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Digital Control for a PV Powered BLDC Motor

Slamet Riyadi
Department of Electrical Engineering, Soegijapranata Catholic University Semarang, Indonesia

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ABSTRACT

Stand-alone applications of Photovoltaic (PV) can be found in water pumping systems for rural area. The proper electric motor must be chosen for optimal considerations. One of the modern electric motor called brushless motor (BLDC) can be an alternative for this application although it has complexity in control. Powering such a motor by using electric energy generating by PV modules will be an interesting problem. In this paper, a PV powered BLDC motor system is proposed. The PV modules must produce maximum power at any instant time and then this power must be able to rotate the motor. By combining sequential stator energizing due to a rotor detection and a PWM concept, the speed of BLDC can be controlled. Meanwhile, to get maximum power of PV modules, detection of voltage and current of the modules are required to be calculated. Digital Signal Control (DSC) is implemented to handle this control strategy and locks the width of the PWM signal to maintain the PV modules under maximum power operation. The effectiveness of the proposed system has been verified by simulation works. Finally the experimental works were done to validate

Corresponding Author:

Slamet Riyadi,
Department of Electrical Engineering,
Soegijapranata Catholic University,
Pawiyatan Luhur IV-1, Bendan Dhuwur, Semarang 50234, Indonesia.
email: s_riyadi672003@yahoo.com

1. INTRODUCTION

Photovoltaic (PV) can be implemented in stand-alone applications or in PV grid systems. Most of the stand-alone applications can be found in water pumping systems. The systems commonly implement AC induction motors to rotate the water pump with or without batteries. Although the AC motor requires higher voltage rating for operation, this kind of motor is more preferable. PV has characteristic that a combination between current and voltage sources, so the operation of PV modules should regard the maximum power point (MPP), it is a point where the PV modules produce maximum power. Solar irradiance and temperature take effect the location of its MPP. Application of PV modules commonly require a maximum power point tracker (MPPT) to ensure the maximum power will be generated. Some methods of these have been described [1],[2].

Some applications of PV powered water pumping system utilize AC motors to drive water pumps. Two converter was also used in the system, the push-pull converter was operated as a MPPT and to increase the voltage level, the inverter was implemented to convert DC voltage into AC [3]. Implementation the standard DC-DC was applied for its simplicity [4],[5]. For high power rating, three phase AC induction motors were often used. These motors required three phase inverters to drive as the second converter and a MPPT can apply push-pull converter [6]. An induction motor doesn't have characteristic as good as the characteristic of a DC motor but the induction motor has some advantages. The problem of a DC motor is due to its commutator, but as the power electronics and digital technology advance the commutator can be replaced by an electronic circuit. An electric motor which adopts this concept then is called brushless DC motor, this motor has been implemented in many applications. A BLDC motor is preferable after digital control has been growing rapidly. Some techniques have been developed in controlling BLDC motors, conduction angle control and current mode control can be used as a basic concept [7] or four quadrant operation that is suitable for electric vehicles [8]. For better performance, an adaptive control using fuzzy inference [9] and direct torque control using fuzzy logic controller for BLDC can be implemented [10].

Some of the previous methods used advanced strategies to obtain high performance BLDC drive. For certain applications such as water pumping system, simplicity become an important consideration so the simple control strategy should be implemented. The proposed system consisting of PV modules powered BLDC motor is described in this paper. A three-leg inverter is used as an interface between the PV modules and the BLDC motor, this inverter must operate as a MPPT and a BLDC driver. To adjust the speed of the BLDC motor, the duty cycle of the inverter static switches are modulated. The system has to lock the operating point at MPP that is represented by a certain speed of the BLDC motor. The dsPIC30F4012 is implemented as a core of the controller. Finally, the effectiveness of the proposed system has been proven by simulation and experimental works.

2. THE PV POWERED BLDC MOTOR SYSTEM

Connecting a load to a BLDC motor will make the motor run at a speed where the torque of the load equals to the torque of the motor. The multiplication of the torque and the speed results in the power required by the motor. When the power is increased, the speed will also be higher to achieve the power equilibrium. The proposed system can be seen in Figure.1, PV modules are used to supply a BLDC motor via an inverter. The proper operation of the system will force the PV modules generate maximum power at any condition. When the solar irradiation is high the power produced will be high and vice versa. The inverter will transmit this power to the BLDC motor then results in the speed of the motor achieve the power equilibrium where under ideal condition, all the power generated by the PV modules equals to the power absorbed by the BLDC motor. The two functions of the inverter as a MPPT and a motor driver can be controlled by the implementation of the DSC as the core of the controller.

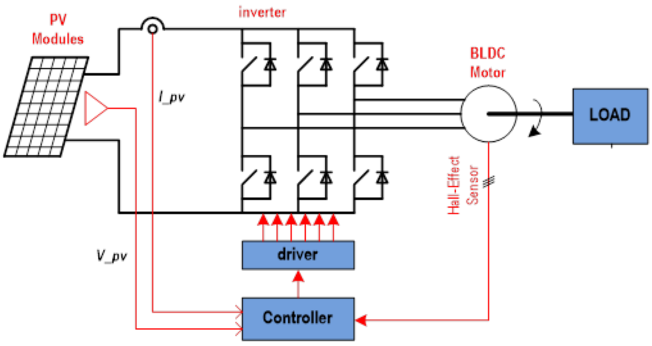

Figure 1. The proposed system blocks

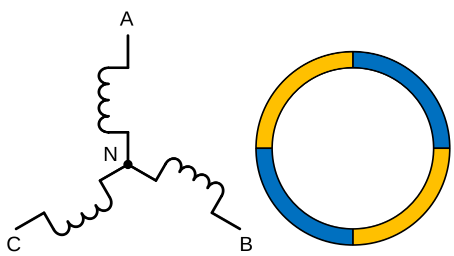

Figure 2. Stator windings and rotor of the three-phase BLDC motor

2.1. BLDC Motor and Inverter

A Brushless Direct Current (BLDC) motor has permanent magnets on its rotor and the stator consists of phase windings. A three phase BLDC motor may have four permanent magnet rotor poles and six stator windings. The stator windings are configured as a three phase winding as shown in Figure.2. To make easier to be understood, the motor is cut then the stator and rotor can be depicted in Figure.3. The rotor poles are named as N1, S1, N2, S2 while the stator poles are A1, B1,C1, A2, B2, C2. For the stator pole B1 and B2 are aligned with the rotor poles, they are not energized. In order to make the rotor move to the right, the stator pole-A must be energized to be North pole of magnet and the stator pole-C must be energized to be South pole of magnet. This condition can be assumed that current flows from stator A to C. The rotor position is sensed by three hall-effect sensors H1, H2 and H3 results in 101 in Figure.3.

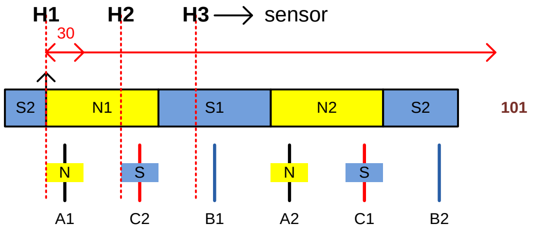

Figure 3. Spread-view of the three-phase BLDC motor for phase-B aligned

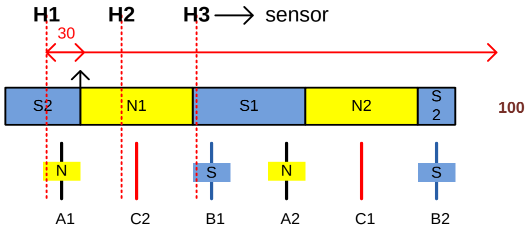

Figure 4. Spread-view of the three-phase BLDC motor for phase-C aligned

The next step is shown in Figure.4 when the phase-C is aligned. This condition is detected by hall-effect sensor as 100, in order to make the rotor move to the right, the stator pole-A must be kept to be North pole of magnet and the stator pole-B must be energized to be South pole of magnet. This condition can be assumed that current flows from stator A to B and so on. To derive the equations of a three phase BLDC motor, some assumptions are taken, for every phase stator winding has resistance R, inductance L and back electro motive force (EMF) then they can be stated

$$v_a = R.i_a + L\frac{di_a}{dt} + e_a \tag{1}$$

$$v_b = R.i_b + L\frac{di_b}{dt} + e_b \tag{2}$$

$$v_c = R.i_c + L\frac{di_c}{dt} + e_c \tag{3}$$

where v, i and e are phase voltage, phase current and back EMF. For back EMF depends on the rotor speed then it can be derived as

$$e_a = K_e.f(\theta_e).\omega_m \tag{4}$$

$$e_b = K_e.f\left(\theta_e - \frac{2\pi}{3}\right).\omega_m \tag{5}$$

$$e_b = K_e.f\left(\theta_e + \frac{2\pi}{3}\right).\omega_m \tag{6}$$

where ω_m $, K_e, f(\theta_e), \theta_e$ are the rotor speed (rad/s), back EMF constant, trapezoidal function (V/rad.s) and electric rotor angle (rad). Then finally, electromagnet torque can be calculated as

$$T_e = \frac{e_a.i_a + e_b.i_b + e_c.i_c}{\omega_m} \tag{7}$$

or

$$T_e = K_T\left[f(\theta_e).i_a + f\left(\theta_e - \frac{2\pi}{3}\right).i_b + f\left(\theta_e + \frac{2\pi}{3}\right).i_c \right] \tag{8}$$

Based on the above equations then the motor characteristic can be represented in Figure.5.

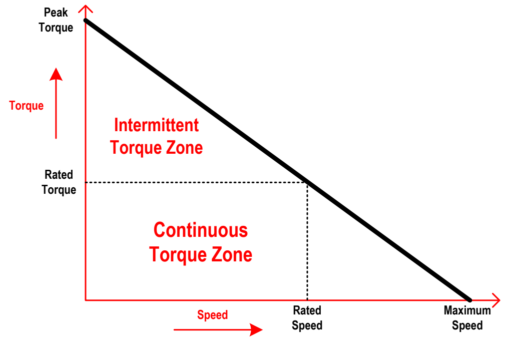

Figure 5. Torque-Speed characteristic of three-phase BLDC motor

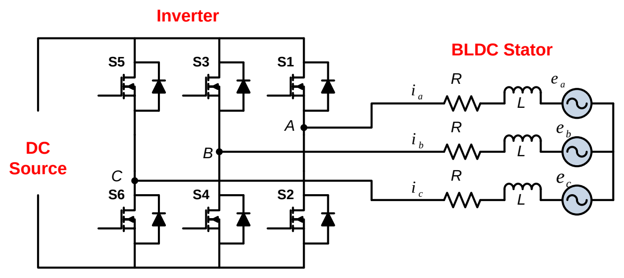

Figure 6. Three phase three leg inverter for driving a three-phase BLDC motor

To make the BLDC motor runs, current must flow through two windings in the stator. The proper sequence must be chosen. This can be obtained by using a three phase three leg inverter as shown in Figure.6. At any instant time an upper side switch and a lower side switch from different leg will be ON state. For example, if the phase-A stator and phase-B stator will be made as North pole and South pole of magnet, the point-A and point-B must be connected to the positive and negative polarity of the DC source. This condition is achieved by closing the switches S1 and S4, and it is assumed as the first step. The second step may be selected to make the phase-A stator and phase-C stator will be as North pole and South pole of magnet then the switches S1 and S6 must be closed and so on

2.2. Photovoltaic Modules

To provide electricity in the remote area where there is no utility, PV modules can be used. These convert solar energy into DC electric energy. A PV module is not a voltage source or current source, but the combination of both. PV characteristics curve can be seen in Figure.7, to generate maximum power, the PV module must be operated at the point called maximum power point (MPP). The location of this point is influenced by solar irradiance and the module temperature. Operation under this MPP, the modules will produce current IMPP and voltage VMPP, so the power generated is stated as

$$P_{MPP} = V_{MPP} . I_{MPP} \quad (9)$$

Connecting any loads to a PV module will have an operating point anywhere. A controller is required to move the operating point location closer to the MPP, this controller is also called as a maximum power point tracker (MPPT). Implementation of PV modules with MPPT will reduce the number of modules for a certain value of power generated.

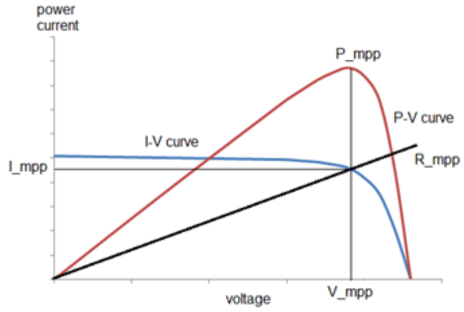

Figure 7. Characteristic curve of photovoltaic module

2.3. The Control Scheme of The Proposed System

The BLDC motor-water pump in the proposed system is supplied by the electric energy generated by the PV modules. The three phase inverter is used as a MPPT and a driver for the BLDC motor. If the electric power generated increases then the motor will run faster, if the electric power decreases then the motor runs slower. Under ideal condition, the power absorbed by the motor always equals to the power generated by the PV modules.

The controller of the proposed system require three quantities, these are PV voltage, PV current and hall-effect sensor as a rotor position detector. Due to (7) or (8), the BLDC motor speed can be controlled by changing the values of its phase current or voltage. From the previous analysis, the current flowing into the stator winding is regulated by the action of two switches from upper and lower side. For example, to make the current flow from phase-A to phase-B, the switch S1 and S4 must be ON while the others are OFF. By making the upper switch S1 ON and OFF based on PWM (Pulse Width Modulation) concept and keep S4 still ON, the average value of current flowing in the stator winding can be regulated. This method is then used to control the motor speed. Finally, the duty cycle of the PWM waveform will determine the average value of the current flowing in the stator winding.

To locate the operating point of PV modules, P&O (Perturb & Observe) method is used in this paper. This method is combined with the PWM concepts to achieve the power equilibrium. When the operating point of PV modules is on the left side of MPP then the controller will move the point to the right. At this time, the duty cycle will increase to make the BLDC motor runs faster. But if the operating point passes the MPP then the power generated by the PV modules goes down, the duty cycle will decrease and the motor runs slower. This condition will force the operating point moves to the left in order to increase electric power generated. The flowchart of the proposed control strategy is depicted in Fig.8.

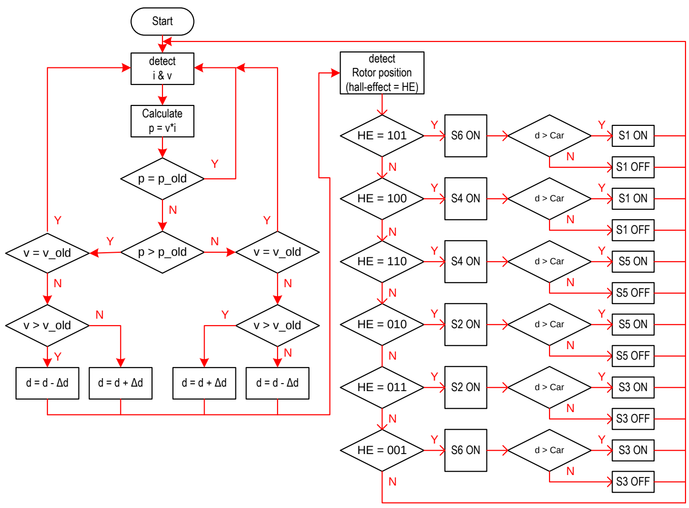

Figure 8. Flowchart of the proposed system controller

3. RESULTS AND ANALYSIS

Referring to the Figure.1, computer simulations were done by using PSIM to verify the above analysis. Digital control is implemented by C-Block in PSIM based on the flowchart depicted in Figure.8. Detailed parameters for simulation works are presented in Table 1.

Table 1. Parameters for the simulation works

PV modules 60 Wp (each module)	4 modules in series connection (240 Wp) Vmpp = 17.1 Volt Impp = 3.5 Ampere
Inverter	Three phase three leg inverter with DC-Link Capacitor 2000 uF
Controller	Digital Control using C-Block
BLDC Motor	Three phase stator winding
Load	0.8 Nm

To make the current of the PV modules has nearly constant value, a capacitor is inserted between the modules and the inverter. The duty cycle influences the speed and the power absorbed by the motor, this can be seen in the Figure.9 – Figure.12. To observe the effectiveness of the control method, Figure.13 and Figure.14 shows that the PV modules are capable to generate electric power close to the maximum power while the power absorbed by the inverter always fluctuates but its average value equals to the power generated by the PV modules. At the beginning, the instantaneous power will fluctuate at higher value because the motor requires higher torque to compensate its inertia then the peak power will decrease. The higher torque is needed to increase the speed of the motor. From the figures, it is seen that the profile of the current is the same as the power.

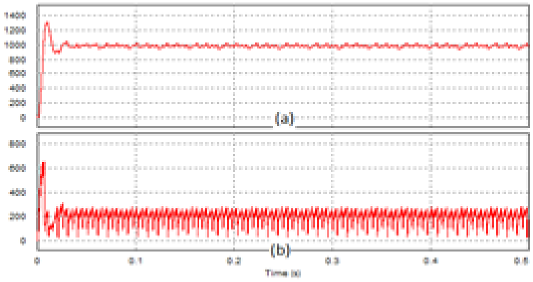

Figure 9. Simulation results of the BLDC motor under d = 0.4 (a) the motor speed (b) average power absorbed by BLDC motor

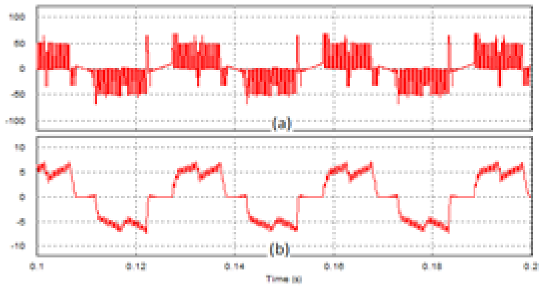

Figure 10. Simulation results of the BLDC motor under d = 0.4 (a) the motor phase voltage (b) the motor phase current

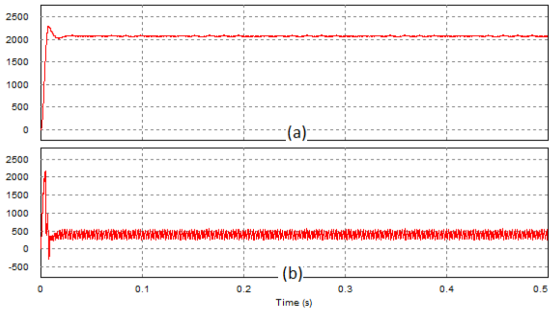

Figure 11. Simulation results of the BLDC motor under d = 0.8 (a) the motor speed (b) average power absorbed by BLDC motor

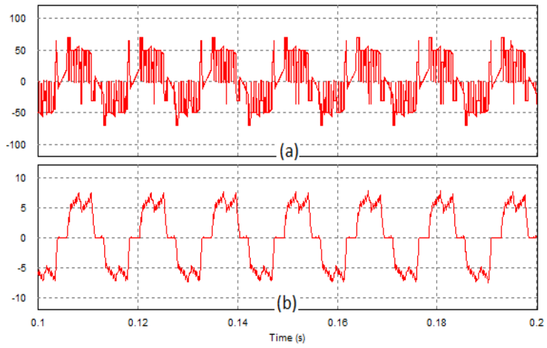

Figure 12. Simulation results of the BLDC motor under d = 0.8 (a) the motor phase voltage (b) the motor phase current

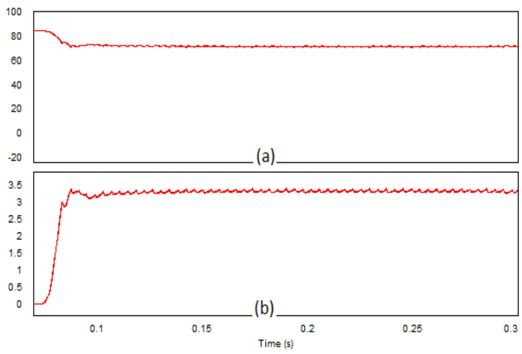

Figure 13. Simulation results (a) PV module voltage (b) PV module current

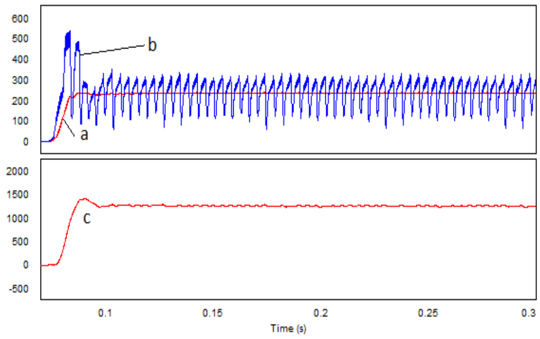

Figure 14. Simulation results (a) power generated by the PV modules (b) average power absorbed by BLDC motor (c) the BLDC motor speed

Under different value of solar irradiance, the PV modules will generate different value of power. This condition makes the proposed controller change the motor speed in order to keep the power equilibrium. The average value of power absorbed by the motor will fluctuates near the maximum power generated by the PV modules. Figure.15 depicts the change of solar irradiance from 800 W/m2 to 1000 W/m2 that makes the change of the motor speed.

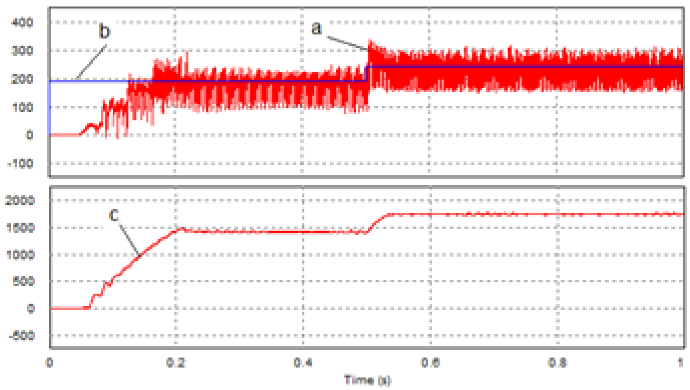

Figure 15. Simulation results for different solar irradiance (a) average power absorbed by BLDC motor (b) maximum power generated by the PV modules (c) the BLDC motor speed

Under power equilibrium, Eq. (7) equals to Eq. (9) then it can be stated as

$$P_{MPP} = e_a.i_a + e_b.i_b + e_c.i_c \tag{10}$$

The output phase voltage of the inverter operated at duty cycle d is determined as

$$V_{ph} = d.V_{MPP} \tag{11}$$

if we assume that $V_{ph} \approx e_{ph}$ then

$$P_{MPP} \approx d.V_{MPP}\left(i_a + i_b + i_c\right) \approx T_e.\omega_m \tag{12}$$

Under constant power and load, the value of ω_m will be constant. Referring to the flowchart depicted in Figure 8, it is shown that the value of duty cycle d will be modulated to achieve the power equilibrium. When the power generated by the PV modules rises, the greater duty cycle is obtained and finally the speed of the motor will be faster.

Table 2. Parameters for the experimental works

PV modules 80 Wp (each module)	3 modules in series connection (240 Wp) Vmpp = 17.3 Volt Impp = 4.63 Ampere
Inverter	Three phase three leg inverter with DC-Link Capacitor 2000 uF
Controller	Digital Control using C-Block
BLDC Motor – Water Pump	Three phase stator winding 50 V/250W Max 60L/min

Finally, the prototype was designed to make laboratory works. the three phase three leg inverter implemented by using IGBT CPV364M4U as the static switches. The dsPIC30F4012 was used as digital controller and LEM HX-10P is implemented as a current detector. Three PV modules NE-080T1J 80 Wp are installed in series connection to supply BLDC motor-water pump via the inverter. Figure.17 shows the experimental result of the phase voltages of the BLDC motor and Figure.18 represents the relationship between the phase voltage and current. These profiles are almost the same as the current and voltage profiles simulated previously. The input current of the DC-link inverter is shown in Figure.19, this profile happens due to the PWM strategy.

Figure 16. Prototype of the proposed system for experimental tests

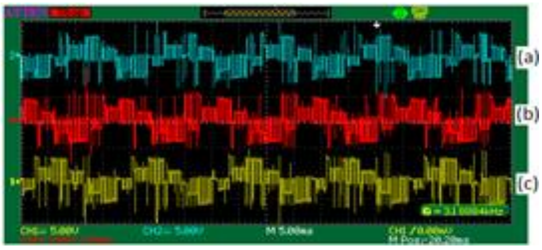

Figure 17. Experimental results of output voltages of the inverter [scale = 50V/div]

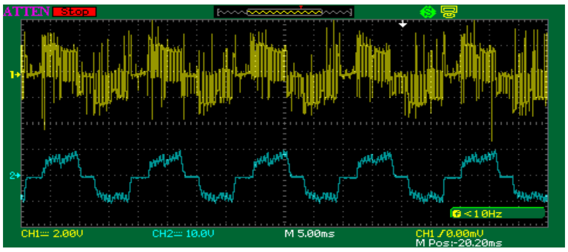

Figure 18. Experimental results of the BLDC motor (a) voltage of phase-A (b) current of phase-A [voltage transducer gain = 20, current transducer gain = 1]

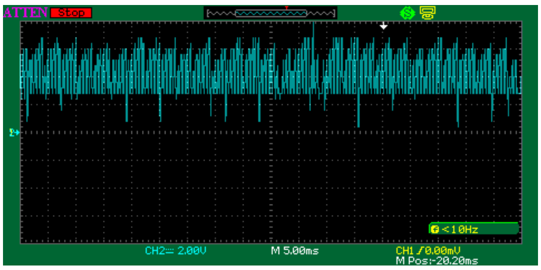

Figure 19. Experimental results of input current of the inverter [current transducer gain = 5

4. CONCLUSION

The PV powered BLDC motor system has been presented, the system consisted of a BLDC motor, an inverter and PV modules. A single converter that implemented by a three phase three leg inverter was used as an interface between the PV modules and the motor. This inverter was functioned as a MPPT and a motor driver by using dsPIC30F4012 as the core of the controller. The simple control strategy can achieve the power equilibrium by modulating the duty cycle. The simulation and experimental works show the effectiveness of the proposed system.

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BIOGRAPHY OF AUTHOR

Slamet Riyadi was born in Semarang-Indonesia, in 1967. He received B.S. degree from Diponegoro University, Semarang in 1991 and M.Eng. degree from Bandung Institute of Technology, Bandung-Indonesia in 1997. In 2006, he received Ph.D degree in Electrical Engineering from Bandung Institute of Technology with Partial Research done in ENSEEIHT-INPT Toulouse, France. Currently, he is with the Departement of Electrical Engineering, Soegijapranata Catholic University, Semarang-Indonesia as a lecturer and researcher. His current research is focused on power factor correction techniques, active power filtering, PV-Grid Systems and electric motor drives. Some of his researches were supported by, ASEM duo-France, The Ministry of Research and Technology- Indonesia, The Directorate Generale of Higher Education-Ministry of National Education-Indonesia, etc. He is also an IEEE member.