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Current derivative measurement using closed-loop hall-effect current sensor

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Abstract: This paper discusses a method of the current derivative measurement using a standard closed-loop Hall-effect current sensor. The proposed method can operate with PWM-driven inverters and provides the estimation of motor-phase inductances required for an encoderless or self-sensing control. The method is based on the current transformation feature of the closed-loop sensor where a sensing inductor is connected in series with the measuring resistor. The voltage drop across the inductor is proportional to the current derivative. The experimental results are demonstrated that the measurement of the current derivative can be performed under a good accuracy, though the measurement should be executed while inverter is in the steady-state condition.

1 Introduction

Encoderless (or self-sensing) control has received much attention in the last decade for design of electric drive systems. Many investigations have been recently conducted in order to implement the self-sensing approach into control systems for various electrical machines including induction motors [1], permanent magnet synchronous motors [2, 3], synchronous reluctance motors [4], switched reluctance drives [5] etc. The operation principle of self-sensing control strategies is based on analysis of motor saliency using measurement of phase inductance. It provides a correct estimation of the instant rotor position required for execution of field-oriented and direct torque control algorithms.

The inductances of the motor phases can be evaluated through the analysis of reflection of high-frequency current or voltage injected into a supply voltage. However, an injection results in audible effect and torque pulsation on the motor shaft. Therefore, it was suggested to obtain a current derivative from the current deviation occurred due to PWM nature of the voltage source inverter. Under any PWM pattern, there are at least two (usually three) voltage vectors sequentially applied to the stator windings. These voltages cause the phase current deviation that are used to evaluate allocation of the inductance locus of the motor [6, 7].

Several different methods were suggested to evaluate the current derivative. Basically, they can be split into two main groups. The first group represents the methods based on evaluation of the current before switching state of the inverter [8]. Under this approach, the difference between the current at the beginning and the current in the end of the steady state of inverter is used for derivative evaluation. The second group comprises of the methods which implement a differentiator circuit built using an additional operational amplifier and filter [9]. Although the method in [9] was introduced to be utilised in sensorless control, the experiments were performed under pure sine-wave current only; no results for PWM-driven inverter have been provided.

This paper describes a solution of the current derivative measurement problem. The proposed solution utilises a closed-loop Hall-effect sensor, which is capable to operate as a current transformer where the voltage drop across an inductor connected to the sensor circuit output is proportional to a current derivative. This solution operates with PWM-driven inverters and is applicable for encoderless or self-sensing control.

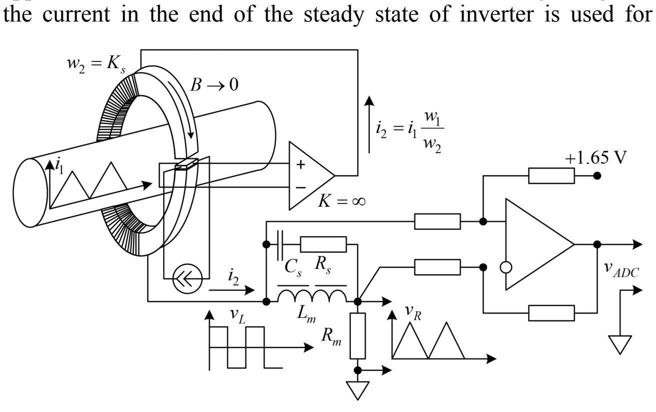

Fig. 1 *Circuit for current derivative measurement*

2 Current derivative measurement circuit

The closed-loop Hall-effect current sensor has a primary-side winding, which is actually a conducting part of the power-electronic device (see Fig. 1). The measured current flown through the primary conductor produces a magnetic flux in the core of the sensor. A Hall-element located in the gap of the core produces a signal proportional to the flux value. This signal is amplified and then applied to the secondary winding which has usually 1000 turns. Thus, the current of the secondary winding produces a magnetic flux in the opposite direction to the primary-side flux. The opposite flux is increased until the signal from the Hall-effect sensor becomes zero. The number of turns in the secondary winding w_2 is usually equal to the current sensor transformation coefficient K_s. Therefore, the output of the current sensor is a transformed current converted into a voltage across of the measurement resistor R_m. This voltage follows shape of the current in the primary winding including AC and DC components. However, as the output of the current sensor is originally the current output, the inductor in the secondary circuit produces a voltage drop which is proportional to the derivative of the phase current.

The circuit in Fig. 1 shows the implementation of the proposed derivative measurement circuit. The measurement inductor is connected in series with the measurement resistor whereas the RC-snubber circuit is connected in parallel to the inductor. The differential operational amplifier removes common mode voltage and provides a filtered signal to the microcontroller ADC.

The value of measurement inductor can be selected with respect to the phase inductance of the motor. The voltage over inductance should be large enough for noise immunity. Considering the phase

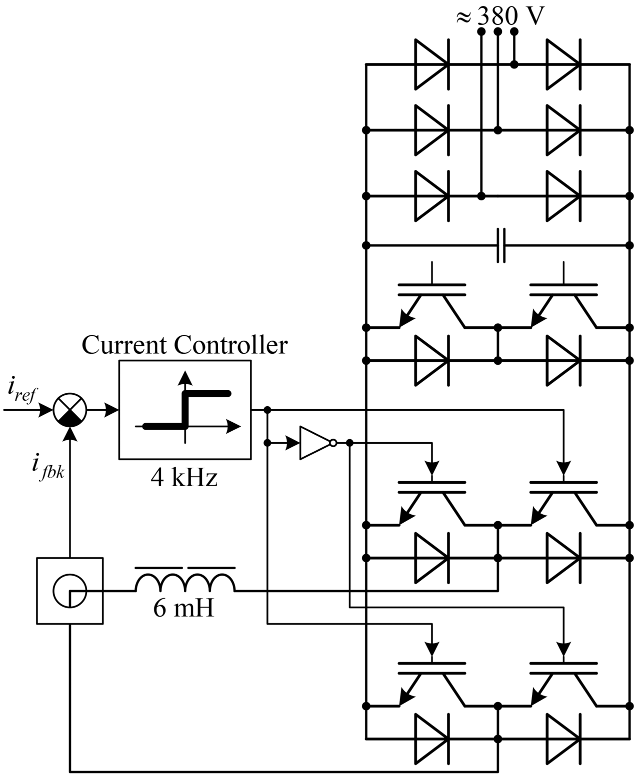

Fig. 2 *Experimental setup control system*

inductance of an IPM motor of 100 kW (traction motor) of ∼1 mH, the voltage drop across the inductor of 1 mH is in 1000 times smaller than the voltage applied to the motor winding. The output voltage can be expressed according to:

$$v_L = L_m \frac{w_1}{K_s} \frac{\mathrm{d}i_1}{\mathrm{d}t}. \tag{1}$$

The current derivative can be evaluated from the measured voltage according to:

$$\frac{\mathrm{d}i_1}{\mathrm{d}t} = \frac{K_s}{L_m w_1} v_L, \tag{2}$$

where $(K_s/L_m w_1)$ is the coefficient of the derivative estimation circuit, K_D.

3 Experimental results

3.1 Experimental setup

The experimental setup consists of a frequency converter with diode rectifier, DC-link capacitors, a three-phase inverter, and a control system based on TMS320F28335 microcontroller. Two phases of the inverter have been connected to the choke with inductance of 6 mH. This control system operates under a 4 kHz control loop execution frequency and produces sawtooth current in the choke. The sawtooth shape of the signal simplifies analysis of the processes in the derivative measurement circuit. The change in the reference current adds an offset to the sawtooth current signal.

The current measurement has been conducted using a Rogovsky current probe and the sensing resistor R_m of the circuit under test. The current derivative has been measured across the terminals of the sensing inductor $L_{m,}$ whereas the snubber circuit having C_s and R_s has been removed. The complete set of parameters is presented in Table 1 (Fig. 2).

3.2 Zero current reference experiment

During the first experiment, the current reference was set to zero and the sawtooth current was swinging around zero (see Fig. 3).

Table 1 Set of parameters of experimental setup

Item	Value
current sensor	LA 125-P
current transformation coefficient, K_S	1000
number of turns in the primary winding, w_1	4
sensing resistor, R_m [Ohm]	83
current to voltage coefficient [V/A]	0.33
voltage to current coefficient [A/V]	3.0
choke in the load [mH]	6.0
sensing inductance at 1 kHz, L_m [mH]	1.02
resistance of the sensing inductance, R_L [Ohm]	1.9
calculated coefficient of the derivative	—
estimation circuit, K_D [(kA/s)/V]	245
snubber resistance, R_S [Ohm]	470
snubber capacitance, C_S [μF]	0.47

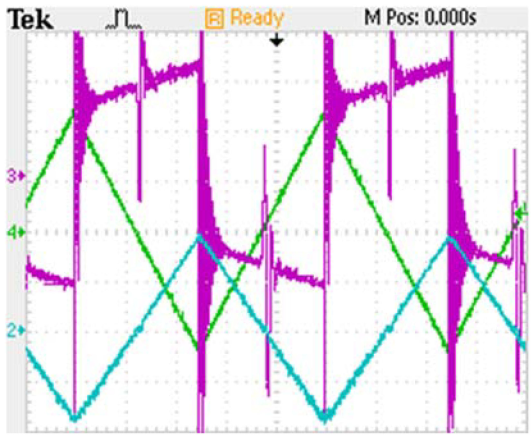

Fig. 3 *Operation of the current derivative measurement circuit (green — Rogovsky current probe output; cyan — signal from the sensing resistor — 6 A per division; magenta — signal from the sensing inductor — 200 mV per division; time — 100 μs per division)*

The shape of the signal from the Rogovsky probe is clean from any noises and repeats the signal from the resistor. The current derivative can be measured as a voltage drop across the sensing inductor, but this experiment highlights several issues that should be taken into account.

First, the voltage drop across the sensing inductor is changed significantly during single commutation cycle while the visible current derivative from the shape of the current signal seems to remain constant. This happens because the sensing inductor has a very small but non-zero ohmic resistance. This resistance is ∼1 Ohm which is much smaller than the measurement resistance R_m. However, the voltage drop in the sensing inductor is also small. Therefore, the impact of the ohmic component cannot be neglected.

The next interesting result is that the current measured by the closed-loop sensor is stuck for a while when crossing zero. This problem occurs with different models of the sensor and has impact on the current derivative measurement. The magnified oscillogram of the zero crossing is displayed in Fig. 4.

The last issue is that the derivative signal has huge oscillations during derivative changes. The frequency of these oscillations lies in the range between 200 and 1000 kHz depending on the design of the closed-loop current sensor and sensing inductor. For this particular experiment, it was ∼330 kHz (see Fig. 5). The snubber RC-circuit can be used to supress these oscillations.

3.3 Operation with snubber circuit and offset in the current reference

To supress the oscillations, the RC-snubber is connected in parallel to the sensing inductor as shown in Fig. 1. The resistance value is 470 Ohm and capacitor value is 470 nF. The problem with the zero

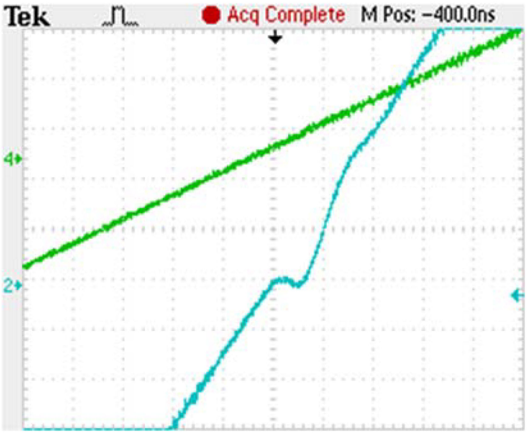

Fig. 4 *Zero crossing in the closed-loop Hall-effect current sensor (green — Rogovsky current probe output; cyan — signal from the sensing resistor — 60 A per division; time — 10 µs per division)*

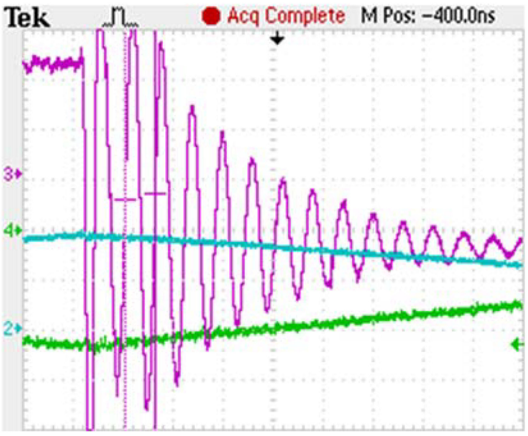

Fig. 5 *Oscillations of the current derivative signal on derivative change (green — Rogovsky current probe output; cyan — signal from the sensing resistor — 6 A per division; magenta — signal from the sensing inductor — 200 mV per division; time — 5 µs per division)*

crossing was solved by adjusting the current reference to the control system, so that the current stayed positive all the time. The results for these conditions are shown in Fig. 6.

According to the oscillogram in Fig. 6 and data in Table 1, the accuracy of the derivative measurement can be estimated. The current rises or fall for 125 µs and its deviation is 10.8 A, which corresponds to 86.4 A/ms. The current in the secondary winding of the current sensor is 250 times smaller:

$$i_2 = w_1 \frac{i_1}{K_s} = 4 \frac{i_1}{1000} = \frac{i_1}{250}. \tag{3}$$

The derivative is in the same times smaller and the voltage drop can be evaluated by its multiplication by the sensing inductor:

$$v_L = L_m \frac{\mathrm{d}i_2}{\mathrm{d}t} = 1.02 \cdot 10^{-3} \times \frac{86.4 \cdot 10^3}{250} = 352\,\mathrm{mV}. \tag{4}$$

The curve of the derivative signal contains both derivative and current components. The voltage drop across the inductor can be evaluated from this signal by the following equation:

$$v_L' = v_L - i_2 R_L = v_L - w_1 \frac{i_1}{K_s} R_L. \tag{5}$$

For the point of the maximum current that gives:

$$V_{L\,\max} = 500 - 4 \times \frac{18}{1000} \times 1.8 = 370\,\mathrm{mV}, \tag{6}$$

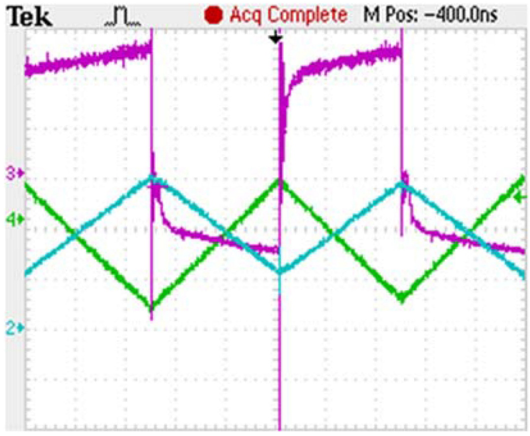

Fig. 6 *Operation with snubber circuit in without zero crossings (green — Rogovsky current probe output; cyan — signal from the sensing resistor — 6 A per division; magenta — signal from the sensing inductor — 200 mV per division; time — 50 µs per division)*

and for the minimum value:

$$V_{L\,\min} = -320 - 4 \times \frac{7.2}{1000} \times 1.8 = -372\,\mathrm{mV}. \tag{7}$$

This result shows that the positive and negative values of the current derivative are approximately the same as it should be according to the test conditions. The difference between measured values according to (6) or (7) and the estimated value according to (4) is caused by inaccuracy of the oscilloscope data processing and the initial accuracy of the inductor value. In order to use the proposed method in a self-sensing control system, the inductor value should be calibrated for each current derivative sensor installed in the system for each motor phase.

The signal itself is clean from the noise after 20 µs from the last inverter state change. The results can be improved by precise adjustment of the snubber circuit. In any case, the control system should take into account the PWM pattern at which the inverter is operating in order to avoid current derivative measurement during or right after commutation of the switches.

4 Conclusions

The proposed current derivative measurement circuit is designed to provide the instant measurement of the phase current derivative. The measured current derivative and the applied voltage can help to estimate the phase inductance of the motor which is used for observation of the rotor position in encoderless or self-sensing control systems. The proposed circuit is simple and requires an inductor and a differential input amplifier only, and an extra ADC input in the microcontroller.

The current derivative cannot be measured straight after commutation of the inverter switches. At least a 20 µs time interval is required to skip the oscillation process after each inverter state change, although this interval can be decreased by proper selection of the snubber circuit parameters. In order to increase the duration of the steady states of the inverter, the special PWM patterns should be implemented at slow speeds where self-sensing control strategies are to be run. This issue will be investigated by authors as a further work.

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