suitable range was used for each case. Table V shows the results for the different values of I_o where I_i , $P_{i,2}$ and $P_{i,4}$ were obtained as described in Section III. For the current measurement, the used range is shown (I range). Finally, as with the PA, relative uncertainty is calculated for $P_{i,2}$. Here, uncertainty is indirectly calculated from that of voltage (shown before) and current (range dependent). To reduce uncertainties, a user calibration (valid during 1 day) was performed before. Even so, due to the large current range used (200 mA) to accommodate the large peak of i_i (200 mA, Figs. 3 to 5), unacceptable uncertainties are again obtained up to $I_o = 1$ mA. As before, only the cases with uncertainties below 10 % are considered, i.e. I_o equal to 10 mA and 70 mA.

Table VI shows the results when $C_{i,add} = 100 \mu\text{F}$ for those cases whose uncertainty (for $P_{i,2}$) was smaller than 10 %. As can be seen, the current range was kept to 200 mA even when the peak current was smaller (see Fig. 6) since it did not fit

within the ensuing smaller range of 20 mA. So, the feasible cases were again for I_o equal to 10 mA and 70 mA.

Table VII shows the calculated efficiency from (5) using the power values of Tables V and VI. Values mainly agree with that of Table IV. Fig. 8 shows the results graphically. As with the PA, efficiency is underestimated when using η_2 and no input capacitor is added. Here, the use of $C_{i,add}$ does not reduces the instrument uncertainty since the same current range had to be used and thus is not useful for estimating $P_{i,2}$ and η_2 .

TABLE IV. RESULTING EFFICIENCIES USING THE PA

I_o (mA)	$C_{i,add} = 0$		$C_{i,add} = 100 \mu\text{F}$	
	η_2 (%)	η_4 (%)	η_2 (%)	η_4 (%)
1	-	-	90.7	90.2
10	93.4	90.3	93.5	93.3
70	93.9	92.5	93.8	93.7

Fig. 7. Efficiencies using the PA for P_i with and without $C_{i,add}$.

TABLE V. RESULTS WITH THE CWA WITHOUT ADDING AN INPUT CAPACITOR

I_o (mA)	P_o (mW)	I_i (mA)	$P_{i,2}$ (mW)	$P_{i,4}$ (mW)	I range (mA)	Uncertainty $P_{i,2}$ (% reading)
0.1	0.3285	0.167	0.385	0.401	200	479
1	3.285	1.56	3.54	3.65	200	53
10	32.87	15.14	35.2	36.3	200	7.0
70	230.0	103.69	245.9	250.1	200	2.5

TABLE VI. RESULTS WITH THE CWA ADDING AN INPUT CAPACITOR

I_o (mA)	P_o (mW)	I_i (mA)	$P_{i,2}$ (mW)	$P_{i,4}$ (mW)	I range (mA)	Uncertainty $P_{i,2}$ (% reading)
10	32.88	14.68	35.17	35.23	200	7.2
70	230.5	102.69	246.5	246.5	200	2.5

TABLE VII. RESULTING EFFICIENCIES USING THE CWA

I_o	$C_{i,add} = 0$		$C_{i,add} = 100 \mu F$	
	η_2 (%)	η_4 (%)	η_2 (%)	η_4 (%)
10 mA	93.4	90.6	93.5	93.3
70 mA	93.5	92.0	93.5	93.5

Fig. 8. Efficiencies using the CWA with and without $C_{i,add}$.

V. CONCLUSIONS

This paper has tackled the problematic issue of correctly measuring the power efficiency of DC-DC converters operating in PFM mode, which are used to achieve high efficiencies with light loads, such as that presented by wireless sensor nodes. For estimating the input power two measurement methods as well as two instruments (a PA and a CWA) have been used. The two methods are respectively based on the following calculations: 1) exact from the voltage and current samples and 2) approximate from the average values of voltage and current. Tests performed on a commercial boost converter (TPS61020) have shown that for both instruments, the first method provides correct values whereas the second, which is the most commonly used, leads to overestimating the input power and thus to underestimating the efficiency, in particular around 3 % and 1.5 % at load currents of 10 mA and 70 mA, respectively. Just adding an input capacitor of 100 μF solves the problem. Its use is also beneficial when using the first method and the PA since reduces the instrument uncertainty. Future work will include the use of larger input capacitors to reduce the input peak currents and allow the use of smaller current ranges at the instruments, which should lead to smaller uncertainties for the instruments. This will also lead to feasible measurements at lower load currents. In addition, multimeters will also be used with the second measurement method and their performance assessed.

ACKNOWLEDGMENT

The authors thank the technical staff of the Castelldefels School of Telecommunications and Aerospace Engineering, and in particular to Juan-José Tomeo for producing special cables and an adaptation board for the added input capacitor.

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