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MEASURING AVERAGE CURRENT THROUGH INDUCTIVE LOADS VIA TRIANGLE APPROXIMATION INTEGRATION USING A MICROCONTROLLER

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Abstract: *The aim of this study is to analyze from point of view of accuracy the method of software integration using a microcontroller for measuring the average current through an inductive load driven with pulse-width-modulation. It involves measuring the voltage on a series shunt resistor taking samples at the two edges of the drive signal and performing integration in software using triangle approximation. The influence of the relation between the driving frequency and the load's inductance/resistance (L/R) time constant is studied as well as the hardware and software elements which introduce measurement errors. The study confirms the method provides an easy and feasible way of measuring average current in the appropriate context.*

Key words: *microcontroller, current, pwm, embedded, motor, actuator.*

1. Introduction

Today electronics are omnipresent with the aim of for example improving performance and/or efficiency of tasks and processes either for improving quality of life through automatisation. Embedded systems represent a very relevant example and this study addresses an important element of such system which is data acquisition as feedback for control processes.

Many control elements such as actuators, proportional-valves or motors are inductive loads by nature which need to be precisely controlled in sensitive applications and thus the quality of the feedback is very important. By the quality of the feedback it is understood the nominal accuracy taking into account its variations over a range of operating conditions meaning variations in temperature or humidity as well as with age or due to production tolerances of the hardware components.

All these factors are taken into consideration especially for example in the automotive industry where identical models of vehicles are produced in large quantities and are sold in different parts of the globe and of course travel due to their mobility which of course means they are present predominantly outdoors.

Due to costs of research and development and of mass-production, an additional

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challenge arises which is present in any domain and is especially critical in the automotive industry, namely cost-effectiveness. Thus the implemented technical solutions must cost-effective without compromising functionality and reliability. The study presented in this article is actually oriented towards the automotive industry due to its aforementioned challenges and the author's interest and professional experience in this domain. Actually the motivation behind the study originates from the author's experience in a workplace project as a possible alternative technical solution for a specific or similar context characterised by the parameters of the load (like inductance, resistance, current range) and driving circuit requirements like specific Pulse-Width-Modulation (PWM) frequency.

1.1. Presentation and Analysis of Existing Methods

In terms of the usual methods of measuring currents in embedded systems the most cost-effective is using shunt resistors and a microcontroller's analogue to digital converter. Depending on the value of the shunt resistor amplification may be required for the microcontroller's analogue input which is mostly implemented with operational amplifiers because they are prevalent and quite cheap. However an additional problem arises due to the automotive industry's specifics namely for safety and convenience reasons loads are mostly permanently grounded and so they are high-side switched (i.e. the driving circuit switches the positive voltage). For the shunt resistor method in high-side topology this implies the additional use of a differential amplifier which adds cost and tolerances.

Due to the fact that inductive loads integrate the current waveform, more or less depending on their inductance, determining the average current requires implementing hardware or software filtering of the analogue input signal. A very common used hardware method is to implement resistor-capacitor (RC) low-pass filter(s) to further integrate the analogue signal at the microcontroller to minimise or eliminate any ripple in which case a clean stable DC signal is achieved. This method however affects the response time of the system due to the delay introduced by the low-pass-filter(s).

Another known solution is to make use of software averaging in which multiple samples of the analogue signal are taken during one or more periods of the PWM signal and averaged. This software method improves the response time and could also be done automatically by the hardware peripheral on newer generations of microcontrollers. This method however requires CPU time when done purely in software (especially for a large number of samples) or, when using the the hardware averaging function of the peripheral, may not be possible to be configured to take all the target samples during one period of the signal or multiples of one period. Both of these software averaging methods also have the downside that the analogue peripheral, or at least one of the analogue peripherals, are exclusively locked for this purpose during fetching of these analogue samples.

For example 200 us allocated CPU time (which is not a lot of time but also not negligible) for performing software averaging corresponds a PWM frequency of 5 kHz. Thus at frequencies above 5 kHz, at least in terms of CPU-time, software averaging is not excessively time-consuming however below 5 kHz it could be troublesome.

When it comes to driving inductive loads PWM frequencies are chosen also from point of view of acoustics such that they are no audible effects by choosing at least 20 kHz. However in the automotive industry Electromagnetic Compatibility is a big concern and so PWM frequencies even go down to the lower range of hundreds of hertz.

This is the case especially with externally located loads connected with cables harnesses. At these low frequencies, unless the inductance of the load is quite high, the ripple of the current waveform is significant making average current calculation more difficult. This was the case in the author's workplace project whose challenges inspired the idea behind the study.

1.2. The Proposed Method Analysed in the Study

For software averaging at PWM frequencies of hundreds of hertz the total software CPU time ranges for a 100 and 1.000 Hz from 10 ms to 1 ms respectively. So even at the higher end at 1 kHz the PWM period is 1 ms which is very time consuming for the software. Thus for these situations, when response time is also very important, the above mentioned technical solutions are not feasible or at least not without compromises which prompts for a different approach.

The proposed method in this study involves performing integration in software using only two analogue samples per PWM period taken at the two edges of the PWM driving signal. The idea behind the method is to take advantage of the behaviour of PWM driven inductive loads which integrate by nature their current waveform due to their inductance like for example in buck DC-DC converters. Depending on the relation between the PWM frequency and the load's time constant the triangle-shaped waveform of the current ripple through the load is more or less linear rather than exponential in terms of its rising and falling edges. This is illustrated in Figure 2 showing triangle approximation error at low frequencies due to the exponential shape of the waveform.

Thus, for certain load parameters, the value of the PWM frequency could be chosen such that a certain level of average current calculation accuracy through software integration could be obtained with only two analogue samples per PWM period. This approach requires significantly less CPU time in software compared with the above mentioned methods. In addition, referring strictly to the process of fetching the two analogue samples, in most newer microcontrollers this analogue fetching can be done completely in hardware thus requiring only minimal software intervention.

The mathematical relation for computing the average current using the two analogue samples, in reference to Figure 1, is the following:

$$
\begin{aligned}
Average\ Current &= A + \frac{\dfrac{Area\,of\,X}{2} + \dfrac{Area\,of\,Y}{2}}{T_{period}} \\
&= A + \frac{\dfrac{(B-A)\cdot T_{on}}{2} + \dfrac{(B-A)\cdot T_{off}}{2}}{T_{period}} \\
&= A + (B-A)\cdot\left(\frac{D.C.}{2} + \frac{(1-D.C.)}{2}\right) = A + \frac{(B-A)}{2}.
\end{aligned}
\tag{1}
$$

where: A and B refer to the analogue samples A and B; $D.C.$ is the duty cycle: $\dfrac{T_{on}}{T_{period}}$.

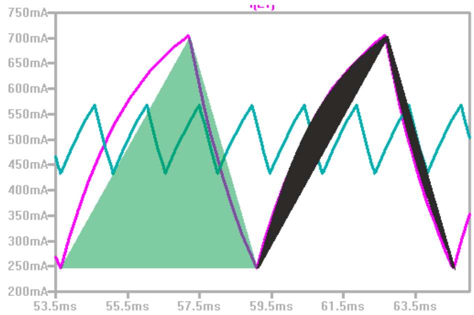

Fig. 1. *Trinagle waveform (green) and error area (black) at lower frequencies*

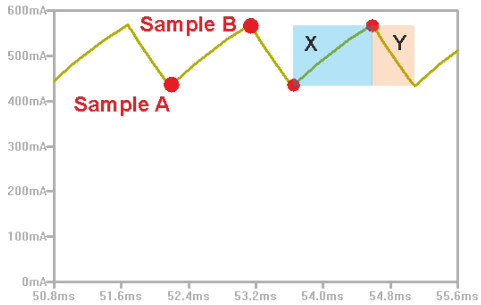

Fig. 2. *Sample points and triangle approximation*

2. Objectives

The objectives of this study are as follows:

- determine the impact of the relation between the PWM frequency and the load's time constant on the calculation of the average current using triangle integration approximation
- determine the additional errors introduced by the tolerances of the circuit elements in computing in software the average current
- perform the same as above considering calibration carried-out at the end-of-line during the production

3. Material and Methods

The study was carried out mainly using SPICE simulations in Linear Technology's LTSpice and as well as Microsoft Excel for calculations and for structuring the results. A circuit schematic was made and simulated with varied parameters like PWM frequency, tolerance of the components, disabled or enabled parasitic currents and/or voltages etc. For determining the worst-case results due to tolerances of the components a Monte-Carlo Analysis method was implemented in LTSpice with 300 iterations.

The schematic, seen in Figure 3, consists of a high-side P-Channel Mosfet controlled by the PWM signal, a series shunt resistor, a load modelled as a series inductance and resistance and also two operational amplifiers. The operational amplifiers were chosen due to their low cost and availability as two-in-one package and they are configured one as a differential amplifier followed by a non-inverting amplifier.

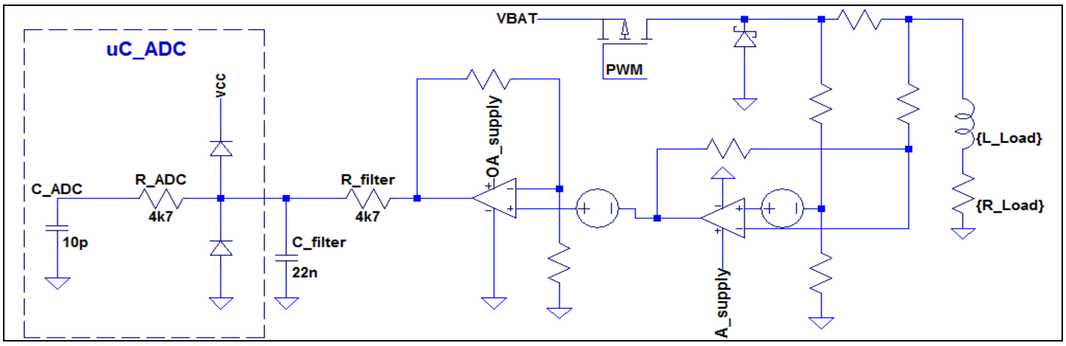

Fig. 3. *Spice Simulation Schematic*

3. Results and Discussions

In Figures 4 and 5 there can be seen the results of the average current approximation errors in percent versus the ratio of the PWM frequency to 1/L/R (the inverse of the load's time constant) when using the triangle approximation.

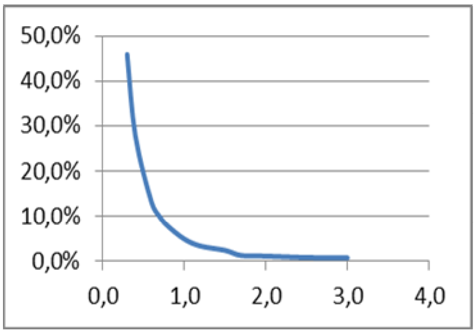

Fig. 4. *Approximation error at 25% PWM duty cycle*

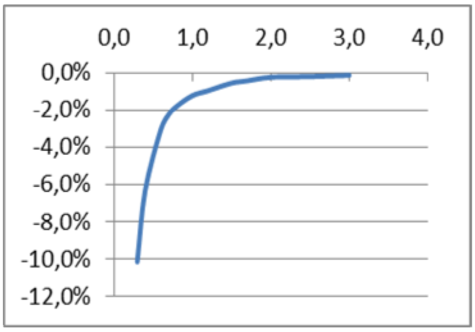

Fig. 5. *Approximation error at 75% PWM duty cycle*

Table of values of accuracy for PWM Frequency Ratio study Table 1

PWM Frequency ratio	0.3	0.4	0.6	0.7	0.8	1.0	1.2	1.5	1.7	2.0	2.5	3.0
Accuracy at 25% PWM [%]	45.91	27.82	13.01	9.83	7.73	4.86	3.29	2.35	1.21	1.07	0.74	0.69
Accuracy at 75% PWM [%]	-10.16	-6.33	-3.06	-2.24	-1.80	-1.22	-0.96	-0.55	-0.43	-0.23	-0.20	-0.13

The above graphs and table of values show that after a certain value of the PWM frequency the accuracy approaches 1% which a very good one is considering the computations are done using just two points of the load current waveform.

For determining the additional errors introduced in the software determined current in ideal and worst-case conditions by the circuit elements, certain values and parameters were needed to be given for them for a particular scenario. The most relevant presented here are the nominal values for the logic VCC supply voltage of 3.3 Volts, the value of the shunt resistor 1 Ohm and the gain of the amplifier which is 3. For the tolerance parameters they are 3% for the resistors, 3% for the VCC voltage, 1 uA leakage current of the analogue pin and 10mV input offset error of the amplifiers.

The monte-carlo simulation showed a total voltage error at the analogue pin due to all the hardware tolerances of +203 mV respectively -218 mV compared to the nominal ideal voltage. Thus disregarding at first the variation of the VCC supply voltage, the current error values are +67.6 mA respectively -72.6 mA given the ideal transfer function $I_{load} = V_{ADC} / 3$. For an actual current of 550 mA this means -13.2% and +12.3% respectively.

When considering the 3% variation of the VCC supply voltage which serves as the ADC's reference voltage the error is an additional 3%. This is due to the fact that the software computes the current using AD counts which are linked to volts by the reference voltage (for the same voltage at the analogue pin but different VCC the current computed by the software differs). This is to be understood considering the worst-case variation of all the components especially the resistors which set the differential and simple gain of the amplifiers and also their input offset voltages.

In the case of calibration at end of line the only tolerances left are the aging and temperature variations. This translates into the remaining error tolerances being 1% for the resistors, typically 1% for the VCC voltage and the leakage current of the analogue pin of the microcontroller.

The proposed calibration involves having the production line provide two very steady and accurate currents (preferably the minimum and maximum to be expected) and having the microcontroller read the analogue voltage at these two currents.

The transfer function is then computed by the software in AD counts via linear interpolation of the form Ax+B where A is the slope of the two AD voltages versus the two known currents in the production line and B is the voltage at the pin at zero current.

In this case the Monte-Carlo simulations displayed a tolerance from the calibrated values of +42 mV and -39 mV respectively which at the same 550 mA current represents an error of 2.5% and -2.36% respectively. Adding the tolerance of the VCC supply of 1% the obtained accuracy is 3.5% and -3.36% respectively.

4. Conclusions

The results obtained in this study show very optimistic results. The proposed method proves to give good results given the appropriate scenario in which the desired PWM drive frequency must be in the 1 kHz area and it is allowed to be changed to make it possible to be implemented. On the other hand if the conditions are already met then it could be an alternative implementation to read the average current. A rapidly improving integration approximation accuracy can be observed when the PWM frequency factor passes upwards the value of ~1.2.

It proves to allow good current measurement accuracy with minimal required software resources especially if calibration is performed.

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