Stability Analysis of FPGA-Based Control of Brushless DC Motors and Generators Using Digital PWM Technique

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Abstract— **BLDC drives have received significant attention owing to their high efficiency, EMI, and high mechanical reliability due to the absence of brushes in commercial, residential and industrial applications. In generating mode, they are very suitable for small wind & hydro generator applications, as well as integrated starter alternators (ISA) in hybrid electric vehicles. This paper discusses digital Pulse Width Modulation (PWM) control for a BLDC drive in both motoring and generating modes of operation. This control strategy is simple, robust, requires no current sensors and is not computationally intensive. Owing to these attributes, the technique can be implemented on a low-cost FPGA. This paper investigates potential stability issues due with the simplicity of this control under various conditions of load disturbances and also owing to the reduction in processor capability. Lyapunov stability criteria have been used to analyze closed loop stability of the system. Furthermore, an approximate discrete model has been developed and stability of the system is analyzed to ensure closed loop operation under various sets of loads, speeds and input voltages. Simulation and experimental results have been presented to verify the claims.**

***Index Terms*—BLDC drives, digital control, PWM control, stability analysis.**

I. Introduction

Electric drives form an integral part of industrial plants with over 5 billion motors built worldwide every year [1]. Typical residential and commercial applications tend to use conventional motor drive technologies, such as single phase induction or brushed DC motors. However these machines are characterized by low efficiency and high maintenance, respectively [2]. The last decade has also seen an increase in the use of variable speed generators for wind and hydro generation for sustainable energy production in rural and urban areas [3].

Among the different machine configurations available, Brushless DC (BLDC) machines have been considered as strong contenders. This is due to several reasons including higher efficiency, robust operation, lower maintenance and higher mechanical reliability since they do not have any brushes. Control strategies for three-phase BLDC machines are typically implemented using a power converter made of IGBTs or MOSFETs. In order to generate appropriate control signals to perform the desired operation, a special-purpose processor or a programmable logic device (PLD) is usually necessary [4]. Although special purpose processors can have higher development time, it can be a compact solution, and is typically less expensive. Such a system can decrease the overall cost of the system without any loss in performance. However, the complexity of BLDC drives' strategies requires microcontrollers with high computational capability for executing multifarious regulation algorithms such as PI or PID regulation loops. Besides, complex control strategies (used for BLDC current/speed regulation) can be sensitive to parameters variation, magnetic saturation, un-modeled disturbances etc, which makes entire system less reliable [5].

For BLDC drives used in domestic appliances or simple industrial applications, where variation in operating parameters is not frequent, there is a need for low cost control strategies that utilizes simple hardware and does not require major memory or processing capabilities. Such low-cost wide speed range BLDC drive can be very suitable for four-quadrant operation in renewable and hybrid vehicle applications as well. In addition, digital control strategy can be used as a cost-effective solution for flywheels (as part of large scale wind turbine) where the capability of digital control to operate in two-quadrants can be utilized to full potential [6].

One of the major considerations in the development of a robust digital control strategy is its stability when the drive is exposed to sudden variations in operating conditions such as load torque changes, variable speed requests etc. This is similar to sliding mode control, where key concern is actually

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in load [7]. Although sliding mode control is insensitive to motor parameter variations, stability of its normal operations has to be verified [8], [9].

The proposed control strategy treats the motor as a digital system. In other words, the controller selects a high duty- D_H or low duty- D_L state based on the calculated speed error. Speed regulation is achieved by alternating between these 2 predefined states. Owing to its simplicity, this control strategy is easy to implement onto a DSP or an FPGA [10]. It also does not require the use of any additional hardware, which makes it an attractive solution for most applications. With minimization of processor capacity and feedback mechanisms, there is a need to verify the ability of the strategy to operate for sudden changes in demanded load torque and speed profiles. This paper presents a comprehensive stability analysis of the proposed digital PWM control strategy for closed loop BLDC drive operating in motoring and generating modes to address this issue and makes a case for its suitability for industrial, domestic and distributed generation systems.

Stability analysis of discrete-time systems can be carried out using two different techniques. One of them is direct stability analysis in z-domain such as the Jury test and the Schur-Cohn criterion. The other covers the techniques used for continuous time systems including Lyapunov criterion [11], [12]. In this study, the stability analysis of closed loop system under varying load torque and varying input voltages is carried out.

II. Speed regulation of BLDC machine using Digital PWM control

For applications that do not demand a highly precise control, only hall-effect sensors are used for generating switching signals for power switches. Such drives have several uses, ranging from a few watts up to a few kilo watts such as water/oil pumps, blowers, mixers, conveyers, etc [13], [14]. In applications that require high performance from the drive, it is common to employ an encoder instead of the hall sensors. An example of such drives is integrated starter/alternator, which is used for automotive applications or four-quadrant BLDC drives used for propulsion in hybrid/electric vehicles [15], [16].

In recent years, the rapid development of distributed generation systems has led to the development of several advanced variable speed generator control strategies. Renewable energy applications, mainly micro hydro & wind, as well as automotive are common examples of such systems. Variable speed generators typically perform better over a wider operating region, which results in better utilization of the machine, as well as efficient energy conversion.

Hydro turbine is considered a reactive type of machine with a standard power-speed characteristic shown in fig 4. In this system, the turbine and drive are designed to operate at the speed that results in maximum output power. Any variation in turbines speed can cause reduction in output power. Therefore it is important to control the speed of the generator [17]. Authors in [18] show several power characteristics of the hydro turbine for different “head” and shaft speeds, showing that turbine’s efficiency also has a peak value for a given shaft speed. Similarly for wind turbine applications, variable speed PM generators are very suitable for stand-alone units or wind farms. Turbine power vs. rotational speed for different wind velocities is presented on the fig. 4 [19], [20]. From the figure it can be seen that the power delivered by the generator depends on rotational speed of the turbine, with a maximum value at only one operational point.

- ***Speed Regulation Using Digital PWM Control***

In a BLDC motor, speed is directly proportional to the voltage applied to its terminals. Therefore, in order to achieve speed regulation of a BLDC motor, a variable voltage dc supply is usually required [21]. If a three-phase inverter is employed, only 2 phases are active at the time (six-step algorithm). Therefore digital PWM signal controls the switches by generating variable phase voltages that are applied to terminals of BLDC machine [22].

The main principle of digital PWM control strategy is illustrated in fig. 1. This control strategy treats the BLDC machine as a digital system. In other words, one of only two predetermined values of PWM duty cycles are applied to the IGBT switches based on speed error, i.e. the drive can operate in 2 possible states: state 1 (high value of PWM duty cycle D_H is applied to inverter switches) of state 2 (low value of PWM duty cycle D_L is applied).

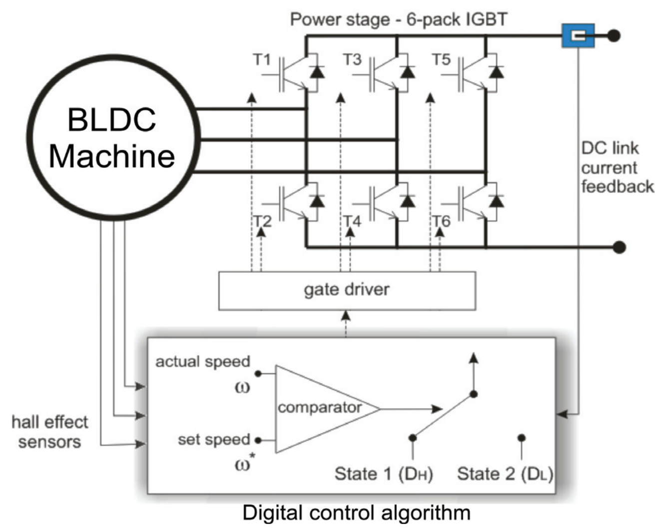

Fig. 1: Principle of digital control of PM machine

In other words, the digital controller essentially generates PWM signals and converts them into commutation functions for the power switches based on logic obtained for the speed regulator. Digital control algorithm is basic, and takes actual speed and reference speed as only inputs, while the output is PWM logic signal for gates of the inverter switches [23], [24]. Such PWM voltage control is uncomplicated to put into practice; it however advisable to include over current protection in the form of a DC link current sensor to ensure the safe operation of the machine [25], [26].

In motoring mode, if the measured speed is higher than commanded reference, duty cycle D_L is applied which results in smaller phase current. This reduces torque generated at the shaft. On the other hand, if actual speed is less than reference value, additional torque is needed to speed up the motoring system, which warrants a higher value of PWM duty cycle DH to be applied. Values of DL and DH are predetermined constants that do not change with time. The only variable is the instant at which either duty cycle is applied, resulting in speeding up or slowing down the motor shaft.

For BLDC generators, the opposite logic can be used to choose high and low values of duty cycle in this technique. If the generator speed needs to be reduced, higher duty cycle is applied, resulting in higher value of opposing torque to the prime mover. If speed of the generator needs to be increased, lower value of duty cycle excites the machine with smaller value of phase currents, which results in lower opposing torque [27].

The values of PWM duty cycle D_L and D_H are determined based on the desired (reference) speed for different loads and operating range of the drive. If a narrow operating range is desired (speed range of 10-20%), then difference in D_L and D_H needs to be in the order of a few percent. On the other hand, if a wider operating range is to be achieved, a bigger difference between higher and lower values can be used. However it could also result in higher torque ripple and higher noise in the BLDC drive [28].

III. Stability and Dynamics of Digital PWM Controller

Due to the nature of the digital control strategy, the algorithm is used is in a form of variable structure control. This type of control is non-linear, which changes the dynamics of the system depending on the state of the system. Therefore, the stability analysis of such systems can be investigated by using candidate Lyapunov function. The function reflects the characteristic of the digital control used in this paper, and is given by (1) [29]:

$$V(s(x)) = \frac{1}{2}s^T(x)s(x) = \frac{1}{2}\|s(x)\|_2^2 \tag{1}$$

where s is a parameter called: "switching surface", which can be used for the digital control stability analysis. Therefore, depending on the switching surface sign, digital controller chooses between higher and lower value of control input.

According to Lyapunov stability theory, a system is stable around $s(x)=0$, if the first derivative of candidate function $dV(s(x))/dt$ is negative, as shown by (2) [30, 31].

$$\frac{dV}{dt} < 0 => \frac{\partial V}{\partial s}\frac{\partial s}{\partial t} < 0 => s^T(x)\dot{s}(x) < 0 \tag{2}$$

Based on the equation (2), for system to be stable, $s(x)$ and its first derivative $d(s(x))/dt$ should always be opposite signs. That is in essence the Lyapunov criteria, which the digital controlled system should comply by. In order to get proper system equations for stability analysis, it is necessary to generate a block diagram, shown on figure 2. Based on the speed error (ω_{err}) and current limitation (as shown on fig. 2a and 2b), the algorithm chooses proper duty cycle value (D_ω), which is between two predetermined duty cycle values (DL and DH).

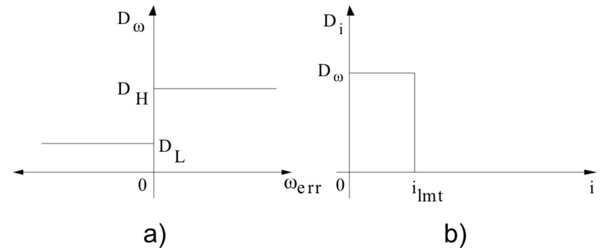

Fig. 2: Digital control logic for motoring mode

However, current limitation is calculated according to tolerated value Δω, which is shown on the fig. 3. Therefore, if the speed error is too high, then current limitation is set to its maximum value, in order to achieve machine's reference. As the machine speeds up, the error diminishes and the current limitation decreases as well, to protect system from overshoot. Hence, rise time is as small as possible.

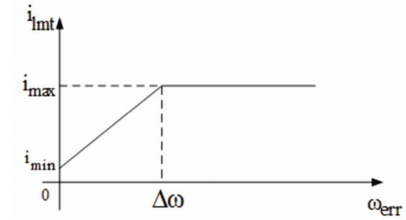

Fig. 3: Current limitation function representation of digital control

The proposed control logic of digital control can be represented by the block diagram as shown in fig. 4. If speed error is bigger than zero (ω_{err}>0) then higher duty cycle is applied, otherwise lower duty cycle is selected. Function blocks Gw and Gi are defined by the functions presented in fig. 2(a) and 6(b) respectively. The remaining constants in the block diagram are parameters of the BLDC machine.

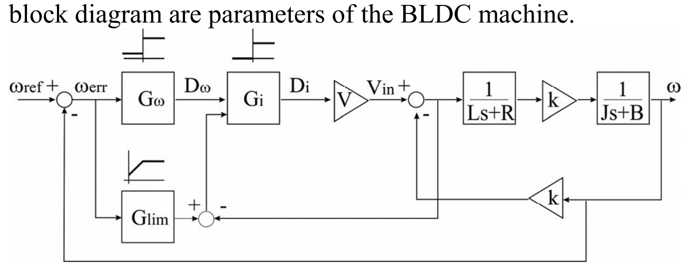

Fig. 4: Block diagram of the overall digital control system

In the stability analysis the magnitude of DC link current limit is neglected, since it does not affect operation of the digital control where current is always kept within the limits. Based on this assumption, a new variable u is introduced as a control input of the system:

$$u = sign(s)\frac{D_H - D_L}{2} + \frac{D_H + D_L}{2} \tag{3}$$

where s is the switching surface defined by (4):

$$s = \omega_{ref} - \omega \tag{4}$$

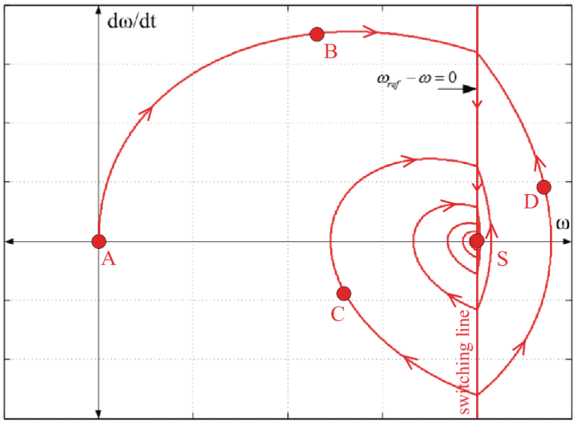

Fig. 5: State plane for Digital control

Fig. 5 shows state plane that is usually used to describe the variation of structure of one dynamical system. X and Y axes represent state variable of the system. Therefore, state of the system is represented by a point on the state plane, that can take only positive value of the speed ω (positive part of x-axes), while its $d\omega/dt$ value can be both positive and negative (acceleration/deceleration), which is y-axes on the fig. 5.

Switching line on the fig. 5 ($s=0$) presents the variation of the structure i.e. switching from low state DL to high state DH, or vice-versa. The initial point of the system can be anywhere on the state plane. The red line represents an example of state variable trajectory for BLDC drive. It can be observed that if system initial point is anywhere on the plane (any of the A, B, C, D points), the system eventually goes to stable point - S. In conclusion, this graphically proves that digital control takes the system from its initial point to its stable point, making the system stable in general. In addition, it also shows that steady state error for reference voltage tacking is small.

As mentioned above, if $s(x)$ from (4) and its first derivative $d(s(x))/dt$ have opposite signs, the system is Lyapunov stable. In order to obtain first derivative of s(x), it is necessary to derive the state equation independent from the current, which will be performed in next several equations. The default state functions are given by (5) and (6):

$$\frac{di}{dt}L = uV_{dc} - k\omega - Ri \tag{5}$$

$$\frac{d\omega}{dt}J = ki - B\omega \tag{6}$$

where L is phase inductance of the machine, Vdc is DC link voltage, K is back-emf constant, R is phase resistance, J is machine inertia and B is friction of the machine. Both equations can be combined into second order differential equation that presents system dynamics of digitally controlled BLDC machine:

$$\frac{d^2\omega}{dt^2} = -\left(\frac{BL+JR}{JL}\right)\frac{d\omega}{dt} - \left(\frac{BR+k^2}{JL}\right) \tag{7}$$

Following constants can be defined in order to simplify upper differential equation:

$$a_1 = \frac{BL+JR}{JL} \tag{8}$$

$$a_2 = \frac{BR+k^2}{JL} \tag{9}$$

$$b = \frac{K \cdot V_{dc}}{J \cdot L} \tag{10}$$

Simplified differential equation is then used to generate state matrix, which is shown by (11):

$$\frac{d}{dt}\overbrace{\begin{bmatrix}\omega \\ \dot{\omega}\end{bmatrix}}^{x} = \begin{bmatrix}0 & 1 \\ -a_2 & -a_1\end{bmatrix} \cdot \overbrace{\begin{bmatrix}\omega \\ \dot{\omega}\end{bmatrix}}^{x} + \begin{bmatrix}0 \\ b\end{bmatrix} \cdot u \tag{11}$$

Variable x representing speed (ω) and its first derivative (dω/dt) form the state variable. It can be used for obtaining remaining part of Lyapunov stability criteria which is mentioned before, where $s(x)$ and its first derivative have to be opposite sign. Therefore, first derivative of switching surface - function $s(x)$, is given by (12):

$$\dot{s} = \frac{\partial s}{\partial x}\frac{dx}{dt} = -1\frac{d\omega}{dt} \tag{12}$$

Derivative of speed ($d\omega/dt$) can be obtained by taking the integral of equation (7), which results in:

$$\dot{s} = \int\left(a_1\frac{d\omega}{dt} + a_2\omega - bu\right)dt \tag{13}$$

The equation can be also presented as:

$$\dot{s} = a_1\omega + a_2\int\omega\,dt - b\int u\,dt \tag{14}$$

Thus, if the sign of the switching surface is negative, then equation 14 should be positive, in order for system to be stable, by Lyapunov criteria. Therefore, the following equation should be in place:

$$a_1\omega + a_2\int\omega\,dt - b\int u\,dt > 0 \tag{15}$$

By taking derivative of both sides of equation 15 we get:

$$a_1\frac{d\omega}{dt} + a_2\omega > bD_L \tag{16}$$

On the other hand, if the sign of the switching surface is positive, then equation (14) should results in negative value:

$$a_1\omega + a_2\int\omega\,dt - b\int u\,dt < 0 \tag{17}$$

Where by taking the derivative we get:

$$a_1\frac{d\omega}{dt} + a_2\omega < bD_H \tag{18}$$

In summary, digitally controlled BLDC system is stable if its predefined values Dl and DH are selected by equations (19) and (20) that are derived from above mentioned Lyapunov criteria:

$$\frac{a_1}{b}\frac{d\omega}{dt} + \frac{a_2}{b}\omega > D_L \tag{19}$$

$$\frac{a_1}{b}\frac{d\omega}{dt} + \frac{a_2}{b}\omega < D_H \tag{20}$$

Thus, there is a maximum value of DL and minimum value of DH for which system is stable depending on the application. Those DLmax and DHmin define stable operating range of digitally controlled BLDC drive in general.

IV. Simulation and Experimental Results on Transients and Stability of Digital Control

In order to verify the stability of the drive, a model of the machine was created using software PSIM controlled by a power converter with 6 IGBT switches. The control algorithm was set to keep the mechanical speed constant at a desired value for different loads (torque values) in motoring and generating modes.

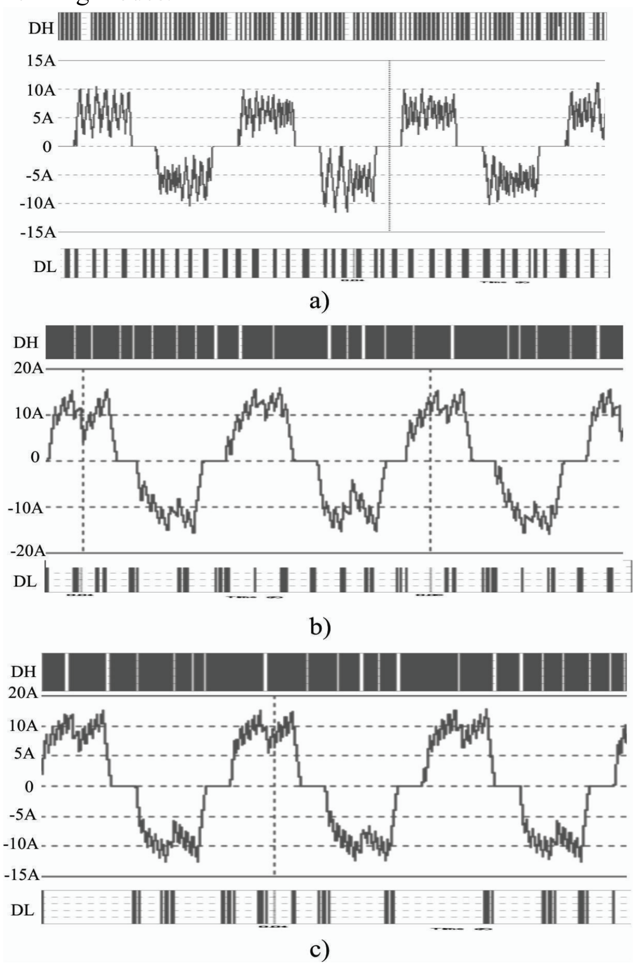

Fig. 6: Phase current waveform and duty cycle for high and low state of PM brushless motor at constant speed of 1500rpm for different torque loads: a) 0.2Nm, b) 0.5Nm and c) 0.8Nm

Fig. 6 presents analysis for the BLDC drive controlled in motoring mode at a rotor speed of 1500rpm for different load torque values. For the given condition, D_H and D_L were set to 0.9 and 0.2 respectively. It was observed that when a low value of torque (0.2Nm) was applied, the digital drive used states D_H and D_L almost equally, and phase current had a large ripple with a low RMS value corresponding to the load. For mid-range load torque (0.5Nm), state D_H was found to be more dominant than D_L, since the motor was required to develop higher torque to maintain constant speed operation (fig. 9b). In order to overcome high load torque, duty cycle D_H is used much more than D_L (fig. 9c). Consequently, the shape of the phase current waveform gets closer to over-modulation condition. It can be seen that when high duty cycle is applied, phase current shows higher value and speed increases, while when using D_L, current has lower value and speed declines. This keeps speed relatively constant with a small ripple.

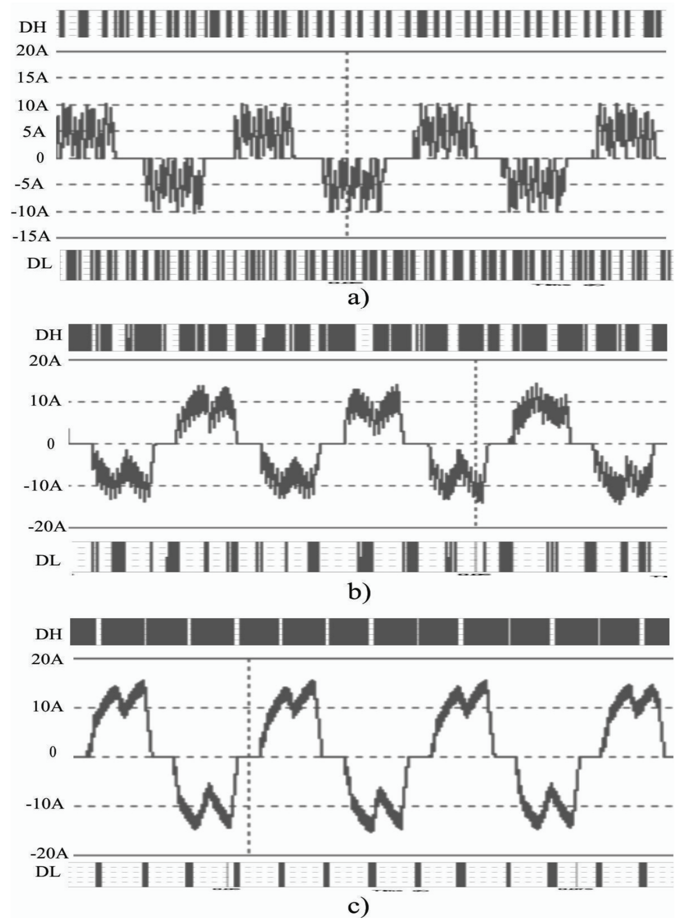

Fig. 7: Phase current waveform and duty cycle for high and low state of PM brushless generator at constant speed of 1500rpm for different torque loads: a) 0.2Nm, b) 0.5Nm and c) 0.8Nm

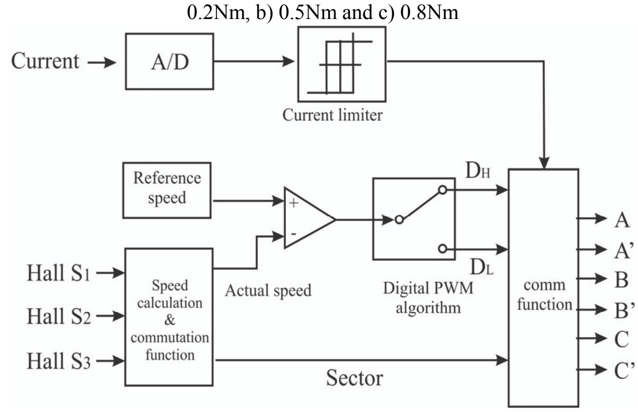

Fig. 8: Block diagram showing operations and functions implemented in FPGA device

In generating mode of operation, the states D_H and D_L were set to 0.6 and 0.1 respectively. The reason for the selection of lower values was that in this mode, lower duty cycle develops higher electromagnetic torque. This torque opposes prime mover torque to achieve the desired speed. Fig. 7a shows phase current and PWM for low and high states when low magnitude of torque is applied to the drive from the prime mover. The duty cycle D_L is used more often than D_H and therefore phase current waveform has high ripple with a small RMS value. For medium value of prime mover torque, D_H state is dominant (fig. 7b) and phase current has a higher RMS, which results in a higher electromagnetic torque. Lastly, if the prime mover torque is set to 0.8Nm, then switching state D_L is barely in use, resulting in phase current waveform shown in the fig. 7c. In order to validate the simulation results for motoring and generating modes of operation, an experimental set-up was developed. A variable Permanent Magnet DC (PMDC) machine with variable voltage supply was used as a prime mover when the BLDC machine was operated as a generator. This PMDC machine was connected to a variable resistor as load when the BLDC was controlled in motoring mode. The power stage consists of an inverter with a DC link capacitor. The inverter is built using PWRX 7-pack IGBT modules with intelligent driver modules. Square wave BLDC drive commutation function (six-step commutation) was achieved using hall-effect sensors, which were connected via pull-up resistors. The values obtained from the Hall sensors were compared with reference speed to obtain speed error. This speed error was used to determine whether D_H or D_L was applied to each phase.

Owing to its simple "digital" algorithm, this technique does not require any phase current or voltage sensors. Current protection was realized using a single current transducer in the DC link circuit. The energy storage system was realized using two 12V 46Ah lead acid batteries in parallel with max continuous current of 50A. The algorithm of digital voltage PWM control was implemented on an FPGA platform, Spartan 3 family. The key reason for choosing FPGA was due to its modifiable architecture and its capability to be optimized for switching frequencies of PWM signals, sampling time for A/D converters etc [32], [33]. Figure 8 shows the block diagram of the digital PWM control logic implemented in the FPGA.

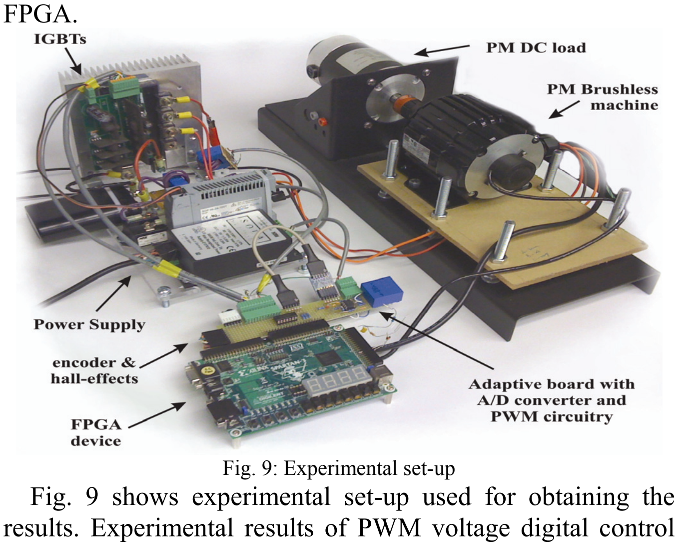

Fig. 9: Experimental set-up

Fig. 9 shows experimental set-up used for obtaining the results. Experimental results of PWM voltage digital control implementation are shown in figures 10 through 16. Waveforms of phase current speed and D_H and D_L demonstrate the behavior of the BLDC drive in both motoring and generating modes of operation.

A. Motoring mode of operation

In order to verify the stability of proposed digital PWM control of BLDC motor, several tests were conducted where the drive was run at constant speed for different load values. The results are shown on the fig. 10 where 3 different load values are applied in motoring mode. These results match simulation results from fig. 7, showing the use of D_H and D_L for loads of 0.2Nm, 0.5 Nm and 0.8Nm respectively (fig.10). It can be seen that as shaft torque increase in magnitude, D_H is used more than D_L.

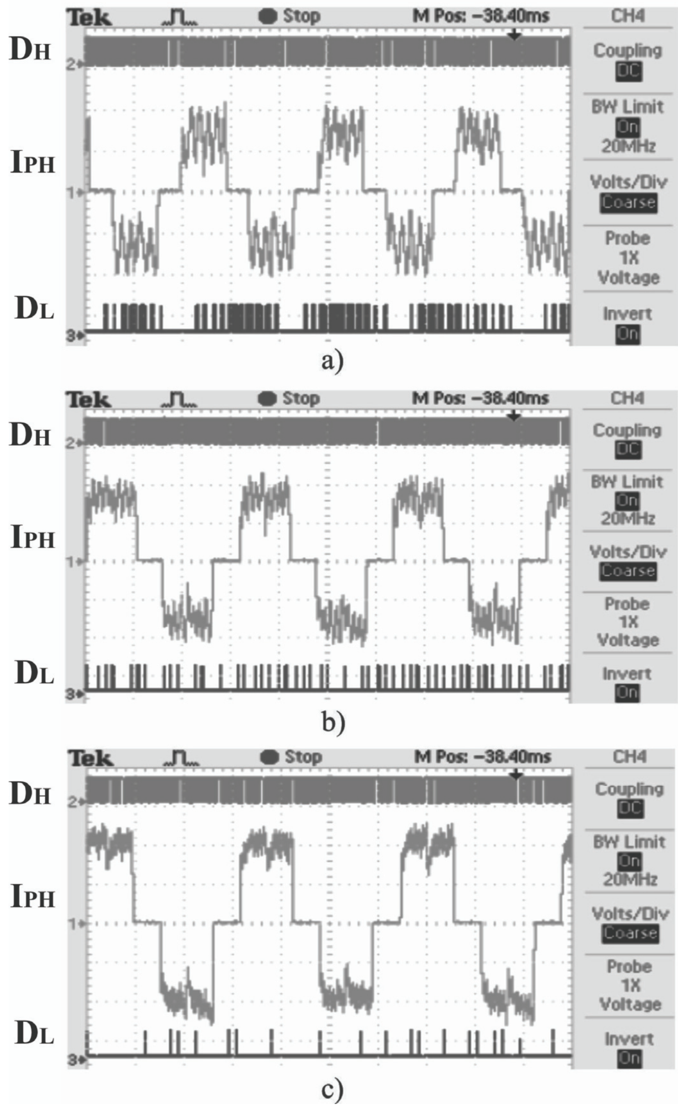

Fig. 10: Phase current waveform, speed signal and D_H and D_L signals, in motoring mode, at 1500rpm for three load torque values: a) low load torque 0.2Nm, medium load torque of 0.5Nm and c) high load torque of 0.8Nm

Figure 15 shows the phase current response for the BLDC machine in motoring mode under the load of 0.3Nm, when a sudden speed change is applied (from 1000rpm to 2000rpm). It also shows the PWM signals with D_H and D_L during the speed change. While speeding up, D_H state is utilized more than D_L, which results in higher RMS value of phase current. On the other hand, when the drive slows down (fig. 11), D_H is not employed until speed reduces to desired value.

Fig. 16 presents the response to a sudden change in load torque from 0.2 to 0.7 Nm. Phase current waveform changes significantly during the transient with a corresponding drop in speed. It can be seen that digital control regulates speed using D_H state more than D_L.

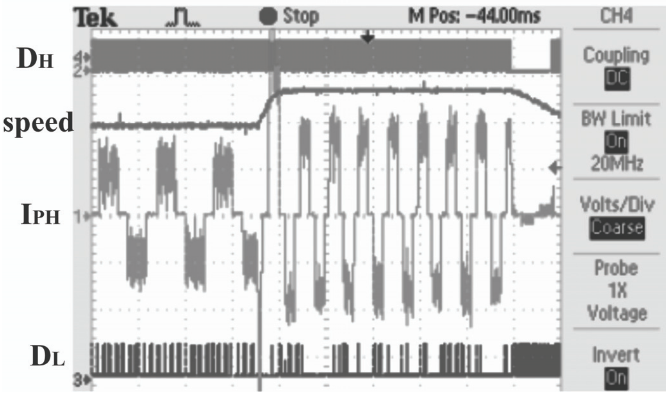

Fig. 11: Phase current waveform, speed signal and D_H and D_L signals, for speed change: 1000-2000rpm, motoring mode

In the next test, a BLDC motor operating at the speed of 1500rpm under the load of 0.5Nm was subjected to a sudden drop in supply voltage from 24V to 18V. It can be seen from figure 13 that PWM digital control strategy tries to keep up reference speed by applying more of D_H duty cycle. Phase current waveform shows drop in its peak and RMS values due to the lower DC link voltage level.

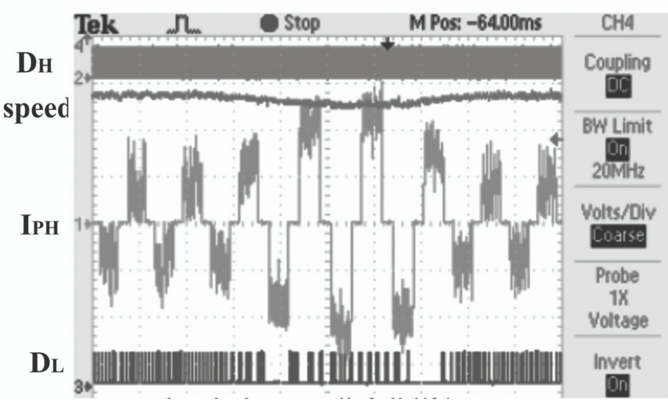

Fig. 12: Phase current waveform, speed signal and D_H and D_L signals, for sudden load change: 0.2-0.7Nm, motoring mode

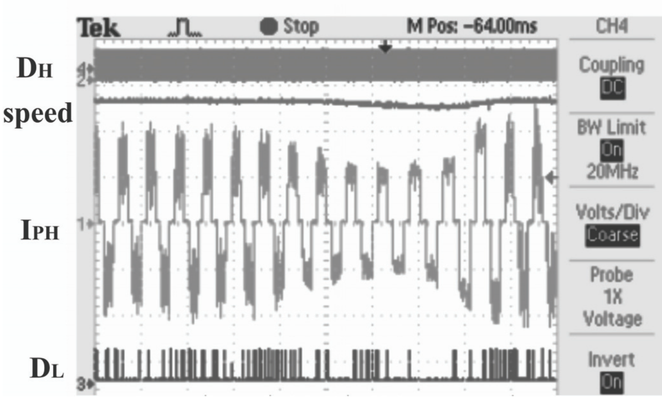

Fig. 13: Phase current waveform, speed signal and D_H and D_L signals, during sudden voltage drop, in motoring mode

B. Generating mode of operation

Digital PWM voltage control can be used to control BLDC drive in generating mode. The results of controlling the speed of the BLDC generator at constant value for different prime mover torque are shown in fig. 14. It must be noted that D_H and D_L in motoring mode have the opposite effect on speed of the machine is used in generating mode. For a low value of prime mover torque (0.2Nm), D_L is used much frequently than for higher values of prime movers torque. For higher torque from the prime mover, D_H state is employed more frequently in order to keep speed at 1500rpm, developing opposing (electromagnetic) torque for the prime mover. Hence, duty cycle D_H increases the electromagnetic torque value, which slows down the drive.

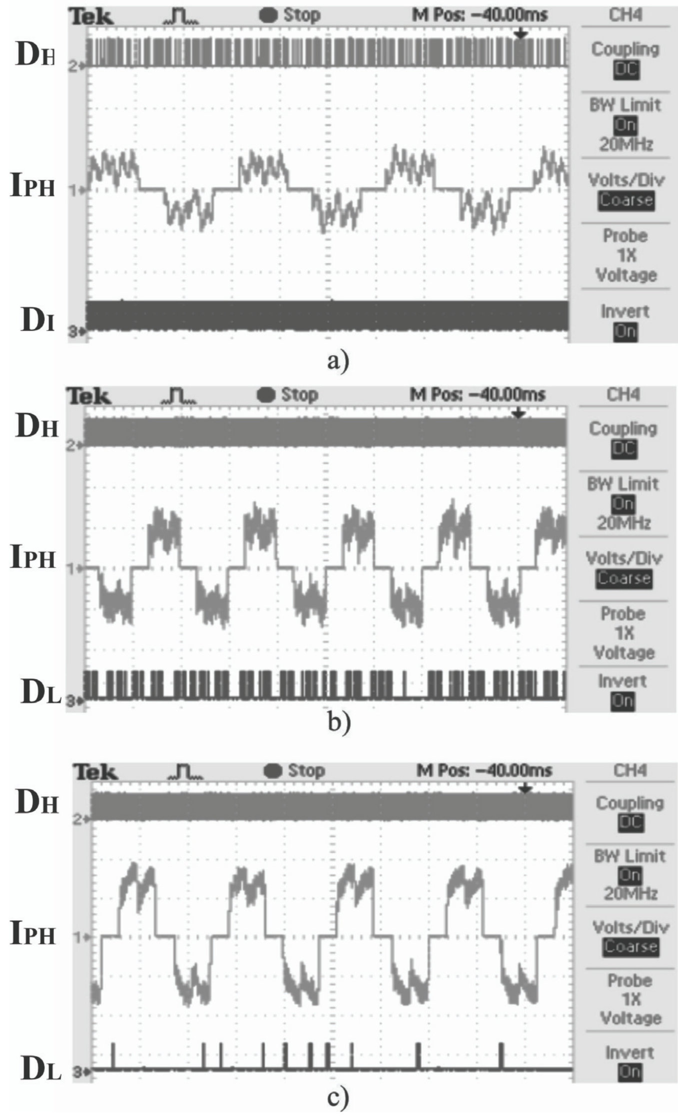

Fig. 14: Phase current waveform, speed and D_H and D_L signals, in generating mode, for the speed of 1500rpm for three different torque values: a) 0.2Nm load torque, 0.5Nm load torque and c) 0.8Nm load torque

For a sudden change in reference speed change from 1500 rpm to 1000rpm, digital controller uses D_H state more often, resulting in generator's higher torque value which helps slow down the system. As a result, rms value of the phase current increases as shown in fig. 15. On the other hand, if prime mover torque increases suddenly for a short period of time, the controller mainly uses D_H to develop opposing torque to regulate speed (fig. 16).

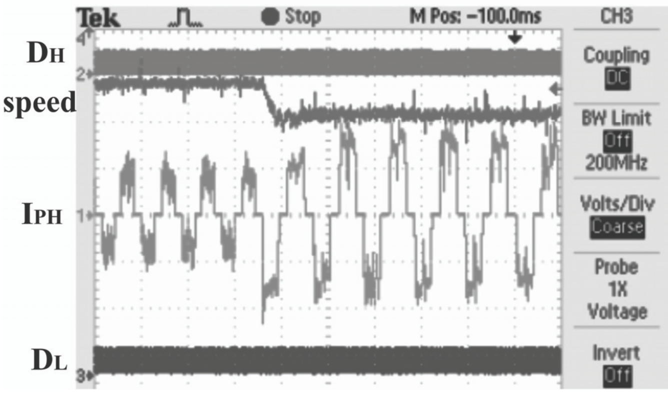

Fig. 15: Phase current waveform, speed signal and D_H and D_L signals, for sudden torque change

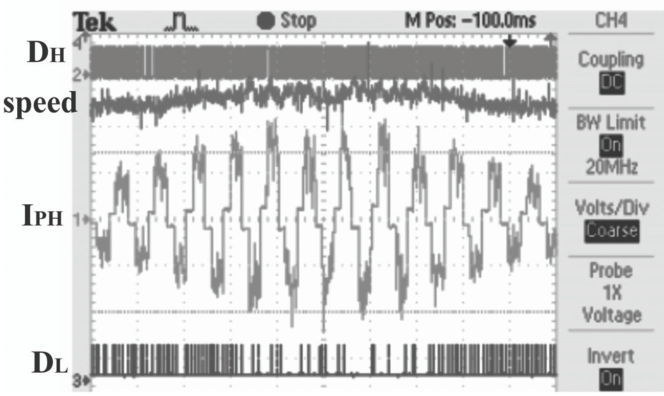

Fig. 16: Phase current waveform, speed signal and D_H and D_L signals, for speed change in generating mode

For a BLDC drives in motoring and generating modes of operation, experimental results show that the system is stable for different fluctuations in load torque and reference speed, as well as for sudden change of DC link voltage.

V. CONCLUSION

Digital control of BLDC machines has several benefits including simple implementation, requirement of no additional hardware and is not computationally intense. Owing to this simplicity, the technique can be implemented on an FPGA instead of expensive signal processing devices. This paper discusses stability issues of digital control strategy for BLDC machines in motoring and generating modes. It also investigates the response of the control strategy for sudden changes in load and commanded speed. In order to assess stability of the proposed control scheme, the system has been analyzed using Lyapunov stability criterion. System response was further evaluated by simulations and verified experimentally for several different operating scenarios.

The proposed strategy is a good fit for several emerging applications including wind, small/micro hydro systems which require a wide speed range and stability. This technique can also be applied as an effective solution for small motors in home appliances with a very narrow speed range (HVAC, multispeed mixers, blowers, vents) due to its low-cost, simple implementation and robustness.

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