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Switching Pattern-Independent Simulation Model for Brushless DC Motors

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Abstract

In order to verify the performance of brushless DC (BLDC) motors, the simulation method has been widely used. The current of a BLDC motors flows on two phase windings to obtain a constant torque. However, the freewheeling current caused by the inductance component of a BLDC motor exists at the commutation point so that the current can flow on three phase windings at the same time. Due to the changes of the excited phases, the model equations are frequently changed during BLDC motor drive operation. The model equations can be also changed by the applied switching pattern since the current path in the inverter circuit changes according to switching pattern. A BLDC motor system can utilize various switching patterns for many different purposes. However, such changes of the model equations complicate the simulation procedure. In this paper, the technique to set up model equations is proposed to ease the simulation of a BLDC motor system through an inverter circuit analysis. The proposed technique will be verified using the C language. Although this method does not provide the level of detail obtainable from commercial simulation tools like PSIM or SIMULINK, it can provide an efficient way to quickly compare various conditions.

Key Words: Brushless DC motor, Model equation, Simulation

I. Introduction

BLDC motors have become a popular choice in many applications due to ease of control, low system cost and good torque control performance. They also have high power density and are capable of highly efficient operation since the main flux is produced by permanent magnets. Therefore, the study of BLDC motors has been a topic of interest for many researchers [1], [2].

The simulation of a motor drive system is a necessary process for the evaluation of motor system since it is inefficient to verify motor performance under various conditions using the experimental method. A motor drive system is generally driven by voltage source inverter, so that both the inverter and the motor are considered in a motor system simulation. A circuit analysis of the inverter is also a major part of the simulation of a BLDC motor system. The current path of a BLDC motor is changed by six conduction intervals and the switching pattern of the inverter, so that the model of a BLDC motor has to be reconfigured to reflect the change in current path. Due to such complex set-up processes, the model of a BLDC motor tends to be fixed to one switching pattern in most of the existing papers [3]–[6]. In this paper, a self-adapting technique is proposed which sets up the model equations in a way that takes the changes made by the applied switching patterns into consideration. The proposed technique allows setting the model equations utilizing the motor system information. It will be presented in detail in the following sections and verification will be made by comparing the results with the data obtained from a commercial simulation tool.

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II. Model of BLDC Motor

The model equations of a BLDC motor are composed of a voltage equation, a torque equation and a motion equation. The stator of a general BLDC motor has three windings like an induction motor or a permanent magnet synchronous motor. The voltage equations of the three windings are:

$$v_i = Ri_i + (L-M)\frac{d}{dt}i_i + e_i + v_m\,,\ i = a,b,c \tag{1}$$

where v_i and e_i are the voltage of the motor terminal and the back-emf voltage, L and M are the stator self and the mutual inductances and v_m is the neutral voltage of the motor. The torque equation of a BLDC motor is:

$$\tau_d = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_r} = k_t(\lambda_a i_a + \lambda_b i_b + \lambda_c i_c) \tag{2}$$

where τ_d is the developed torque of the motor, ω_r is the rotor speed, k_t is the torque constant and λ_i is the flux linkage. The motion equation is:

$$\tau_d = J\frac{d\omega_r}{dt} + B\omega_r + \tau_l \tag{3}$$

where J is the inertia, B is the damping ratio and τ_l is the load torque.

III. Analysis of BLDC Motor Operation

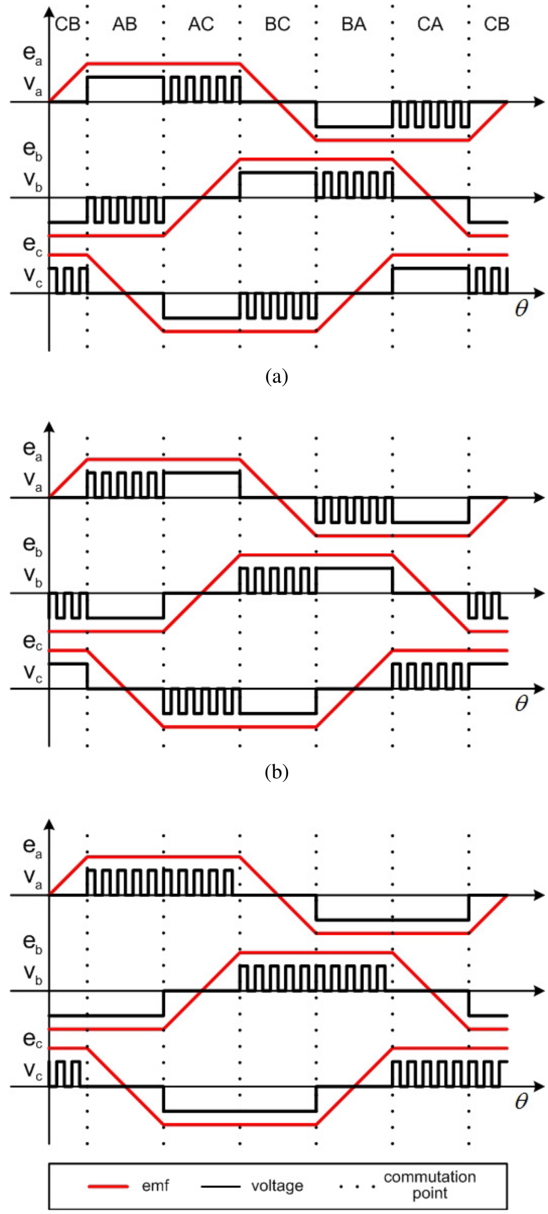
The first step of a BLDC motor operation simulation is to set up the model equations of the system. The torque equation and the motion equation do not change, but the voltage equation can change since the current paths in the inverter vary according to the current commutation, the applied switching pattern and on/off states of the switch.

The phase current of an ideal BLDC motor is controlled to flow in the flat section (120 electrical degrees) of a trapezoidal shape back-emf voltage, which results in a current flow on two phase windings among the three existing phase windings. When the phase current flows on only two phase windings, two voltage equations are needed to simulate the BLDC motor operation. Two excited phases are changed six times in every electrical cycle as shown in Fig. 1 so that two voltage equations have to be changed in every conduction interval. However, a freewheeling current caused by the system inductance can exist in a real system. Three phase windings can be excited for a short moment until the freewheeling current disappears. In the commutation interval, three voltage equations are needed to analyze the BLDC motor. Such a commutation interval appears six times at each commutation point so that the voltage equations also have to be changed in every commutation interval.

In addition to the influence of the commutation, the applied switching pattern and the on/off states of the switch have to be considered to set up the voltage equations. The current paths of the inverter during the AB conduction intervals when the switching pattern of Fig. 1(a) is applied are presented in Fig. 2. The switches and diodes of the inverter are designated by S1∼S6 and D1∼D6 as shown in Fig 2. $s_1 \sim s_6$ and $d_1 \sim d_6$ are the switching functions of the switches and diodes. A switching function is 1 when a device is conducting and 0 otherwise. During the AB conduction interval in Fig. 1(a), the upper switch of the phase A (S1) is always on and the lower switch of the phase B (S6) changes quickly between on and off. In the front part of the AB conduction interval, the freewheeling current flows on the diode of phase C (D2). The current paths of this moment are shown in Fig. 2(a) and (b). In the normal AB conduction interval, the current paths are shown in Fig. 2(c) and (d). Fig. 2(e) is the current path when the terminal voltage of phase C (which is the sum of the back-emf voltage and the motor neutral voltage since the phase current of phase C is zero) is larger than the dc link capacitor voltage. A case like Fig. 2(e) can appear in the high speed range. The voltage equations in Fig. 2 can be summarized as follows:

- In Fig. 2(a) and (b): (4)

$$V_{dc} = Ri_a + (L-M)\frac{d}{dt}i_a + e_a + v_m$$
$$(1-s_6)V_{dc} = Ri_b + (L-M)\frac{d}{dt}i_b + e_b + v_m$$
$$0 = Ri_c + (L-M)\frac{d}{dt}i_c + e_c + v_m$$
$$v_m = \frac{(2-s_6)V_{dc} - e_a - e_b - e_c}{3}$$



(a) (b) (c)

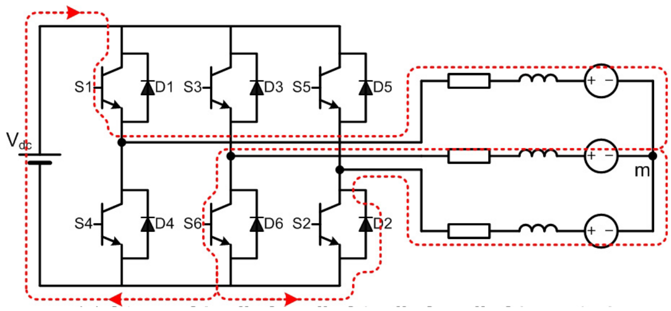
Fig. 1. Variable switching patterns.

- In Fig. 2(c) and (d): (5)

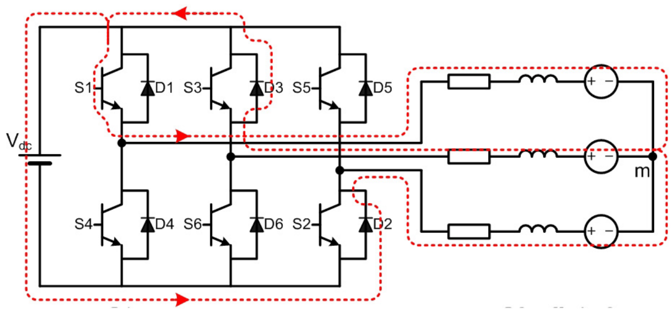
$$V_{dc} = Ri_a + (L-M)\frac{d}{dt}i_a + e_a + v_m$$
$$(1-s_6)V_{dc} = Ri_b + (L-M)\frac{d}{dt}i_b + e_b + v_m$$
$$v_m = \frac{(2-s_6)V_{dc} - e_a - e_b}{2}$$

- In Fig. 2(e): (6)

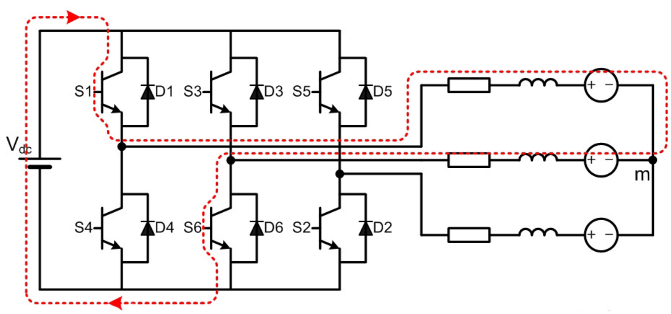
$$V_{dc} = Ri_a + (L-M)\frac{d}{dt}i_a + e_a + v_m$$
$$V_{dc} = Ri_b + (L-M)\frac{d}{dt}i_b + e_b + v_m$$
$$V_{dc} = Ri_c + (L-M)\frac{d}{dt}i_c + e_c + v_m$$
$$v_m = \frac{3V_{dc} - e_a - e_b - e_c}{3}$$



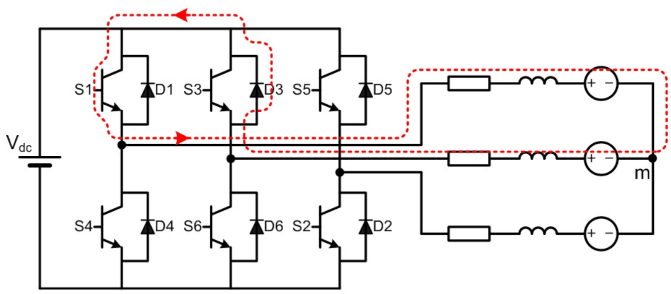
(a) S1:on, S2:off, S3:off, S4:off, S5:off, S6:on, $i_c > 0$.



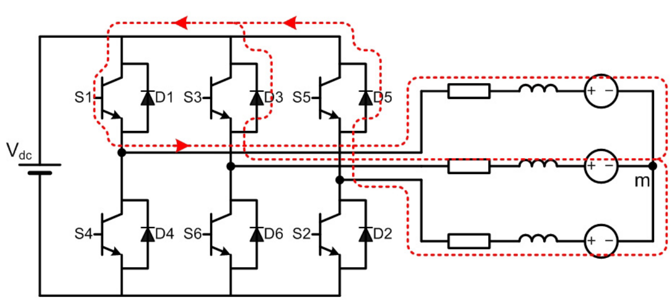
(b) S1:on, S2:off, S3:off, S4:off, S5:off, S6:off, $i_c > 0$.



(c) S1:on, S2:off, S3:off, S4:off, S5:off, S6:on, $i_c = 0$.



(d) S1:on, S2:off, S3:off, S4:off, S5:off, S6:off, $i_c = 0$.



(e) S1:on, S2:off, S3:off, S4:off, S5:off, S6:off, $e_c + V_m > V_{dc}$, $i_c < 0$.

Fig. 2. Current paths during AB conduction interval.

The neutral voltage of the motor is calculated from the sum of all the voltage equations. The change of the current path shown in Fig. 2, occurs six times in every electrical cycle, and the voltage equations of the BLDC motor have to be set up again when the current path is changed. Such a set-up task is also repeated, if another switching pattern is applied. Therefore, applying a variable switching pattern in a BLDC motor simulation is very troublesome.

IV. Techniques for Setting up Voltage Equations

In voltage equations, the resistance and inductance are constants, the phase current is a known value, and the back-emf voltage is a given value from the rotor position and speed. Therefore, the terminal voltage and the neutral voltage are determined to set up voltage equations.

Fig. 3 is the set-up process for voltage equations. The first step is to distinguish the on/off states of the freewheeling diode to determine what phases are excited. A terminal of the motor winding is connected to an inverter leg, and the phase current necessarily flows to one out of four parts, which are two switches and two freewheeling diodes. As an example, for phase A, the four parts are S1, S4, D1 and D4. The on/off states of the two switches are decided from the applied switching pattern such as the one in Fig. 1 for example. The two diodes of the inverter leg can conduct the phase current when both switches of the same inverter leg are off. The on/off states of the freewheeling diode are determined by the external conditions of the diode. One of these conditions is the voltage between the anode and the cathode, and the other is the direction of the phase current. The process for obtaining the on/off state of diodes is expressed as Boolean expression. The *if* function is not a general mathematical function, but it is used in the following equation to provide a concise expression. The condition for phase A is summarized as follows:

- For phase A: (7)

$$\begin{aligned}
&if\,((s_1=0)\wedge(s_4=0))\\
&\{\\
&\quad if\,((i_a<0)\vee(e_a+v_m>V_{dc}+v_F))\\
&\qquad d_1=1,\ d_4=0\\
&\quad else\ if\,((i_a>0)\vee(e_a+v_m+v_F<0))\\
&\qquad d_1=0,\ d_4=1\\
&\}\\
&else\ d_1=0,\ d_4=0
\end{aligned}$$

v_F is the forward voltage drop of the diode. If any switch or diode of an inverter leg is on, the corresponding phase is excited. The variable used to distinguish an excited phase can be summarized as follows:

$$\begin{aligned}
PhaseA &= s_1 \vee s_4 \vee d_1 \vee d_4\\
PhaseB &= s_3 \vee s_6 \vee d_3 \vee d_6\\
PhaseC &= s_5 \vee s_2 \vee d_5 \vee d_2
\end{aligned} \tag{8}$$

The variable *PhaseA* is 1 when phase A is excited, and 0 when phase A is open. From these variables, we can determine

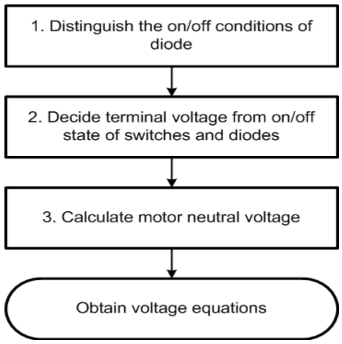


Fig. 3. Set-up process of voltage equatons.

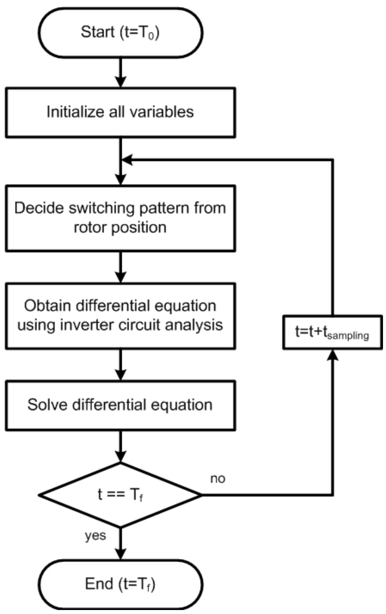


Fig. 4. Flowchart of simulation procedure.

which phases are excited. Then, the terminal voltage can be obtained from the on/off states of the switches and diodes, and it is summarized as follows:

- For phase A: (9)

$$
\begin{aligned}
& if(PhaseA = 1) \\
& \{ \\
& \quad if((s_1 \vee d_1) = 1)\ v_a = V_{dc} \\
& \quad else\ v_a = 0 \\
& \} \\
& else\ if(PhaseA = 0)\ v_a = e_a + v_m
\end{aligned}
$$

Finally, the neutral voltage can be easily calculated since the excited phases are known from *PhaseA*, *PhaseB* and *PhaseC*

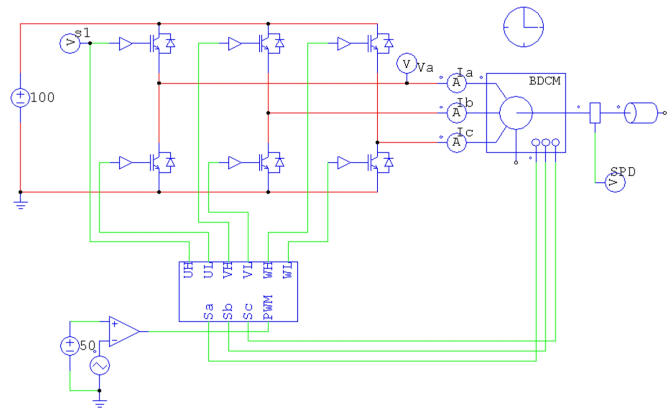


Fig. 5. Schematic of PSIM.

as follows:

$$
\begin{aligned}
& if(PhaseA \wedge PhaseB \wedge PhaseC = 1) \\
& \quad v_m = (v_a + v_b + v_c - e_a - e_b - e_c)/3 \\
& else\ if(PhaseA \wedge PhaseB = 1) \\
& \quad v_m = (v_a + v_b - e_a - e_b)/2 \\
& else\ if(PhaseB \wedge PhaseC = 1) \\
& \quad v_m = (v_b + v_c - e_b - e_c)/2 \\
& else\ if(PhaseC \wedge PhaseA = 1) \\
& \quad v_m = (v_c + v_a - e_c - e_a)/2
\end{aligned} \tag{10}
$$

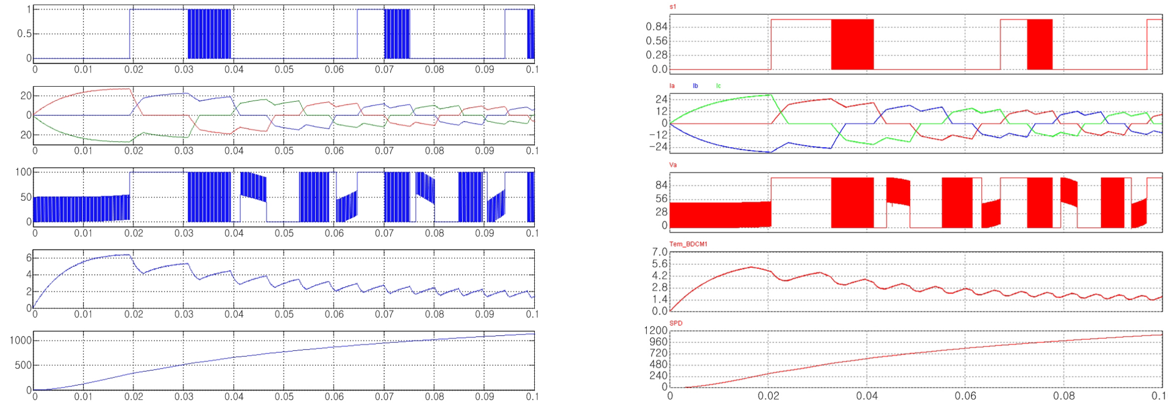
Using the determined terminal voltage and neutral voltage, voltage equations can be obtained.

V. Simulation Results

C language is utilized to verify the proposed technique, and it is easy to apply other control algorithms. Also the results can be obtained faster by using C language when compared to other methods. The differential equations of the BLDC motor are solved using the converted ode45 function of MATLAB for an accurate result. The simulation results are saved in a text file using the fprint function of C language, and are presented through MATLAB.

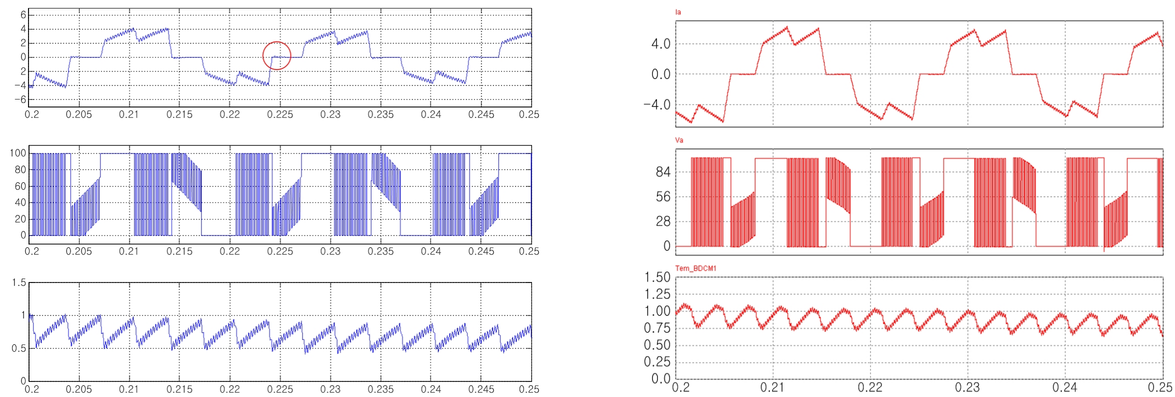
A flowchart of the simulation procedure is presented in Fig. 4. After all of the values are initialized, the program loop, which contains the functions for setting up model equations and solving differential equations, is repeated until the final results are obtained. In the simulation procedure, model equations are set up using the proposed technique. The sampling time of the simulation and the motor specifications are presented in Table I.

In order to verify the validity of the proposed technique, the simulation results using the proposed technique are compared with the simulation results from PSIM. The PSIM schematic used is presented in Fig. 5. The two simulation methods are carried out under the same conditions. A 50% duty cycle is applied and other control algorithms, which can improve the motor performance, are not applied. First, the simulation results which utilize the switching pattern in Fig. 1(a) are compared. The results for the motor start up state are presented in Fig. 6 to compare the changes in the transient-state. The



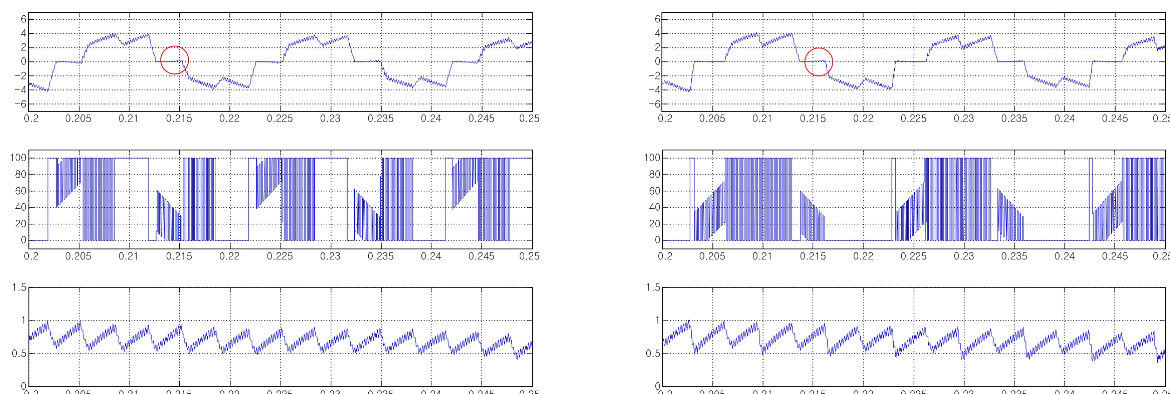
(a) (b)

Fig. 6. Simulation Results in the transient-state using the proposed technique (a) and from PSIM (b). Figures from top to bottom are switching pattern of phase A, three phase currents, terminal voltage of phase A, developed torque and rotor speed.



(a) (b)

Fig. 7. Simulation Results in the steady-state using the proposed technique (a) and from PSIM (b). Figures from top to bottom are switching pattern of phase A, terminal voltage of phase A and developed torque.



(a) (b)

Fig. 8. Simulation Results in the steady-state applied switching pattern Fig 1 (b) and (c). Figures from top to bottom are current of phase A, terminal voltage of phase A and developed torque.

TABLE I
SAMPLING TIME AND MOTOR SPECIFICATIONS

Sampling time, $T_{sampling}$	2.5 [usec]
Phase resistance, R	0.7 [ohm]
Phase inductance, L-M	5.21 [mH]
Friction coefficient, B	0.001 [Nm/(rad/s)]
Inertia of moment, J	0.0022 [kg·m^2]
Back-emf voltage coefficient, K_e	0.0143 [V/rpm]
Number of pole, P	4 [EA]

results in the steady-state are presented in Fig. 7. Fig. 6(a) and Fig. 7(a) are the results using the proposed technique, and Fig. 6(b) and Fig. 7(b) are the results from PSIM. Even though a small difference exists between the two results, since PSIM has a more realistic analysis for mechanical motion, it can be verified that the propose technique is valid.

Fig. 8(a) and (b) are the simulation results in the steady-state for the switching patterns in Fig. 1 (b) and (c) respectively. Fig. 6, 7 and 8 show that the proposed technique can work with various switching patterns. The parts emphasized with red circles in Fig. 7(a) and 8 are the phase current waveforms when the terminal voltage of the motor is larger than the dc-link voltage or smaller than zero. Such a minor result is also obtained using the proposed technique.

VI. CONCLUSIONS

A technique to set up voltage model equations is presented in this paper. Based on the proposed technique, a simulation can be performed without modifying the model equation even when changes are made to the applied switching pattern. The proposed technique is also simple to implement in the widely used C language. The total simulation time for Fig. 6 took 1.80s in C language and about 6s on PSIM. Therefore, simulations using the proposed technique are more efficient for the analysis of the complex BLDC motor systems in which many control algorithms can be applied. The proposed technique allows for quick and efficient comparisons of various conditions by eliminating the steps to create new model equations for different switching patterns.

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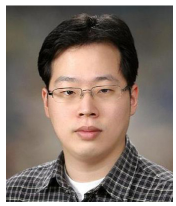

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