High Performance Rectifier/Multilevel Inverter Based BLDC Motor Drive with PI Controller

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Abstract. BLDC motor has many applications in high power systems. Whereas, it is easy to construct and design, cheap and needs less maintenance, with high efficiency, high output power, and high torque. By taking advantage of power electronics drives, a rectifier/multi-level inverter can improve the operation of BLDC motor in medium and high applications. In this research, a mathematical model of BLDC motor drive by rectifier/MLI has been simulated using Matlab/Simulink. Whereas, a proposed model system was built, with a two-part motor drive circuits: a three-phase full-wave fully controlled rectifier, and a three-level inverter. The pulses circuit is designed for rectifier and three-level inverter individually using PWM. Also, THD in the output of a three-level inverter has been reduced by using a modern SFO-PWM topology. In addition, the system is equipped with a PI controller to control the speed and torque of BLDC motor. Also, there is a high-quality control upon the speed and torque of the motor due to the use of PI controller, which resulted in constant torque with low ripple and constant speed as a load of the motor changed, with a high increasing in the stability and reliability of the system.

1. Introduction

Achieving the process of converting electrical power from direct current DC power to alternating current AC power requires an inverter. Whereas, to form an alternating output voltage close to sinusoidal waveform from a DC voltage, a multi-level inverter can be used [1].

However, the multi-level inverter has been introduced in 1981 as an alternative in high power and medium voltage situations by (Nabae et al). Reducing THD of output voltages requires an increase in the number of levels of multilevel inverter, thus the output will look like a staircase waveform (Sadeghi et. Al., 2011). In two decades, a group of Massachusetts Institute of Technology researchers have developed power converters based on the principle of multiple voltages and have received numerous patents about the effort (R.H. Baker, 1980) [1 and 2].

There are many advantages to multi-level inverter, including reducing distortion in output voltage, reducing stress of changing of voltage with time $dv/dt$; in addition multi-level inverters induce a smaller common-mode (CM) voltage, so it decrease problems of electromagnetic compatibility...
(EMC); as well, there is a great decrease in stress upon bearings of a motor which connected to a multi-level motor drive [3, 4 and 5]. One of the most important advantages of multi-level inverters is that it can produce input current with small distortion, which protects the source voltage from high THD [5].

The Brushless DC motor provides the advantage of a permanent magnet, which means that all the power applied to be employed to induce mechanical torque. There is also a preference for these motors in issues such as dissipate of heat resulting by their windings. However, depending on the internal structure of this motor, whereas, its windings are located close to its outer casing, which assists in overcome of heat, unlike DC motor the absence of brushes assist to reduce the sparks, friction, and the ring fire also called as ring of fire which prohibits access to high speeds in DC motors. Simply, the interaction between forces of a permanent magnet and electromagnet is the basic principle of the BLDC motors. Additionally, an electronic drive is needed to accomplish the operation of energize and de-energize coils of BLDC motor [6, 7 and 8].

On the other hand, brushless DC motors also known as electronically commutated motors (ECMs) are synchronous motors that are driven by AC voltage. an inverter is used to induce this AC voltage by control on switching topology of inverter switches to synthesis AC signal from DC voltage source. This electronic control on BLDC motor rotation results in a complexity in terms of knowing the location of the actual mechanical rotation axis to excite only two windings of a three phases windings of the motor at each interval to maintain high torque and constant speed of the motor. This requires precise control of the operation of the multilevel inverter switch to maintain this condition. [6].

In this paper, a mathematical model of the BLDC motor is described, the motor drives through a three phase ac voltage source supply a three phase full wave fully controlled rectifier. The resulting DC voltage delivered to a series bulk capacitors, a three-level inverter with diode clamped work on splitting DC voltages into three levels and supplies them to the BLDC motor. However, the PWM technique used to generate pulses of inverter switches work on reduce THD caused by high switching frequency. The motor speed and torque are controlled by a PI controller. Due to the presence of PI controller, a high stability in torque, and speed with a high reliability in operation of BLDC motor were obtained.

2. General description of the system of 3-level-inverter driven a BLDC motor

The circuit design is Modelled using MATLAB simulation. The diagram in figure 1 represents the full layout of the circuit.

![Figure 1](image-url)  
Figure 1. scheme of system multi-Level inverter Based BLDC Motor Drive.

3. Mathematical model of BLDC motor
The mathematical model of a brushless DC motor can be modeled as a manner as in a three phase synchronous motor. As with modelling of polyphase synchronous motor, the brushless DC motor can be modelled using MATLAB software. On the bud of that similarity, there are some differences in dynamic characteristics between these two motors. The main reason for these differences due to presence of permanent magnets in brushless DC motor see figure. 2 [6 and 9].

Similarly, equations (1-3) represent three phase armature coils in the mathematical model of brushless DC motor [10, 11]:

\[ v_a = R_a i_a + L \frac{di_a}{dt} + e_a \]  
\[ v_b = R_b i_b + L \frac{di_b}{dt} + e_b \]  
\[ v_c = R_c i_c + L \frac{di_c}{dt} + e_c \]

where \( L \) is self-inductance of armature, \( R_{a,b,c} \) is resistances of the armature, \( v_{a,b,c} \) are phase voltages at input terminals, \( i_{a,b,c} \) are input currents of the motor, and \( e_{a,b,c} \) are back EMF in motor windings.

In three phase BLDC motor, the back EMF is relying in rotor site. Indeed, the back-EMF of each phase has 120° phase angle difference, so the equation that describes each motor phase is [6]:

\[ e_a = \partial_w f (\varphi_e) \omega \]  
\[ e_b = \partial_w f (\varphi_e - \frac{2\pi}{3}) \omega \]  
\[ e_c = \partial_w f (\varphi_e + \frac{2\pi}{3}) \omega \]

where \( \partial_w \) express of back EMF constant for each phase, \( \varphi_e \) represent rotor electrical angle, \( \omega \) is the speed of the rotor.

The rotor’s electrical angle \( \varphi_e \) is equal to the rotor’s mechanical angle \( \varphi_m \) multiplied by half number of poles \( p \) as in equation (7) [6 and 11]:

\[ \varphi_e = \frac{p}{2} \varphi_m \]  

The total output electrical torque \( T_{et} \) is a summation of each single phase torque [10]:

\[ T_{et} = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega} \]  

The equation of mechanical part is represented as follow [10 and 12]:

\[ T_{et} - T_m = J \frac{d\omega}{dt} + B \omega \]

Where \( T_m \) is the mechanical torque, \( B \) represents frictional constant, \( J \) represents inertia of rotation part.

4. Drive circuit construction
The drive circuit of brushless DC motor consist of three stages: electrical power supply, waveform rectification, and inversion. A three phase AC voltage with line voltage 240 V, and frequency 60 Hz. The next stage is the rectification AC power of AC input voltage supply into a DC voltage, second one is inversion DC voltage to AC voltage with trapezoidal waveforms.

However, three phase full wave fully controlled rectifier, with six thyristors, is used to accomplish the first drive stage. The rectifier is fully controlled which allow to control on the magnitude of DC voltage in output and then controls on magnitude of voltage delivered to the BLDC motor. The period of conducting for each thyristor of the six thyristors is 60°. As a result of that, the ripple in output voltage has a six times frequency of input frequency. As a conclusion, there is a need for a slight filtering requirements to get pure DC voltage in rectifier output terminals. Actually, to get a perspicuous DC output voltage with a minimum value of ripple factor, a capacitor filter should be connected at the output of the rectifier. Now, before apply DC voltage to inverter, it must be applied to two capacitors with neutral centre point “n” to get three levels of voltages.

Nevertheless, a three level inverter usually used to accomplish the conversion of DC voltage to a trapezoidal waveform alternating voltage. Three phase inverter consists of three arms to generate a three phase voltages. Each arm contain four MOSFETs, and 2 neutral point clamping diodes, the main profit of this arm construction is that each composite switch must be block half of DC voltage produced in rectifier terminals. Certainly, power electronics switches must be chosen to be of the same type to ensure that they share the voltage evenly, when it switched off. There are two MOSFETs for each part of waveform (positive and negative) to carry a higher value of current. In either case, there must be a diode in parallel with each MOSFET to handle inductive kick or flyback currents. This is built into most devices nowadays.

4.1 Pulses of rectifier
A three phase full wave fully controlled bridge rectifier used to produce a controlled DC link voltage at input terminals of 3 level inverter, so it is possible to control on output of a 3 level inverter and so on the voltage delivered to BLDC motor.

To achieve fully controlled on rectifier circuit, which consists of 6 thyristors, each thyristor will be trigger for 60° interval, in order to period (90° + α ≤ t ≤ 150° + α), a thyristors T_A1 and T_C2 is in conduct condition and the line voltage V_ac appears across the terminals of the inverter. The sequence of firing a thyristors must be as follow (TA1 & TC2, TB1 & TC2, TB1 & TA2, TC1 & TA2, TC1 & TB2, TA1 & TB2) to make sure that thyristors turn ON and OFF in time with line to line voltages (V_ab, V_bc, V_ac) to get a DC voltage on Capacitors.

4.2 Pulses of three-level inverter
To create three scales of voltage, 2 of the 4 MOSFETs in each arm ought to switch on at each time. Eventually, two evenly capacitor C_1 and C_2 is needed to split DC-link voltage into three levels (+ve, zero, - ve).

The switching frequency optimal PWM (SFO-PWM) topology is used to generate switches pulses for the multi-level inverter. This topology reduces the harmonics in the output voltage of the inverter [13].

Indeed, to explain how will synthesize a trapezoidal voltage in inverter output, as consider any single arm of the three levels inverter. The topology of triggering the switches are as follows: when turn on switches MA1 and MA2 get a positive voltage level equal to Vab = +Vdc/2, and when turn on switches MA2 and MA3 will get a zero level voltage Vab = 0. Lastly, when turn on switches MA3 and MA4 will get a negative level of output voltage Vab = -Vdc/2.

5. PI speed and torque controller
The proportional integral PI controller is used to get a speed and torque control. The modified deferent evaluation is used to evaluate Kp and Ki factors [14]. Indeed, to achieve this mission, two stages of PI controller is needed. The first one is the speed controller, which compare between reference speed and
The output of this stage is a torque set point applied to the second stage "torque controller" as a current controller block. Torque control is actually regulate on motor current, so the current controller contains four main stages. The first one is to convert chosen reference torque to a reference maximum current quantity. This process assumes that the currents in the motor coils are pure square waves.

The Hall Effect is the most common method to measure the magnetic field, and the Hall Effect sensor is very widely known and used in many applications. The second stage is the sensor of block emf. It is used to detect the exact position of the rotor. The output of the sensor contains three voltage levels (-Ve, 0, +Ve), these three levels represent the actual injected currents in three phase coils of the motor rotor at motion mode to get a high density output torque.

The third stage is the current regulator. Actually it works on compare between reference phase currents (converted reference torque) and actual torque in motor. Last stage is switching controller. This part control on pulses generation of three level inverter to the value specified in reference.

6. Modelling and simulation
All circuits design is modelled using MATLAB Simulink. The diagram in figure. 3 represents the Virtual mathematical model of brushless DC motor.

![Figure 3. Virtual mathematical model of BLDC motor.](image)

Figure 4 represented the design of three phase full wave fully controlled rectifier circuit.
Figure 4. three phase full wave controlled rectifier.

Figure 5 represented clamping diode three level inverter with dc link two capacitors to get three levels input voltages.

Figure 5. clamping diode three level inverter.

While, Figure 6 represented pulse generation fully controlled bridge rectifier, with possibility to choose firing angle to control voltages in the output.
Figure 6. Pulses circuit generation for three phase full wave fully controlled bridge rectifier. Figure 7 represented pulse generation circuit for three level inverter with clamped diode. The SFO-PWM topology is used to eliminate third harmonic and reduce harmonics in general.

Figure 7. pulse generation circuit for three level inverter. Figure 8 described, PI speed controller of brushless DC motor, to produce two signals one for speed control and other delivered to torque controller.
Figure 8. PI controller for BLDC motor speed. PI torque controller designed by Matlab Simulink shown in figure 9, with its four stages.

Figure 9. PI controller for BLDC motor torque.

7. Results and discussion
In this section of paper, the results obtained from proposed mathematical model system will discuss and shown.

Figure 10 represent the pulses trigger for thyristors (TA1, TA2, TA3, TA4, TA5 and TA6) for full wave controlled rectifier.

Figure 10. trigger pulses for switches of a full-wave controlled three-phase rectifier.

Figure 11 represents switching frequency optimal PWM (SFO-PWM) topology that used in generate switches pulses for the multi-level inverter switches.
Figure 11. Switching frequency optimal PWM topology.

Figure 12 shows the pulses trigger for four MOSFETs (M_{A1}, M_{A2}, M_{A3}, and M_{A4}) switches which consist of one arm (arm-A) of three phase 3-levels inverter.
Figure 12. Pulses of MOSFETs in arm A (MA1, MA2, MA3 and MA4) of the 3-level inverter.

The output of three phase full wave bridge rectifier is doomed by firing triggers angle to control on the output voltage of the rectifier. Of course, a capacitor filter has been connected to the output rectifier to minimize ripple in output voltage. Figure 13a shows the filtered output voltage of rectifier at $\alpha = 0^0$ with $V_{av} = 330$ V, when figure 13b represent the same output at $\alpha = 60^0$ with output voltage $V_{av} = 165$ V.
Figure 13. Output voltage of controlled rectifier (a) at $\alpha = 0^\circ$, (b) at $\alpha = 60^\circ$.

The output DC voltage has been delivered to a 3-level inverter through two series connection capacitors to get three levels (- Vdc, 0, + Vdc). Currently, any of these three levels can be selected to appear on the output terminals of 3-level inverter. This is achieved by control on pulses that have been given to the MOSFETs that comprising the 3-level inverter circuit. Figure 14 shows the three-phase output voltages of 3-level inverter.

Figure 14. $V_{oa}$, $V_{ob}$ and $V_{oc}$ three phase output voltages of three level inverter.
Certainly, THD is a very important factor to measure distortion in waveforms. THD measured in output voltage $v_{oa}$ is about (14%) of the nominal frequency component as shown in figure 15a. Also, there is a maximum decreasing in third and fifth harmonic components about (8% and 5.5%) of nominal frequency component respectively, with a small value for 7$^{th}$ harmonic component. This decreasing in harmonics components due to a switching frequency optimal Pulse with modulation (SFOPWM) topology used in pulses generation of 3-level inverter shown in figure 11.

Comparing with the results of THD mentioned above, if phase disposition (DP) PWM is used resulting a THD about 29% of nominal frequency component, with higher value in third, fifth and seventh harmonic components about (12%, 6%, and 16%) of nominal frequency component respectively, as its obvious in figure 15b.

![Figure 15. THD analysis for $v_{oa}$ of 3-level inverter (a) with SFOPWM topology, (b) with SPWM topology.](image)

8. **BLDC motor with PI controller results**

The output voltages of inverter have been supplied to a BLDC motor. The speed and torque of the motor are controlled by PI controller. Figure 16 represents stator current $I_{stator}$, rotor speed $N_r$, and electromagnetic torque $T_e$ of BLDC motor. The reference speed equals 300 rpm, and constant torque load equals 5 N-m. In this mode, the conformity between motor speed and reference speed of PI speed controller is very obvious. Also, as well as less conformity between electromechanical torque of motor with PI torque controller. This difference between reference torque and actual torque induced by the motor due to present assumption of a square wave currents in the motor coils, whereas in fact these currents are not pure square wave due to inductive effect. So the resultant output torque is developed on the motor just below the reference torque.
Figure 16. response of BLDC motor at constant load with PI controller a- stator current $I_{\text{stator}}$, b- rotor speed $N_r$, and c- electromagnetic torque $T_e$.

However, to proof the performance of both PI speed, and torque controls to govern speed and torque of BLDC motor, variable reference speeds and torques have been inserted to PI speed and torque controls. Figure. 17 shows how the speed of the rotor and electromechanical torque act with variable speeds and load torques, also it shows changes in stator currents. The speed alters as (500, 800, 600) rpm at time (0, 0.8, 1.2) sec, and load torque alters as (5, -10, 4) N-m at time (0.6, 1.7, 2) sec, with fully conformity between PI speed and torque controllers and rotation speed and torque of motor.
9. Conclusion
When inspecting and operating the proposed model system, where a complete BLDC motor/drive system has been simulated by using MATLAB/simulation, a new SFO-PWM topology was used with a carrier wave aim to significantly reduce THD in three phase output voltages. In addition, speed and torque of the BLDC motor were also controlled through PI control system. Considering two states, constant and variable mechanical torque on the machine, as a result, comparison between reference speed and reference torque with the actual machine speed and torque was well matched.

However, it was noted that this applicability between reference speed and reference torque and actual machine speed and torque reduced as machine speed increases. Whereas, this system features high torque and stability, and precise control with speed using the PI controller. The presence of this dominant controller leads to getting high reliability of motor operation.
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