

A Novel Method for Measuring Current Derivative Signal with Closed Loop Hall-Effect Current Sensor

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Abstract

In this paper, a novel method is proposed for measuring the current derivative signal with a closed loop Hall-Effect Current Sensor. For obtaining a current differential di/dt signal, an optimal internal signal of the sensor is used, which is proportional to the primary current in the conductor. A differentiator circuit is built in the sensor circuit in order to generate the current differential signal. The components of the differentiator, the low-pass filter and the amplifier are optimized for getting a useful differential output signal. Experiment results show that the developed analog circuit gives an optimal current derivative signal, which corresponds to the differential relation to the sinusoidal primary current, i.e., the phase shift between the both signals is 90° . The developed circuit can be applied to all kinds of closed loop Hall-Effect current sensors, which are used in electrical drive systems etc.

1. Introduction

Current sensing is an important operation for many electric power, drive and communication systems. Hall-Effect current sensors are preferred towards other competitive technologies like shunt resistors, because they provide many benefits such as wide measuring range, good linearity, high accuracy, galvanic isolation between input and output, and wide variation of sensor configurations etc. [1, 2, 3].

The current differential di/dt is an important parameter of closed loop Hall-Effect current sensors. It indicates the sensor performance of following the current change and response time. Nowadays, however, it is difficult to find such a sensor on the market, which has a di/dt output. A di/dt output would be very useful for the application of sensorless control to electrical drive systems [4, 6, 7], because closed loop Hall-Effect current sensors are widely used in such systems. Therefore it is motivated to develop closed loop Hall-Effect current sensor with an additional current differential signal di/dt .

2. Measuring the Current Differential di/dt

For measuring the current differential di/dt , a differentiator has to be built in a closed loop current sensor [8]. The key of obtaining the di/dt signal is to use an optimal internal signal, which is proportional to the primary current under test. According to the measuring principle of closed loop current sensor, the current output I_s is directly proportional to the primary current I_p , i.e. $I_s = I_p/N$ with N as the number of the secondary coil windings. One can use the secondary current I_s and an additional sampling resistor R_s to get a sampling voltage $V_s =$

$I_s \cdot R_s$ for generating the di/dt signal. In addition the voltage output of the integrating amplifier in sensor is also directly proportional to the primary current. Therefore the following methods can be used for generating a di/dt output of closed loop current sensors. As example these methods are tested in the circuit of the current sensor CYHCS-SH1000A. From the results the most suitable method can be found for the applications.

2.1. Sampling Voltage between the Secondary Coil Connections

The coil of a Closed Loop Hall-Effect current sensor has its own inner resistance of about 50Ω , i.e. $R_s = 50\Omega$. One can take the voltage between the two connections of the coil as sampling voltage V_s , as shown in Fig. 1.

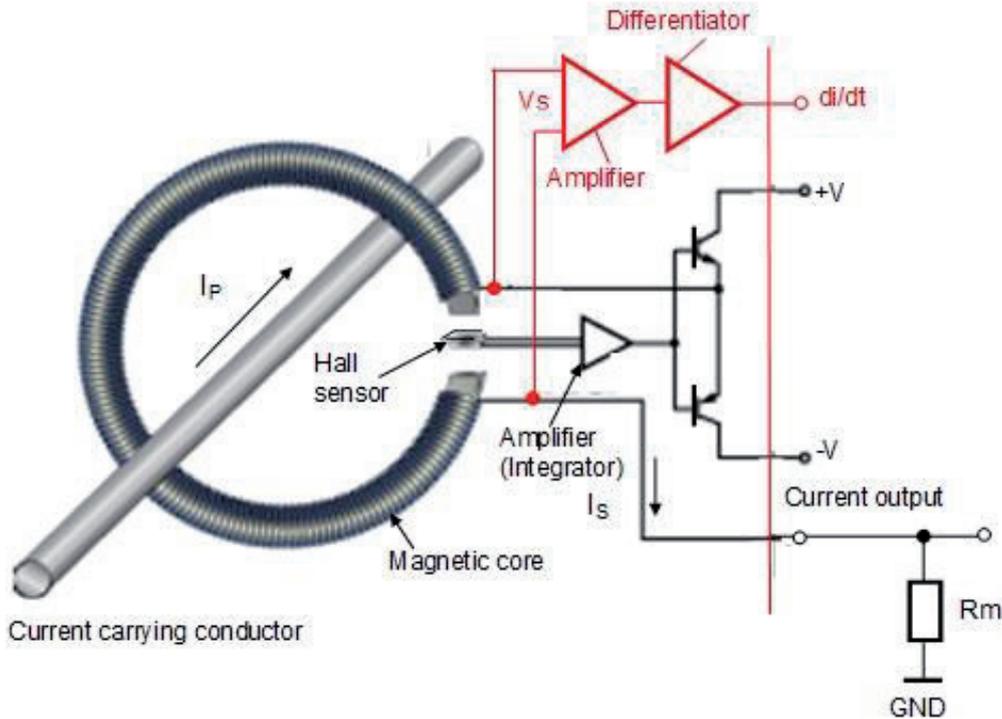


Fig. 1. Diagram of Sampling Voltage between the Secondary Coil Connections.

Theoretically, the DC part of the voltage V_s at the coil is directly proportional to the DC part of the secondary current I_s and can be easily determined by

$$V_s = R_s \cdot I_s = R_s \cdot I_p / N \tag{1}$$

with N as the number of coil windings.

But experiment results have indicated that the AC output voltage is very high and in proportion to the frequency of the primary current I_p . Due to the high windings ($N = 5000$) and a not ideally compensated residual magnetic field in the core, the secondary coil has a relative high inductivity L_s which affects the measurements. So the more correct equation in this case is as follows

$$V_s = Z_s \cdot I_s = (R_s + j\omega L_s) \cdot I_p / N \tag{2}$$

with Z_s as the sampling impedance of the secondary coil.

Therefore this method is unfeasible, because the sampling voltage is frequency dependent. In this case the output signal of the differentiator will be influenced by the inductivity of secondary coil.

2.2. Sampling Voltage by using an Additional Sampling Resistance

Fig. 2 illustrates two possible positions for connecting an additional sampling resistor R_s in the secondary current circuit. It can be connected at the current input or output of the coil. Because R_s will reduce the value range of the measuring resistance R_m outside the sensor, the value of this resistor should be very small.

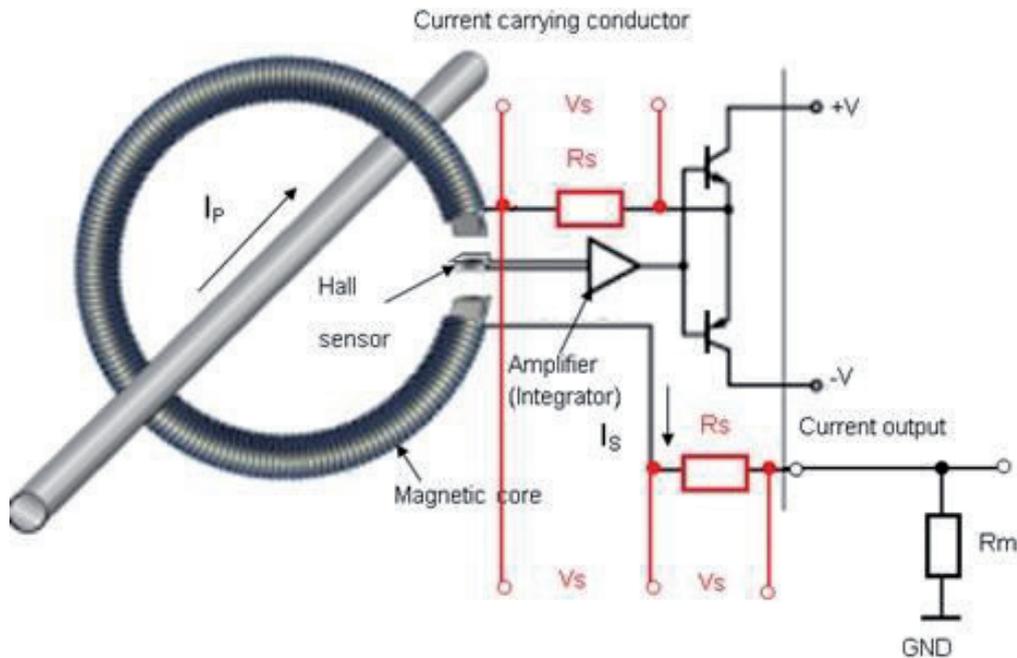


Fig. 2. Diagram of Sampling Voltage by using an Additional Sampling Resistance.

For obtaining a sufficient sampling voltage, V_s has to be amplified by a differential or instrumentation amplifier like AD8428. The AD8428 is a low noise and low gain drift instrumentation amplifier with a fixed gain of about 2000. Fig. 3 shows a concrete implementation circuit with a sampling resistance of 1.8 Ohm. The measuring results are given in Fig. 4. With increasing frequency in the primary conductor, the voltage output, which is proportional to di_s/dt , increases in a linear behavior.

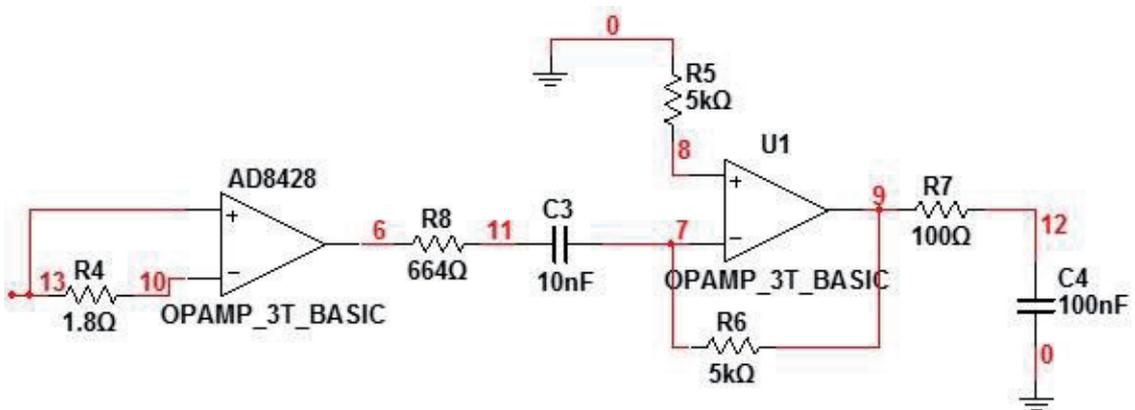


Fig. 3. Implementation Circuit (Sampling Resistance $R_s = R_4 = 1.8 \Omega$).

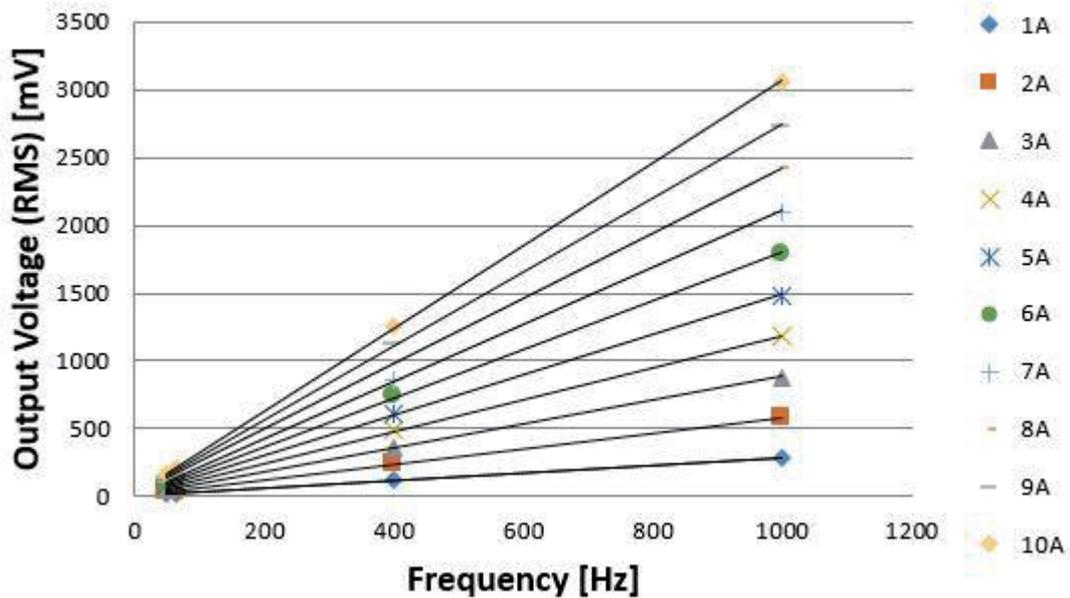


Fig. 4. Derivative Signal as Function of Frequency under different Primary Current.

Although the results are acceptable, this method is still not optimal for the practical applications. Due to the limitation of the measuring resistance R_m , the sampling resistance is very small so that the voltage drop becomes also very low. In this case the sampling voltage must be processed with amplifier of very high gain and good signal filtering performance. Otherwise noises will influence the measuring results.

2.3. Sampling Voltage at the Output of the Integrator

The output voltage V_s of the integrator of the current sensor is also proportional to the output current I_s of the sensor. This has been proved by experiments. Thus this voltage can be used as sampling signal for generating the di/dt signal, as shown in Fig. 5.

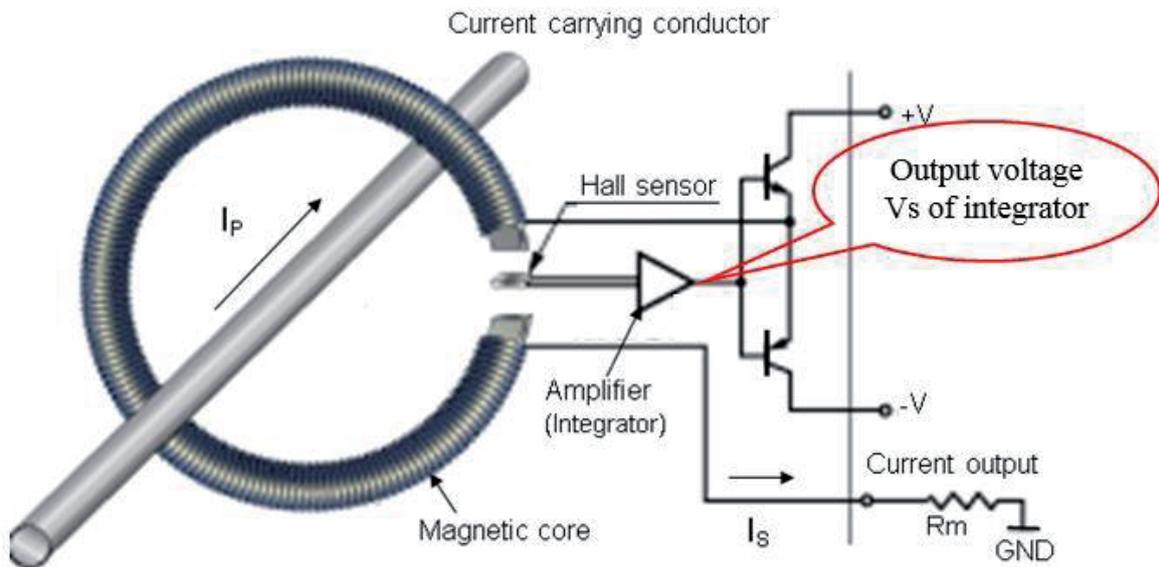


Fig. 5. Taking the output voltage of the integrator as sampling signal.

In order to avoid any influences from the additional signal processing circuit to the original sensor system and to get a better result, the sampling voltage should be connected to a voltage follower before it is differentiated, see Fig. 6. The voltage follower has a high input impedance and a low output impedance. Therefore the interaction between the sensor system and the added differentiator circuit is prevented by the voltage follower.



Fig. 6. Block Diagram of Implementation Circuit for Signal Processing.

Fig. 7 shows an example of implementation circuit of a differentiator with passive low-pass filter. The resistor $R8$ has the function of damping high frequency oscillations generated by the differentiator. The input voltage of the differentiator is reduced to V_i due to the voltage drop on the resistor $R8$. The time constant T of the differentiator can be calculated by

$$T = R6 \cdot C3 \quad (3)$$

The parameters $R6$ and $C3$ are important for adjusting the phase shift between the input and output voltages of the differentiator. The phase shift of the differentiator should be 90° .

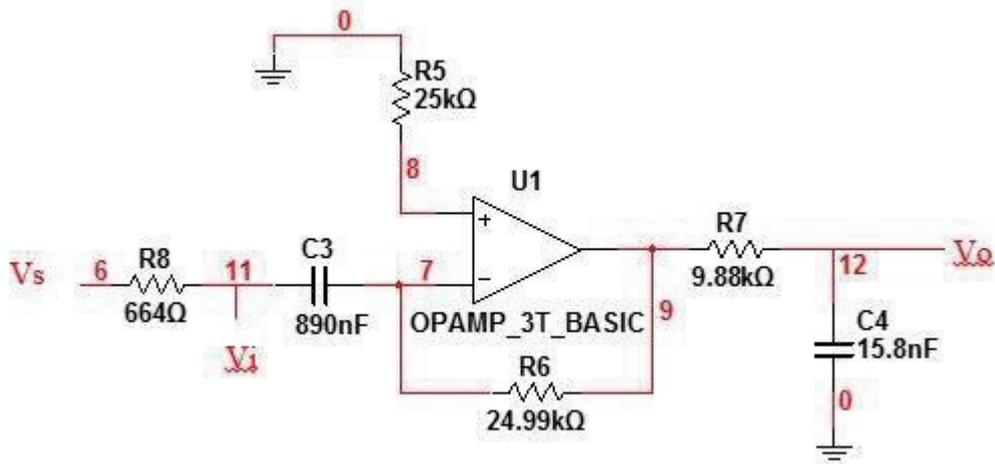


Fig. 7. Implementation Circuit of Differentiator with Passive Low-Pass Filter.

A low-pass filter is needed to reduce the noises because the differentiator is a sensitive circuit. The cut-of-frequency f_p should be ten times higher than the frequency of the useful signal. It can be calculated by

$$f_p = 10 / (2\pi \cdot R7 \cdot C4) \quad (4)$$

For designing the differentiator, some points have to be taken into account. If $R6$ and $C3$ are chosen too high, the time constant T is long, so that the charge and discharge of the capacitor becomes slow. The circuit won't work properly at high frequencies. If $R6$ and $C3$ are chosen too low, the output signal will be overwhelmed with noises. In this case, $R7$ and $C4$ have to be optimized for getting a suitable cut-off-frequency f_p .

Fig. 8 shows an Implementation circuit of differentiator with an active Low-Pass-Filter and voltage follower. The circuit is optimized for sinusoidal primary current with a frequency of 50 Hz.

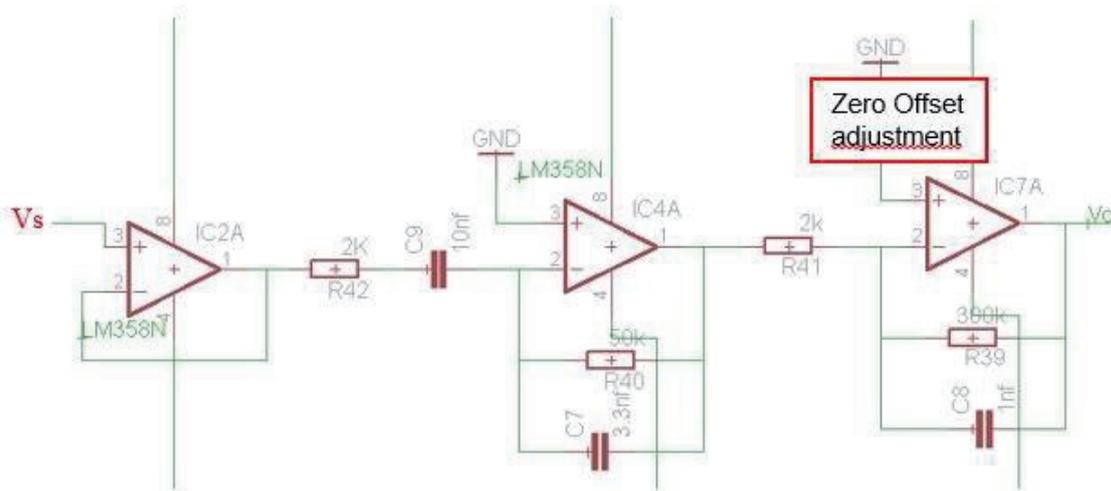


Fig. 8. Implementation Circuit of Differentiator with Active Low-Pass Filter and Voltage Follower

3. Experimental Results

Fig. 9 shows the comparison of sinusoidal differential voltage to the sensor output voltage after offset adjustment. The orange curve is the voltage, which is measured at the measuring resistance R_m (see Fig. 5). This voltage is directly proportional to the primary current according to the equation:

$$V_{out} = R_m \cdot I_s = R_m \cdot I_p / N \quad (5)$$

The blue curve represents the voltage output of the differentiator with active low-pass filter. Without any signal processing, this voltage signal is directly proportional to the derivative of the primary current:

$$V_o = k \cdot (dV_s/dt) + V_{os} = k \cdot k_1 / N \cdot (dI_p/dt) + V_{os} \quad (6)$$

with k and k_1 as calibration factors and V_{os} as output offset of the differentiator. The output offset must be reduced by a zero offset adjustment circuit. So the offset-free output signal can be written as:

$$V_o = k \cdot (dV_s/dt) = k \cdot k_1 / N \cdot (dI_p/dt) \quad (7)$$

From the graphics (Fig. 9), the phase difference between the original sensor output signal and the derivative signal is approximately 90° . The results agree with the theoretical value.

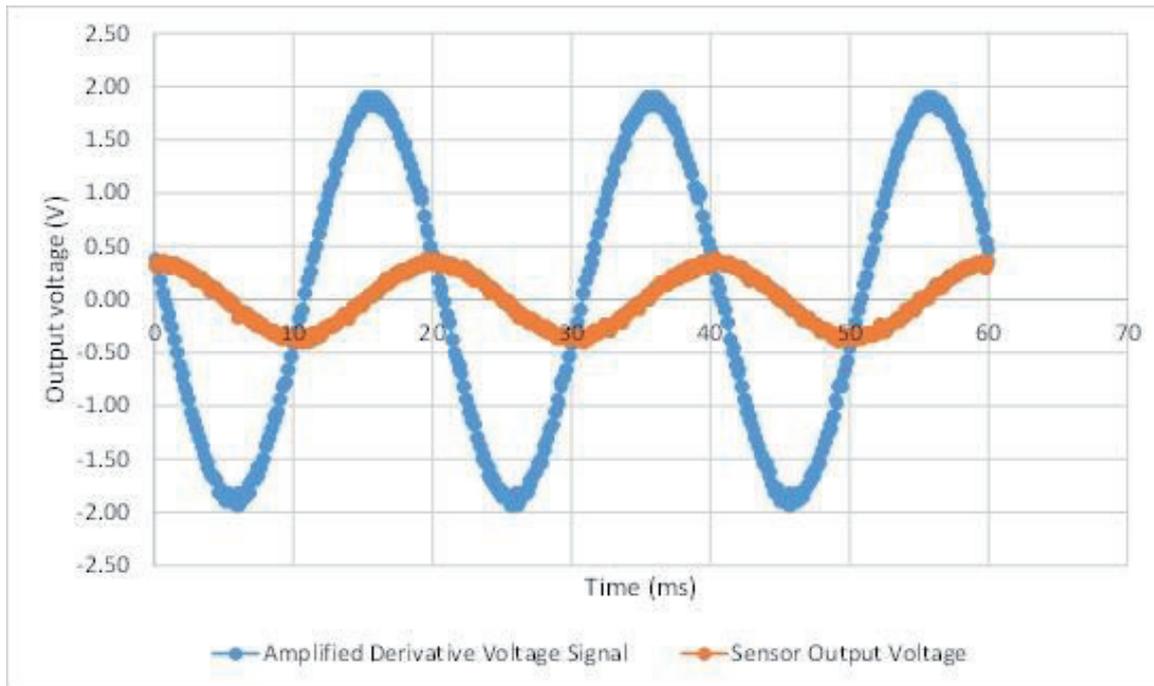


Fig. 9. Sensor Output Voltage and Amplified Derivative Voltage after Offset Adjustment.

4. Calibration

In order to get a reliable current derivative signal, the sensor has to be calibrated. The calibration can be carried out with a sinusoidal primary current. In general, a sine wave can be written by

$$i(t) = A \cdot \sin(2\pi f t + \phi) \quad (8)$$

with A as amplitude, f as frequency and ϕ as initial phase of the current. Therefore, the derivative of this signal is:

$$di(t)/dt = 2\pi f \cdot A \cdot \cos(2\pi f t + \phi) \quad (9)$$

For the calibration one should pay attention on the following points:

- The phase shift between original and derivative signal should be 90° .
- The amplitude of the differential signal is increased with a factor $2\pi f$ in comparison to the primary current. This factor is frequency dependent, so that higher frequency means higher amplitude.

The differentiator and the low-pass amplifier have to be optimized in order to fulfill these criteria.

5. Conclusions

In this paper, three methods for getting a current derivative signal have been proposed. From the analysis and experimental results, one can conclude that the third method of using the output voltage of the internal integrator amplifier as sampling signal is the most suitable signal for building the current differential di/dt signal output. In order to achieve optimal results, it is necessary to optimize the components and parameters of the differentiator, the low-pass filter and the amplifier. A calibration is also needed by using AC currents of different frequencies. A sensor with additional current differential signal output can be used in sensorless control of electrical machines and drive systems.

6. Reference

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