INVESTIGATION OF THE EFFECTS OF CURRENT MEASUREMENT METHODS ON SERVO MOTOR DYNAMICS

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***Abstract* - Electric Drive Applications, which we actively use in our daily lives, increase the usage area with developing technology. In order to increase the efficiency of these applications and to control the motors more accurately; measurement of motor currents with less loss, accuracy and reliability of measurements, cost of design are important design criteria in motor control systems. There are two main reasons why motor currents need to be measured with high accuracy and appropriate bandwidth. The first is to provide information to the controller with minimal delay when the overcurrent condition occurs in the motor phases and the other is to optimize the dynamic responses of the physical variables (position, speed, torque).**

In this study, the effects of different criteria such as proper bandwidth, maximum accuracy and linearity according to temperature change on servo motor systems were investigated. Fault tolerance and power loss analyzes in measuring motor current with shunt resistor or closed loop Hall Effect sensor are also compared. The bandwidth of the current measuring circuits was measured by oscilloscope. The measured bandwidth was used in the feedback transfer function. Finally, in the current measurement method with resistance; when torque reaches its rated torque, two percent more overshoot occurs.

Keywords — Motor Current Measurement Methods, Permanent Magnet Synchronous Motor Model, Field Effect Control Method, Dynamic Response

I. INTRODUCTION

Accurate measurement of the motor current is very important for the drive system of a current-controlled permanent magnet synchronous machine (PMSM). Again, the precise measurement of stator currents is of great importance in the vector control of Alternating Current (AC) motor drives because the current measurement error causes not only transient but also steady state errors in the stator currents [1, 2]. In both cases, torque control performance can be directly affected. The torque of the motor, which cannot be controlled correctly, may cause additional losses as the motor operates outside the maximum torque point.

There are many studies on motor current measurement methods. In the studies, advantages and disadvantages of motor current measurement methods are compared. In this paper, besides the advantages and disadvantages of measurement methods; the dynamic effects of current measurement on servo system are also examined.

Considering electrical and dynamic parameters; suggestions were given to the designers about the types of current measuring sensors.

Common Mode Rejection Ratio (CMRR) calculations are presented to ensure accurate and reliable measurement of current and to reduce the noise / signal ratio of the differential amplifier in the design [3].

One of the difficulties in the design of the current sensing circuit; galvanic isolation at large common mode voltage. The other is the precision measurement of an analog signal in a noisy environment caused by high frequency capacitive currents produced by switching of inverter's semiconductor switchs.

In addition, measurement errors that can be caused by parasitic parameters such as thermal EMF and self-inductance of the resistor were investigated in the motor drive using current measurement method with resistance [4]. Two different current measurement methods, error analysis and loss analysis were calculated in detail.

The effect of the current measuring feedback block in the control loop on the dynamics of the system was modeled as a low pass filter. The low-pass filter feature of the current measuring circuit was found to cause phase and amplitude differences between the actual motor currents and the measured motor currents. This causes the motor to fail to operate at its maximum torque point. Fig. 1 shows the field oriented control scheme.

The feedback block in the control loop was modeled as a low-pass filter due to the characteristic of the sensor.

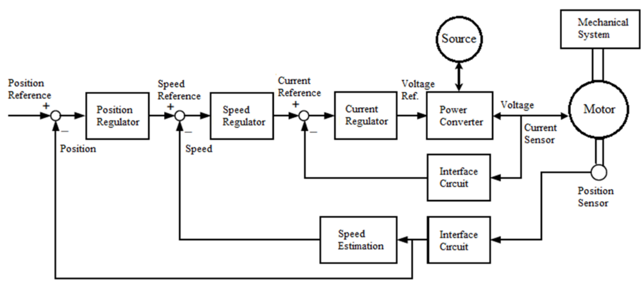

Fig. 1. Block diagram of the control systems of the electrical machine and power converter [5].

II. APPLICATION INFORMATION

The predicted loss, accuracy analysis was tested on the designed 750W Servo Motor Drive. The test setup is shown in Fig. 2.

In practice, the sensor was used for the U and V phases, considering the loss and cost-oriented, and the W phase current was calculated by the algorithm in the software.

Fig. 2. Test setup for measuring motor currents.

A. Current Measurement Method With Resistance

The simplest method of obtaining a motor winding current is to measure each phase current directly in the phase node by placing a suitable shunt resistor in the phase connection. Depending on the motor winding connections (Y-Δ), this measurement requires at least two sensors to be applied directly to the motor phases.

Shunt resistors are popular current sensors because they provide low-cost measurement. The voltage drop across the shunt resistor is monitored to determine the current flowing through the load. In most cases, the voltage drop is too small to be used for direct processing. Therefore, you need to use amplifiers. The magnitude of the current should be limited due to the ohmic loss caused by $I.V_R$. Furthermore, in order to reduce loss, the value of the resistor should be minimized, but in this case it decreases with the magnitude of the perceived voltage and the signal-to-noise ratio worsens further. Furthermore, if the current changes rapidly, measurement errors occur due to the interference itself's interference inductance [5].

However, the CMRR value should be satisfactory to increase the signal to noise ratio which affects the accuracy of the measurement. The circuit diagram for the isolated measurement of motor currents with shunt resistor and the standard differential configuration of the operational amplifier is shown in Fig. 3 Output voltage of operational amplifier;

$$V_O = \frac{R_f}{R_i} \cdot (V_{IN1} - V_{IN2}) + V_{offset} \tag{2}$$

this is true when the exact ratio of R_f / R_i resistors is maintained. It should be noted that the basis for differential operation and achieving satisfactory CMRR values (Common Mode Reject Ratio) is the precise selection of the four resistors. In practice, the resistance cost of 0.1% tolerance is unacceptable. Variation of CMRR according to R_f and R_i resistances is given (3).

$$CMRR = 20\log\left[\frac{\frac{1}{2}\cdot\left(1+\frac{R_f}{R_i}\right)}{\frac{\Delta R}{R}}\right] \tag{3}$$

We can calculate the CMRR values obtained for hand-matched resistors. For example, if $R_2 / R_1 = 1$, the best CMRR ratio is obtained. It should also be noted that in order to avoid the loading effect, R_1 and R_2 values should be much larger than shunt resistor R_{Shunt} [3, 10].

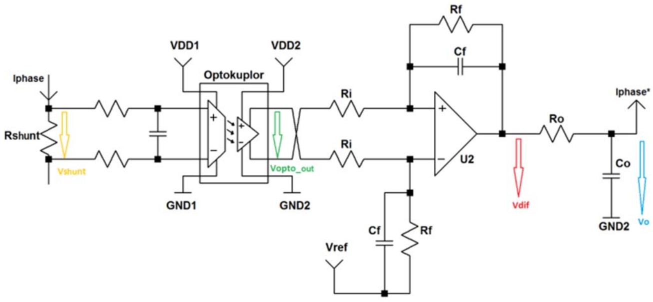

Fig. 3. Motor phase current measurement circuit with shunt resistor.

The time constant of the system created by the shunt resistance current sensor is 12us. The oscilloscope view of the measurement is given in Fig. 4. This time constant was used to model the Servo Motor Control Dynamics with MATLAB. The time constant of the measured system was used in the transfer function block of the first order low pass filter (1).

$$H(s) = \frac{1}{1+\tau s} \tag{1}$$

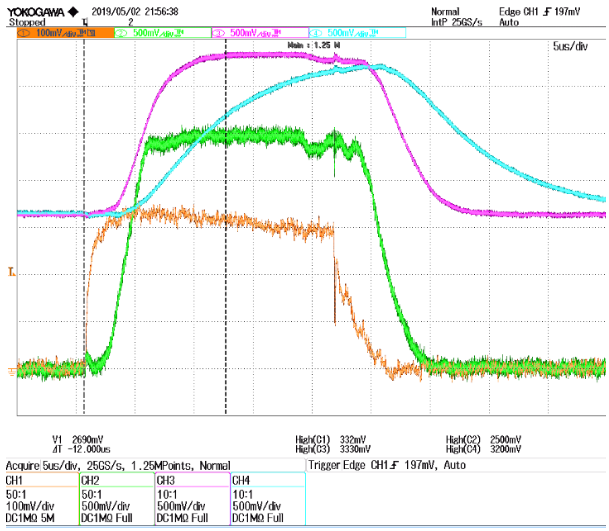

Fig. 4. Response time of motor current measuring circuit with shunt resistor.

B. Measuring Motor Current with Hall Effect Sensor

The magnetic field is formed around a conductor through which current flows. The magnitude of the magnetic field is proportional to the current and there is no time delay between the current and the magnetic field. Thus, by measuring the magnetic field, the current can be measured indirectly. A Hall Effect Sensor can be used to measure the magnetic field. Fig. 5 shows the operating principle of the Hall Effect current sensor [7].

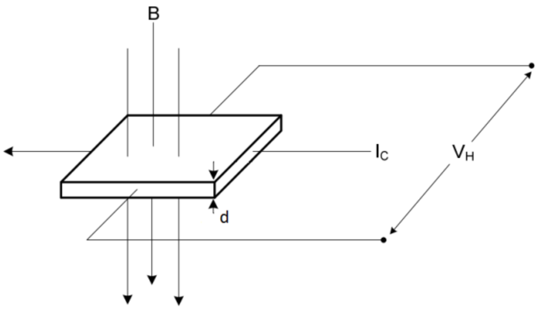

Fig. 5. Hall effect sensor working principle.

I_C, the magnetic flux density generated by the current-carrying conductor, K is the constant of a conductive material, d is the thickness of the layer, V_{OH} is the shift of the Hall sensor in the absence of current. The output voltage generated by the Hall effect sensor relative to the passing current is given by V_H (4).

$$V_H = \frac{K}{d} B I_C + V_{OH} \tag{4}$$

Although an analogue output sensor is considered to be linear along its range, practically no sensor is completely linear. The specification linearity defines the maximum error resulting from the assumption that the transfer function is a straight line. Hall effect sensors are sensitive sensors that show linearity, typically -0.5% -1.5% [7,8].

The general form of the Hall effective current measuring circuit is shown in Fig. 6.

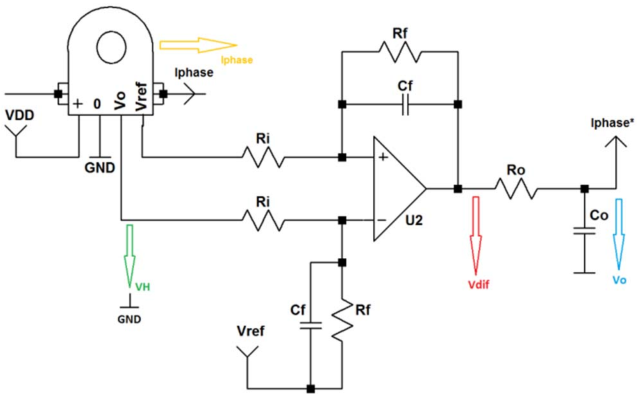

Fig. 6. Motor phase current measuring circuit with Hall Effect Sensor.

The time constant of the system created by Hall effective sensor is 9.9us. The oscilloscope measurements of the response time of the system are shown in Fig. 7.

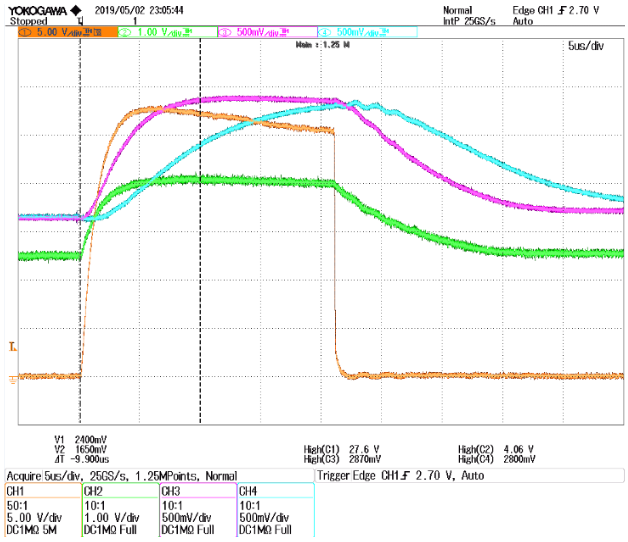

Fig. 7. Response time of current measuring circuit with Hall effect sensor.

C. *MATLAB Simulation Model of the System*

MATLAB simulation program was used to access the data related to the dynamic response of the system. In the model of Servo System, which is formed as in Fig. 8, the parameters of the motor used in the application shown in Table 1 were entered.

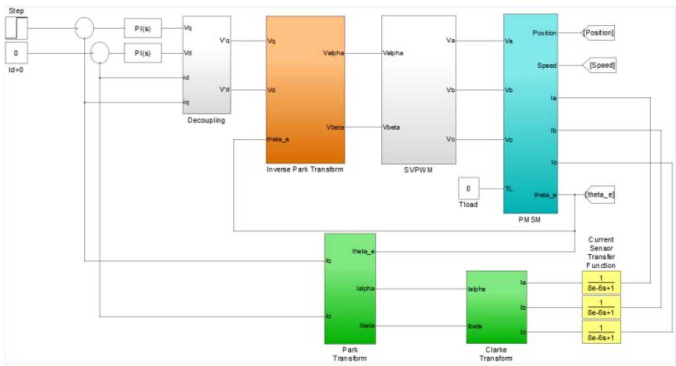

Fig. 8. MATLAB model of the system.

The parameters of the servo motor drive used in the measurements are given in Table 1.

TABLE I. TECHNICAL INFORMATION OF THE PERMANENT MAGNET SYNCHRONOUS MOTOR USED

Parameter	Unit	Value
Rated speed	rad/s	3000
Rated torque	N.m	2,4
Rated current	I (A_{rms})	5,1
Stator line resistance	R (Ω)	0,713
Line inductance	L (H)	0,00316
Number of pole pairs	p	5
Magnet Flux	ψ (V.s)	0,045255
Moment of Inertia	J ($kg.m^2$)	0,00011
Viscous damping	B	$4{,}047 \times 10^{-5}$

Due to the electronic design and the structure of the sensors; the low-pass filter as shown in Fig. 9, causing the feedback signal to be delayed; cause the controller unit to generate a higher controller signal to approximate the current with the reference.

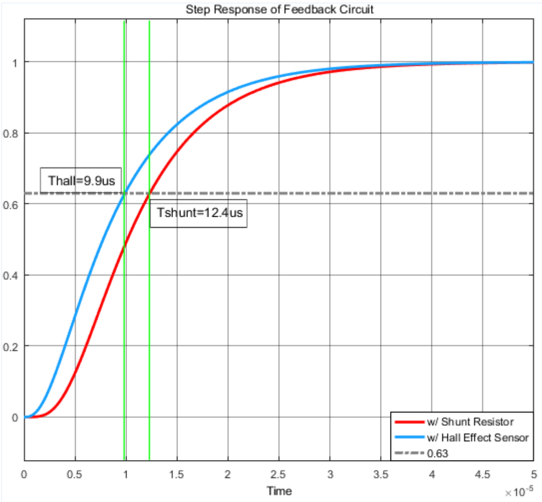

Fig. 9. Step responses of current feedback circuits.

Accordingly, as can be seen in Fig. 10, when the current constant with a relatively high shunt resistance is used, overshoot is observed as a result of controller signals generated by the controller's calculations.

As a result of the simulation, in the current resistive measuring method, the torque exceeds the rated torque by more than 2%. Since torque is a function ,

$$Te=\frac{3}{2}pp\left(\lambda_{PM}i_q+\left(L_d-L_q\right)i_di_q\right) \tag{5}$$

of I_q current, it will cause unwanted torque fluctuations in sudden load changes in the system. T_e is the electromagnetic torque, pp is the number of pole pairs, λ_{PM} is the permanent magnet flux, L_d and L_q are the stator inductances in the synchronous rotating reference frame, and id and I_q are the stator currents in the synchronous rotating reference frame [9].

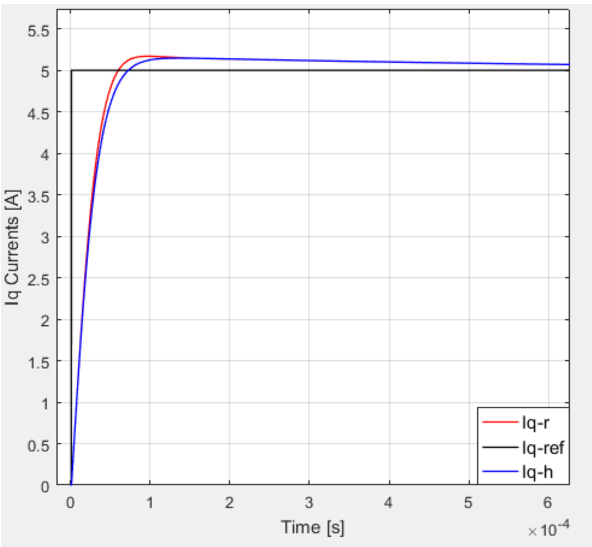

Fig. 10. Iq currents according to sensor type.

The amplitude and phase change caused by the transfer function of the low pass filter sensor is shown in Fig. 11 Here, the sinusoidal current flowing from the U phase of the motor; I_u is the actual phase current, I_u (Shunt) is the resistance output, I_u (Hall) is the area of the sensor with the measuring output. The problem of measuring the phase currents effective by the phase shift in calculating the I_q current effective in the torque equation of the surface magnet PMSM by Clarke and Park transformations will have different results in the orientation of the magnetic field according to the sensor type. The phase shift in sinusoidal signals will be reflected as an angular error in the orientation of the magnetic field. This causes the motor to run outside the MTPA point. As a result, the intensity of the phase current required to achieve the desired torque will increase. Therefore, losses will increase due to I^2x R.

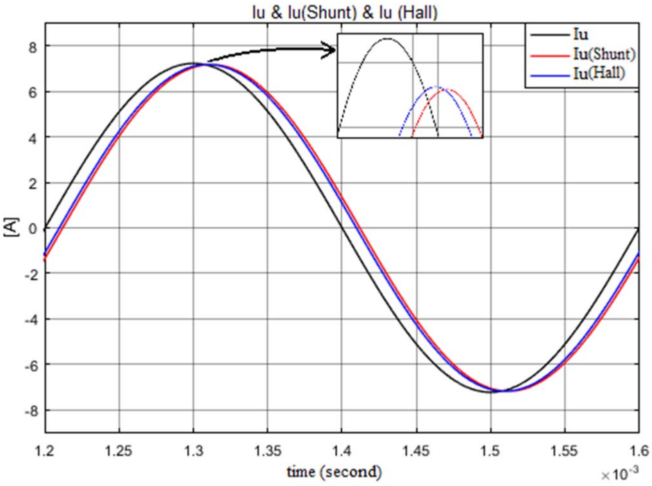

Fig. 11. Periodic view of detected motor currents according to the measurement method.

D. Loss Analysis

On the measuring resistors placed in the motor windings, a voltage drop occurs due to motor currents and measuring resistance. This voltage causes a loss as much as P_{loss} by multiplying the motor current by the effective value. P_{loss} loss calculations,

$$V_S = R_S \text{ x } I_{mot\_rms} \tag{6}$$

$$P_{loss} = V_S \text{ x } I_{mot\_rms} \tag{7}$$

Designed to produce 750W spindle power, the output power of the motor drive will be 882W, when 85% of the motor efficiency is taken. If the efficiency of the motor drive is 95%, the input power of the motor drive is 928W. Thus, the lost power in the motor drive is 46W (928W - 882W). This efficiency analysis belongs to the motor drive where the resistance and current measurement is made. Likewise, when the field effect sensor is used, the lost power will be 40W since 2 sensors (2 x 3W) are used, since the difference is 3W according to Fig. 11 In this way, the efficiency of the backward motor drive will be 95.7% when calculated. In other words, there will be an increase of 0.7% (95.7 - 95) in the efficiency of the motor driver. As the measured motor current increases, so does the effect on the efficiency of the motor drive.

In the field effect sensor, the loss is due to the supply voltage and the rated welding current. Magnetic losses are neglected because they are too small. Loss analysis by sensor type is given in Fig. 12.

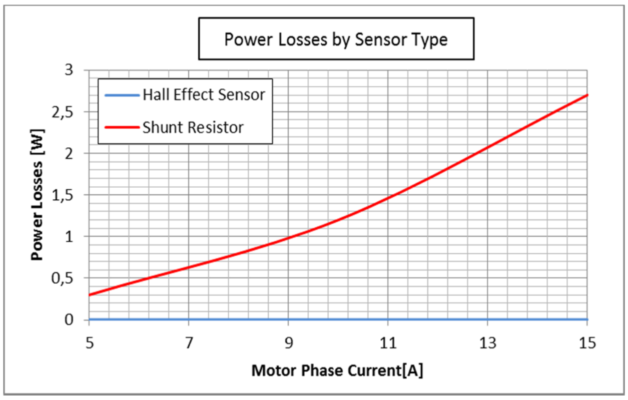

Fig. 12. Power loss according to sensor type.

The accuracy of the shunt resistance depends on parameters such as thermal strength coefficient (TCR), offset voltage and tolerance of the resistance value. In addition to the TCR of the resistor element, low-value sensing resistors may encounter an additional error resulting from the much higher TCR of the copper connections [10].

The Hall effect sensor will cause erroneous measurements due to temperature, linearity, magnetic and electrical offset. Fig. 13 gives the% error information measured at certain currents according to the sensor type. The maximum error in current measurement with resistance is 2.6%, while the maximum error with field effect sensor is 0.5%.

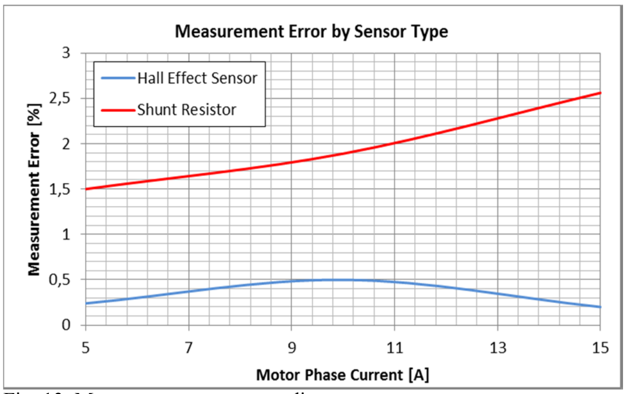

Fig. 13. Measurement error according to sensor type.

III. CONCLUSION

In this paper, the effects of current measurement methods for servo motor drives on motor drive dynamics are investigated. As a result of the simulation, in the current resistive measuring method, the torque exceeds the rated torque by more than 2%. Since torque is a function of Iq current, it will cause unwanted torque fluctuations in sudden load changes in the system.

In addition to this, data related to loss and error tolerance analysis of current measurement methods are presented. The main approach is to measure the motor current accurately with low loss and low cost and correct operation of the motor control block.

Advantages and disadvantages of flow measurement methods according to design criteria are given in Table II.

TABLE II. COMPARISON OF CURRENT MEASUREMENT METHODS

Current Measurement Method	**Shunt Resistor**	**Hall Effect Sensor**
Accuracy	Good	Good
Temperature dependence	Good	Bad
Cost	Low	High
Isolation	No	Yes
High current measurement	Bad	Good
DC offset problem	Yes	No
Saturation problem	No	Yes
Power consumption	High	Low
Unwanted noise measurement	Yes	No
AC / DC measurements	Both	Both

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