EXPERIMENTAL ASSESSMENT OF TRAPEZOIDAL COMMUTATION AND FOC PERFORMANCES OF 3-PHASE PERMANENT MAGNET BRUSHLESS MOTOR

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ABSTRACT

In this paper, we present experimental results of 3-phase permanent magnet brushless motor speed control using trapezoidal commutation (BLDC mode) and Field Oriented control (BLAC mode). Two control applications have been developed in C language and implemnted using the Texas Instruments TMS320LF2812 digital signal processor (DSP). This new processor enables intelligent control for motors. We used to test the drive a professional development kit available from Technosoft company. This paper discusses the DSP real implementation of speed control (*Current sensing and scaling*, software organization, etc.). Dynamic performances are compared for the two modes in the case of speed reversal test at no-load conditions. We also present the real-time armature current logged at load conditions in both BLAC and BLDC modes. An evaluation of the results is presented and digital implementation aspects are discussed.

Keywords: PM Brushless motor, Digital speed control, BLDC and BLAC controls, DSP implementation.

1. INTRODUCTION

Because of their higher efficiency and power density, permanent magnet (PM) motors have been widely used in a variety of applications in industrial automation and consumer electric appliances (Murugan, Nandakumar and Mohiyadeen 2008).

A brushless Permanent Magnet Synchronous motor has a wound stator, a permanent magnet rotor assembly and internal or external devices to sense rotor position. The sensing devices provide logic signals for electronically switching the stator windings in the proper sequence to maintain rotation of the magnet assembly. The combination of an inner permanent magnet rotor and outer windings offers the advantages of low rotor inertia, efficient heat dissipation, and reduction of the motor size. Moreover, the elimination of brushes reduces noise, EMI generation and suppresses the need of brushes maintenance.

Two configurations of permanent magnet brushless motor are usually considered: The trapezoidal type and the sinusoidal type. Depending on how the stator is wounded, the back-electromagnetic force (BEMF) will have a different shape. To obtain the maximum performance from each type of PM motor, an appropriate control strategy has to be implemented. The trapezoidal BEMF motor uses a "two phases on" strategy, whereas the sinusoidal BEMF motor offers its best performances when driven by sinusoidal currents (three phases on strategy). This paper presents the DSP implementation of a speed control for the two strategies. In BLAC mode, the sinusoidal voltage waveform applied to this motor is created using sinusoidal PWM technique. This method will enable real-time control of torque and rotation speed and is accurate in every mode of operation (steady state and transient). The transient currents are constantly controlled in amplitude. However, such a control requires precise motor position sensor like encoder. In BLDC mode (MadhusudhanaRao, SankerRam, Smapath Kumar and Vijay Kumar, 2010; Dixon and Leal, 2002), a special commutation scheme is used to generate the PWM commands to motor phases. Based on the Hall sensor information, only two of the motor phases are supplied, while the third phase is not powered, for each Hall signals combination. After each change of 60 electrical degrees of motor position, a new combination of motor phases is supplied. Two phase's currents and motor position are measured. The measured phase currents are used to compute the equivalent DC current in the motor, based on Hall sensors position information. The speed controller generates the reference of the equivalent DC current.

In this work, we compare real-time results in the case of a speed reversal test. Figures show the good dynamic behavior of the FOC method.

2. THEORETICAL BACKGROUND

2.1. PM motor model

The operation of a brushless PM motor relies on the conversion of electrical energy to magnetic energy and then from magnetic energy to mechanical energy. It is possible to generate a magnetic rotating field by applying sinusoidal voltages to the three stator phases of a three phase motor. A resulting sinusoidal current flows in the coils and generates the rotating stator flux. The rotation of the rotor shaft is then created by attraction of the permanent rotor flux with the stator flux.

To create the rotating stator flux, the commonly applied phase voltages present a phase shift of 120 electrical degrees from one to another and are given by:

$$\begin{aligned} v_a &= V\cos(\omega_e t) \\ v_b &= V\cos(\omega_e t - 2\pi/3) \\ v_c &= V\cos(\omega_e t - 4\pi/3) \end{aligned} \tag{1}$$

where ω_e corresponds to the electrical speed. A one phase electrical equation can be written like:

$$v = R\,i + L\frac{di}{dt} + E(\theta) \tag{2}$$

Where $E(\theta)$ corresponds to the back-emf (induced voltage) and can also be written like:

$$E(\theta) = \frac{d\ \psi_m(\theta)}{d\ t} = \frac{d\ \psi_m(\theta)}{d\ \theta} * \omega_e \tag{3}$$

where $\psi_m(\theta)$ corresponds to the amplitude of the natural magnetic flux of the permanent magnets.

Electrical speed ω_e is related to mechanical speed ω_m by the following equation :

$$\omega_e = p * \omega_m \tag{4}$$

where p is the number of pole pairs.

From the electrical power delivered to the motor, a part of it ($R\ i^2$) is transformed in Joule losses, another part (L.i.di/dt) is going to the energy stored in the magnetic field and the last part ($i.d\psi_m(\theta)/dt$) is transformed in mechanical energy (torque production).

Electromagnetic torque can be expressed by :

$$T_e = p\ (E_a i_a + E_a i_a + E_a i_a)/\omega_e \tag{5}$$

Supposing that the machine is sinusoidal, the induced voltage has the following form:

$$\begin{aligned} E_a(\theta) &= -\omega_e \psi_{max} \sin(\theta_e) \\ E_b(\theta) &= -\omega_e \psi_{max} \sin(\theta_e - 2\pi/3) \\ E_c(\theta) &= -\omega_e \psi_{max} \sin(\theta_e - 4\pi/3) \end{aligned} \tag{6}$$

where ψ_{max} is the flux amplitude and θ_e is the electrical position of the rotor.

It can be proven that the best solution to produce a constant torque is to drive a sinusoidal motor by sinusoidal currents. In the case of a phase shift of β between currents i_a, i_b et i_c and back-emfs E_a, E_b et E_c, the torque expression becomes :

$$T_e = \frac{3}{2}\ p\ \psi_{max}\ I_{max}\ \cos\beta \tag{7}$$

where I_{max} is the current amplitude. It is easy to see that maximum torque is obtained when phase shift β is zero. This objective can be achieved by electronically switching the PM motor windings in concordance with rotor electric position. This enables a real time control of the torque demand without ripples.

The torque created by the energy conversion process is then used to drive mechanical loads. Its expression is related to mechanical parameters via the fundamental law of the dynamics as follows:

$$J\frac{d\omega_m}{dt} + B\,\omega_m + T_L = T_E \tag{8}$$

where J is rotor inertia, B is viscosity coefficient, T_L is load torque and Te is electromagnetic torque.

2.2. Field oriented control (BLAC mode)

The goal of the Field Oriented Control is to perform real-time control of torque variations demand, to control the rotor mechanical speed and to regulate phase currents in order to avoid current spikes during transient phases (Texas Instrument SPRA588 1999). To perform these controls, the electrical equations are projected from a three phase nonrotating frame into a two co-ordinate rotating frame. This mathematical projection (Clarke & Park) greatly simplifies the expression of the electrical equations and removes their time and position dependencies. A block diagram for a Field Oriented Controller can be seen in figure 1. This decouples the torque and flux producing components of the stator currents allowing the PM motor to be controlled in such the same way as a separately excited DC machine.

In this new system, the expression of the electrical equations is greatly simplified:

$$\begin{aligned} v_{sd} &= R\ i_d + \frac{d\psi_{rd}}{d\ t} - \omega_e\ \varphi_{rq} \\ v_{sq} &= R\ i_q + \frac{d\psi_{rq}}{d\ t} + \omega_e\ \varphi_{rd} \end{aligned} \tag{9}$$

and for a multiple pole synchronous motor, the expression of the torque in (d,q) is:

$$T_e = \frac{3}{2}\ p\ (\psi_{rd}\, i_{sq} - i_{sd}\, \psi_{rq}) \tag{10}$$

In the specific case of a permanent magnet synchronous motor without salient poles, most of the natural magnetic flux is on the d axis. In order to optimize the torque production for a given stator current i_s value, the appropriate strategy is to set reference direct current i*sdref* to zero.

The action of the current regulators is then to shift the current vector Is onto the q axis. The torque is now given by:

$$T_e = k\,\psi_{rd}\, i_{sq} \tag{11}$$

which is similar to DC machine torque expression. The relationship between mechanical speed and torque is given by the mechanical differential equation.

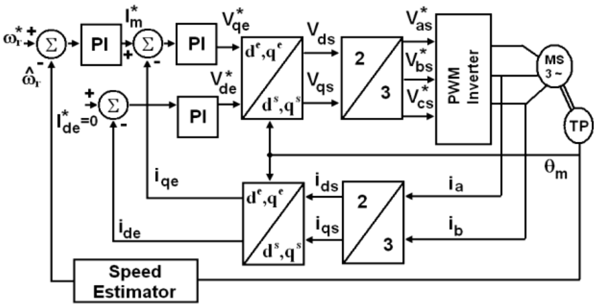

Figure 1 : FOC Bloc Diagram (BLAC mode)

2.3. BLDC control Structure

The BLDC application control scheme is presented in the figure 2 (Singh, B., Singh, B.P. and Jain 2003). As one can see, the scheme is based on the measure of two phase's currents and of the motor position. The speed estimator block is a simple encoder position difference block over one sampling period of the speed control loop. The measured phase currents, ia and ib, are used to compute the equivalent DC current in the motor, based on the Hall sensors position information (see Table 1).

Table 1: DC current I_q generation

Rotor Position Signal θ_r	Equivalent DC current
0° - 60°	i_a
60° - 120°	i_b
120° - 180°	i_a
180° - 240°	$- i_a$
240° - 300°	$- i_b$
300° - 360°	$- i_a$

The Hall sensors give a 60 electrical degrees position information. The speed and current controllers are PI discrete controllers.

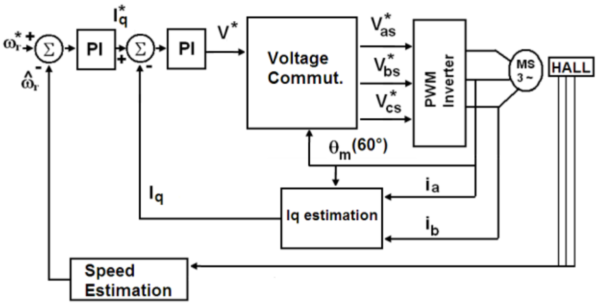

Figure 2 : Trapezoidal comutation Control Scheme (BLAC mode)

Only one current controller is needed in this case, similar to a DC motor case. The voltage commutation block implements (by software) the computation of the phase voltages references, V^*_{as}, V^*_{bs} and V^*_{cs}, applied to the inverter. Practically, the six full compare PWM outputs of the DSP controller are directly driven by the program, based on these reference voltages. In this case, only four of the inverter transistors are controlled for a given position of the motor.

The scheme will commute to a specific command configuration, for each of the 60 degrees position sectors, based on the information read from the Hall sensors.

3. DSP REAL IMPLEMENTATION

This chapter covers each components modules used to implement the solution of the PM motor drive.

3.1. The PM motor

The PM motor used for the application is a trapezoidal Back EMF 4-poles three phases motor equiped with 500 lines encoder. The characteristics of this motor are given in table 2.

Table 2: Motor Characteristics

Motor parameter	Value
Rated Voltage (V) (Y-connexion)	19,10
Nominal torque (mN)	0,029
Maximum current (A)	3,64
Stator Inductance (mH)	0,46
Stator resistance (Ω)	5,25
Rotor Time constant (ms)	7,92
Electrical constant (ms)	0,09
Rotor inertia (kgm²)	$0{,}9\ 10^{-6}$

3.2. *DSP* development kit

A professional development kit (MCK2812) available from Technosoft compagny has been used for the application. The kit includes :

- A 3-phases AC power module PM50 : it consists of a 50 W six IGBT inverter with integrated phases current sensors and protection hardware.
- The TMS320LF2812 DSP based development board with on-board peripherals : DACs, RS232 connector, etc. The PLL unit is set for 150 MHz CPU clock speed (Texas Instrument SPRU430B 2002).
- A Digital motion control development software called DMCD-Pro enabling data logging, real-time debugging and other useful features.

3.3. Software organization

The code is developed mainly in C/C++ language (both the main structure of the application and the time-critical parts as controllers, coordinates transformation, etc.). Using DMCD-Pro, the motion reference can be defined at high-level from the windows environment. The data logger feature allows the user to visualize any of the global variables of the program such those presented in this paper (speed and quadrature current). The program is based on two modules : initialization and magnetic stall module and the interrupt module (see figure 3). The interrupt module handles the whole control algorithm. It’s periodically computed according to a fixed PWM period value.

The two applications use a specific real-time environment, structured on two levels :

- a high priporiy interrupt function triggered every 100 µs, mainly for current control implementation
- a lower priority interrupt function triggered every 1 ms, for speed reference and speed control implementation.

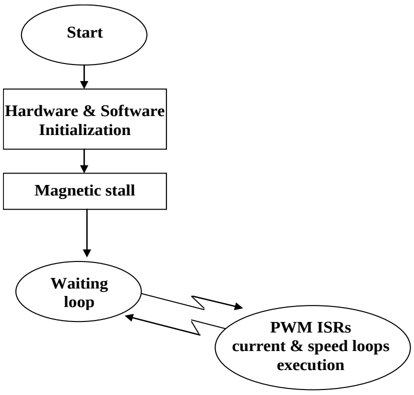

Figure 3: General Software Flowchart

The choice of the PWM frequency depends on the motor electrical constant. In this application, the PWM frequency has been set to 20 kHz. After the initialization module has completed, a magnetic stall is performed by applying a constant voltage vector to the stator phase : the constant phase currents flowing in the coils create a fixed stator flux. As a consequence, the rotor flux aligns itself naturally onto this stator flux (the rotor is stalled in this position).

Then, a waiting loop starts, and corresponds to an interruptible communication between the DSP monitor and the graphical user interface. If the user sends the start command, the control algorithm start executing. The data-logging allows real-time debugging of the application.

3.4. Current sensing and scaling

The control structures require two phase currents as input. PM-50 current measurement scheme is based on shunts mounted on each lower leg of the inverter. The voltage drop on a shunt is amplified and sent to TMS320LF2812 A/D channels. The complete process of acquiring the current is depicted in figure 4. Note that Imax (6,33A) represents the maximum measurable current, which is not necessarily equal to the maximum phase current. This information is useful at the point where current scaling becomes necessary. The ADC input voltage is now converted into a twelve bits digital value.

Note that reading the 12 bits value in the TMS320F2812 DSP is done with a shift of 4 bits to left, i.e. the 12 bits of the measured value are stored in the 12 most significant bits of a 16-bit value.

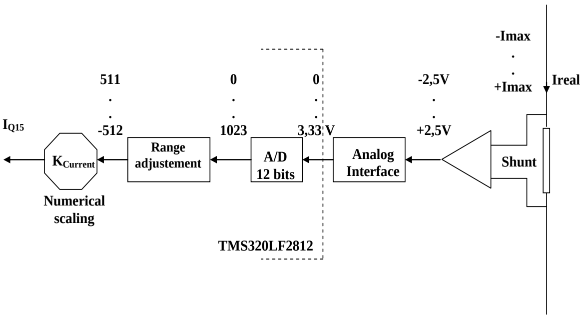

Figure. 4: Current Sensing and Scaling Block Diagram

3.5. The PI regulators

The PI regulators design has been done in continuous domain. We used poles cancellation method for PI regulator parameters calculation. The continuous PI regulators are then converted to their equivalent digital forms using time discretization. The PI regulators are implemented with output saturation. Electrical (current loop) and mechanical (speed loop) open loop transfer functions are considered as first order systems in both BLAC and BLDC modes.

Though the theory and simulation assist in calculating the controller parameters for a pratical implementation of the drive, further tuning of the PI regulator coefficients still be necessary.

We found that current loop PI controller parameters are the same for the two modes. It is not the case for speed loop because the two strategies have different real-time torque controls.

3.6. PWM outputs generation

The sinusoidal voltage waveforms are generated using the full compare PWM unit of the DSP controller. The PWM outputs are applied to the six transistors of the power inverter, based on sinusoidal reference values for the motor phase voltages. These are computed at the output of the current controller routine. The voltage references are used to compute the value of the compare registers corresponding to the three phases of the motor.

3.7. Clarke and Park transformations

Clarke and Park transformations have been developed as C/C++ functions which takes as input the sinus and cosines values of electrical angle as input parameters. To obtain cosines and sinus values from the electrical angle, a built-in sinus look-up table has been used.

4. REAL-TIME RESULTS

Experimental tests have been carried on the MCK2812 kit, which is a professional DSP development kit available from Technosoft compagny. The real-time logged data are speed and stator current quadrature component. In BLDC mode, Iq corresponds the equivalent DC current in the motor based on hall sensors position information. Experimental results are compared for the two modes in the case of speed reversal test at no-load conditions (figures 6 and 7). The speed reference is a 1,25 Hz - ± 50 rad/s square function.

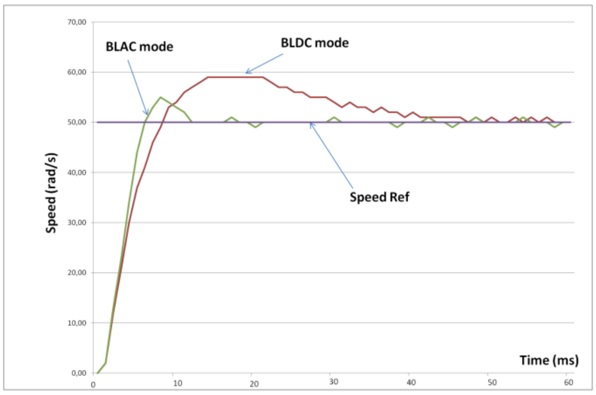

Figure 5 : Real-Time Variation of Speed

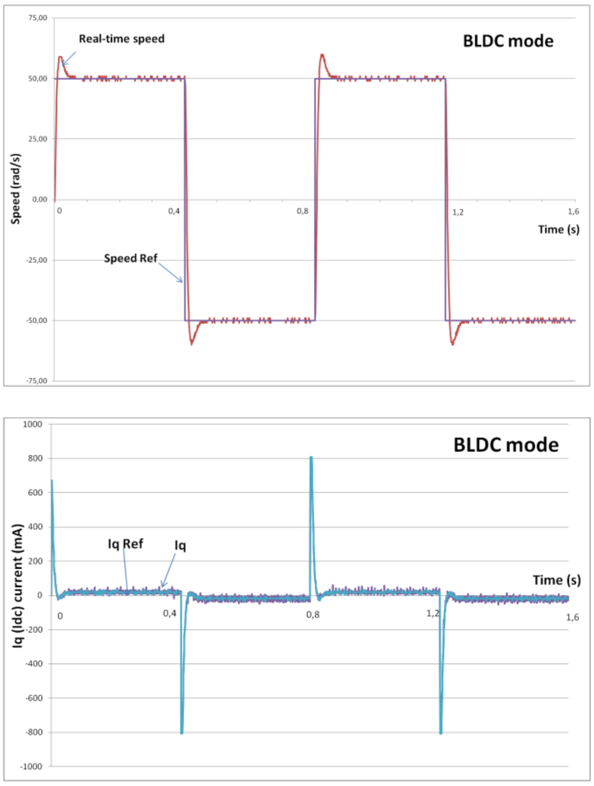

Figure 6 : Time variation of speed and Iq current at no load conditions (BLDC Mode)

The results show that good dynamic behaviour has been achieved by the implemented control. Indeed, during speed reversal phases, torque demand causes large q-current spikes and when speed tends to be equal to ± 50 rad/s, q-current decreases to a non zero steady state value due to viscous damping. The plots show clearly the effectiveness of speed PI regulator. Notice also that stator current torque component follows the output reference value calculated by speed PI regulator. As expected, zooming in the real-time speed plot (see figure 5) shows that BLAC control presents better dynamic performance (good response time) than BLDC control.

Figures 8 and 9 shows a current (armature and Iq current) comparaison between two modes at load conditions. The load torque is constant and speed is 157 rad/s. As expected, the PM motor is driven by sinusoidal current in BLAC mode whereas quasisquare current waveform are obtained in BLDC mode.

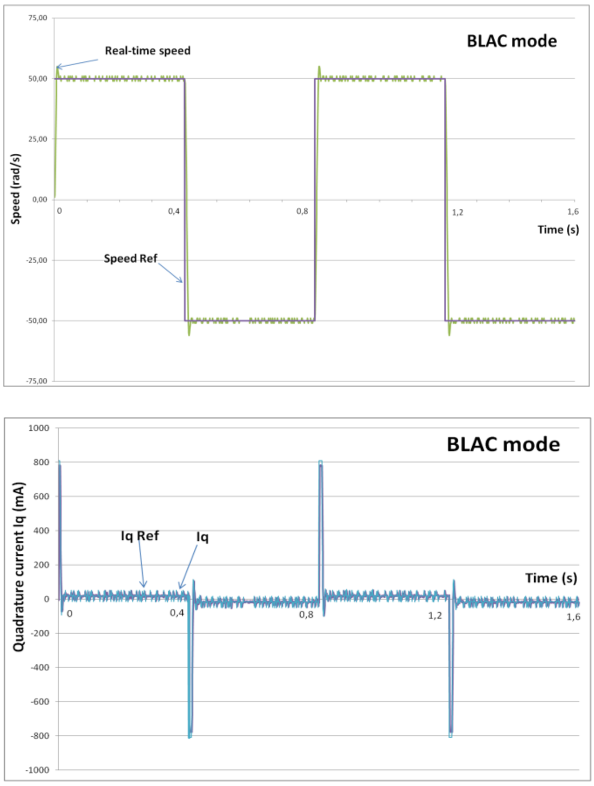

Figure 7 : Time Variation of Speed and Iq Current at No Load Conditions (BLAC Mode)

5. CONCLUSION

In this paper, an analysis of the performances of the BLDC motor using two control strategies : FOC and trapezoidal commutation, is presented. Experimental results were satisfactory and show differences in term of transient responses. Trapezoidal commutation control is found to be interesting as a low cost solution where high efficiencies and dynamics are not required. Indeed, this control structure has several advantages :

- very simple control scheme;
- only one current at a time needs to be controlled.

On the other hand, a great part of the software was written in C/C++ langage. The use of a higher level language (especially, the use of C++ classes) eases greatly programming and is well suited to managing variables and controlling program flow. This application implements some common real-time motion control features (real-time kernel, inverter control, current and speed measuring, regulators, etc.) which can be used in further control implementations such as sensorless or adaptive control.

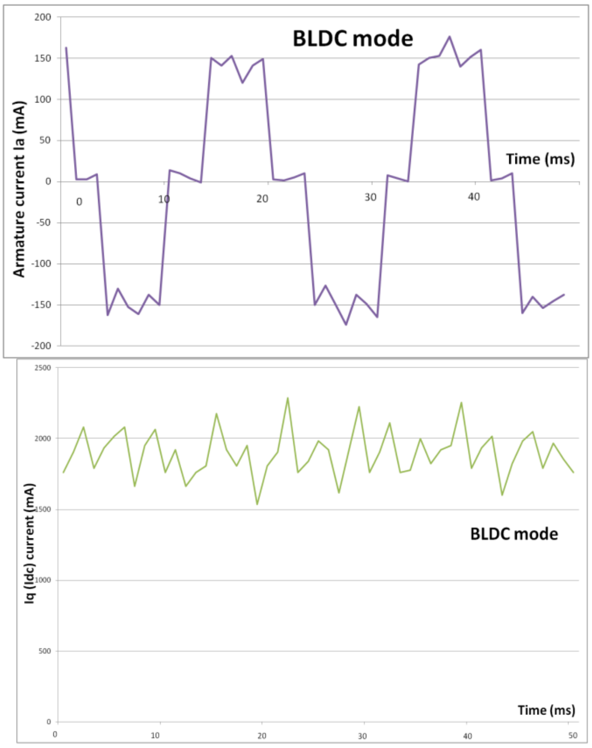

Figure 8 : Time Variation of Armature Current and Iq Current at Load Conditions (BLDC Mode)

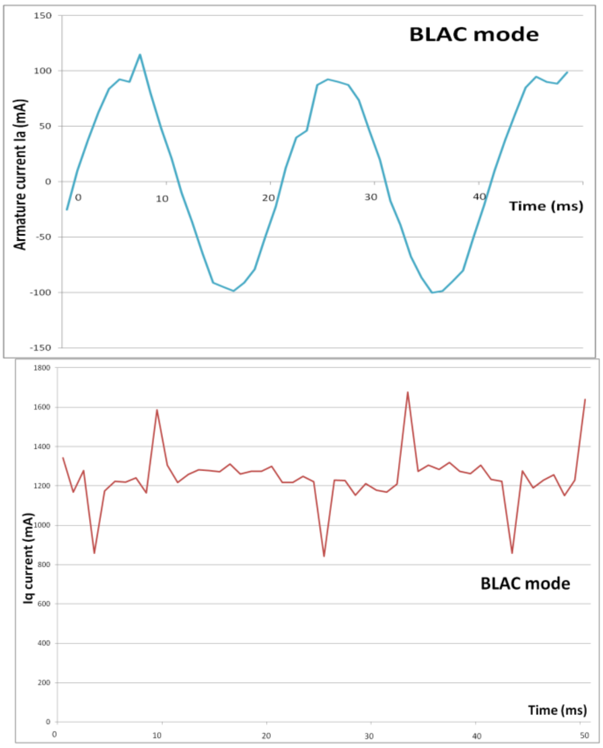

Figure 9 : Time Variation of Armature Current and Iq Current at Load Conditions (BLAC Mode)

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