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High-performance multilevel inverter drive of brushless DC motor

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Abstract: The brushless DC (BLDC) motor has numerous applications in high-power systems; it is simple in construction, is cheap, requires less maintenance, has higher efficiency, and has high power in the output unit. The BLDC motor is driven by an inverter. This paper presents design and simulation for a three-phase three-level inverter to drive the BLDC motor. The multilevel inverter is driven by discrete three-phase pulse width modulation (DPWM) generator that forced-commuted the IGBT's three-level converters using three bridges to vectored outputs 12- pulses with three levels. Using DPWM with a three-level inverter solves the problem of harmonic distortions and low electromagnetic interference. This topology can attract attention in high-power and high-performance voltage applications. It provides a three-phase voltage source with amplitude, phase, and frequency that are controllable. The proposed model is used with the PID controller to follow the reference speed signal designed by variable steps. The system design is simulated by using Matlab/Simulink. Satisfactory results and high performance of the control with steady state and transient response are obtained. The results of the proposed model are compared with the variable DC-link control. The results of the proposed model are more stable and reliable.

Keywords: Brushless DC Motor, Multilevel Inverter, High-Performance Drive, Pulse Width Modulation (PWM), Maltlab, Simulink

1. Introduction

The brushless DC (BLDC) motor is a permanent-magnet synchronous machine. It is supplied by a six-transistor inverter whose on/off switching is determined by the rotor position of the motor. It has neither brush nor commutator. Its torque-speed characteristic is similar to that of a permanent-magnet conventional DC motor, minus possible brush/commutation failure. It is becoming more popular in high-performance variable-speed drives. It requires relatively little maintenance and has lower inertia, larger power-to-volume ratio, lesser friction, and lesser noise than a conventional permanent-magnet DC servo motor of similar output rating. However, these advantages are costly, and the controller of a BLDC motor is more complex than that of a conventional motor. Good armature current response is also necessary to drive a BLDC motor satisfactorily [1]–[6].

BLDC motors have higher power density than other motors (e.g., induction motors) because no loss of rotor copper and no commutation occur. The structure is compact and robust, which contributes to the popularity of BLDC motors in efficiency-critical applications or where commutation-induced spikes (which are unwanted) exist. Commutation necessitates using an inverter and a rotor position sensor. However, position sensor can add to drive cost and machine size and reduce reliability and noise immunity. Numerous studies reported on sensorless drives that can control position, speed, and/or torque without shaft-mounted position sensors

Four conventional sensorless control methods exist. One is open-phase current sensing, which detects the conducting interval of freewheeling diodes connected anti-parallel with power transistors. At low speeds, the synchronization is simple and the control is excellent. At high speeds, the resolution of the rotor position decreases. Detecting the freewheeling current requires supply of additional isolated power to a comparator. Another method detects the third harmonic of back Electro – Motive Force (EMF) [4, 5], removing all the fundamental and other polyphase components through simple summation of three-phase voltages. Not so much filtering is required for the integration function of a signal with a frequency three times the fundamental. The filter is much smaller than that in flux detection through back EMF. It is insensitive to filtering delays and performs well at many speeds. However, measuring phase voltages requires a neutral point not considered in the manufacture of the motor. At low speeds, the third harmonic is difficult to detect [12],[13].

Yet another method, integration of back EMF, uses the principle that integration is constant from zero crossing point (ZCP) to 30°. Operation of the main processor decreases because calculating an additional conversion point of the switching mode is unnecessary. This method does not synchronize the phase current with back EMF at the sensorless drive. Using a flux-weakening drive is also impossible. The most popular sensorless control method is open-phase voltage sensing, which indirectly estimates rotor position through ZCP detection of open-phase terminal voltage. However, its response deteriorates at the transient state, and to detect the terminal-voltage ZCP, its operational speed must be sufficiently high [14]–[16].

Multilevel inverter (MLI) topologies have been widely used in the motor drive industry to run induction machines for high-power and high-voltage configurations. Traditional multilevel converter topologies, such as neutral point clamped (NPC) MLI, flying capacitor (FC) MLI, and cascaded H-bridge (CHB) MLI, have catered to a wide variety of applications. The CHB MLI might be the only type of MLI where the energy sources (capacitors, batteries, etc.) can completely be the isolated DC sources. Induction motors have been traditionally used for mostly all types of commercial, industrial, and vehicular applications. However, studies in the last decade have shown that vehicular applications demand high performances that are delivered by certain special machines, which include BLDC machines, switched reluctance machines, and permanent magnet synchronous machines [17].

The obvious reasons for traditionally using induction motor is that the motor technology and control methodologies are understood by both the academia and the industry. The paradigm shift toward using permanent magnet synchronous machines and BLDC machines is the result of the increased demand in high performance, faster torque response, and enhanced speed and efficiency from vehicles [18].

BLDC motors offer numerous advantages including high efficiency, low maintenance, greater longevity, reduced weight, and more compact construction. They have been widely used for various industrial applications based on inherent advantages. They are the most suitable motors in application fields that require fast dynamic response of speed because they are highly efficient and can be easily controlled in a wide speed range. This paper consists of introduction to BLDC motor and MLI, mathematical model of BLDC motors, inverter topologies, design MLI-fed BLDC motor drive, simulation results, and conclusion.

2. Mathematical Model of BLDC Motors

BLDC motor is a rotating electric machine with a classic three-phase stator similar to that of an induction motor. Its rotor mounts permanent magnets (see Fig. 1). The magnet rotates, and the conductors are stationary. This motor equals a reversed DC-commutator motor. Commutator and brushes alter the current polarity of a DC commutator motor, whereas a BLDC motor has its polarity reversed by power transistors synchronously switching with rotor position. Therefore, BLDC motors must often incorporate either internal or external position sensors that discern the actual rotor position or use sensorless detection [4],[8].

Fig. 1 shows the block diagram of the BLDC motor drive. Assuming the stator resistances of all the windings are equal and the self-inductance and mutual inductance are constant, the voltage equation of the three phases can be expressed as Equation (1), neglecting the magnets, the high-resistivity stainless-steel retaining sleeves, and the rotor-induced currents, and not modeling the damper windings [18].

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} + \begin{bmatrix} L_s - M & 0 & 0 \\ 0 & L_s - M & 0 \\ 0 & 0 & L_s - M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

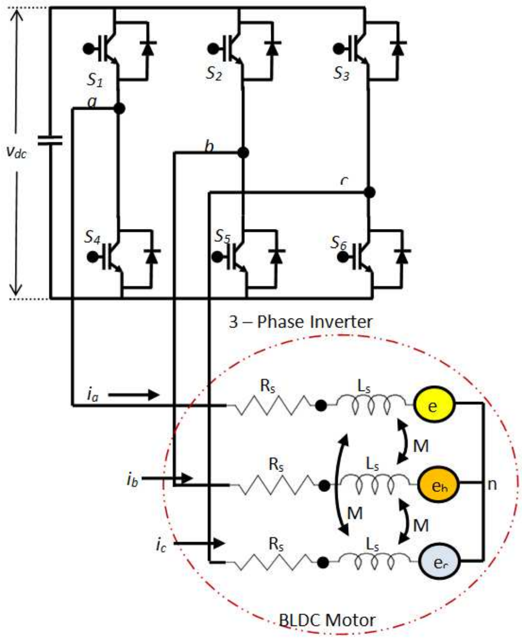

Figure 1. *Block diagram of a BLDC motor drive [18].*

va, vb, and vc denote the phase voltages; Rs the stator resistance; ia, ib, and ic the phase currents; Ls the stator inductance; M the mutual inductance; and L = Ls–M. The back EMFs of the phase are ea, eb, and ec, and the mechanical angular velocity is wm. Fig. 3 shows that injecting the square-wave phase current into the part that has the magnitude of the back EMFs fixed will reduce the torque ripple and stabilize control [19].

3. Inverter Topologies

The MLI has five basic types: isolated H-bridge, diode-clamped inverter, FC inverter, combinational multilevel topologies, and cascading fundamental topologies. Using MLI device in voltage sharing is automatic because of the independent DC supplies. No restriction is also observed on the switching pattern. With N devices (each capable of operating at voltage Vdc) per phase, the circuit can produce an output that varies between ± (N/2)*(Vdc/2). Very high voltage converters can be made by using a large number of H-bridges [17], [19].

The modular circuit is an advantage for manufacture and maintenance. The voltage stress on each of the switch also decreases. Using MLIs divides the main DC supply voltage into several DC sources that are used to synthesize an AC voltage into a stepped approximation of the desired sinusoidal waveform. The stepped approximation is also popularly known as the staircase model. An exhaustive literature survey was conducted to investigate the research previously performed in the area of MLIs [20].

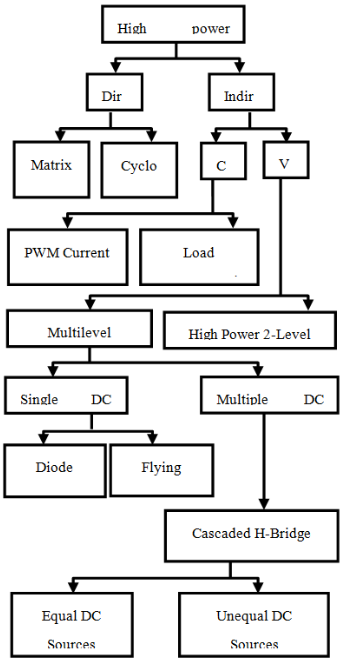

Figure 2. *Classification of high-power converters.*

The number of stages (cells or capacitors depending on the respective topology) helps decide the power capacity of the converter as a whole. Suitable connections in either series or shunt mode or both are performed to achieve higher voltage and/or current ratings. One of the biggest advantages of using an MLI is that the transformer can be eliminated, which helps enhance efficiency and cost effectiveness. The three popular topologies in MLI are as follows: NPC, FC, and CHB. Fig. 2 shows the classification of high power converters. Out of all power converters, cascaded bridge configuration is the most effective and popular. Cascaded bridge configuration is again classified into two types: half bridge and full bridge [21-22].

4. Design MLI-fed BLDC Motor

The proposed three-phase MLI fed to the BLDC motor is shown in Fig. 3. This model represents modeling a 50 kW, 380 V, 50 Hz, three-phase, three-level inverter. The IGBT inverter uses the discrete three-phase pulse width modulation (DPWM) technique (8 kHz carrier frequency) to convert DC power from a +/− Vdc source to V AC, 50 Hz. The inverter feeds a 50 kW resistive load through a three-phase transformer. L–C filters are used at the converter output to filter out harmonic frequencies generated mainly around multiples of 8 kHz switching frequency. The 12-inverter pulses required by the inverter are generated by the discrete three-phase PWM generator. The system operates in open loop at a constant modulation index. The inverter is built with individual IGBTs and diodes.

In a three-level voltage-sourced converter (VSC) using ideal switches, the two pairs of pulses sent to each arm could be complementary. For example, for phase A, IGBT1 is complementary of IGBT3 and IGBT2 is complementary of IGBT4. However, in practical VSCs, the turnoff of semiconductor switches is delayed because of the storage effect. Therefore, a time delay of a few microseconds (storage time + safety margin) is required to allow complete extinction of the IGBT that is switched off before switching on the other IGBT. Otherwise, a short circuit could result on the DC bus.

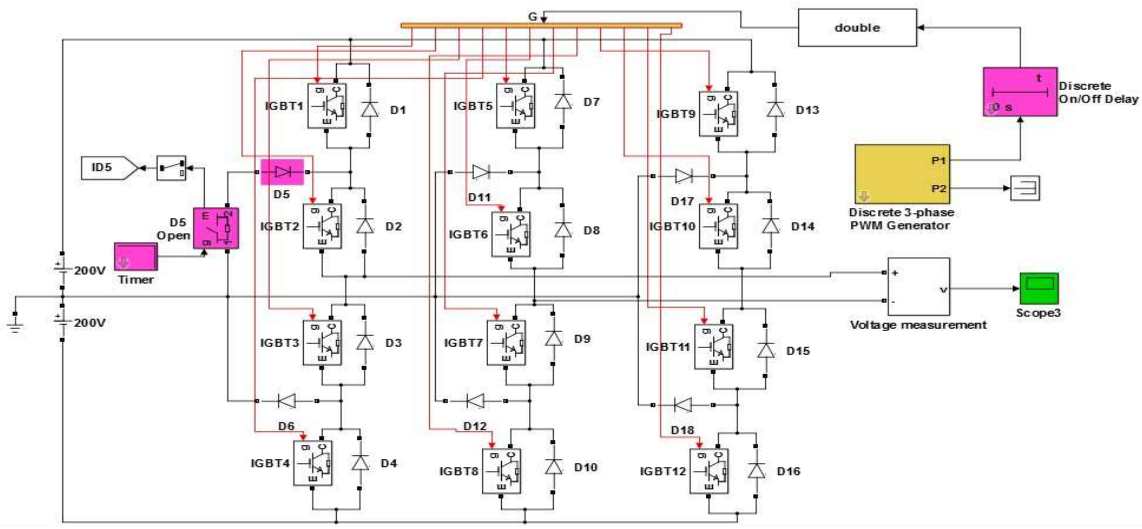

Figure 3. *Three-phase three-level inverter with DPWM*

5. Simulation Results

Table 1. *The numerical values for system design.*

Parameter	Value	Parameter	Value
Stator phase resistance Rs (ohm):	2.8750	Torque Constant (N.m / A_peak)	1.4
Stator phase inductance Ls (H) :	8.5e-3	Back EMF flat area (degrees)	120
Flux linkage established by magnets (V.s)	0.175	Inertia, viscous damping, pole pairs, static friction [J(kg.m^2) F(N.m.s) p() Tf(N.m)]:	[0.8, 1e-3 1e-3, 4]
Voltage Constant (V_peak L-L / krpm)	146.6	Initial conditions [wm(rad/s) thetam(deg) ia,ib(A)]	[0,0,0,0]

The parameters of PID controller are: Proportional K_P= 20, Integral k_I=0.1, derivative k_d=1

The simulation of the system design in this study was conducted by employing Matlab/Simulink version 2013b. In this simulation used same numerical values for system design to make compression, table 1 presents the numerical values. The variable DC-link voltage controller technique was utilized to obtain the BLDC motor, and the results were compared with the proposed model. The technique of using a variable DC voltage source to control the applied voltage and consequently to control the motor phase currents is cheaper than a traditional PWM control, but the losses can be high at low voltage and high current conditions. However, at high speed, a linear power stage can be the best alternative when the switching losses and commutation delay of a pulsed power stage are significant. The variable DC-link voltage control technique is the only technique that does not cause high-frequency disturbances. Its performance was similar to that of the PWM method, but it produced much smoother torque because of the absence of high-frequency switching. In the frequency domain, the variable DC-link voltage control technique contains only harmonics caused by the current commutation. The full simulation for this technique is shown in Fig. 4. Its performance was similar to that of the traditional PWM method, but it produced much smoother torque because of the absence of high-frequency switching. In the frequency domain, the variable DC-link voltage control technique contains only harmonics caused by the current commutation.

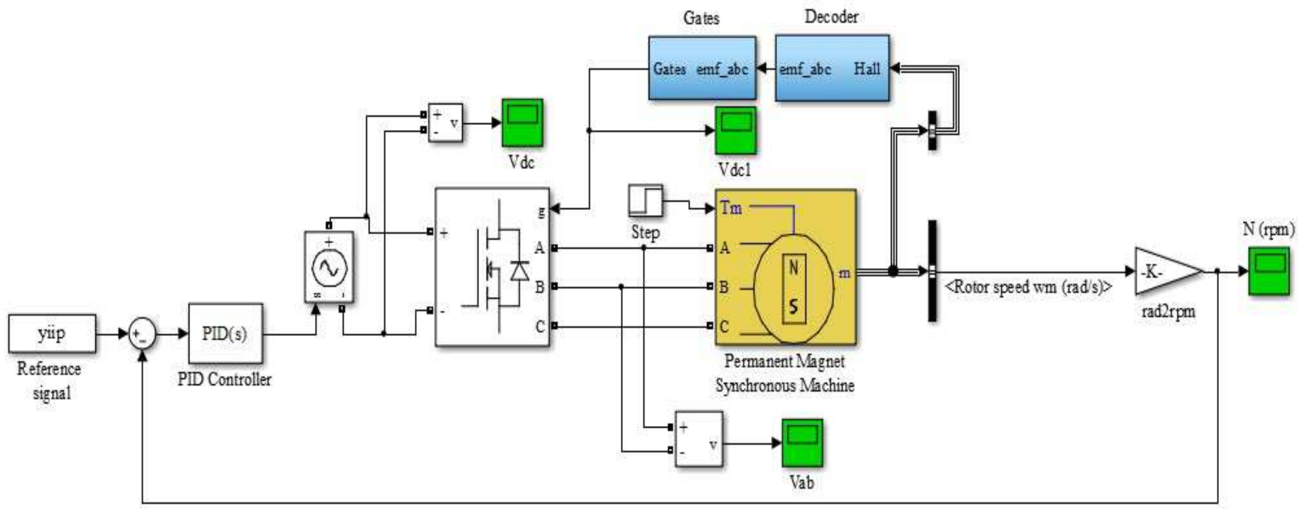

Figure. 4. *BLDC motor controlled by variable DC-link voltage controller.*

Proposed MLI

The proposed model of multilevel technique synthesizes the AC output terminal voltage with low harmonic distortion, thus reducing the filter requirements. In particular, MLIs are emerging as a visible alternative for high-power, medium-voltage applications. One of the significant advantages of multilevel configuration is the harmonic reduction in the output waveform without increasing the switching frequency or decreasing the inverter power output. The output voltage waveform of an MLI is composed of the number of levels of voltages, typically obtained from capacitor voltage sources starting from three levels, the number of levels can increase until the output is a pure sinusoidal. The output of the simulation for system design for MLI model described in Fig. 3 and used with BLDC motor is shown in Fig. 7. The output of this inverter based on DPWM with 12 pulses sequences, Fig. 6 explains the sample from the sequences used for operation MLI.

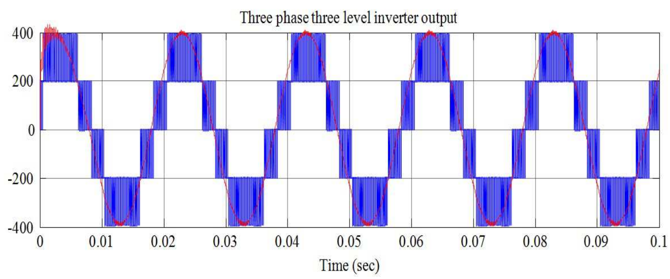

Figure. 5. *Output of three-phase three-level inverter with DPWM.*

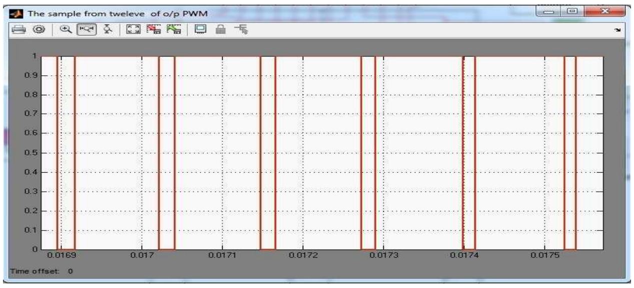

Figure 6. *The sample from output of the DPWM*

The full system design of speed control for BLDC motor based on MLI inverter driven by DPWM is shown in Fig. 7. A simple type of PID controller will be used with the proposed model of MLI-driven BLDC motor. A new DPWM strategy based on modulation that requires only a single carrier at 5 kHz and two reference signals is proposed, which is used to generate 12 PWM signals using the DPWM method, as shown in Fig. 7, with terminal G. If Vref1 exceeds the peak amplitude of the carrier signal Vcarrier, Vref2 is compared with the carrier signal until it reaches zero. At this point onward, Vref1 takes over the comparison process until it exceeds Vcarrier.

The simulation for control system design was described in Fig. 7, and the output is shown in Fig. 8. The test signal has a reference speed of 2000 rpm, and the desired high-performance input is achieved with small value of rising time (0.01 sec) and with accepted value of settling time (0.035 sec), with a steady-state error of less than 0.01% and maximum percent overshoot value of 3.48%; therefore, this response is reliability with high performance.

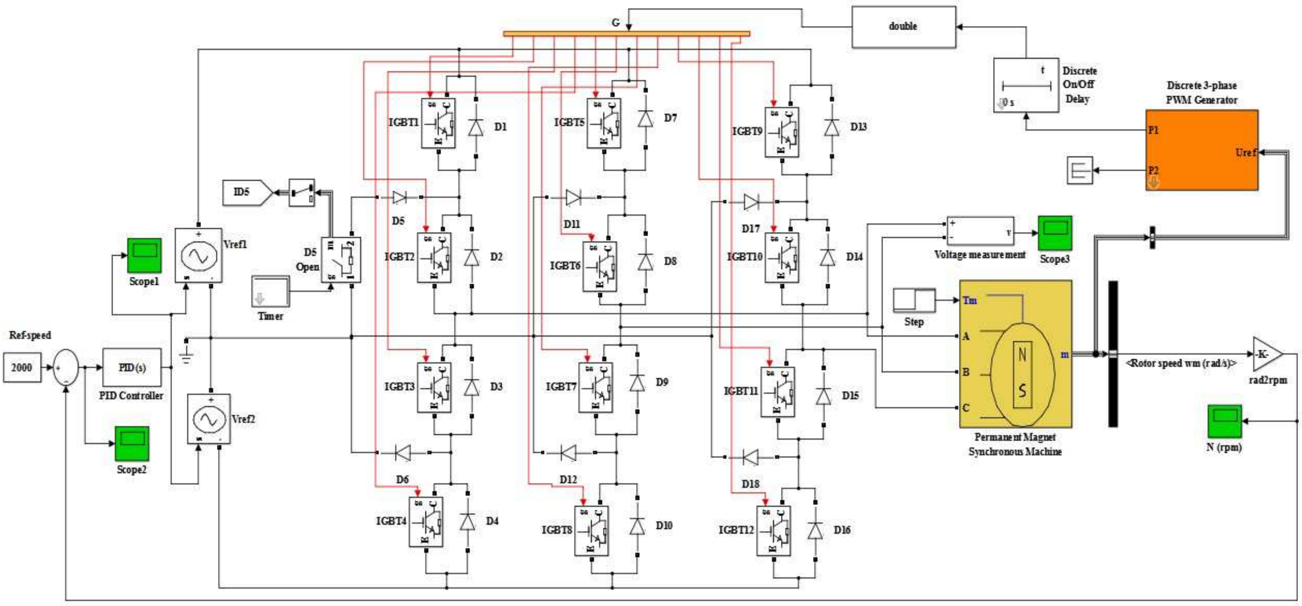

Figure 7. *BLDC motor with MLI driven with PID controller.*

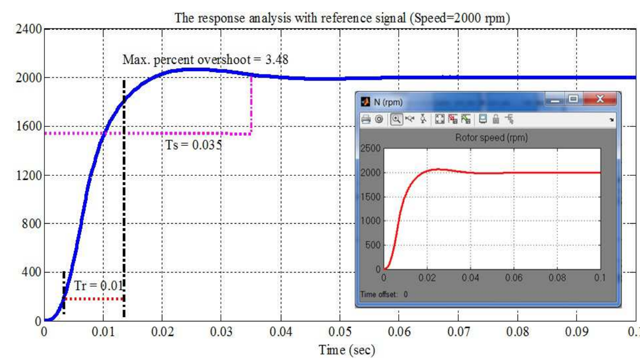

Figure 8*. Analysis of response for the proposed MLI with PID controller of BLDC motor.*

Fig's. 8&9 show the compression response between two models. The proposed model was described in Fig. 6 and the model of variable DC-link voltage control in Fig. 4. The input of the two models was designed with hard variable test signal values of 3000, 1000, and 2500 rpm and with time (0.5 sec) for each step. Fig. 9 shows that the output of the proposed model responds better than the variable DC-link model and is more stable and reliable.

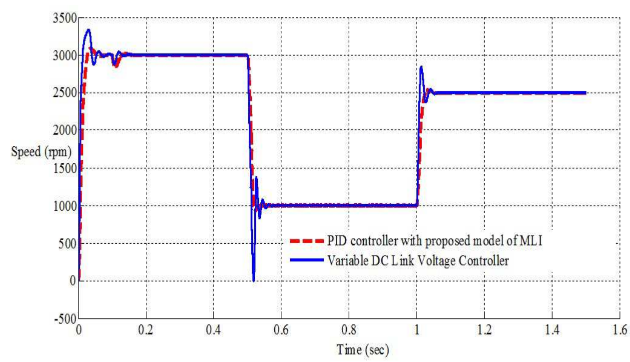

Fig. 9. *Two outputs of controllers with proposed MLI and variable DC-link*

6. Conclusions

The proposed MLI performance analysis was successfully presented by using Matlab/Simulink software. The proposed topology can be easily extended to a higher-level inverter. The simulation results were sine waves and exhibited fewer ripples and low losses. This system would show its feasibility in practice. The vector control was described in adequate detail and was implemented with a three-level MLI. This method enabled the operation of the drive at zero direct axis stator current. Transient results were obtained when a DPWM was started from a standstill to a required speed. The performance of the vector control in achieving a fast reversal of PDPWM even at very high speed ranges is quite satisfactory. The performance of the proposed three-phase MLI was investigated and was found to be quite satisfactory. A comparison was made between the PID controller–based proposed model MLI and the controller with variable DC-link voltage. The results showed that the proposed model responded better in transient and steady states and was more reliability with high performance.

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