Available Online at www.ijecse.org ISSN- 2277-1956

Development of a Practical Low-Cost µC based Brushless DC Motor Controller using Proteus

Y. L. Karnavas [1] , Ch. L. Liagkos [2]

[1 2] *Department of Electrical Engineering, Lab. of Electric Machines & Installations,*
Technological Educational Institution of Crete, Heraklion, Hellas
[1] *Email- karnab@staff.teicrete.gr*

Abstract- Simulation, design and prototype construction of a low cost three phase permanent magnet (PM) brushless DC (BLDC) motor controller for low power applications is studied in this paper. The drive circuitry is based on the PIC16F877A microcontroller (µC), which –among others- performs pulse width modulation (PWM) control for a 6-step, 120-degree trapezoidal PM BLDC motor drive. The specific processor is a widely used one and its characteristics are judged excellent in conjunction with its low cost. The prototype controller developed can perform rotation direction control, commutation sequence, speed control and reading Hall sensor signals. The controlling technique chosen is a "sensored type" one. The main reason for that, except control simplicity is the need for both low-speed and high-speed applications. The application of Proteus Virtual System Modelling (VSM) software is also introduced in the paper. This software is used as a real-time simulation tool, in order to verify the performance of the BLDC motor drive, prior to its hardware implementation. Through virtual simulation of all the components used, the relevant results can be analyzed and monitored. Verification of the experimental results and validation of the simulated circuit has been done through the comparison of the results.

Keywords – Brushless DC motors, Microcontrollers, Proteus VSM, Pulse Width Modulation, Permanent Magnet Machines.

I. INTRODUCTION

BLDC motor consists of a permanent magnet synchronous machine (PMSM), with either sinusoidal or trapezoidal back EMF, driven by an inverter. BLDC motors in general, have fast dynamic response, good torque–speed characteristics, high efficiency, long life, etc., and therefore are increasingly penetrating the market of home appliances, HVAC industry, and automotive applications in recent years. In terms of construction, PM-BLDC motor is an inside–out brushed DC motor as the armature is in the stator and the permanent magnets are in the rotor. There are four main parts comprising the relative drive system of this kind of motor: a power converter, a PMSM, current transducers and a suitable control algorithm. The electromechanical conversion is being performed by a 3-phase inverter which transforms power from DC source to a proper AC form to drive the PMSM [1]. A crucial feature of these drives concerns the rotor position detection i.e. to know the exact time instant in order for the winding currents to be commutated. There are actually two ways of doing that: a sensored and the sensorless method, with the first one to be the easiest. A typical sensored PM-BLDC motor drive system topology is shown in Fig. 1. The Hall sensors' feedback signals (rotor position loop) are being eliminated in sensorless type control, but then, the need for a higher performance µC, as well as a larger code and memory is inevitable [2]. However, in spite the fact that the material cost reduction is obvious and seems as an advantage in sensorless control, there are two main disadvantages coming out regarding its performance: a) it is non-applicable for very low speed applications since the rotor should be rotating in a certain speed in order for the back- EMF being generated to be sufficiently large to be sensed, b) the back-EMF drive loop can go "out of lock" when anomalous load changes happen to the motor rotor [3]. There are quite a few characteristics by which a PM- BLDC motor can be classified. Some of them are the placement of the magnets, the material of the magnet (i.e. ceramic, ferrite, rare earth etc), and the shape of the back-EMF waveform (i.e. sinusoidal or trapezoidal). Another important issue is the torque ripple. The electronic current commutation and the back-EMF type influence that [4]. When sinusoidal back-EMF is used, the torque ripple is smoother and smaller; while in trapezoidal back-EMF the torque ripple is larger but the produced torque is higher [5]. Fortunately, if the motor armature phases will be supplied by quasi-square currents then the ripple-free operation is guaranteed (in sinusoidal type the currents should be sinusoidal for the same effect). In sinusoidal back-EMF type and for optimal operation, the rotor position is necessary to be known at any time instant. Thus, a high resolution position sensor should be used and also this leads to the complexity of the software and hardware design. Instead, the simplicity that is introduced in trapezoidal type makes it a more attractive choice as well as cheaper and yet high efficient [6]. The development, design and prototype construction of a low cost PM BLDC motor drive for low power applications is shown in this work. The application of Proteus VSM is also introduced here. Real-time simulations have been performed and used for the prototype construction. Through the relative comparison of the simulation and the experimental results, the verification and the validation of the circuit has been done.

II. PM BLDC Motor Controller Operation

A. Power Inverter –

Power inverters are relatively simple circuits which use appropriate semiconductor switching devices (i.e. MOSFET, BJT, IGBT etc). Also, inverters can be constructed to supply 1-phase or 3-phase AC signals to motor windings. In a 3-phase inverter, the control signal can be either with 120^o conduction or 180^o conduction. In this work, 120^o conduction is used, whereas each transistor (Q_1-Q_6) is turned "on" for duration of 120^o (Fig. 2). Due to the fact that only two power switches are "on" at any instant, only two load terminals are connected during any interval, while the third one is left open (Y-connected windings). Thus, the resulting voltages (v_a, v_b, v_c) are of a quasi-square waveform (Fig. 2). On the other hand, since sensored controlling technique is used, a suitable sensor (widely used) is Hall effect sensor, even if it is a low resolution one. The latter is not a disadvantage because the trapezoidal type back-EMF waveform is adopted. The main μC unit gets feedback from the three Hall sensors and each one of them is out of phase to each other by 120^o. Based on the polarity of the magnetic pole close to the sensor, a logic signal ("1" or "0") will be provided. This is actually an indication that the certain pole (i.e. south or north) is passing nearby. As it can be seen in Fig. 3, one of the Hall sensors appears a logic transition every 60^o. In order for the electronic commutation to be performed by the main μC unit, the signals from the sensors are fed to it. Certain sequence patterns are already stored in its memory, and this commutation mechanism is shown in Fig. 3. With respect to the figure, each sensor is conducting every 180^o and for a duration of 180^o. After 120^o from the conduction of the first sensor, the next sensor starts to conduct and so on. To satisfy the need for constant output power and constant output torque, the motor stator windings are driven with current during the flat portion of the back-EMF waveform [7].

B. Trapezoidal Control of BLDC

It is known that the use of μC and suitable electronic circuitry is necessary for a highly efficient variable torque and variable speed motor control system. At the same time, a PM BLDC motor is preferred due to its advantages over other electric machines for low-cost electric drive applications [7], [8]. The controlling method adopted can also compensate any possible high-cost setup. A very popular controlling method due to its simplicity is the 120^o 6-step method one [9].

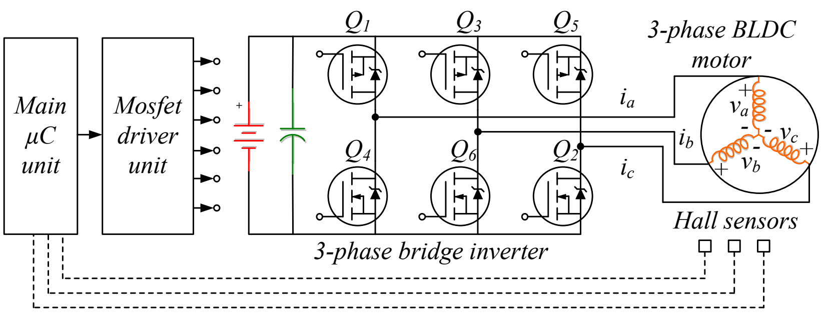


Figure 1. Typical sensored PM BLDC motor drive system topology.

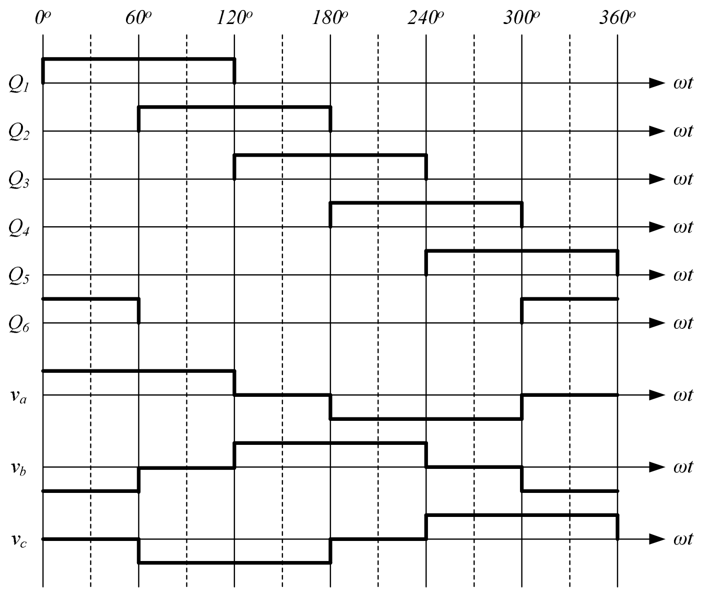


Figure 2. Power transistors' gating signal for 120° conduction.

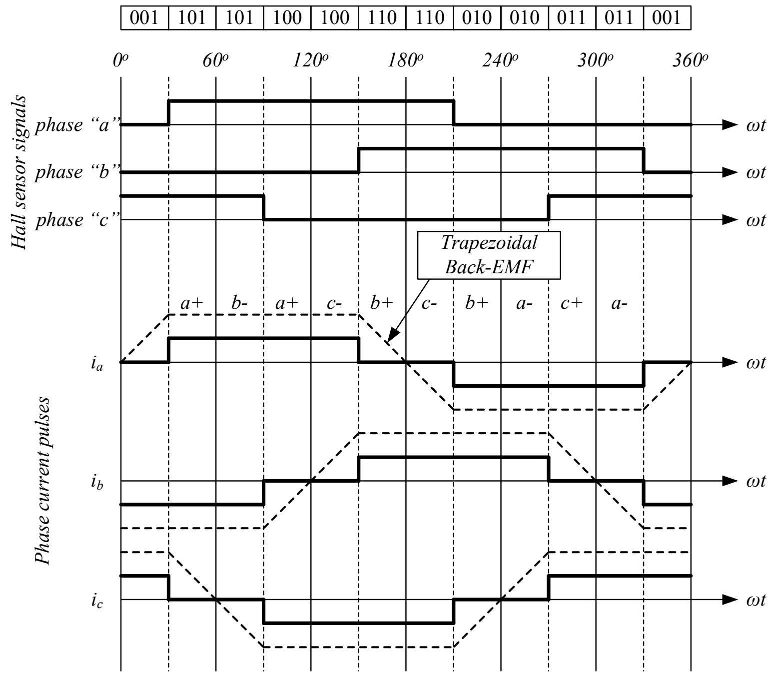


Figure 3. Signalling of Hall sensors, back-EMF and reference currents.

The idea behind this method is that, at any time instant, the stator current conduction is performed such that two phases (of a stat connected winding) are connected in series with the DC bus, while the third one is left open. In this controlling type, the stator current conduction happens such that only two phases of star connected winding are

IJECSE
International Journal of Electronics and Computer Science Engineering
WWW.IJECSE.ORG

connected in series with DC bus and the third winding is open [7]. PWM through a full bridge inverter (working in open loop voltage mode) is the most common and reliable technique for variable speed control applications [10], [11]. The desired speed regulation point is obtained by just setting the duty cycle ratio (0%-100%) of the PWM and that is why simplicity and efficiency are secured. If we assume that there are two sides in the bridge (Fig. 1), the high (HS) and the low one (LS) then it can be seen from Fig. 2 that at any time instant only two transistors are ON, one in HS and the other in LS [12]. By this way of conduction, the Kirchoff's Current Law is satisfied since (during any 60^o interval) one phase has zero current, one phase has "positive" current and the last one has "negative" current (indicated by "+", "-" in Fig. 3).

III. APPLICATION OF "PROTEUS VSM" SOFTWARE

A. The Platform –

The usual practice followed by an industry embedded designer includes: a) experiment equipment setup, b) μC "flashing" with the source code, c) debug the program, d) taking the μC out of the development board, e) put it on the circuit under test and f) run it. When there is even a simple error, the aforementioned steps should be repeated until the desired design target is achieved (Fig. 4). It should be noted that this procedure refer also to any of the external printed circuit boards (PCB) needed. Since it is impossible for the developer (and for us) to design, built and test the overall prototype with one trial [13], a modeling and simulation technology should be used before Establishing the BLDC motor system model and, at the same time, reduce cost, risk and design cycles. Matlab/Simulink is a powerful simulation platform for BLDC motor drive systems. The main disadvantage though, is that it cannot give simulation results based on the hardware implementation, real-time hardware analysis and real component operations and performance [14]. Since for industrial applications, low-cost is of primary concern, the use of another powerful software package is introduced here the Proteus VSM by Labcenter Electronics Ltd. In order to come out with the complete BLDC motor drive circuit, every necessary component needed is simulated first and the final ("first-time" working) hardware construction follows (Fig. 4).

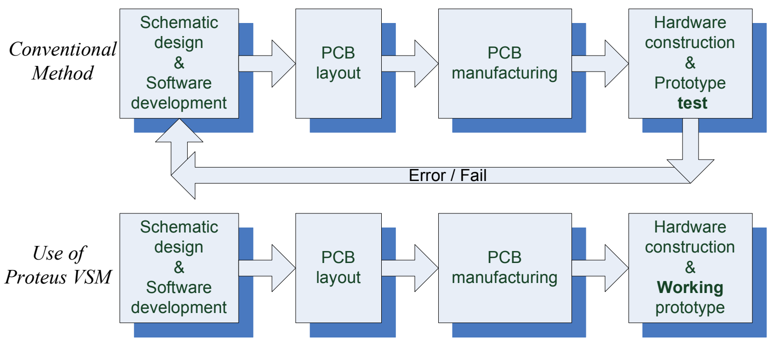
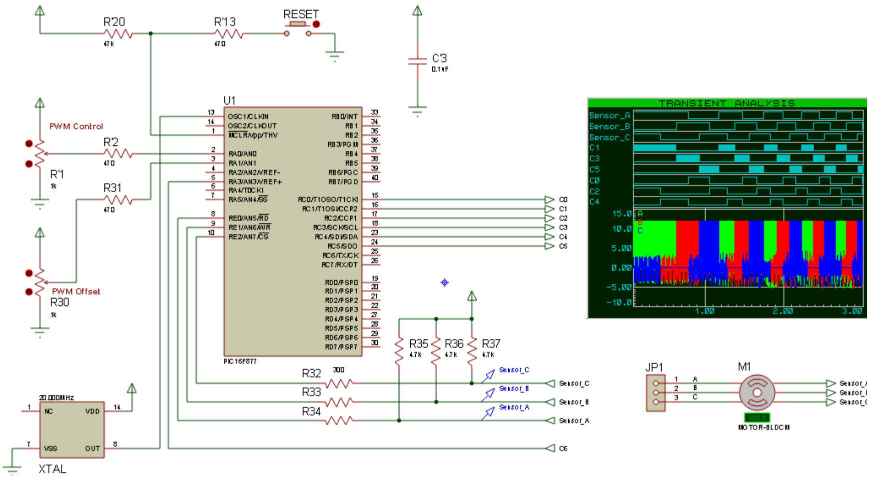


Figure 4. Hardware prototype development steps.

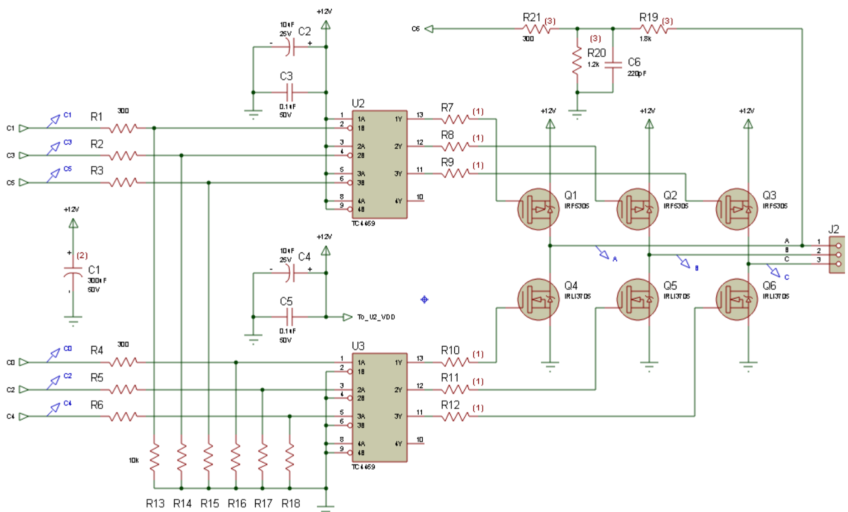
As it was mentioned before, the traditional process of designing o PM BLDC controller is an intuitive trial and error process [10]. That is why Proteus VSM can be considered an attractive solution to this problem. It offers the ability to simulate low and high level μC code which works with assembler and compiler. The real-time interaction of the software running on a μC and any other component (either analog or digital) connected to it is a unique ability of the Proteus VSM and its most important feature. [13]. Furthermore, it is the only package (currently) with the largest range of μC models and extremely large components libraries, which gives the designer the ability to test any variation of them for the same application. [15]. As far as embedded system design, Proteus VSM is the best simulation software up to now [16]. The actual procedure for testing the μC performance and functionality includes three main steps: a) the creation of the external schematic circuit to which the μC is connected, b) the program source code writing and its building (assembled) and c) the attachment of the build code to the μC and the simulation running. After these steps, the Proteus VSM can provide the BLDC motor drive model and all the circuit and motor operations can then be animated and simulated in real-time.

B. Design and Simulation Results of BLDC Motor Drive –

Fig. 5 shows the schematic circuit of the BLDC motor drive system. It consists of two main parts a) the main μC circuit and its interactive elements and b) the motor drivers' circuit. As it can be noted, a few components besides the μC are needed for a complete and functional structure of the BLDC controller. In particular, one needs, a μC (here we chose the PIC16F877A for its characteristics and low-cost), a crystal resonator (of a 20MHz frequency) for the μC clock, some resistors and capacitors, 2 logic-input CMOS quad MOSFET drivers (the TC4469 used are ideal for driving high current motors in a H-bridge configuration) and 6 MOSFET (3 of P-channel type –i.e. IRF5305-and 3 of N-channel type –i.e. IRLI3705-) for the bridge inverter, all of them very cheap. Finally, both the PWM duty-cycle ratio (DCR) and the PWM offset are tuned with the aid of two potentiometers.



(a)



(b)

Figure 5. BLDC motor controller schematic a) μC circuitry, b) motor drivers and MOSFET circuit.

From the software perspective, Proteus VSM allows debugger compatibility (as a plug-in) with the MicroChip's MPLAB IDE through its viewer (Fig. 6). Then, the designer is able to check his assembly code and run the simulation of the schematic he has create as there is an embedded capability in the package. The main advantage of this is that there is no need for an in-circuit debugger (like i.e. ICD2) in conjunction with the development board. Thus, the design, modification and testing of the source code is much easier and faster. Fig. 6 shows the MPLAB IDE main window where the simulated circuit, the software debugging window and the output window are depicted. The transient analysis capability of the software (by which digital and analogue data can be viewed at the same time) was used in order to obtain the simulation results presented next.

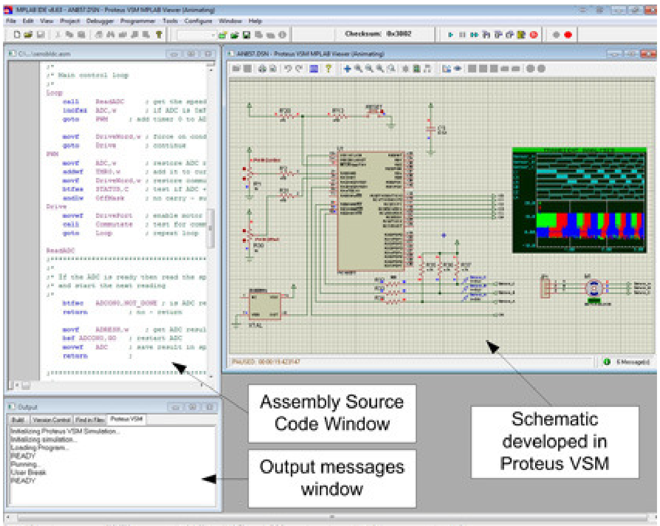


Figure 6. The Proteus VSM as a debugging tool in MPLAB IDE.

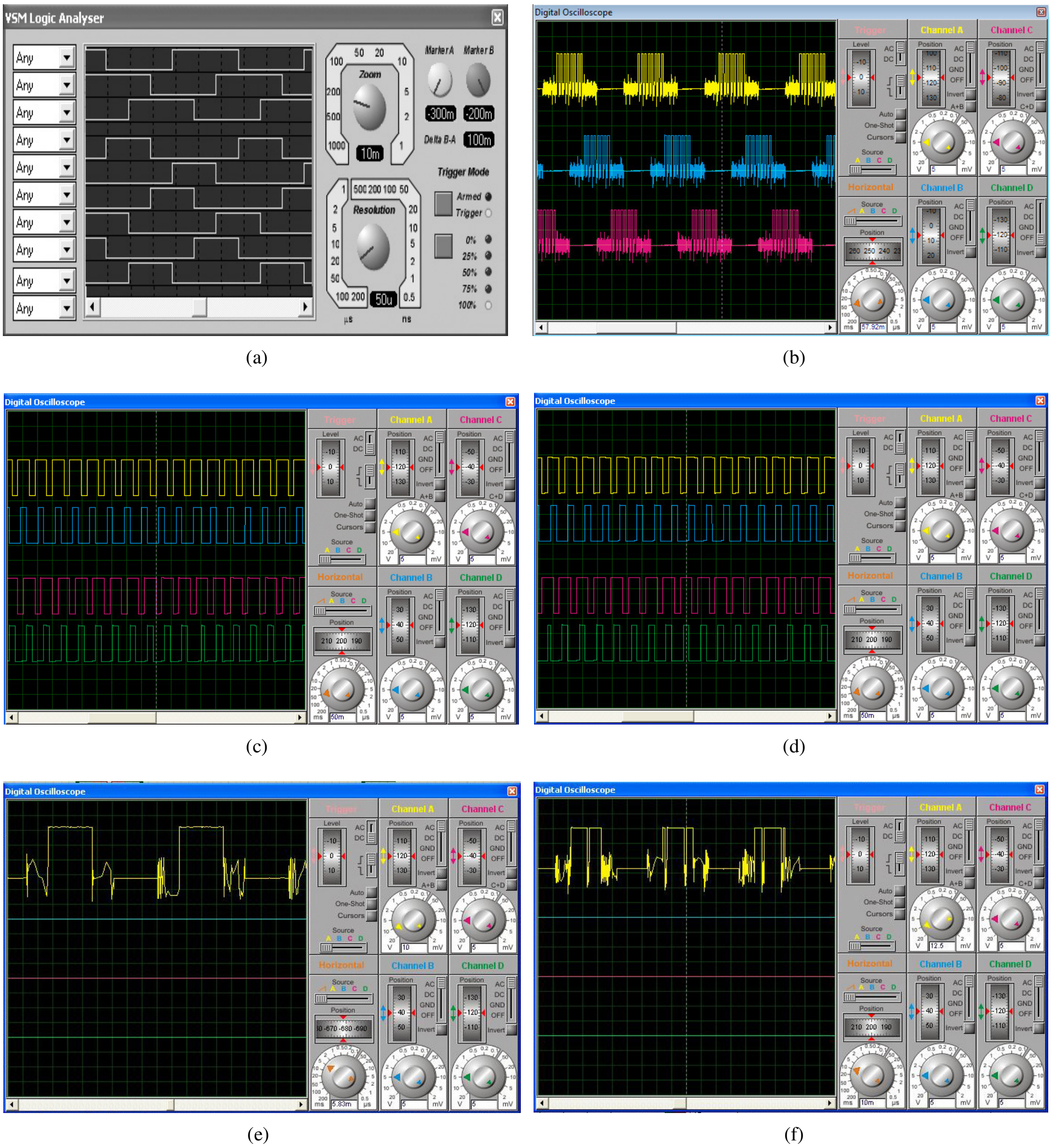
Fig. 7(a) depicts the three Hall sensor signals (the first 3 waveforms) versus μC's output port "C" signals (the rest six waveforms). Actually the μC generates 3 PWM signals to feed the HS of the bridge inverter. Fig. 7(b) shows the three terminal voltages of the BLDC motor (phases "a", "b", "c" with the order shown). The MOSFET drivers' output pulses are shown in Figs. 7(c)-(d). These signals refer to the high side and low side of eash of the three phases and are responsible for the correct current commutation according to the controlling method used. Finally, the MOSFET output pulses for phase "a" are depicted in Figs. 7(e)-(f), for PWM duty cycle 100% and 75% respectively. These indicative results prove that Proteus VSM and the built circuit are performing current commutation as should be. Now, the electronic components used in this circuit simulation can "transferred" into hardware construction.

IV. Hardware Implementation & Results

A. BLDC Motor Controller Hardware Construction –

At this crucial stage, we are ready to validate the simulation performed by Proteus VSM. For practical reasons, the hardware circuitry comprises from three separate modules: a) the μC main module, b) the bridge driver module and c) the bridge itself. Additional protection circuits for over-heating and/or over-current have not been implemented here as this is just a prototype, but they should be included in an industrial product. Fig. 8 shows the first two modules while Fig. 9 shows the third module and the overall bench setup along with the BLDC motor and relevant measurement equipment. It should be noted that all the components used are exactly the same as the designed/ simulated circuit in Proteus software. Experimental results were mainly obtained with a dual channel, 60MHz Tektronics oscilloscope. The BLDC motor is a Hitachi model, type BOGO9A152F50, 35 volts, 3 amperes. The CMOS quad MOSFET drivers (TC4469) could not be found in the market in DIP package, so used SMD package was and relevant adaptors were constructed.

IJECSE
International Journal of Electronics and Computer Science Engineering
WWW.IJECSE.ORG



(a) (b) (c) (d) (e) (f)

Figure 7. Indicative simulation results: a) Hall sensors ("a", "b", "c") and μC output port signals (C0-C5) with the order shown, b) Typical waveforms of BLDC motor terminal voltages, c) MOSFET drivers' output pulses (with the order shown): high side for phase "a", low side for phase "a", high side for phase "b", low side for phase "b", d) MOSFET drivers' output pulses (with the order shown): high side for phase "a", low side for phase "a", high side for phase "c", low side for phase "c", e) MOSFET output for phase "a" (duty cycle 100%), f) MOSFET output for phase "a" (duty cycle 75%).

B. Experimental Results –

Fig. 10 shows typical experimental results obtained from the operation of the prototype described. In Fig. 10(a)-(b) MOSFET drivers' outputs are shown, which drive the high side of the MOSFETs (Q_1-Q_3), for the three phases

ISSN 2277-1956/V1N3-01-06

(“a”, “b”, “c”). The corresponding outputs on the low side are shown in Fig. 10(c)-(d). The relation between feedback Hall sensors’ signals (from motor to the μC) on either of the three phases are depicted in Fig. 10(e)-(g). Finally, the bridge inverter output for phase “a” at different PWM duty cycles (100% and 75%) are shown in Fig. 10(h)-(i) respectively. The operation voltage of the circuit for all measurements was 15.2V. For 100% duty cycle, the total load current was measured at 2A, the current per phase at 0.66A and the rotor speed 280rpm. For 75% duty cycle, the total load current was 3.5A, the current per phase 1.16A and the speed measured at 187rpm. Another critical component value, which can alter the overall performance of the controller, is the capacitance connected parallel to the power supply. The capacitance used here was 42.3mF. These results, and other not shown here, are crucial and important because they actually provide validation both for the relevant theory and for the reliability of the Proteus VSM used for the designed PM BLDC motor drive.

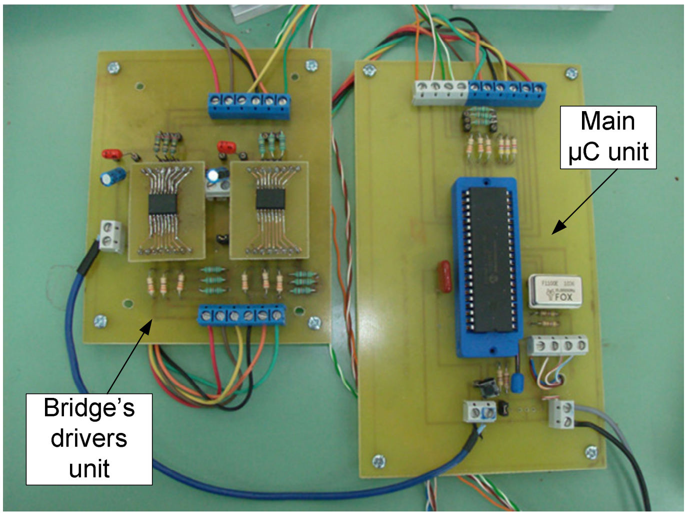


Figure 8. BLDC motor controller prototype developed (inverter module not shown here).

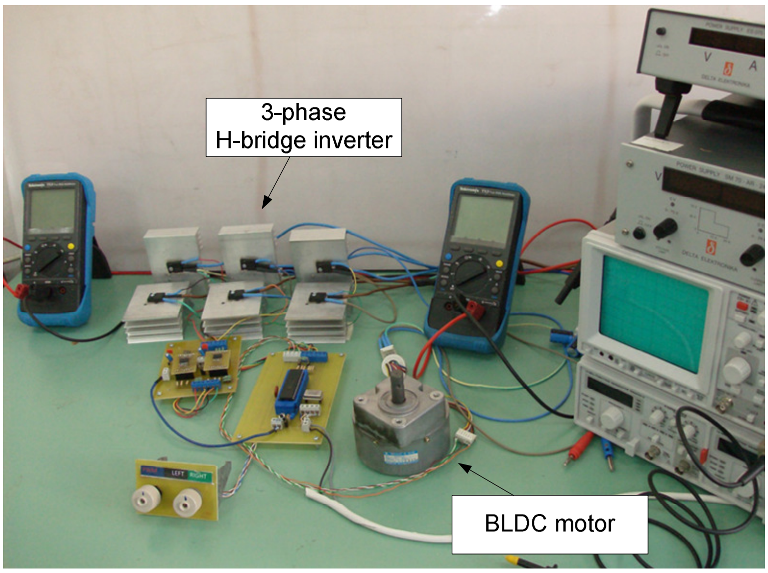


Figure 9. Overall hardware bench setup including BLDC motor.

ISSN 2277-1956/V1N3-01-06

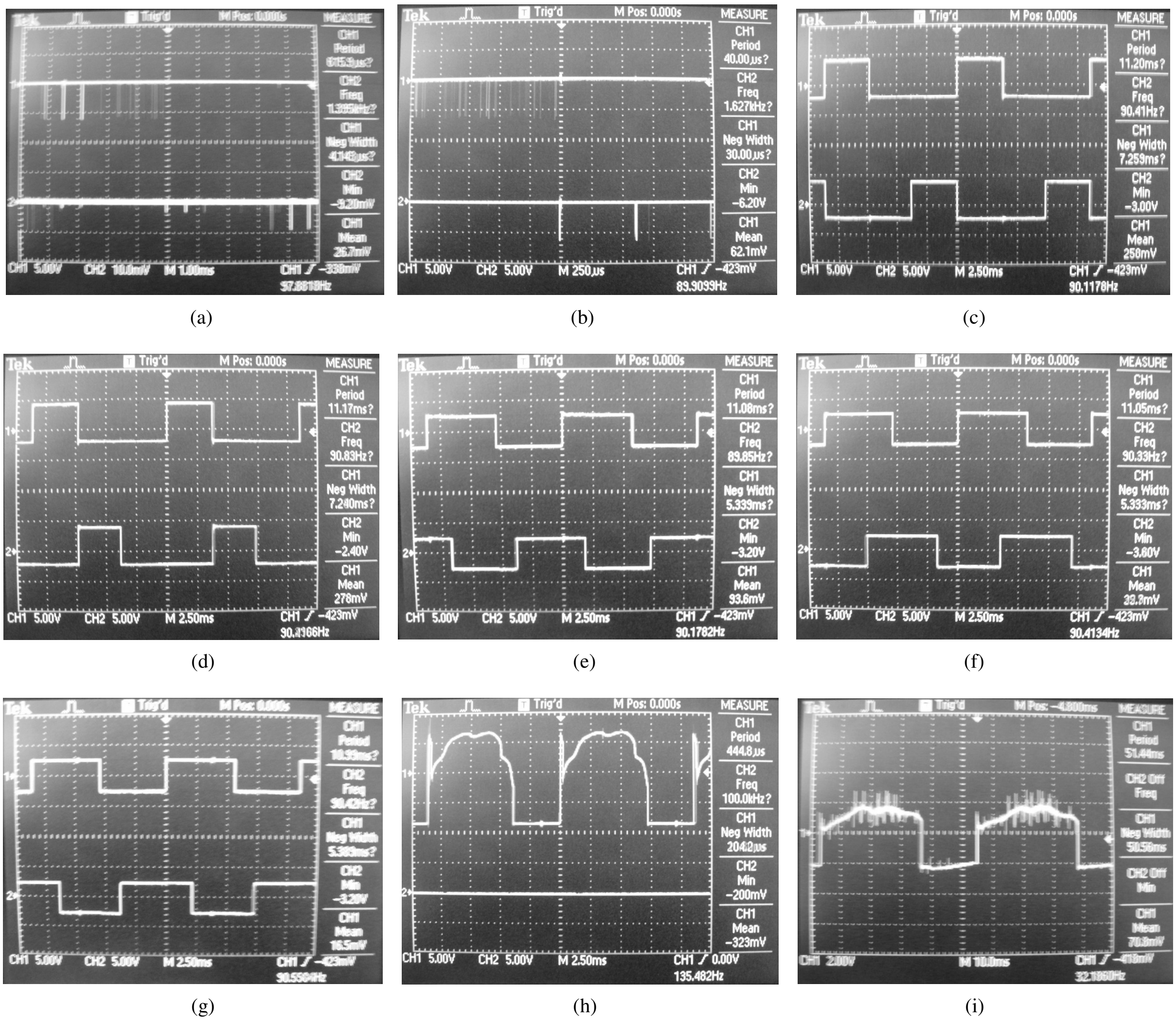


Figure 10. Indicative experimental results: a). high side for both phase “a” and phase “b”, b) high side for both phase “a” and phase “c”, c) low side for both phase “a” and phase “b”, d) low side for both phase “a” and phase “c”, e) Hall sensor feedback signals from phases “a” and “b”, f) Hall sensor feedback signals from phases “a” and “c”, g) Hall sensor feedback signals from phases “b” and “c”, h) MOSFET output for phase “a” (duty cycle 100%), i) MOSFET output for phase “a” (duty cycle 75%).

V. CONCLUSIONS

A low-cost μC based BLDC motor controller for low power applications has been developed through both simulation and hardware modern procedures. The switching technique used is the 120^{o}, 6-step commutation and the performance of the motor drive system was investigated. A sensored type controlling method which utilizes low-resolution Hall sensors was adopted. Since the main controller is based on the very inexpensive PIC16F877A microprocessor, it is believed that the product could have potential capabilities and strong commercial appeal in low power applications. The usefulness and the capabilities of the Proteus VSM software was also applied here, and it was shown that the design and hardware production of a prototype can be easily done through successful simulations, in oppose with the traditional trial and error procedures. The virtual BLDC motor drive model created has been verified through experimental results by comparison with those of the simulation. Since the overall production cost has

ISSN 2277-1956/V1N3-01-06

become a major concern in industrial environments nowadays, it has been made clear that the application of powerful and accurate software packages is an important contribution; their use can lead effectively to the reduction of the product development time. Thus, the reduction of the relevant development cost can be much lower for industrial applications.

VI. REFERENCES

[1] P. C. Krause, O. Wasynczuk and S. D. Sudhoff, "Analysis of Electric Machinery", Wiley-IEEE Press, 2nd Ed., 2002.
[2] T. H. Kim and M. Ehsani, "An Error Analysis of the Sensorless Position Estimation for BLDC Motors", *IEEE Industry Applications Conference, 38th IAS Annual Meeting*, Salt Lake City, UTA, October 2003, vol.1, pp. 611-617.
[3] W. Brown, "Brushless DC Motor Control Made Easy", Application Note AN857, 2002, Microchip Technology Inc.
[4] W. Hong, W. Lee and B. K. Lee, "Dynamic Simulation of Brushless DC Motor Drives Considering Phase Commutation for Automotive Applications", *IEEE of International Electric Machine & Drives Conference, IEMDC '07*, Antalya, Turkey, May 2007, vol.2, pp 1377-1383.
[5] A. Emadi, "Energy-Efficient Electric Motors", CRC, 2005, USA.
[6] P. C. Sen, "Principles of Electric Machines and Power Electronics", John Wiley & Sons, 2nd Ed., 1997.
[7] A. Sathyan, M. Krishnamurthy, N. Milivojevic and A. Emadi, "A Low-Cost Digital Control Scheme for Brushless DC motor Drives in Domestic Applications", *IEEE International Conference of Electric Machines and Drives, IEMDC '09*, Miami FL, June 2009, pp. 76-82.
[8] B. K. Lee, J. P. Hong and M. Ehsani, "Generalized Design Methodology of Reduced Parts Converters for Low Cost BLDC Motor Drives", *IEEE 18th of Applied Power Electronics Conference and Exposition, APEC '03*, Miami FL, Feb. 2003, vol.1, pp 277.
[9] Q. Han, N. Samoylenko and J. Jatckevich, "Average-Value of Brushless Dc Motors With 120 Voltage Source Inverter", *IEEE Transactions on Energy Conversion*, vol.23, no. 2, June 2008, pp. 423-432.
[10] W. C. Chen and Y. Y. Tzou, "Efficiency Optimization for Single-Phase Brushless DC Fan Motors", *IEEE Power Electronics and Motion Control Conference, IPEMC '09*, Wuhan, China, May 2009, pp. 1913-1918.
[11] Y. L. Karnavas, N. P. Polyzos, D. P. Papadopoulos, "On the Design of a Remote Intelligent Excitation Controller for a Synchronous Generator", *in Proc. of 17th Intl. Conf. on Electrical Machines, ICEM '06,* Sept. 2006, Chania, Crete, Hellas, CD Ref. No 78.
[12] N. Mohan, "Electric Drives - An Integrative Approach", Mnpere Publisher, 2003, USA.
[13] B. Su and L. Wang, "Application of Proteus Virtual System Modelling (VSM) in Teaching of Microcontroller", *Int. Conf. on E-Health Networking, Digital Ecosystem and Technologies (EDT)*, April 2010, vol.2, pp. 375-378.
[14] J. Lu, D. Liang, X. Feng, "Simulation of linear brushless dc motor speed-controlled system based on MATLAB/SIMULINK ", *in Proc. of 6th Intl. Conf. on Electrical Machines and Systems, ICEMS '03*, Beijing, China, Nov. 2003, vol. 2, pp. 696-698.
[15] M. Bates, "Interfacing PIC Microcontrollers, Embedded Design by Interactive Simulation", Newnes (Elsevier), 2006.
[16] S. Wei and L. Jianhui, "The Construction of Single-Chip Virtual Experiment Platform Based on Proteus", *Int. Forum on Information Technology and Applications, IFITA '09*, Chengdu, China, May 2009, vol.1, pp 548-550.

VII. BIOGRAPHIES

Yannis L. Karnavas is Assistant Professor at the Dept. of Electrical Engineering, Technological Educational Institution of Crete, Heraklion, Crete, Hellas. He has engaged in teaching and research activities the last 17 years. His fields of expertise are the analysis and modeling of power systems and electric machines, the design and application of various types of controllers and artificial intelligence methods application to them. Dr.Eng. Y.L. Karnavas has published several papers in various national, international journals and conferences as well as book chapters in international engineering books. He has also participated in research projects as research leader or scientific associate.

Christos L. Liagkos is a graduate Electrical Engineer from the Dept. of Electrical Engineering, Technological Educational Institution of Crete, Heraklion, Crete, Hellas. He has done extensive work on the field of μC electronic circuitry. Currently, he is focusing on analysis of permanent magnet electric machines and their controller implementation.

ISSN 2277-1956/V1N3-01-06