A Novel Digital Control Technique for Brushless DC Motor Drives: Current Control

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Abstract—**This paper presents a digital control technique for trapezoidal brushless DC (BLDC) motor drives. This novel digital control treats BLDC motor as a digital system and regulates speed with the help of two predefined state variables, state-1 designed for high-speed operation and state-2 defined for low-speed operation. A comparator compares actual speed with set speed and then switches between appropriate states. Thus, task of the digital control is to deliver right amount of power to the motor by right numbers of state-1 and state-2 operations so that average power delivery matches required power. It needs few logic gates and comparators to implement digital control, thus making it extremely simple and easy to develop a low cost application specific integrated circuit (ASIC) for speed control of BLDC motor drives. Simulation and experimental results are presented to describe and verify the proposed technique.**

I. INTRODUCTION

BLDC motors are continually gaining popularity for motion control applications, major avenues being industrial applications, consumer appliances, aerospace and automotive applications. Proportional-integral (PI) control with hysteresis or pulse width modulation (PWM) switching is the most widely used speed control technique for BLDC motors with trapezoidal back-emf. It can be easily implemented on analog or digital components because it are well understood, simple, and in practice for a fairly long period of time. To enhance the performance or to reduce the cost has been focus of development work for a long time. Cost and implementation complexity are often the most important factors for design trade-offs between techniques, implementation, and strategy of motor control hardware. More than often, microcontrollers, microprocessors, and digital signal processors (DSPs) are chosen to digitally implement the techniques/controls.

In this paper, we propose a digital control for BLDC motor drives, which is low cost and simple to implement. Simulation results and experimental verification serve to show its performance and practical usefulness. The proposed digital control can be implemented with few logic gates and comparators, which demonstrates ease of developing a low cost ASIC for digital control of BLDC motor drives. This will help reduce the cost and complexity of motor control hardware; this, in turn, can boost the acceptance level of BLDC motors for commercial mass production applications and successfully fulfill the promises of energy savings associated with adjustable speed drives.

II. CURRENT-MODE DIGITAL CONTROL

The proposed digital control treats BLDC motor as a digital system and tries to regulate the speed with the help of two predefined state variables, state-1 designed for high speed (ω_h) operation and state-2 designed for low speed (ω_l) operation. Phase current is chosen as the state variable and hysteresis switching is used for current control. Current I_h is state-1 and is of relatively higher magnitude to deliver more power to the motor. Current I_l is state-2 and is of relatively lower magnitude to deliver less power to the motor. Actual motor speed ω is compared to the set speed ω^* ($\omega_l < \omega^* < \omega_h$) and then digital controller decides to:

- Switch to or stay at ω_h if $\omega^* > \omega$
- Switch to or stay at ω_l if $\omega^* < \omega$

Fig.1 illustrates this concept. A comparator compares actual speed with set speed and then switches appropriate current values to the hysteresis current regulator.

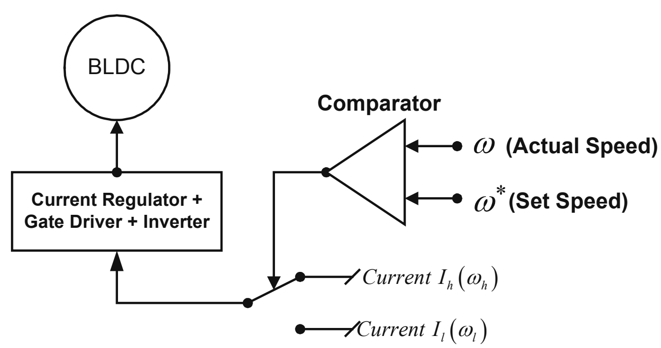

Fig. 1. Schematic of the current-mode digital control.

Fig. 2 shows corresponding waveform of a phase current for digital control technique with hysteresis switching scheme. Currents for other phases would be similar with appropriate phase delay.

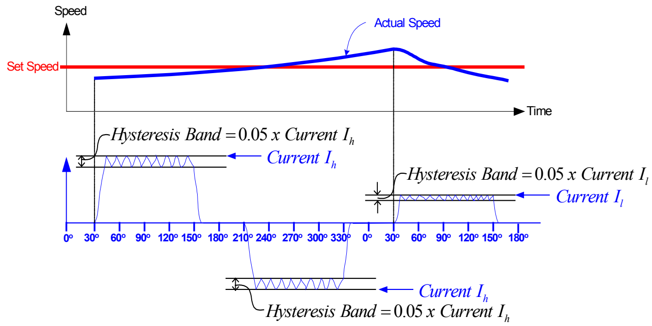

Fig. 2. Phase current waveform for current-mode digital control.

As shown in above Fig. 2, when actual speed is lower than set speed, digital controller choose to provide high current I_h to the motor; this in turn, will increase the motor speed. Current is regulated within band of 5% by the hysteresis current regulator. If actual speed is higher than set speed, digital controller choose to provide low current I_l to the motor, which will decrease the speed.

Obviously, state-1 (high current I_h) is designed to deliver more power to the motor, while state-2 (low current I_l) is designed to deliver less power to the motor. Thus, the task of the digital control is to deliver right amount of power to the motor by applying right numbers of state-1 operations and state-2 operations so that average power delivery matches to that of required power.

III. DESIGN OF DIGITAL CONTROL

Let us take a look at the motor equation below:

$$K_t i(t) - T_L(t) - \beta\omega(t) = J\frac{d\omega(t)}{dt} \tag{1}$$

where K_t is motor torque constant, $i(t)$ is instantaneous phase current, $T_L(t)$ is instantaneous load torque, β is motor viscous damping coefficient, $\omega(t)$ is instantaneous motor speed, and J is rotor inertia.

At steady state, equation (1) would be:

$$K_t i(t) - T_L(t) - \beta\omega(t) = J\underbrace{\frac{d\omega(t)}{dt}}_{=0} \tag{2}$$

And hence, it can be written as:

$$\omega_s = \frac{K_t I_s - T_{L_s}}{\beta} \tag{3}$$

Steady state speed for I_h can be given as:

$$\omega_h = \frac{K_t I_h - T_L}{\beta} \tag{4}$$

And for I_l, it can be given as:

$$\omega_l = \frac{K_t I_l - T_L}{\beta} \tag{5}$$

And, speed ripple can be expressed as a subtraction of equation (4) and (5), and then rearranging them:

$$\Delta\omega = \omega_h - \omega_l \propto (I_h - I_l) \tag{6}$$

Equation (6) suggests that speed ripple is directly proportional to difference of current I_h and current I_l, in other words, to current-band, $\Delta I = I_h - I_l$.

From these discussions, we found that it is better to have as small current-band as possible to reduce the speed ripple. From equation (3), we know that speed is a function of load torque and current. In other word, for same current, we may get different speed as the load torque changes.

In perceptive of digital control, the definition of I_h and I_l determines highest speed with highest load and lowest speed with highest load, respectively. As a designer, we have to design current I_h and current I_l in such a way that they can regulate the speed over a wide range for varying load torque. Selecting full load current value as I_h leaves us with the task of finding highest value of I_l that can guarantee satisfactory operation for entire range of torque-speed characteristics. We can use following equation for this purpose:

$$\omega_l = \frac{K_t I_l - T_L}{\beta} \tag{7}$$

Solve this equation for ω_l with different load torque value while keeping I_l constant. Initially, start with no-load current value (which would be nearly equal to zero) as I_l and solve the equation (7) for increasing values of load torque. Then increase the value of I_l in steps of 10% of full load current and repeat above process iteratively for all other values of I_l. The results can be tabulated and used to plot a 3-dimensional curve for current I_l, speed ω, and load torque T_L.

Figure 3 shows such a curve for experimental motor when I_h is full load current (20 amps) and I_l is changed from 16 to 20 amps.

The value of I_h determines the capabilities to run at highest speed with highest load, and value of I_l determines the capabilities to run at lowest speed with highest load. Since I_h is the full load current, we may operate the motor to full speed and full load. But since I_l is limited to 16 amps, it is not possible, for example, to run the motor at 1000 rpm with any load from no load to full load. So basically, choice of I_h and I_l determines operating area for torque-speed characteristics, as demonstrated in figure 3.

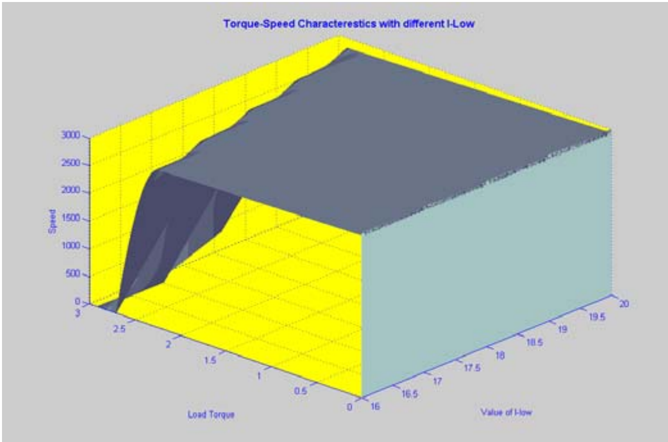

Fig. 3. Torque-speed characteristics when $I_h = 20$ & $I_l = 16\text{-}20$.

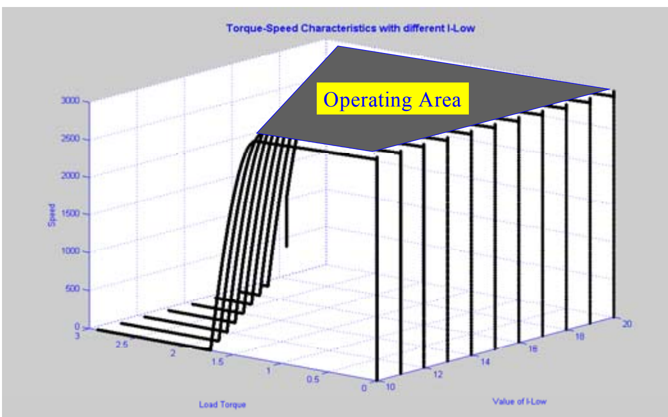

Fig. 4. Torque-speed characteristics when $I_h = 20$ & $I_l = 10\text{-}20$.

Area covered by the curve is operating area for a given choice of I_h and I_l, while area under the curve depicts non-achievable torque-speed points. To illustrate this point further, few more such figures are shown for different values of I_l. Figure 4 shows torque-speed operating points when I_l is changed from 10 amps to 20 amps. As expected, this gave bigger operating area than in figure 3, at the price of higher ripple in actual speed.

Figure 5 shows the torque-speed characteristics when $I_h = 20$ & $I_l = 2$. As illustrated on top of the figure, now it is possible to operate the motor for almost entire torque-speed capabilities of the motor. Please note that it is also possible to fix I_l at no-load motor current (which would be near zero) and than change I_h to derive similar 3-D curves. The design process and methodology would remain same; the only difference would be that now we shall see an increasing area from low-speed high torque toward high-speed high torque.

From the above discussion, we can outline design process of digital control as below:

- Determine the application requirements of the load in terms of torque-speed characteristics.
- Use equation (7) for different values of I_l from no load current to full load current to solve for speed at no-load to full load torque.
- Plot I_l, torque, and speed on X, Y, and Z-axis, respectively, to get the variation of torque-speed characteristics for different values of I_l.
- Find the highest value of I_l that can guarantee to cover whole torque-speed requirement of the load.
- This is the final value of I_l with I_h being full load current of the motor, for digital control. It is advisable to reduce value of I_l by some factor (usually 5% to 15%) to add margin to the torque-speed characteristics of the load.
- It is also possible to obtain optimum value of I_l by solving equation (7) for current with lowest speed and highest load torque. This would directly give the value of I_l.

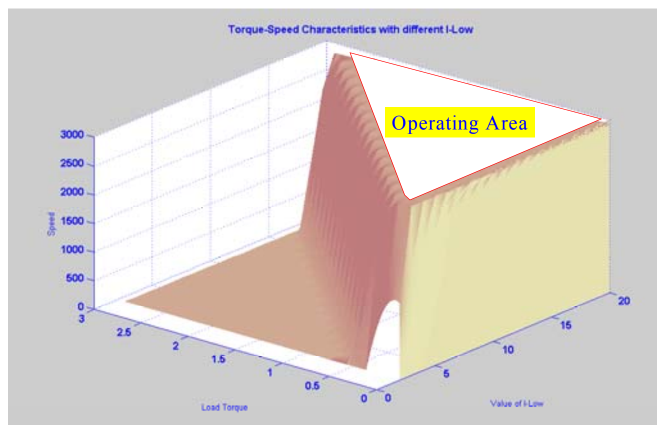

Fig. 5. Torque-Speed Characteristics when $I_h = 20$ & $I_l = 2\text{-}20$.

IV. SIMULATION RESULTS

PSIM, a simulation tool for system level analysis of power electronics and motor drives, is used to verify the concept of digital control. Since BLDC motor is a three-phase balanced system, it is sufficient to sense currents in to any of the two phases; this will save the cost of one current sensor and current sensing circuitry. Also it forces the system to be balanced. Fig. 6 shows simulation model of digital control for BLDC motor drive system.

Motor parameters are based on Poly-Scientific make BLDC motor model BN42-53EU-02LH with following specifications:

Rated Speed/Torque:	2820 RPM/2.92 Nm
Rated Current:	20.2 A

Torque Constant:	0.164 Nm/A
Back-emf Constant:	0.164 V/rad/sec
Phase Resistance:	0.53 Ohms
Phase Inductance:	214 mH
Rotor Inertia:	0.000494 Nm-sq.sec
Mech. Time Constant:	1 sec

Fig. 7a and Fig. 7b shows simulation waveforms for set speed and actual speed and three phase currents for steady state operation at different torque-speed points. For set speed of 1500 rpm with 0.1 Nm load, digital control maintains the speed within +9/-26 rpm (+0.6%/-1.73% of set speed). As in Fig. 7b, digital control maintains set speed with in +11/-47 rpm (+1.3%/-4.85% of set speed) for this case.

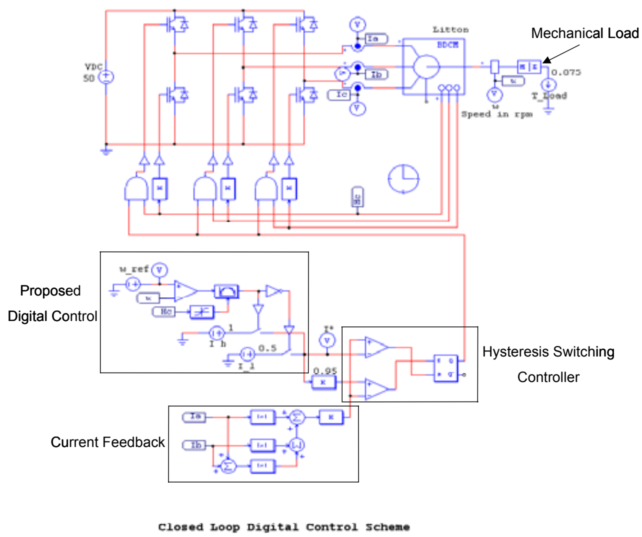

Fig. 6. Simulation model of digital control for BLDC motor drive system.

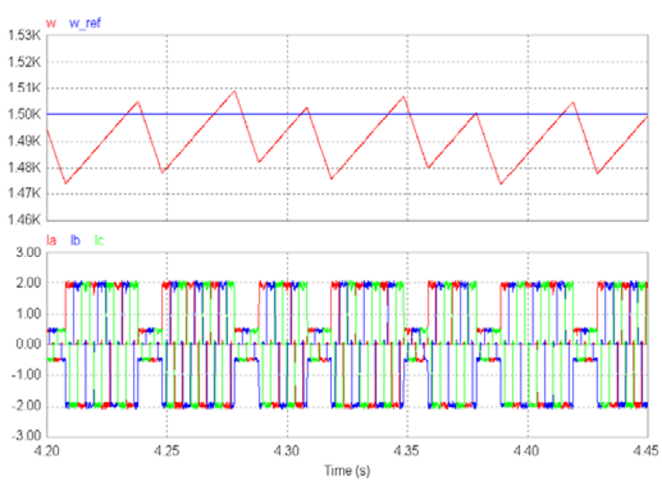

Fig. 7a. 1500 RPM set speed, 0.1 Nm Load

$I_l = 0.5$ A, $I_h = 2$ A.

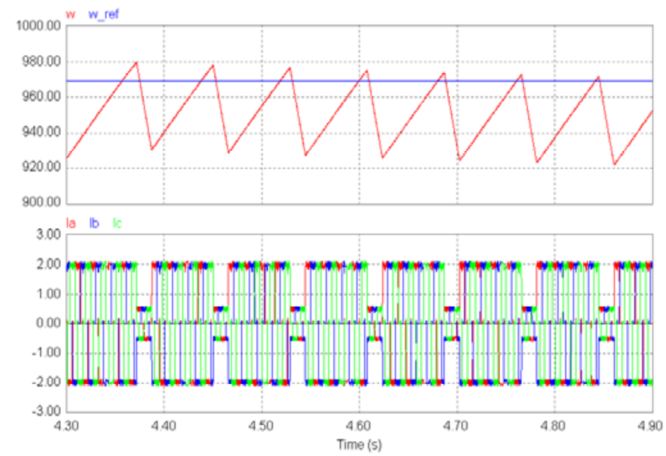

Fig. 7b. 969 RPM set speed, 0.3 Nm Load

$I_l = 0.5$ A, $I_h = 2$ A.

V. EXPERIMENTAL VERIFICATION

Single processor dSPACE system with real time interface through simulink block set is used for experimental verification. Hysteresis current controller was built using analog comparators. Fig. 8 shows experimental set-up for digital control of BLDC motor drive.

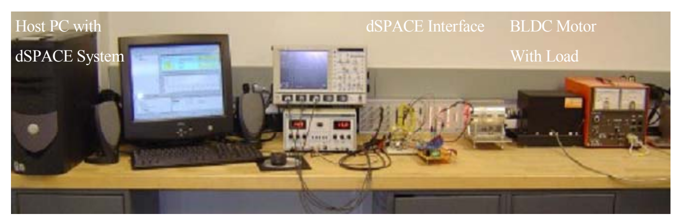

Fig. 8. Experimental set-up for digital control of BLDC motor.

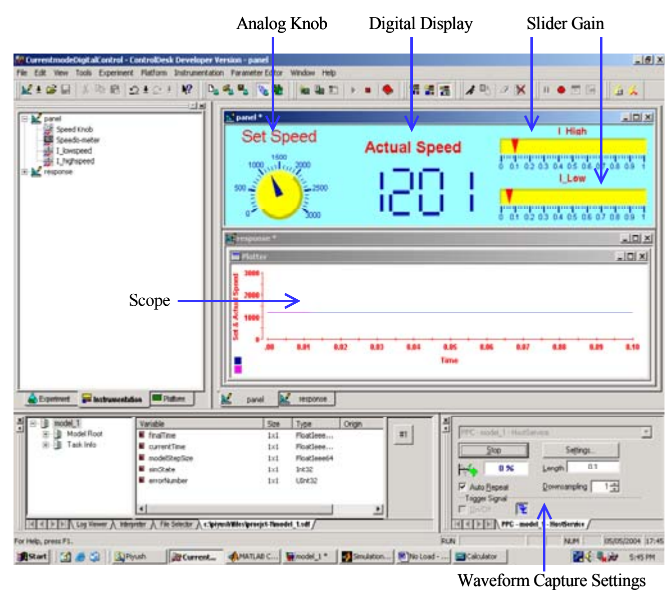

Fig. 9. GUI of dSPACE system for digital control of BLDC motor drive.

dSPACE system has in-built library for graphical-user-interface (GUI). Fig. 9 shows GUI screen of digital control. An analog knob for speed setting, a digital display for actual speed, slide-bars to change I_l and I_h, and a real time waveform capture for virtual scope are part of this GUI screen.

We shall use the same operating points for experimental results as we used for simulations for a direct comparison between them. Fig. 10 shows the closed loop no-load operation. Graph is enlarged to demonstrate output speed ripple. We get +12/-18 (+1%/-1.5% of set speed) as average speed ripple, with highest and lowest speed being 1210 and 1180 respectively for a set speed of 1198 rpm.

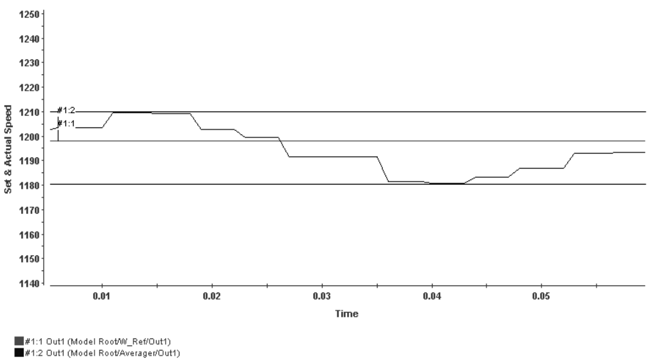

Fig. 10. Enlarged view of closed-loop no load operation.

As shown in enlarged view of Fig. 11a, for the case of 1500 rpm set speed with 0.1 Nm load, digital control maintains set speed with in +3/-31 rpm (+0.2%/-2.06% of set speed). For the case of 969 rpm with 0.3 Nm load in Fig. 11b, digital control maintains set speed with in +13/-29 rpm (+1.34%/-3% of set speed).

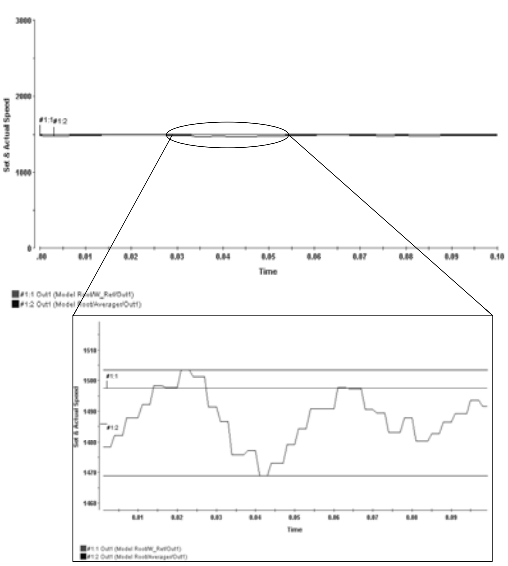

Fig. 11a. 1500 RPM set speed, 0.1 Nm load

I_l = 0.5 A, I_h =2 A.

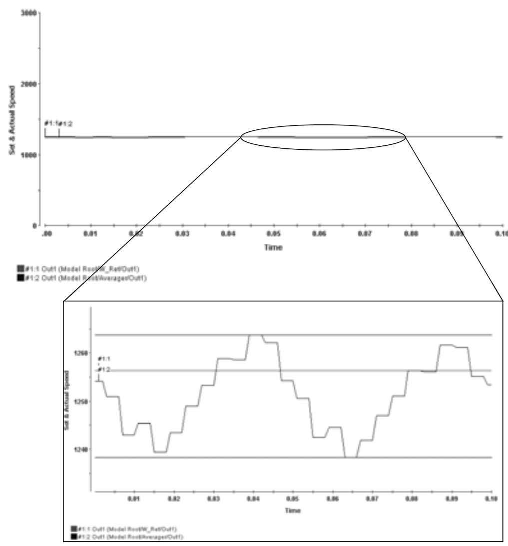

Fig. 11b. 969 RPM set speed, 0.3 Nm load

I_l = 0.5 A, I_h =2 A.

Similarly, Fig. 12 shows the case with 1256 rmp as set speed and 0.2 Nm load. As before, digital control is able to maintain set speed. The area of large speed ripple is enlarged to find out the exact magnitude. We get +3/-31 (+0.64%/-1.43% of set speed) as average speed ripple, with highest and lowest speed being 1264 and 1238 respectively.

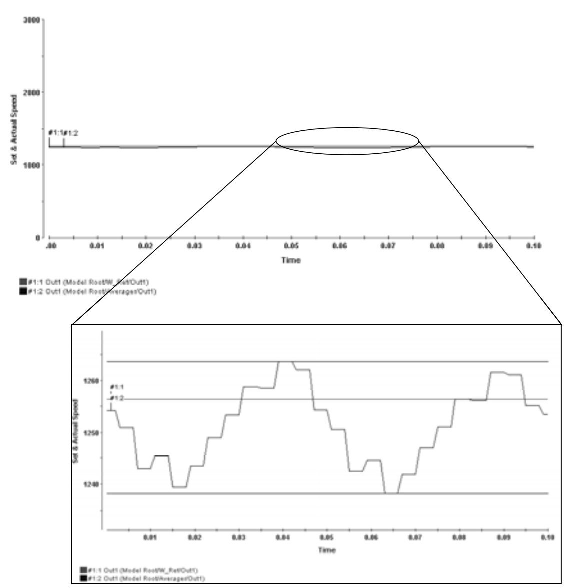

Fig. 12. Steady state and enlarged view of closed loop with 0.2 Nm load.

Table I shows summary of comparison between simulation and experimental results. The basic source of mismatch between simulation and experimental results could be the modeling of BLDC motor for simulation. PSIM model the BLDC motor with a set of linear differential equations and it is not possible to take in to account non-linearity and manufacturing imperfections for simulation purposes. More often than not, back-emf is not flat at the top in actual motor, and also there could be some lead or leg in the back-emfs of all the phases other than 120 electrical degrees depending on the precision of position sensor mounting.

TABLE I
COMPARISON OF SPEED RIPPLE FROM SIMULATION AND EXPERIMENTAL RESULTS

Test Case	Simulation Speed Ripple		Experimental Speed Ripple	
	+	-	+	-
0 rpm/0 load	@0	@0	0.86%	0.86%
2000 rpm/0 load	@0	@0	0.60%	1.06%
1198 rpm/0 load	0.50%	0.75%	1%	1.50%
1500 rpm/ 0.1 Nm load	0.60%	1.73%	0.20%	2.06%
1256 rpm/0.2 Nm load	0.40%	3.10%	0.64%	1.43%
969 rpm/0.3 Nm load	1.13%	4.85%	1.34%	3.00%

Possible cause of discrepancies could be lack of skin effect for winding resistance, mutual inductance, cogging torque, reluctance torque, static friction losses, manufacturing imperfection etc in to the simulations.

VI. CONCLUSIONS

This paper described a novel digital control for BLDC motor drive speed control applications with simulation and experimental results. The proposed digital control is able to maintain set speed with reasonable accuracy. Simplicity of the control technique and low cost implementation are the main incentives for the proposed digital control. Nature of the digital control is very friendly to be implemented with few logic gates and comparators, thus making it feasible to be embedded in an extremely low cost ASIC.

There are applications, for instance, commercially mass-produced appliances like fans, blowers, washers, dryers vacuum cleaners, etc, where torque or speed ripple are not significantly important. They are potential candidates for the applicability of the digital control. And because of their mass-production, low cost and design simplicity could bring manifold benefits. Therefore, it is expected that the digital control for BLDC motor drives will help reduce the cost and complexity of the motor control hardware; this, in turn, can boost the acceptance level of BLDC motors for commercial mass production applications, thus, successfully fulfill the promises of energy savings associated with adjustable speed drives.

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