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Paper

Advanced Torque Control of Permanent Magnet Synchronous Motor Using Finite Element Analysis Based Motor Model with a Real-time Simulator

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This study proposes advanced torque control of permanent magnet synchronous motors (PMSMs) using a finite element analysis (FEA) based motor model with a real-time simulator. This model can simulate the behavior of an actual motor including nonlinear characteristics such as spatial harmonics and magnet saturations. Therefore, model-based control with an FEA based motor model is advantageous for motor control. This study aims to achieve advanced motor control and drive techniques. In this study, high performance torque control techniques for PMSMs are proposed. The proposed torque control is developed based on direct torque control with torque prediction. This method can achieve fast response and smooth torque production. Its effectiveness is verified through simulations and experiments.

Keywords: behavior motor model, direct torque control, permanent magnet synchronous motor control, real-time simulator

1. Introduction

Permanent Magnet Synchronous Motors (PMSMs) are widely used in many applications such as automotive applications and electrical appliances because they have some advantages such as high controllability, efficiency and power density. The adopted PMSMs for the many applications are required high torque performance that means torque smoothness (torque ripple less) and fast torque response.

In general, the shaft torque of PMSM is usually analyzed by the Fleming law defined in the rotor reference frame. In this frame, the shaft torque can be expressed by constant parameters and excited current. However, PMSM typically has nonlinear characteristics such as spatial harmonics and magnetic saturations. The spatial harmonics cause torque ripples and the magnetic saturations cause the error of the output torque to the reference. It is difficult to express actual output torque perfectly and it degrades the torque performance.

The strict torque model of PMSM has been reported to analysis the actual output torque and some torque ripples reduction techniques have been proposed by calculating optimal current reference to reduce torque ripples [(1)(2)]. However, they are usually developed with a current regulator. The torque response is limited by a bandwidth of the current regulator.

Direct Torque Control (DTC) is one of the technique to achieve fast torque response because this control method was developed without current regulator [(3)(4)]. The classical DTC consists of hysteresis comparator and switching table which is arranged according to switching pattern of the three phase inverter. The input voltage vector is decided by the deviation signal of output torque and stator linkage flux. Therefore, only one constant voltage vector is used during one control cycle. Because of this control algorithm, the torque ripples due to hysteresis control depend on DC link voltage and control period may become a problem in the DTC. For this problem, some torque control techniques have been proposed [(5)–(11)]. In (5)–(7), Model predictive control techniques are used in the DTC to predict future behavior of the motor to decide optimal voltage vector. In (8), constructing DTC with PI regulator to calculate voltage phase. The optimal voltage vector to achieve reference at one sample as a dead-beat control based on mathematical model [(9)]. In (10) (11), the duty cycle of input voltage vector is implemented into direct torque control to achieve optimal voltage vector. However, these techniques were developed based on a mathematical model of the motor without nonlinear characteristics. Therefore, torque ripples due to the spatial harmonics will be caused in the output torque. The high performance torque control that can achieve both smooth torque and fast response clearly has not been reported.

Meanwhile, the development of the neighboring technologies of the motor drive such as analysis and controller (calculation machine) should be focused. The Finite Element Analysis (FEA) is a power full method to develop the precise motor model. Adding that, a coupling analysis developed by FEA and circuit simulation can calculate and evaluate exactly behavior of the motor because this analysis technique can consider not only nonlinear characteristics of the motor but also influence of the control and drive conditions [(12)]. In general, an FEA implemented in the coupling analysis needs amount of time to calculate. It is undesirable for the development process of the motor and controller. In contrast, a fast operated motor model has been developed based on FEA [(13)]. Finally, the technique which couples an FEA based motor model and a real-time simulator is researched and used for Hard-ware In the Loop Simulation (HILS) and also used for

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Rapidly Prototype Controller (RPC) in new products development process [14][15].

By using this analyze techniques which is developed with FEA motor model and a real-time simulator, it can be definitely said that a motor control and drive for achieving control method has considering nonlinear characteristics can be developed.

From above discuss, this research aim to achieve high performance torque control of PMSM by using an FEA based motor model with a real-time simulator. Some control methods of the PMSM using this technique have been already proposed and the specification of FEA based motor model have been represented in our prior work [16].

We presented direct torque control using FEA based motor model to reduce torque ripple due to spatial harmonics [17]. However, this method will generate torque ripple by control logic defined as time harmonics. To achieve more high performance torque control method, we propose torque control which focus on the both torque ripple due to spatial harmonics and time harmonics. This proposed method calculates optimal voltage vector by using DTC logic and duty calculation method based on torque predicted technique by the FEA based motor model. Therefore, the proposed torque control method can achieve both smooth torque and fast response. In this paper, the control algorithm and the effectiveness of this technique is evaluated by some simulations and experiments.

2. PMSM Drive System using a Real-time Simulator with an FEA Based Motor Model

In this section, the PMSM drive system using a real-time simulator with an FEA based motor model is described. Figure 1 shows the image of PMSM drive system using an FEA based motor model with a real-time simulator. This system is a unique point of this research. By using FEA based motor model, the nonlinear characteristics of PMSM are clearly considered in the control algorithm. The control algorithm is developed based on a coupling analysis which is constructed a circuit simulator and the FEA based motor model. The coupling analysis is operated in the real-time simulator implemented as motor drive controller. This development process includes following three steps.

2.1 FEA Based Motor Model As the first step, the motor model possessing nonlinear characteristics of the PMSM are developed based on a finite element analysis. This accurate motor model is called “FEA based motor model” in this paper. The FEA based motor model has 3-D table data about inductance, magnetic flux and torque with the dependence of excited current and rotor position. These motor parameters can take into account of the nonlinear characteristics. Spatial harmonics and magnetic saturation can be considered by dependence of rotor position and the dependence of the current respectively. The behaviors of the PMSM are expressed by some equations with motor parameters obtained 3-D table and/or directly obtained from 3-D table.

In this research, acquisition, interpolation and construction of motor parameters are automatically implemented by JMAG-RT provided by JSOL Corporation.

2.2 Coupling Circuit As the second step, the coupling analysis is developed by combination between a circuit simulator with the FEA based motor model. This coupling

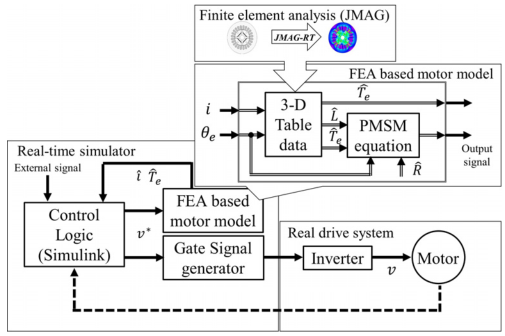


Fig. 1. The image of PMSM drive system using a real-time simulator with an FEA based motor model

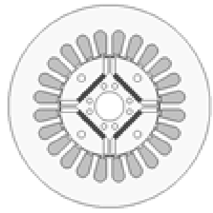


Fig. 2. Tested motor model

Table 1. Specification of test motor model

Output power	1.0kw
Maximum voltage	165V
Rated current	3Arms
Rated torque (3Arms)	1.8Nm
Number of pole	2
Number of slot	24

analysis is implemented in drive system as a control algorithm.

In the coupling analysis, the nonlinear characteristics of all motor drive system can be considered in the simulation. The nonlinear characteristics of motor are analyzed by the FEA based motor model and also effects of control algorithm are analyzed. This rigorous analysis technique gives advanced control algorithm on the simulation.

In this research, MATLAB/Simulink provided by The MathWorks, Inc. is used for the coupling analysis.

2.3 Real-time Simulator As the final step, the coupling circuit is installed and operated in a real-time simulator. The real-time simulator can calculates one coupling analysis cycle less than 100 μsec. And also, the real-time simulator has rapid A/D and D/A unit. It is able to use external signals (measured signals by sensors) in the coupling analysis. By using the real-time simulator as the controller of drive system, the coupling circuit and real motor drives can be operated simultaneously.

2.4 Model-based Control using FEA Based Motor Model A model based control based on the FEA based motor model yields high performance control technique which enables to directly approach for the nonlinear characteristics. It can analysis some behavior of actual motor in the real-time simulation. It takes an advantage that the behavior of the actual motor can be estimated and correctly predicted.

In this paper, the authors conducted developing control method by using 1 kw PMSM. Figure 2 shows model of a tested motor and Table 1 shows specification of the tested

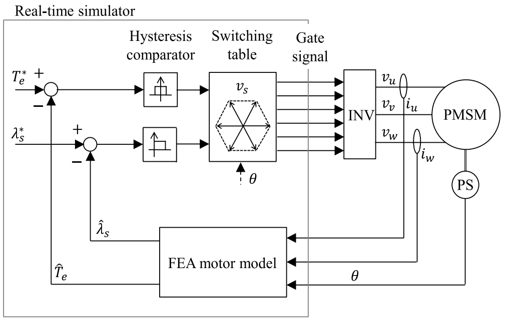


Fig. 3. The block diagram of direct torque control using FEA based motor model (17)

motor. The FEA based motor model is cnstructed based on shown motor specs in Table 1.

3. Direct Torque Control using FEA Based Motor Model (Proposed DTC) (17)

In this section, direct torque control constructed with FEA based motor model which has been proposed by authors and subjects of this method are described. Figure 3 shows the block diagram of this method. This method approaches to reduce the torque ripple due to spatial harmonics by using FEA based motor model used as an instantaneous torque estimator.

3.1 Torque Ripple Due to Spatial Harmonics in the Classical DTC In DTC presented in literatures (3)(4), the stator flux linkage on stationary reference frame is defuned by following equations:

$$\lambda_\alpha = \int (v_\alpha - Ri_\alpha)dt + \lambda_{0\alpha|t=0} \quad (1)$$

$$\lambda_\beta = \int (v_\beta - Ri_\beta)dt + \lambda_{0\beta|t=0} \quad (2)$$

$$\lambda_s = \sqrt{\lambda_\alpha^2 + \lambda_\beta^2} \quad (3)$$

where, λ_α, λ_β, i_α, i_β, v_α, v_β, $\lambda_{0\alpha|t=0}$, $\lambda_{0\beta|t=0}$, and λ_s, are the α-phase flux linkage, β-phase flux linkage, α-phase current, β-phase current, α-phase voltage, β-phase voltage, α-phase initial flux linkage due to rotor magnet, β-phase initial flux linkage due to rotor magnet and stator flux linkage, respectively. In this equation, the estimation error is caused by modeling error of the armature winding resistance due to the temperature variation.

The torque estimator is designed by the Fleming law as follows:

$$T_e = P(\lambda_\alpha i_\beta - \lambda_\beta i_\alpha) \quad (4)$$

where, T_e and P are the shaft torque and number of pole pairs, respectively. In this equation, the spatial harmonics are not included and pulsation torque cannot be perfectly estimated because the equation does not follow the torque ripple due to spatial harmonics component and cogging torque.Therefore, the torque ripple due to spatial harmonics will applier in output torque.

3.2 Direct Torque Control using FEA Based Motor Model (Proposed DTC) Proposed DTC (17) uses the FEA based motor model as estimator to observe torque ripples based on excited current obtained by the current sensor. Moreover, estimated instantaneous torque includes torque ripple is feed backed to DTC logic. Therefore, the DTC logic will work for torque ripple reduction.

This method can reduce torque ripple due spatial harmonics. However, input voltage is calculated as constant vector during one sampling. Therefore, the torque ripples depend on sampling period and DC link voltage will be generated.

4. Proposed High Performance Torque Control

In this section, a proposed high performance torque control is described. In the proposed method, the key point of the model based control technique that can accuracy estimate and predict is used. The output torque can be calculated by the FEA based motor model with input voltage signal. The optimal voltage amplitude is obtained based on this predicted torque to achieve the both torque ripples depend on spatial harmonics and hysteresis control algorithm. And also, quick torque response is realized based on direct torque control method like a dead-beat torque control.

Figure 4 shows the block diagram of a proposed torque control method. The proposed method consists of various sections: DTC logic part that may works to obtain the voltage vector of three phase inverter according to increasing or decreasing of output at next sampling, duty calculation with torque prediction part that calculate optimal voltage vector to achieve torque reference at next sample, torque and stator linkage flux estimation part and rotor position calculation part.

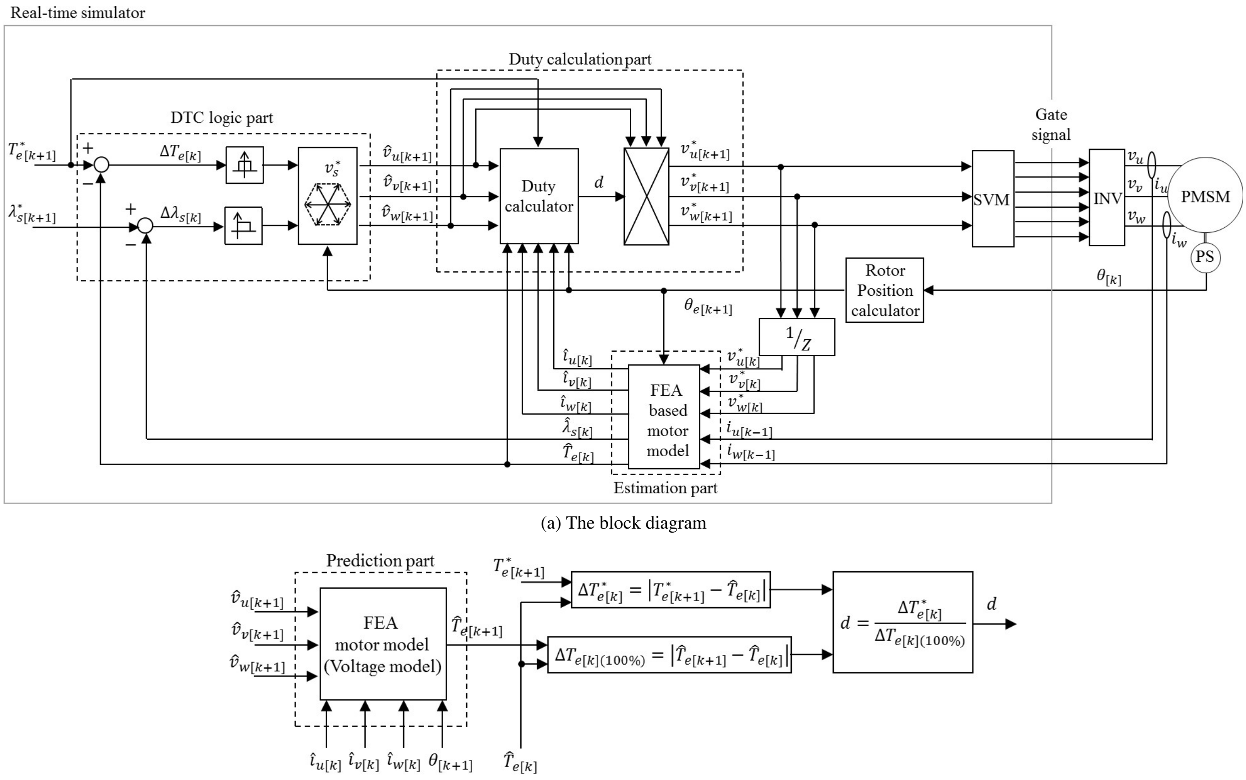
4.1 Output Estimation and Prediction Some output signal of the actual motor can be estimated and predicted by real-time simulating with the FEA based motor model. Estimation or prediction is distinguished according to input signal. An excited current is calculated by differential equation of current with some motor parameters obtained from FEA, input voltage and sampling time. In addition, the output torque and stator linkage flux can be obtained by FEA according to the estimated or predicted current.

The Excited current is expressed as follow:

$$[\hat{\imath}_{uvw\_FEA[n]}] = [i_{uvw[n]}] + \frac{\{[v_{uvw[n]}] - R[i_{uvw[n]}]\}T_s + [\Delta\hat{\Psi}_{uvw\_FEA[n]}] - [\Delta\hat{L}_{\_FEA[n]}][i_{uvw[n]}]}{[\hat{L}_{\_FEA[n]}]} \quad (5)$$

where, $\hat{\imath}_{uvw\_FEA[n]}$, $i_{uvw[n]}$, $v_{uvw[n]}$, R, T_s, $\hat{\Psi}_{uvw\_FEA[n]}$, and $\hat{L}_{\_FEA[n]}$ are calculated current by FEA based motor model, input current signal, input voltage signal, stator resistance, sampling time, magnetic linkage flux by FEA, and inductance by FEA, respectively. In addition, the symbol Δ means the deviation between one sampling. For the estimation of instantaneous excited current: $\hat{\imath}_{uvw\_FEA[k]}$, $i_{uvw[n]}$ and $v_{uvw[n]}$ should be set at measured current by sensors: $i_{uvw[k-1]}$ and voltage reference: $v^*_{uvw[k]}$, respectively. For the prediction of excited current: $\hat{\imath}_{uvw\_FEA[k+1]}$, $i_{uvw[n]}$ and $v_{uvw[n]}$ should be set at estimated current by FEA based motor model: $\hat{\imath}_{uvw\_FEA[k]}$, and voltage reference: $\hat{\imath}_{uvw\_FEA[k+1]}$, respectively.

4.2 Duty Calculation In the case of giving voltage vector obtained from DTC logic during one sampling, it can be considered as that duty ratio is 100 percent (Predicted maximum torque). In the proposed torque control method, the voltage amplitude (duty ratio) can be calculated based on



(a) The block diagram

(b) Duty calculation part

Fig. 4. The block diagram of the proposed torque control method

predicted maximum torque.

The necessary amount of change to achieve the desired output torque is expressed by output torque reference and instantaneous estimated torque as follow:

$$\Delta T^*_{e[n]} = |T^*_{e[n]} - \hat{T}_{e[n]}| \cdots\cdots (6)$$

where, $\Delta T^*_{e[n]}$, $T^*_{e[n]}$ and $\hat{T}_{e[n]}$ are the required deviation amount of torque, torque reference and estimated torque, respectively.

The deviation between maximum duty torque and torque reference is expressed as follow:

$$\Delta T_{e(100\%)[n]} = |\hat{T}_{e(100\%)[n]} - \hat{T}_{e[n]}| \cdots\cdots (7)$$

where, $\Delta T_{e(100\%)[n]}$ and $\hat{T}_{e(100\%)[n]}$ are amount of change of torque and predicted torque by FEA based motor model when duty ratio is 100 percent (maximum torque), respectively. The amount of change of the torque: $\Delta T_{e(100\%)[n]}$ means torque ripple due to hysteresis control logic.

The optimal duty ratio is calculated based on ratio of the between (6) and (7) as follow:

$$d = \frac{\Delta T^*_{e[n]}}{\Delta T_{e(100\%)[n]}} \cdots\cdots (8)$$

where, d is duty ratio.

This calculation method is using the assumption that the relationship between input voltage vector and output torque is linear characteristics. In fact, there are nonlinear relationships depend on magnetic saturation. However, the effects of relationship is very small.

The voltage reference can be expressed as follow:

$$v^*{}_{uvw[n]} = d \cdot v^*{}_{uvw\_DTC[n]} \cdots\cdots (9)$$

where, $v^*_{uvw\_DTC[n]}$ is voltage vector obtained by DTC logic. The actual voltage inputted to an actual motor is given by voltage source three phase inverter with space vector modulation (SVM).

4.3 Rotor Position Calculator In proposed method, the future torque is predicted includes spatial harmonics. It means the position information is important to consider spatial harmonics.

If the variation of motor speed is very small during one sample, the rotor position at next sample can be calculated using present position information and deviation between the sample.

The deviation between the sample is defined as follow:

$$\Delta\theta_{e[k]} = \theta_{e[k]} - \theta_{e[k-1]} \cdots\cdots (10)$$

where, $\Delta\theta_e$ and θ_e are the deviation between the sample about rotor position and rotor position in electrical angle, respectively.

Rotor position at next sample is defined as follow:

$$\theta_{e[k+1]} = \theta_{e[k]} + \Delta\theta_{e[k]} \cdots\cdots (11)$$

5. Simulation Results

In this section, some simulation results include comparison between classical DTC, proposed DTC [17] and proposed torque control method are described. Evaluation items are torque ripples in the steady state, torque dynamics in the transient term and the effects of the DC link voltage in the proposed torque control method. The obtained torque from simulation is calculated MATLAB/Simulink with FEA based motor model. Therefore, the simulation torque equal to analysis results of FEA. The authors considered the validity of

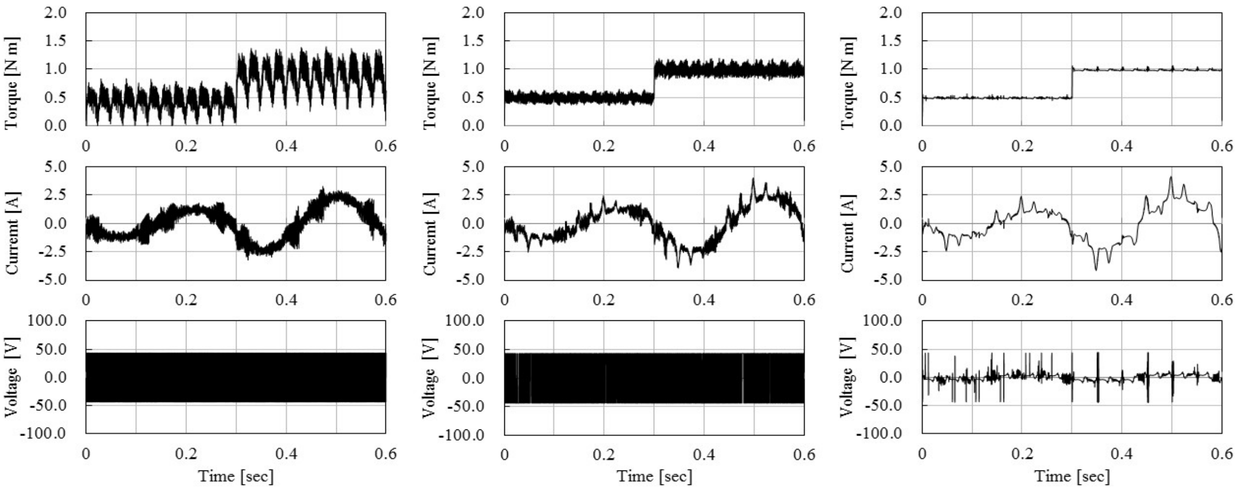


Fig. 5. Simulation results (Output torque, Excited current, Input voltage). (Simulation condition, motor speed: 100 min-1, DC link voltage: 75 V, Control period: 100 μsec

this simulation is high. And resolution of FEA based motor model is already verified that enough to analyze torque ripple of the tested motor in FEA base motor model development process.

5.1 Torque Ripple in the Steady State Figure 5 shows output torque, excited current and input voltage in the steady state. These simulation results of steady state obtained by the coupling analysis developed by MATLAB/Simulink and JMAG-RT to observe torque ripple due to spatial harmonics. In the classical DTC, the output torque pulsation is caused due to the spatial harmonics and hysteresis control logic. In the proposed DTC [17], torque ripples in the output torque is reduced. However, the torque ripples due to hysteresis control logic is caused. In the proposed method, the smooth torque is achieved because the torque ripple due to spatial harmonics is considered by the FEA based motor model and torque ripple due to a hysteresis controller is reduced by the duty calculation method. The excited U-phase current of the classical DTC is sinusoidal with some sharp pulse because this control method works considering only fundamental component according to estimated torque based on the Fleming law. And also, the sharp pulse is generated by the hysteresis controller. In the proposed DTC [17], the excited is pulsation which is effective for reduction torque ripple due to spatial harmonics. Meanwhile, in the proposed torque control method, the excited U-phase current is pulsation like as the current of the FEA based DTC. In addition, the sharp pulse current is not appeared in proposed method compared with the FEA based DTC.

The input U-phase voltage of the classical DTC and proposed DTC [17] is two levels depend on DC link voltage because this method is working based on hysteresis control. Gate signal for each switch is turned on during one sampling. However, the input U-phase voltage of the proposed torque control method is variable. In the proposed method, voltage reference is calculated by the duty ratio. From this result, the input voltage has pulsation which is working for torque ripple reduction.

5.2 Step Response Figure 6 shows the torque step response of the classical DTC, FEA the proposed torque control method and torque control with current regulator. Those simulation results of step response obtained by simulation by MATLAB/Simulink with mathematical motor model expressed by (4) to eliminate torque ripple due to spatial harmonics. And the torque control developed with current feedback control is implemented to compare the torque dynamics performance. The proposed DTC [17] is not mentioned in this graph because torque dynamics is same with the classical DTC. The torque dynamics of the classical DTC and the proposed torque control are same and faster than torque dynamics of torque control with current regulator.

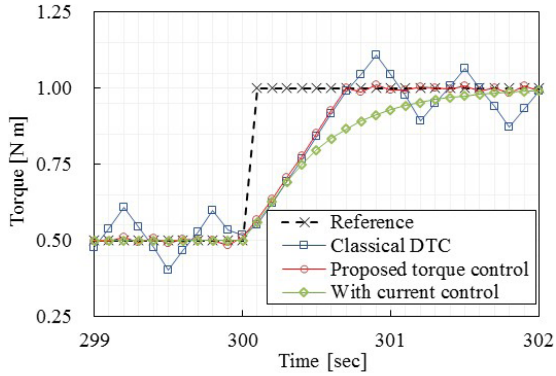
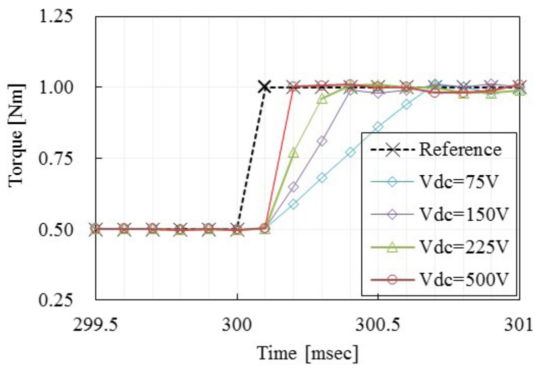


Fig. 6. Simulation results of torque dynamics

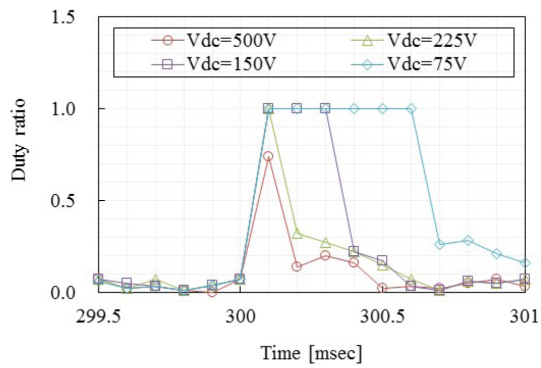
Table 2. Specification of the torque meter

	Magtrol 306TM
Band width	5kHz
Rated torque	5Nm
Maximum speed	20000rpm

5.3 Characteristics of Proposed Method Figure 7 shows torque dynamics according to DC link voltage in the proposed torque control method. In the case of the DC link voltage is enough, the output torque tracks the commanded torque in a single step (dead beat) when the DC link voltage is 500 V. The duty ratio is calculated as not maximum,



(a) Output torque



(b) Duty ratio

Fig. 7. Response characteristics depend on DC link voltage of proposed torque control (Simulation condition, motor speed: 100 min^{-1}, DC link voltage: 75 V, Control period: 100 μsec)

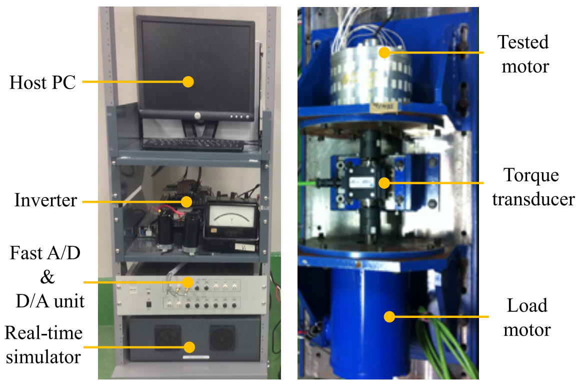


Fig. 8. Experimental setup

it means the duty calculation method works well to achieve good tracking performance. In the case of under the voltage saturation, the proposed torque control method utilizes the maximum duty ratio until own output torque tracks the reference value to achieve fast torque response.

From these results, the proposed torque control method which consists of DTC logic, duty calculation and instantaneous output estimation and prediction can achieve the both torque ripples reduction due to spatial harmonics and hysteresis control and fast torque response.

6. Experimental Results

In this section, some experimental results include comparison between the classical DTC, proposed DTC [17] and the proposed torque control method are described. Figure 8 shows experimental setup and table II shows the specification of torque meter which is used for observing torque waveform including the torque ripple in the steady state to verify the accuracy of the proposed method. The test motor is rotated at constant speed by a servo motor system. The real-time simulator and three phase voltage source inverter are implemented as controller and as a drive circuit, respectively. In addition, the FEA based motor model and actual motor are synchronized each other by detecting the rotor position.

The obtained torque by experiment is estimated value from FEA by using actual current measured by current sensors because the servo motor using this experiment is PMSM which have own torque ripple. Understandably, this torque ripple affects measured torque by torque meter. To eliminate this effects, the authors calculated output torque of tested motor by using FEA and actual current.

The performance of the proposed control method and drive system is required high resolution for FEA based motor model and position sensor because special harmonics has dependence of the rotor position. However, high resolution of FEA based motor model means large amount of date is needed. And this large data requires calculation time and it may makes instability of drive system. Therefore. The authors consider the resolution of FEA based motor model and rotational speed in experiment. The position sensor using this paper has 1024 pulse/res spec. And also, it is enough to consider the torque ripple of this motor in conducted motor speed. So, the authors conducted experiment by low speed to eliminate the effects of position sensor and resolution of FEA based motor model.

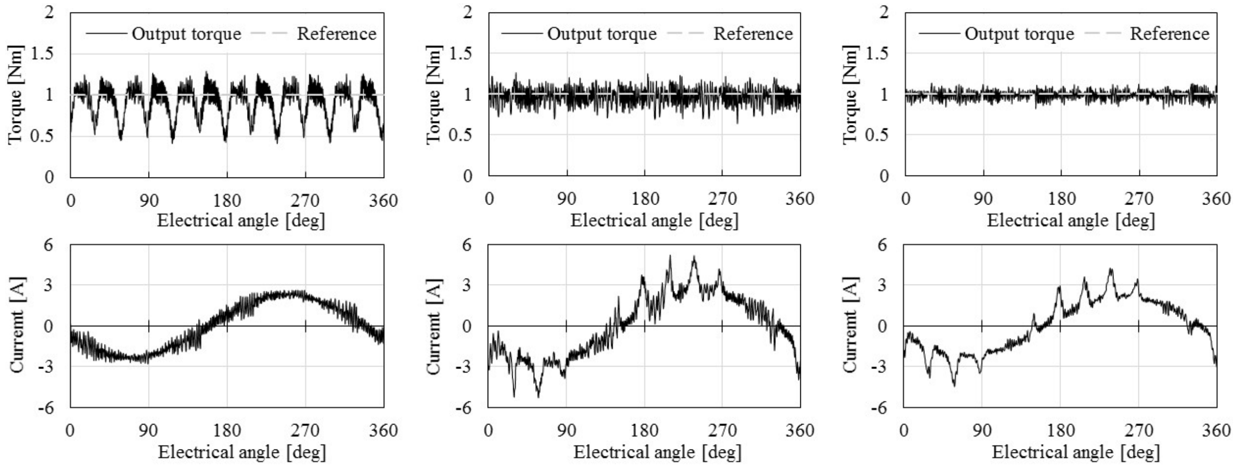
Figure 9 shows the output torque and excited U-phase current in the steady state. In the proposed torque control method, the torque ripples are reduced compared with the classical DTC and proposed DTC [17]. In addition, the excited U-phase current is pulsated due to the spatial harmonics. And also, the high frequency ripple of current is reduced.

Figure 10 shows FFT spectrum of the output torque and excited U-phase current. The main component of the torque ripples due to spatial harmonics (12^{th} and 24^{th}) is reduced. And the spatial harmonics ($5^{th}+7^{th}$ and $11^{th}+13^{th}$) that make main spatial harmonics in the rotor reference frame (6^{th} and 12^{th}) are reduced.

Figure 11 shows a step response of these control methods. The proposed method can achieve fast torque response than torque control with current regulator.

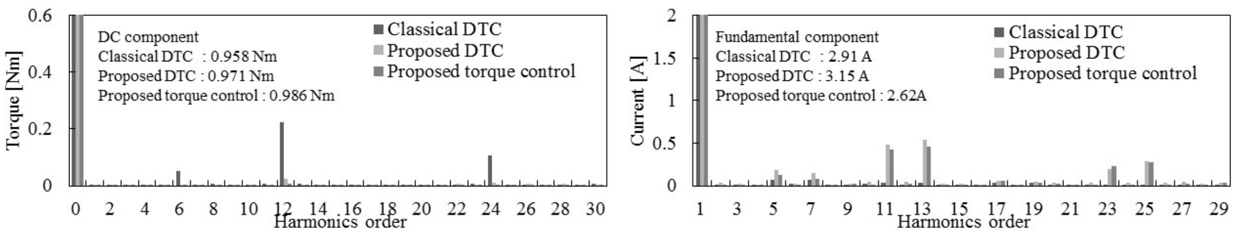
7. Conclusion

This research aimed to achieve the high performance control and drive of the PMSM by using a real-time simulator with the FEA based motor model. In this paper, the high performance torque control method developed based on duty calculation with output estimation and prediction by the FEA based motor model has been proposed as one of the high performance control method of PMSM. The proposed torque control method can achieve both smooth torque and fast torque response. The effectiveness of the proposed torque control method was verified by some simulations and experiment.



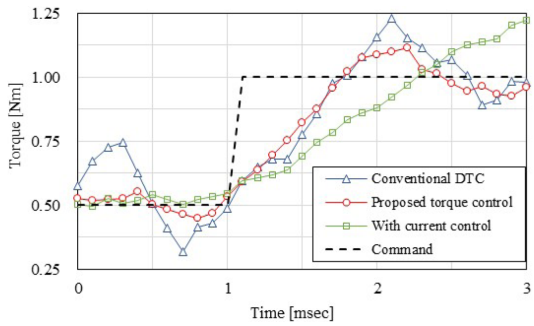
(a) Classical DTC (b) Proposed DTC [17] (c) Proposed torque control method

Fig. 9. Experimental results (Output torque, Excited current, Input voltage) in steady state. (Experiment condition, motor speed: 100 min^{-1}, DC link voltage: 75 V, Control period: 100 μsec)

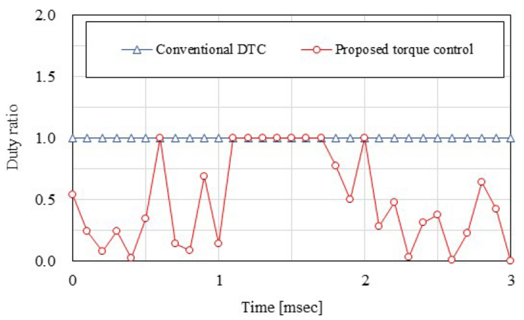


(a) Output torque (b) Excited current

Fig. 10. FFT spectrums



(a) Output torque



(b) Duty ratio

Fig. 11. Experimental results of transient term. (Experiment condition, motor speed: 100 min^{-1}, DC link voltage: 75 V, Control period: 100 μsec)

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