

Development of a Real-time Analytical System for Motor Performance Measurement

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ABSTRACT

A method was devised for utilizing vector analysis to quantify inductance during switching, which is a major factor affecting such motor performances as maximum power and efficiency, and the appropriateness of this method was confirmed. The application of this method makes it possible to measure actual motor inductance during switching and to observe the magnetic saturation of the motor. By systematizing this analysis method, and representing measured values as a circle diagram, it is possible to evaluate motor operating conditions in real-time. This makes it possible for optimum motor control parameters, which are conventionally determined by analysis after testing, to be established during testing. This system reduces the overall manpower used in motor testing and data analysis by 30%. By incorporating the motor inductance value that is calculated with this method into the motor's digital control flow, the torque response is enhanced.

1. Introduction

With the continuing awareness of global environmental issues, there has been an increasing demand for low-pollution vehicles, including hybrid vehicles, fuel cell electric vehicles, etc. In creating the motors that are the source of the drive power of these new vehicles, there is a need to make them more efficient, smaller, and lighter weight. There has been a focus on higher speed motors as one means of making the motors smaller and lighter. Focus has also been placed on brushless DC motor weak field control as a method of creating a higher speed motor. Output limits in the high-speed range with weak field control is greatly affected by inductance during motor switching and the amount of weak field current⁽¹⁾. Therefore, it can be said that the keys to creating more efficient high-

output motors lie in optimizing inductance during switching and weak field current. This paper describes a method of calculating inductance during switching, which until now could not be quantitatively evaluated, and explains the benefits of application of this method as a new measurement system.

2. Aims of Development

Through recent academic papers ^{(1)–(3)} and actual current wave changes, it has become increasingly clear that changes to inductance, which greatly affects maximum motor output as well as responsiveness and efficiency, vary according to the amount of load. Inductance without switching can easily be measured by measurement devices commonly sold in the market, and so simulations can be carried out with good

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accuracy. However, methods for measuring inductance during switching are complex, and those values cannot be evaluated or estimated quantitatively, due to such reasons as the values change according to the amount of switching. Because of this difficulty, there have been no tools to use during the design stage, and this has meant that designing the optimum motor involved repetitions of prototype building and modification, which took much time. Also, with the weak field control — widely used in motor control when aiming for smaller and lighter motors through higher motor speeds — in order to determine the weak field current's switching amount and timing, it is necessary to perform the vector analysis processing that accompanies d-q conversion. Therefore, establishing optimum parameters during testing is difficult, and a post-test process is required to determine the optimum values from the test data. This means much time is required, including the manpower required for re-testing.

Against this background, this research project has established a method for the accurate calculation of inductance during switching, and has made improvements to the efficiency of research and development by creating a system for this method. The goals of this research are:

- (1) to quantitatively calculate inductance during switching, which greatly affects basic motor performance
- (2) to improve the accuracy of, and shorten the time for setting optimum switching amount and timing by showing vector analysis in real-time.

3. Analysis Method

Torque current (I_d), which determines the size of the torque generated by the motor, is driven by the electric potential difference between power-supply voltage (V_b) and motor phase voltage. The greatest phase voltage where it is possible for torque current to flow (maximum phase voltage) is when the motor permeable voltage waveform is the ideal sine wave, $V_b/\sqrt{6}$ (V_b : power-supply voltage). When motor speed and torque increase, motor phase voltage increases, and if the maximum phase voltage is exceeded, torque current is no longer able to flow. Regarding this, as shown in Fig. 1, canceling out the permeable voltage and the voltage rise due to the torque current to flow an electrical current (I_q) at a phase (q-axis) with an electrical angle which is advanced 90° from the torque axis (d-axis) is the method for passing torque current even at higher speeds. This is a widely known method of weak field control for brushless DC motors. In recent years, a major

issue in the high speed motor research, which has been carried out in response to the increasing need for smaller and lighter, higher-speed motors, is the prediction of maximum output values in the high speed range.

Focus has been placed on the vector analysis method as a method for calculating maximum output in high-speed motors that adopt weak field control⁽²⁾. Fig. 2 shows an example of calculations using the vector analysis method, and Table 1 shows the list of symbols used in later calculations. The graph's horizontal axis and the letter d refer to the torque axis (d-axis), while the letter q refers to the flux field axis (q-axis). This method of vector analysis makes the motor drive state visible by separating motor drive parameters that change according to load state into d-axis and q-axis, and expressing them as vectors. Each motor parameter is expressed as a voltage vector, such as $I \cdot R$, $I \cdot \omega \cdot L$. By looking at the relationship between the phase voltage vector on the circle diagram and the circle of maximum phase voltage determined by the power-supply voltage, it is possible to make decisions about the possibility of output, and to calculate the size of the required weak field current. In this way, the method of vector analysis is an effective method for analysis concerning the verification of motor maximum output, particularly in the high speed range. As such, during motor design, it can be used to confirm whether or not output can be achieved with target motor speed and maximum current output using parameters such as K_e , R , L_d , and L_q that are determined in magnetic simulation.

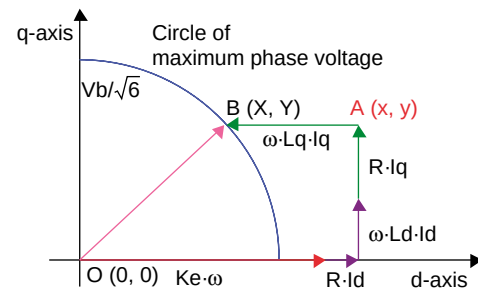


Fig. 2 Vector diagram of the brushless DC motor

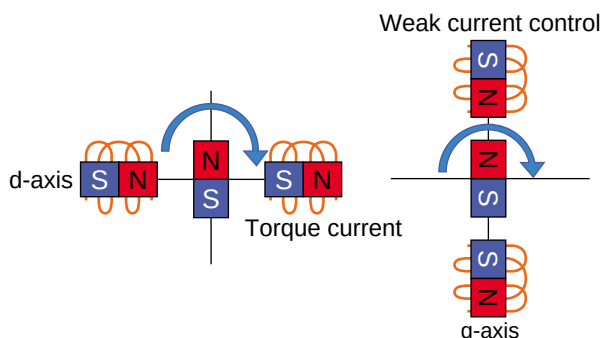


Fig. 1 d-axis and q-axis

Table 1 List of variables

K_e [V/rpm]	back EMF constant
ω [rad/s]	angular velocity
R [Ω]	stator resistance
I_d [A]	d-axis current
I_q [A]	q-axis current
L_d [H]	d-axis inductance
L_q [H]	q-axis inductance
V_d [V]	d-axis voltage
V_q [V]	q-axis voltage
V [V]	phase voltage

The actual motor switching waveforms in the weak field control range for motors that are switching are waves composed of the electrical currents according to torque current I_d and weak field current I_q , as shown in Fig. 3. Therefore, in a quantitative evaluation of each command value component, processing, such as d-q conversion, is required. Also, inductance, which greatly affects motor output characteristics, increases and decreases with changes in motor material permeability. For these reasons, it was very difficult to know the motor driving state during testing or to establish optimum control parameters. However, in recent years, thanks to the development of technology such as FFT analysis devices, it has become possible to elucidate basic phase current and phase voltage basic waves, and to carry out analysis of phases. Using this technology to calculate basic wave phase differences between the actual phase current and phase voltage waves and the poles, and to calculate the root mean square, a method has been devised to carry out vector analysis in the motor's actual load state⁽³⁾. Fig. 4 shows an example of vector analysis using this method. In the diagram, α is the phase difference between the d-axis and the phase current, and β is the phase difference between the phase current and the phase voltage, with $\alpha + \beta$ being the phase difference between the d-axis and the phase voltage. By comparing the equivalent A point coordinates in Fig. 2 and Fig. 4, drawn using different methods, under the same driving conditions (motor speed, torque), it is possible to calculate L_d and L_q in the actual load state.

$$K_e \cdot \omega + R \cdot I_d = V \cdot \cos(\alpha + \beta) + \omega \cdot L_q \cdot I \cdot \sin\alpha$$

...A's X Coordinates

$$\omega \cdot L_d \cdot I_d + R \cdot I_q = V \cdot \sin(\alpha + \beta)$$

...A's Y Coordinates

However,

$$I_d = I \cdot \cos\alpha, I_q = I \cdot \sin\alpha$$

And from this,

$$L_d = (V \cdot \sin(\alpha + \beta) - R \cdot I \cdot \sin\alpha) / (\omega \cdot I \cdot \cos\alpha) \quad (1)$$

$$L_q = (K_e \cdot \omega + R \cdot I \cdot \cos\alpha - V \cdot \cos(\alpha + \beta)) / (\omega \cdot I \cdot \sin\alpha) \quad (2)$$

In this way, inductance of the d-axis and q-axis in the actual load state is expressed as the measured values of phase voltage, phase current, and phase difference between each component.

It is now possible to calculate inductance during motor switching using Equation (1) and (2), and confirmation was made of the fact that inductance drops according to increases in switching amount. However, inductance calculated according to this method includes a variety of error elements, and so, is insufficient in terms of reliable accuracy and the ability to be reproduced. The research here undertaken analyzes the elements causing the drop in calculation accuracy and reproducibility, correcting them and devising a method for calculating inductance with good accuracy and reproducibility. As can be seen in Equations (1) and (2), each inductance equation includes phase voltage as determined in each sample phase resistance in addition to motor speed, and a permeability voltage constant. As for

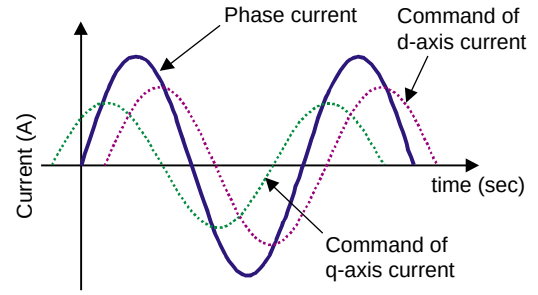


Fig. 3 Relationship between phase current and command current

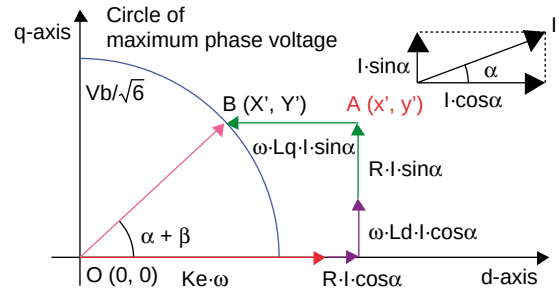


Fig. 4 Vector diagram drawn with measurement data

these values, because the values measured at normal temperatures are used in all driving states, they differ from the value at actual temperatures. In addition, things such as phase characteristics regarding motor speed of speed sensors for detecting pole locations, etc. can affect calculation accuracy. According to Equations (1) and (2), and Fig. 4, carrying out inductance calculations without considering resistance increase due to coil temperature increase gives values larger than the true values. Table 2 summarizes the factors and causes of these errors, and the methods for correcting them.

In preparatory tests prior to switching tests, no-load torque values, motor speed sensor, and magnetic pole location phase differences are obtained, and value corrections are made according to this advance information. Stator resistance correction is carried out according to actually measured coil temperature. Fig. 5 gives an example of analysis of inductance during switching and compares the results both with and without stator resistance temperature correction and no-load inductance. In this example, it is seen that there is a calculation error of about 3% due to

Table 2 Error factors and correction methods

Error factor	Cause	Correction
Torque value of no load	Torque meter hysteresis	Reference of hysteresis map
Phase difference between magnet and position sensor	Phase lag of position sensor	Reference of phase lag map
Stator resistance	Rise of stator resistance with coil temperature	Calculation of resistance

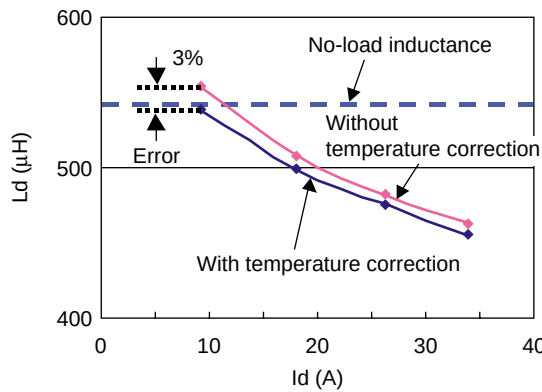


Fig. 5 Result of inductance analysis during switching

coil resistance increase. By correcting these, it is possible to make accurate calculations of motor inductance during switching that are not affected by changes in values due to such things as coil temperature fluctuations. It is also possible to make quantitative evaluations.

4. Creating the System

The following benefits are expected from the utilization of the system created from this analysis method.

- Centralized display of measured data, calculation results
- Automatic correction of measured data
- Real-time display of vector analysis

4.1 Centralized Display of Measured Data,

Calculation Results

At present, there are eight types of measurement devices used in motor performance testing, with approximately 120 items measured using these devices. Conventionally, as the collection of this data is carried out separately for each device, much effort was needed, and there is a concern with data synchronization. Now it is possible to obtain data from all of the devices, carry out the aforementioned vector analysis and efficiency calculations, and save the measured

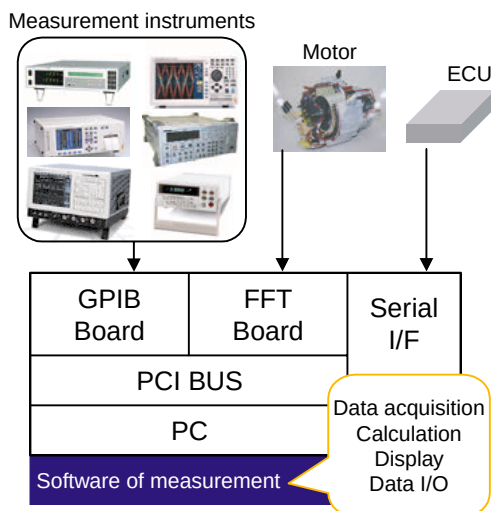


Fig. 6 Schematic diagram of measurement system

values and analysis values with a single action. Further, it is possible to display the information required on the measurement software screen by selecting the information from among all the measured data and calculation results. Through this, data synchronization between measurement devices is improved, and the test period is shortened.

4.2 Automatic Correction of Measured Data

The error factors given in Table 2 also affect inductance during switching at times other than during calculations. Accordingly, a system to correct these items was created, wherein the data that has been corrected is visible in real-time. Thanks to this, improvements in analysis accuracy were achieved for each measured value and loss separation, etc. Fig. 7 provides the data correction flow for the system.

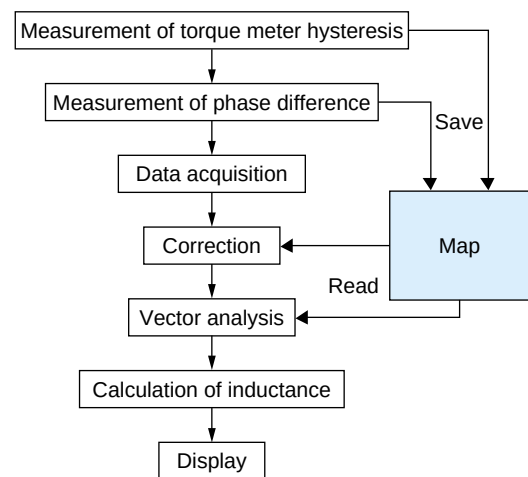


Fig. 7 Flowchart of correction process

4.3 Real-time Display of Vector Analysis

Conventionally, to understand the motor driving state during switching, complex processing, such as d-q conversion was required. Thus, in order to establish control parameters such as optimal switching amount, switching timing, etc., it was necessary to select various parameters from the test data after the test, which was quite time-consuming. By implementing the aforementioned vector analysis in real-time, and by displaying a circle diagram on the PC screen, it is now possible to make an immediate decision on optimum values. To carry out, vector analysis during switching in real-time, it is necessary to calculate motor speed pulse (magnetic pole location), phase voltage, phase current basic wave phase differences, and the root mean square. Also, with conventional measurement devices, concerns occurred with data synchronization, data processing and transmission speed. With this system, these concerns are resolved by fitting a multi-channel FFT board with an on-board DSP to a measurement PC's PCI bus. Fig. 8 shows the real-time vector analysis screens developed in this project. The left side of the screen is a circle diagram indicating the motor driving state, and the right side is a window providing a digital display of information relating

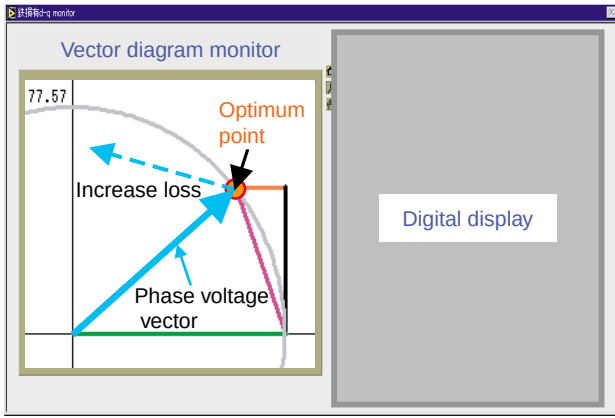


Fig. 8 Vector diagram monitor

to the state. On the circle diagram, the point where the tip of the phase voltage vector is the same as the circle of maximum phase voltage is the optimum driving state for maximum efficiency for a certain motor speed and output. In a driving state where the phase voltage vector shifts to the left of the optimum point, the weak field current is being excessively consumed, and motor efficiency suffers. In this way, it is possible to immediately judge optimum values for motor parameters with a given target motor speed and output by carrying out tests while monitoring the circle diagram. By systematizing this test flow and reducing the time spent in post-test data analysis, the test period is reduced by 30% (Fig. 9).

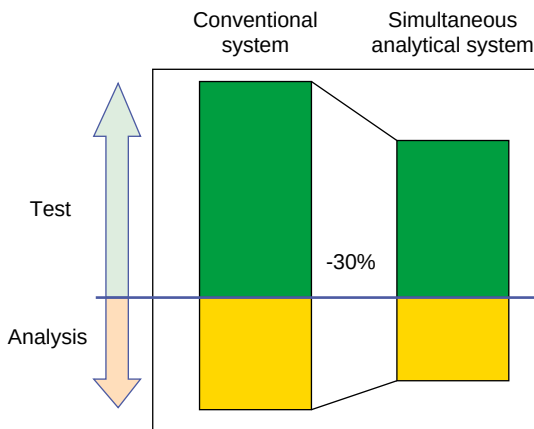


Fig. 9 Reduction of test time

5. Application Examples

5.1 Improved Torque Control Performance

In a motor for the hybrid electric vehicle (HEV) fitted to an Insight IMA, etc., high torque responsiveness is required in order to carry out engine vibration control. Fig. 10 shows a block diagram of an ordinary brushless DC motor⁽¹⁾. As shown in the diagram, in the magnetic circuit there is mutual interference between the d-axis and the q-axis, and a discrepancy occurs between the actual torque and the command value. In order to compensate for this phenomena, it is necessary to add to control various correction items using motor parameters such as L_d , L_q , and R . When doing this, if the inductance value is different

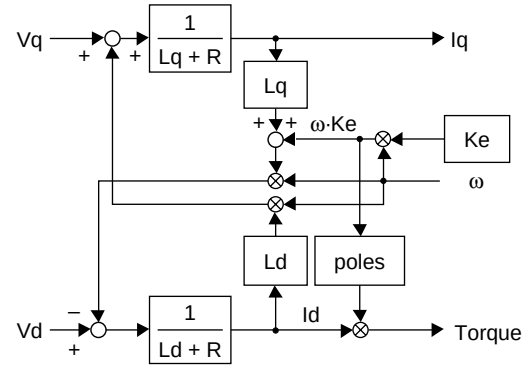


Fig. 10 Block diagram of brushless DC motor

from the true value, the mutual interference cannot be fully compensated for and torque responsiveness degrades. Fig. 11 gives an example of torque responsiveness when operating a brushless DC motor, using a vector control controller that has an added mutual interference correction control. As shown in the diagram, when the inductance is not the same as the inductance during actual motor switching, there is a response delay in vehicle speed changes; in comparison, when the inductance is the same, there is good responsiveness. Accordingly, by carrying out real-time vector analysis and using the measured inductance during switching as the motor control's internal constant, it is possible to enhance torque responsiveness.

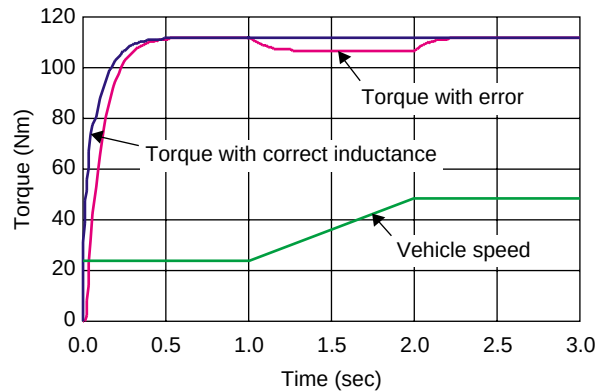


Fig. 11 Comparison result of torque response

5.2 Feedback into Motor Design

Fig. 12 takes the example of an ordinary brushless DC motor and shows the effect of inductance on motor performance. As shown in the diagram, if inductance is too small, the amount of weak field current needed to return the phase voltage vector to the circle of maximum phase voltage is large, and so efficiency drops. If inductance is too large, the voltage drop amount due to coil inductance exceeds the circle of maximum phase voltage so output is not possible in the high motor speed range. The motor inductance value is determined in close relationship with the permeable voltage constant and other magnetic circuits so it is not possible to freely choose this value. However, it

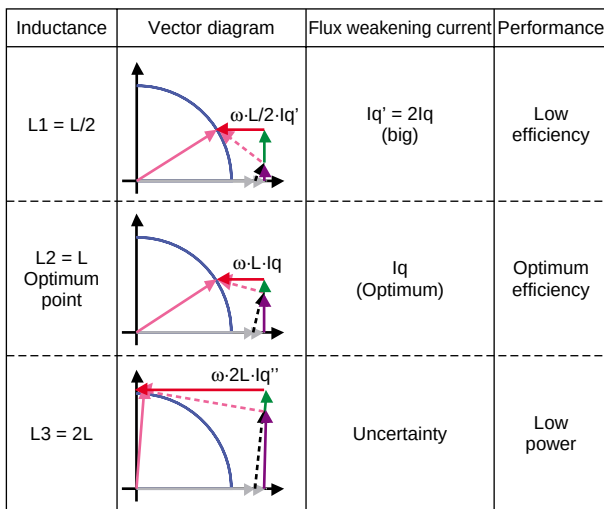


Fig. 12 Relationship between motor performance and inductance

is necessary to establish the optimum value, as it greatly affects motor maximum output and efficiency. By making it possible to accurately measure inductance during switching, which until now has not been quantitatively evaluated, inductance design targets at actual loads are now clear. This should contribute to the development of smaller and lighter motors. Also, it is possible to understand the situation of magnetic saturation in the magnetic circuits due to changes in inductance during switching according to load current (Fig. 13). Thanks to this, improvements to material selection can also be expected. In these ways, by making possible accurate measurements of inductance during switching, which has not been possible until now, optimum motor design is now possible.

Summary

By developing a system for immediate analysis of motor performance, the following are now possible.

- (1) It is now possible to carry out immediate analysis of motor inductance during switching, which could not be calculated until now.
- (2) It is now possible to obtain accurate measurements, thanks to the automatic test flow, which eliminates measurement errors.
- (3) Test manpower has been reduced by 30% thanks to creating a test flow system, automating data processing, etc.

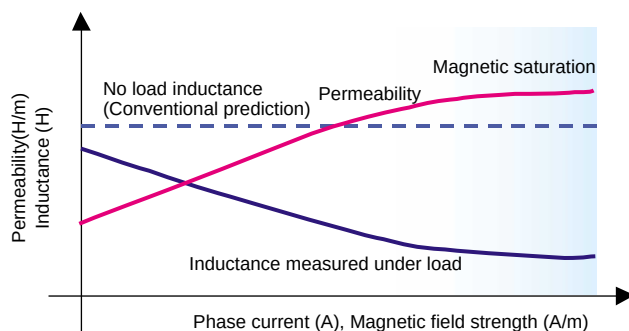


Fig. 13 Relationship between phase current and inductance

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