Transient Analysis of the Fuzzy Logic-based Speed Control of a Three-phase BLDC Motor

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ABSTRACT

The energy-efficient motor is a vital requirement for modern industrial, automobile, and home appliance drives. Among the special machines, the Brushless DC Motors (BLDCMs) are more attractive to the application engineer because they offer high power-to-weight ratio, compact construction, do not require consistent maintenance, and have an efficiency margin of 85–90%. This study uses FPGA to create fuzzy logic-based speed control for a three-phase BLDCM with transient time domain characteristics. The fuzzy logic-based controller algorithm is implemented using the FPGA Xilinx Spartan board, which receives the actual speed from a position sensor located inside the BLDCM. It calculates the ratio of the duty cycle of the Pulse Width Modulation (PWM) pulse. It is triggered by the driver system of the BLDCM drive to attain the reference speed. The performance characteristics of a BLDC motor drive such as steady-state error, peak overshoot, speed drop under loaded conditions, and restoration time after loaded conditions were analyzed using MATLAB/Simulink 2014. The hardware configuration setup is validated by the suggested system's simulation response.

Keywords-fuzzy logic; Brushless DC Motor (BLDCM); steady state error; peak overshoot; transients; Field Programmable Gate Array (FPGA); Pulse Width Modulation (PWM)

I. INTRODUCTION

Energy-efficient industrial drives are becoming more and more necessary in emerging industrial and residential applications. One such advancement is in BLDCMs [1-3], which have much more efficiency than the single-phase induction motor, high torque-to-power ratio, require less maintenance, and have a fast reaction to commands. BLDC motors need an electronic commutator, which is a major shortcoming. Many researchers describe various control methods applied to BLDCM drive applications. Control of the BLDCM is commonly employed with PWM control techniques. This method is simple and efficient. Its main drawback is the slow response, which is always coupled with hysteresis current control. Hysteresis-current control yields a faster speed response than PWM control. In order to achieve well-regulated speed-to torque control, the Proportional (P) or Proportional Integral (PI) actions were introduced. A PI controller offers low deviation from the desired set point. A wide range of control actions can be accomplished [4-9].

Linear control theory is highly complex and requires extensive knowledge to develop efficient controller designs. Digital signal processors, ultra-high speed integrated chips, and FPGAs are employed to design the digital control algorithm, adding to the complexity of the overall system design [10]. When building an energy-efficient industrial drive application, several considerations must be made. Some of the key problems are the compatibility of the selected hardware technology, the efficiency of the application, power utilization, and the area that must suit the requirements of the algorithm to be implemented. FPGA technology has lower power consumption and a high level of parallelism in nature, which offers higher throughput compared to DSP [11]. Hence, the FPGA Xilinx Spartan 3E is used in this paper to implement a PWM module, a speed sensing module, and a fuzzy logic control algorithm for the speed control of a BLDCM drive. The above module program is written in VHSIC (Very High-Speed Integration Circuit) Hardware Description Language (VHDL).

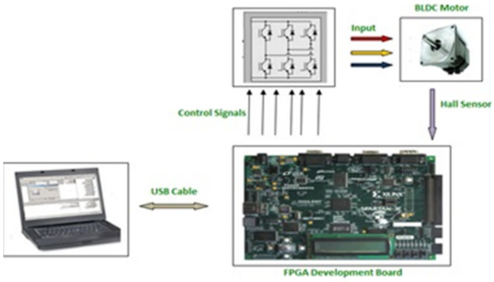

Fig. 1. Proposed block diagram of the 3-phase BLDCM control.

II. SENSOR BASED CONTROLLER FOR BLDC MOTOR

The speed of the BLDC motor is measured by using a Hall sensor [11-12]. It is calculated from the output of the Hall sensor, which senses information about the rotor position of the BLDC motor. The error between the reference and the actual speed of the BLDC motor is given to the fuzzy logic speed controller, which generates the command or reference current. The hysteresis current regulator provides the firing currents to the inverter, whose output is generated based on the difference between the actual phase currents and the reference currents. In this paper, the three position sensors A1, A2, and A3 are installed at the non-rotating end of the motor. They measure the rotor position every 120 degrees. One of the Hall sensors' condition changes. The electrical rotation of a BLDC motor does not imply the motor's single mechanical rotation, which is decided by the rotor pairs [9]. The commutation instants with the PWM signal are driven to the 3-phase inverter of the BLDCM. This helps to create a constant torque and to reach the desired machine speed [13, 17].

III. CONCEPT OF THE FUZZY CONTROLLER

The fuzzy control algorithm has 2 inputs and 1 output. One input is the deviation of the set point speed with the actual speed and the other input is the derivative of error. The output of the fuzzy system is the input of the hysteresis control block. The hysteresis control takes care of the limit of the load current within a limited range [7]. The internal process of the fuzzy logic system is shown in Figure 3 [18]. The membership of the error input and its change spread in (-13, 13) and (-5, 5), respectively [19]. This is because the fuzzy logic controller depends on model behavior knowledge of the data. The membership value for the input and output function of the error values in earlier works with PI controller falls in the zone of (-13, 13). Similarly, the change in error value falls in the zone of (-5, 5) in my earlier works regarding the PI controller. This is the main reason the membership function and the change in error values in the present fuzzy logic controller have been chosen as (-13, 13) and (-5, 5), respectively. The considered membership function is a triangular membership function. In this paper, a triangular membership function of a fuzzy variable is used as shown in Figure 2. The membership function is divided into 7 categories [8]. The next form finds the new duty cycle values from the fuzzy rule base. The 49 rules are formed based on the previous experience and the knowledge about the behavior of the system using the "IF THEN" statements.

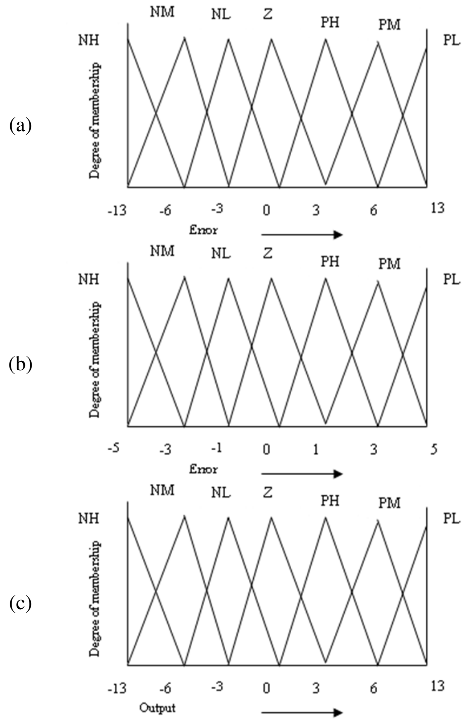

Fig. 2. Evaluated values of the membership function of the fuzzy control algorithm.

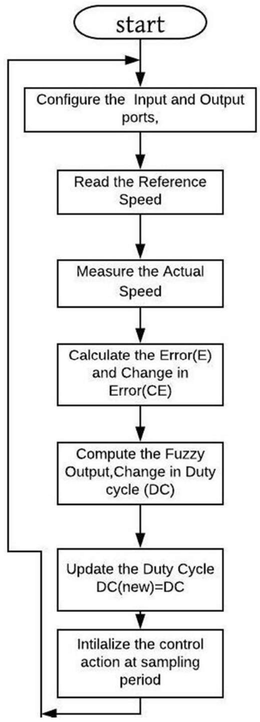

Fig. 3. Flow chart of the speed regulation control algorithm.

This new duty cycle output is in the fuzzy variable, which is to be converted into a real-time numerical value by using the defuzzification process. In this work, the centroid defuzzification method is used. The switches receive a variable duty cycle of the PWM signal. The control regulates the chopping of the provided voltage to the motor thereby controlling the motor speed [20].

IV. SIMULATION RESULTS

Simulations were conducted in MATLAB/Simulink. The fuzzy-based control algorithms are tested against different speed and load conditions. The simulation results are shown in Figure 5.

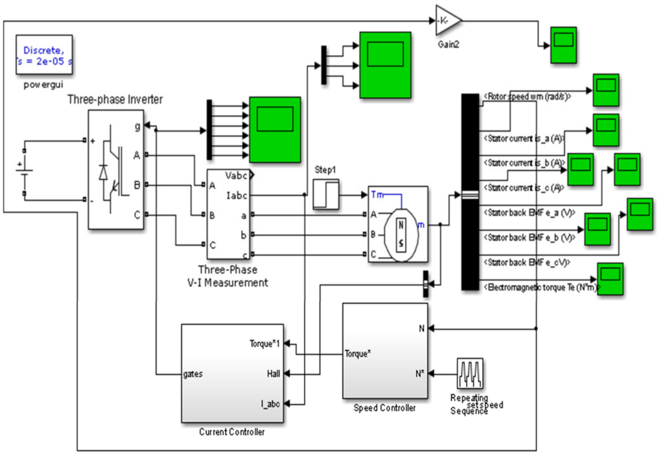

Fig. 4. Three-phase BLDCM fuzzy control algorithm modeled in Simulink 2014.

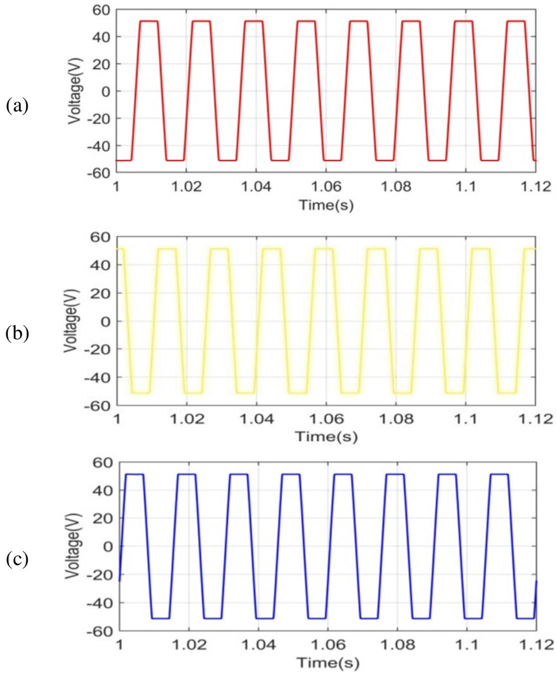

Fig. 5. (a) R phase BEMF waveform, (b) Y phase BEMF waveform, (c) B phase BEMF waveform at the desired rotor speed of 2000 rpm.

The peak overshoot in the speed response of a BLDCM drive using the fuzzy control algorithm is depicted in Figure 7. It can be understood that the motor speed settled down at the reference value with less oscillations and lower magnitude and the speed variable is smooth, for the scheme of fuzzy logic control. From Figure 7, a steady state error with a value of 0.025 % occurs in the BLDC motor, when it is operated during the speed of 2000 rpm.

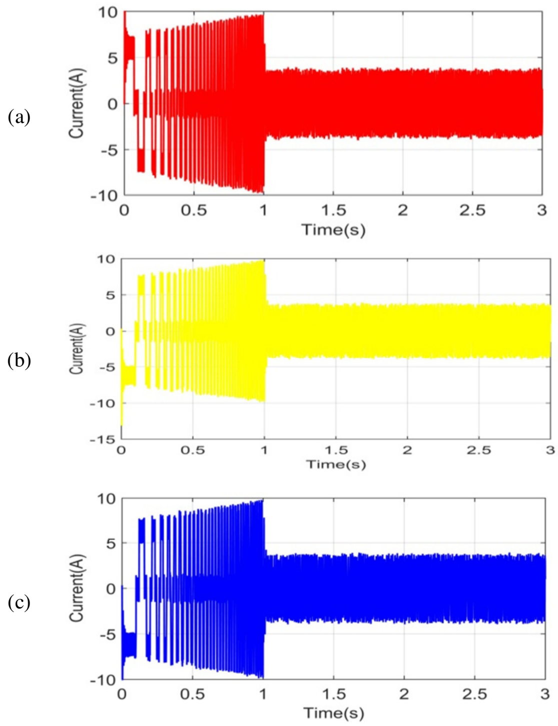

Fig. 6. (a) R phase stator current, (b) Y phase stator current waveform, (c) B phase stator current at the desired rotor speed of 2000 rpm.

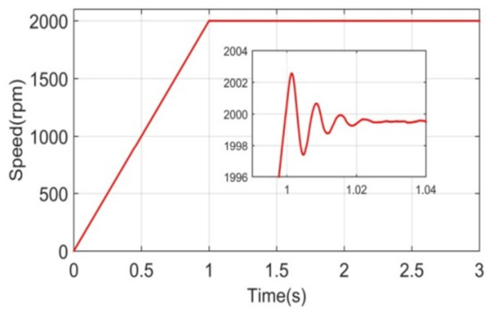

Fig. 7. Siulation rotor speed response when the BLDCM runs at the desired rotor speed of 2000 rpm.

TABLE I. BLDCM SPECIFICATIONS

Specifications	Parameters	Unit
Rated power	60	W
Rated voltage	24	V
Rated torque	0.15	Nm
Rated speed	3000	rpm

V. HARDWARE SETUP

The suggested hardware includes a 3-phase BLDC motor, a 3-phase inverter that uses MOSFETs, an opto isolator, driving circuits, etc. (Figure 9). The Xilinx Spartan FPGA produced the PWM signals. These signals are driven by an IC buffer and the output from the buffer is fed to the opto isolator to isolate the PWM signals from the high voltage section.

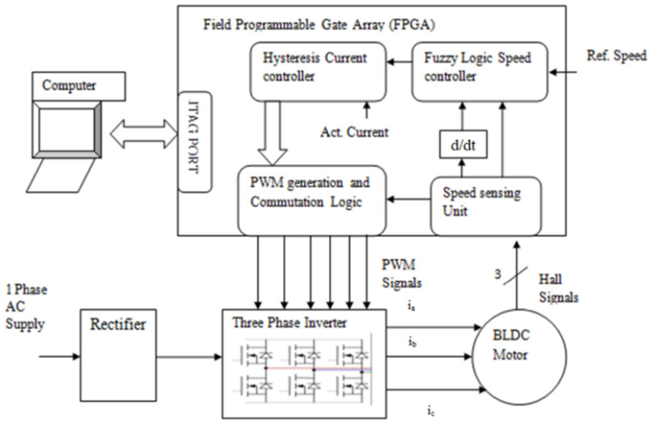

Fig. 8. Detailed block diagram of the fuzzy logic assisted drive – real time implementation by Xilinx FPGA.

The properly installed Hall effect sensor on the 3-phase BLDC motor transmits a signal to the FPGA board, which evaluates the speed and gets the user-desired speed**.** It compares the reference and actual speeds and calculates the difference. After receiving the speed error, the fuzzy logic controller calculates the PWM signal's duty cycle to produce the desired speed. The PWM signal is combined with the commutation logic and is fed to the driver system of the motor. Electronic commutation is needed for motor rotation with the help of the commutation cycle. The FPGA board creates the PWM and the commutation signal depicted in Figure 10.

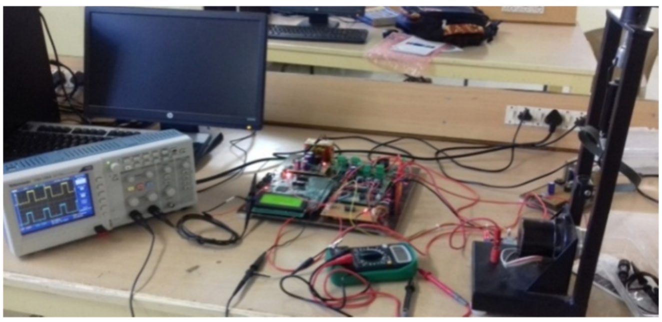

Fig. 9. Real time implementation of the suggest system by Xilinx FPGA.

The Xilinx Integrated System Environment 11.2 is used to edit, compile, synthesize, and download the code onto the Xilinx Spartan 3E board. VHDL language was used to develop the control algorithms like fuzzy logic, hysteresis logic, PWM logic, and speed estimation modules. The switching pulses for the 6 MOSFETs of the driver section and the R-Y, Y-B, and B-R phase voltages of the 3-phase of the BLDC motor were recorded with a digital scope. Channel 1 of the oscilloscope shows the switching pulse for the upper switch of the first leg of the VSI (Figure 10(a)), Channel 2 (Figure 10(a)), shows the PWM output of the fuzzy logic controller, which is fed the switching pulse for the lower switch of the first leg of the VSI. The R-Y, Y-B, and B-R phase voltages of the 3-phase BLDCM running under 2000 rpm were recorded.

TABLE II. SUMMARY OF THE USED COMPONENTS IMPLEMENTED WITH THE XILINX FPGA

Logic components (in numbers)	Available	Utilized components	% of used components
Xilinx slices	768	297	38
Flip flops	1536	177	11
LUT	1536	472	30

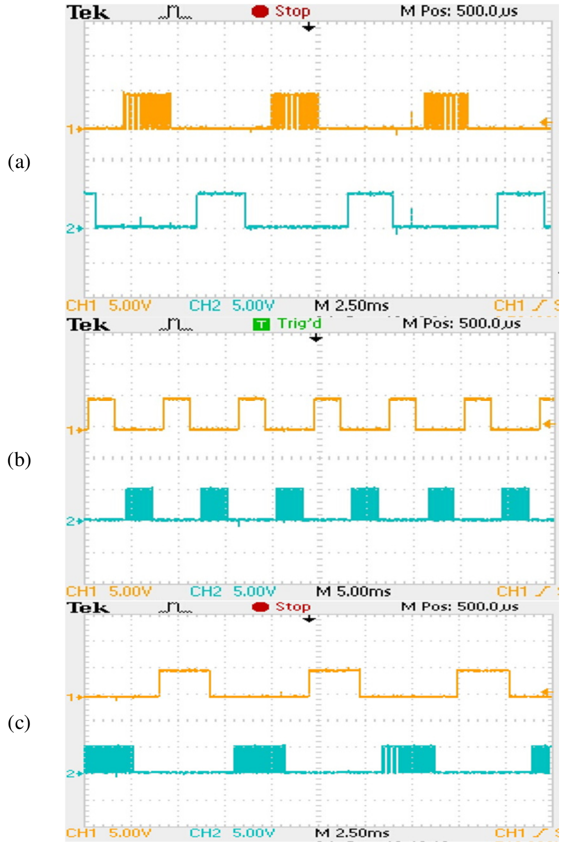

Fig. 10. Switching pulses at the (a) first leg of the inverter, (b) second leg of the inverter, (c) third leg of the inverter when BLDCM runs at 2000 rpm.

VI. TRANSIENT RESPONSE ANALYSIS

The speed drops at a step change in load by 0.5% when 80% of the maximum load is applied to the fuzzy controller-based BLDC motor drive. The speed drops at a step change in load by 0.18% when 20% of the maximum load is applied to a fuzzy controller-based BLDCM drive. Figure 10 demonstrates that a restoration time of 0.024s is required after a sudden change in the load to reach the set speed when 80% of the rated load is applied. Figure 12 demonstrates that a restoration time of 0.02s is required after a sudden change in the load to reach the set speed when 20% of the rated load is applied. The transient performance of the BLDCM drive by a fuzzy algorithm is measured and recorded for various speeds as shown in Table III. The performance characteristic curves are plotted from the simulation results. Figure 15 shows that the speed drops at a step change in load by 0.18 to 0.5% when the applied load varies from 20% to 80% of the maximum load for the fuzzy controller-based BLDCM drive. Hence, when the load torque increases, the speed drop also increases. The restoration time required also increases from 0.02 to 0.025s after a sudden change in the load to reach the set speed when the increased minimum load reaches the full load, as shown in Figure 16.

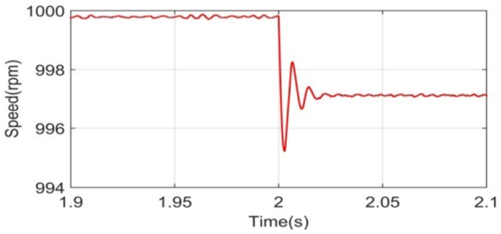

Fig. 11. Rotor speed response under 1000 rpm for the 3-phase BLDCM when 80% of the rated load is applied at 2s.

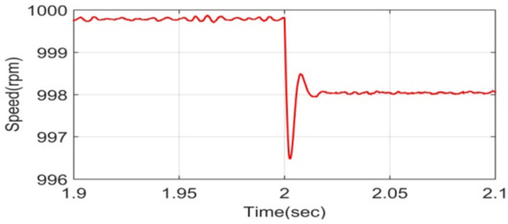

Fig. 12. Rotor speed response under 1000 rpm for the 3-phase BLDCM when 60% of the rated load is applied at 2s.

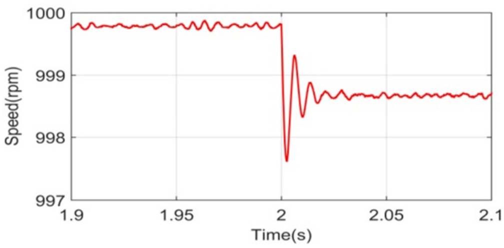

Fig. 13. Rotor speed response under 1000 rpm for the 3-phase BLDCM when 40% of the rated load is applied at 2s.

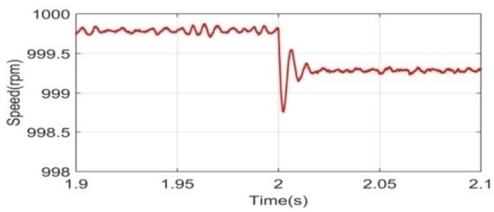

Fig. 14. Rotor speed response under 1000 rpm for the 3-phase BLDCM when 20% of the rated load is applied at 2s.

The cross comparison of Figures 11-16 clearly shows the enhanced control of the fuzzy logic controller in speed and load variations of the BLDCM. While using the fuzzy logic controller and the speed response in steady state condition, the actual speed of the BLDCM is almost the same as the set point speed. The overshoots present in the speed response are lesser and the load disturbance rejection ability is good. The fuzzy logic controller gives a better transient response according to the applied set speed and load variation conditions. The proposed fuzzy logic-based controller of the BLDCM drive is suited for applications where the adjustable speed and load variations frequently occur.

TABLE III. TRANSIENT ANALYSIS OF FUZZY CONTROL ALGORITHMS IMPLEMENTED BY XILINX FPGA

Percentage of load applied at rated load	Speed drop (rpm)	Restore time (s)	Steady state error (%)
20	998.2	0.02	0.7
40	997.5	0.02	1.3
60	996.5	0.023	1.9
80	995	0.024	2.9

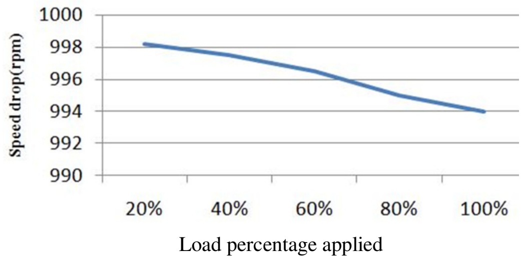

Fig. 15. Variation of load torque to the motor and the speed drop.

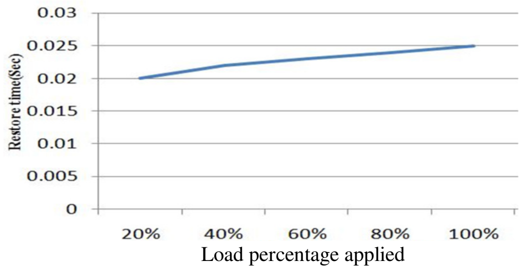

Fig. 16. Variation of load torque to the motor and restoration time to recover the desired speed.

VII. CONCULSION

The findings demonstrate that better characteristics of transient time domain (in comparison with the PI controllers) were obtained when a digital fuzzy control algorithm is implemented on an FPGA in BLDCM speed control [7]. By operating the BLDCM under various load situations, a load test was carried out to confirm the efficacy of the fuzzy control. The performance of BLDCM drive will be enhanced even further by the use of the adaptive fuzzy- neural mechanism.

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