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A COMPARATIVE STUDY OF VECTOR CONTROLLED PMSM DRIVE WITH PI SPEED CONTROLLER FOR LONG CABLE IMPLEMENTATION

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ABSTRACT

A comparative study on vector controlled Permanent Magnet Synchronous Motor (PMSM) drive with Proportional-Integral (PI) speed controller for long cable implementation. As reported by previous research, long cable caused an over voltage problem at motor terminal and could be double from the pulse output voltage at inverter terminal. However, this paper addresses another important application issue, namely increased losses in the motor drive system caused degrade and instability of the speed performances when long cable lengths are required. Two different length cables which are 1 meter and 10 meter connected from dSPACE to PMSM and the results are compared and evaluated. A DS1103DSP embedded with the Real-Time Interface (RTI) provided by dSPACE, hysteresis current controller scheme and PI control has been developed for a high performance control for PMSM drives The robustness of different length of cable over load disturbance, step response and change at command setting with inertia variations are studied.

Keywords: *DS1103, dSPACE, Long Cable, PMSM, Proportional-Integral, Real-Time Interface, Vector Control*

1. INTRODUCTION

With the rapid development of electric power electronic Permanent magnet synchronous motors are progressively replacing dc motors in high-performance applications like robotics, aerospace actuators and industrial applications such as wire bonding, die placement at semiconductor assembly. The PMSM provide high precision, efficient, larger torque inertia ratio and power density when compared to the induction motor for the same output capacity. The PMSM is smaller in size and lower in weight that makes it preferable for certain high performance applications [1]. Vector control is normally used in ac machines to convert them, performance wise, into equivalent separately excited dc machines.

The PMSM is a rotating electric machine where the stator is a classic three phase stator and the rotor has surface-mounted permanent magnets. The use of a permanent magnet to generate a substantial air gap magnetic flux makes it possible to design highly efficient PMSM. Many intelligent control techniques, such as PID, fuzzy control, neural networks control, adaptive fuzzy control, etc., have been developed and applied to the precision position control of servo motor drives to obtain high operating performance. A high performance motor control system should have a fast dynamic response in adjusting its control parameters so that the motor outputs affected by the disturbances can recover to their original status with zero steady state error [2].

In underground mines, fan drives play an important role on providing fresh airflow in very long galleries. In this application, for controlled staring as well as for airflow regulation, adjustable speed fan drives are applied [3]. The main problem caused the winding failures due to overvoltage resonance and reflection phenomena. To overcome the problem with filter installed and the system show failure free with good performances and enhanced reliability [4].

Many new and retrofit industrial adjustable speed drives (ASD) applications required that the inverter and the motor at separate locations, often resulting in long cable lead of 50 – 500ft. It is well known that long leads contributed to over voltages at the motor terminals and thus increased dv/dt of over 600V/us which can damage the motor winding insulation and lead to premature motor failure [5-12]. Another important ASD application issue where increased losses in the motor/drive system and the possible need for de-rating when long cable lengths are required.

An induction-driven fan in the environment control system of livestock closed farm. All the fans in the farm would be spun at the same speed but unfortunately the locations between them are sometime long in a possible range of 50 – 200 meters. The known problems of long cable usage lead to serious damage on the motor insulation and eventually it will reduce the life time of motor. Because the high and fast voltage rise (dv/dt) in PWM inverter voltage waveforms caused the over-voltages at motor terminals when using long cables. [13-16].

In [17], a simulation done on analyses vector control PMSM for different length of cables, the comparison of speed performances over the several tests shows that longer cable connected to motor caused the speed performance degrade due to loss on long cable.

In [18], with the rapid development in microprocessor, the high performance DSP chip becomes a popular research on digital control for ac drives due to their simple circuitry, high-speed performance, on-chip peripherals of a micro-controller into a single chip solution. The experimental results demonstrate that in step command response and frequency command response, the rotor position of PMSM can fast track the prescribed dynamic response well. However, the whole system required a complicated operation of the proposed control algorithm, programming and difficulty on control design modification.

In [19], a vector control implemented on PMSM in real time with ADMC-401 motor control DSP. The performance of vector control is quite satisfactory for achieving fast reversal of PMSM even at very high speed ranges systems. However, the ADMC-401 motor control DSP required programming or debugging control languages to develop the control system and is not practical feasibility on robust control.

In [20], have shown the practical feasibility of the proposed approach that allows robust control of the induction. The control algorithm is build within Simulink environment combined with the Real-Time Interface (RTI) provided by dSPACE and is implemented by the main processor of the DS-1103 board in real-time. The combination of dSPACE DS1103 DSP and MATLAB/Simulink effectively created a rapid control prototype environment. From previous literature review, many investigation and improvement done on long cable overvoltage problems, but in this paper focused on different cables length in term of the load disturbance, step response and changes in command setting with inertia variations are studied.

2. PMSM DYNAMICS

The mathematic model for the PMSM on the synchronously rotating d-q reference frame can be represented as [21]:

$$V_{qs} = r_s i_{qs} + \rho\,\Psi_{qs} + \omega_r \Psi_{ds} \tag{1}$$

$$V_{ds} = r_s i_{ds} + \rho\,\Psi_{ds} - \omega_r \Psi_{qs} \tag{2}$$

$$\Psi_{qs} = L_{qs} i_{qs} \tag{3}$$

$$\Psi_{ds} = L_{ds} i_{ds} + \Psi_f \tag{4}$$

$$T_e = \left(\frac{3}{2}\right)\left(\frac{p}{2}\right)\left[\Psi_f\, i_{qs} + \left(L_{ds} - L_{qs}\right) i_{ds}\, i_{qs}\right] \tag{5}$$

$$T_e = Jp\,\omega_r + B\omega_r + T_L \tag{6}$$

Where:

i_{ds}, i_{qs} : d-q axis stator currents
L_{ds}, L_{qs} : d-q-axis inductances
r_s : stator resistance
Ψ_f : constant magnet flux linkage
ω_r : motor speed
p : number of pole
T_L : load torque
B : damping co-efficient
J : rotor inertia
T_e : electromagnetic torque

Vector control actually is control of phase and amplitude at motor stator voltage or current vector at the same time. There are two types of PMSM, the surface and inside buried. For surface PMSM, the straight axis and cross axis for the main inductance is equal ($L_d = L_q$) and for the inside buried, the cross axis of main inductance is not equal ($L_d \neq L_q$). From the equation (5) show the torque depend on the inductances (L_d, L_q), type of rotor, magnet flux on the permanent magnet mount on the rotor and number of pole. With $L_d = L_q$, the electromagnetic torque can be expressed as

$$T_e = \left(\frac{3}{2}\right)\left(\frac{p}{2}\right)\left[\Psi_f\, i_{qs}\right] \tag{7}$$

An optimal efficiency PMSM is to ensures that stator current phasor contains only a quadrature axis component i_q. This is analogous to the separately excited DC machine, where this is achieved by consecutive switching of the armature coil through the commutator [22].

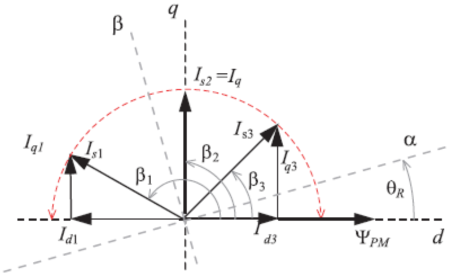


Fig1. Different Locations Of The Stator Current Vector.

General expression of the torque can be written as

$$T_e = \left(\frac{3}{2}\right)\left(\frac{p}{2}\right) \Psi_f \, |i_s| \sin\beta \qquad (8)$$

In the Fig. 1 shown how the I_q is changing with the change of I_s position, which results in a change in angle β. To achieved maximum torque can be obtained with an angle $\beta = 90^o$, this mode of operation gives the maximum torque per ampere of stator current and a high efficiency[22].

3. SYSTEM DESCRIPTION

A speed control system of the vector controlled PMSM drive for long cable implementation is illustrated as Fig. 2. The control system is combination of three major elements: the Simulink/dSPACE, Hardware interface and Long cable connected with PMSM. Data of the motor used are given in Table I. The rotor speed, ω_r is compared with references speed ω_r* and the resulted error is processed in the PI controller. The output of controller is reference torque, T* which is then has been limited by a limiter in order to generate the q-axis reference current, i_{qs}*. (Refer to Fig. 3). As flux in the machine is provided by magnets, there is no need to supply excitation current to the stator winding. Therefore, d-axis reference current, i_{ds}* is set to zero. Both d-axis and q-axis stator currents generate three phase reference currents (i_a*, i_b* and i_c*) through Park's Transformation which are compared with sensed winding currents (i_a, i_b and i_c) of the PMSM. The current errors are fed to hysteresis current controllers which generate switching signals (S_{abc}*) for the voltage source inverter. Optocouplers used as isolator to protect the dSPACE DS1103 from overvoltage damage at inverter. Thus, by obtaining winding currents of the system, the speed response is obtained. The speed and angle signal is obtained from resolver digital converter (RDC).

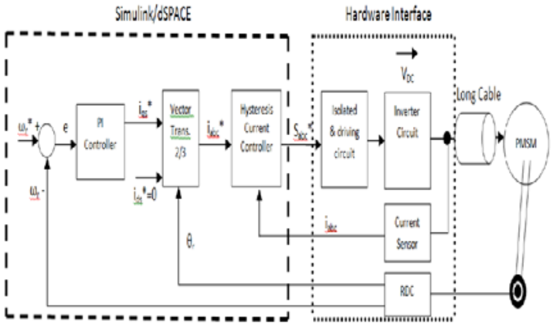


Fig 2. Configuration Of Vector Controlled PMSM Drive For Long Cable Implementation

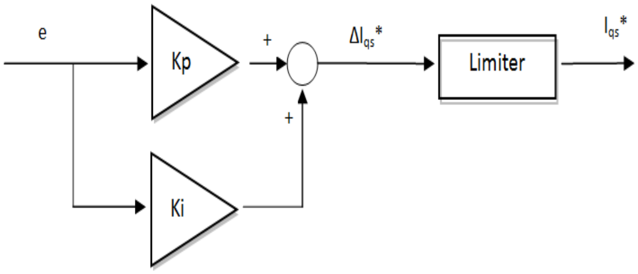


Fig 3. PI Controller With Limiter

The transformation of synchronous machine from the a-b-c phase variables to the d-q variables transforms all are sinusoidal varying inductances in the a-b-c frame into constants in the d-q frame. Park transformation used to convert stator winding quantities such as current, voltage and flux linkage to the d-q references frame that is attached to the machine rotor [23-24].

$$\begin{bmatrix} U_0 \\ U_{ds} \\ U_{qs} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \cos\theta & \cos\left(\theta-\frac{2\pi}{3}\right) & \cos\left(\theta-\frac{4\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta-\frac{2\pi}{3}\right) & -\sin\left(\theta-\frac{4\pi}{3}\right) \end{bmatrix} \qquad (9)$$

As references frame is selected firmly attached to the rotor, only the stator equations need to be transformed from the stationary references frame to the rotating references frame. The two-axis d-q current references are transformed into three-phase stator current references. The correlation between d-q axis current references and stator phase current is given as below:

$$\begin{bmatrix} i_a * \\ i_b * \\ i_c * \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & -\sin\theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta - \frac{4\pi}{3}\right) & -\sin\left(\theta - \frac{4\pi}{3}\right) & 1 \end{bmatrix} \quad (10)$$

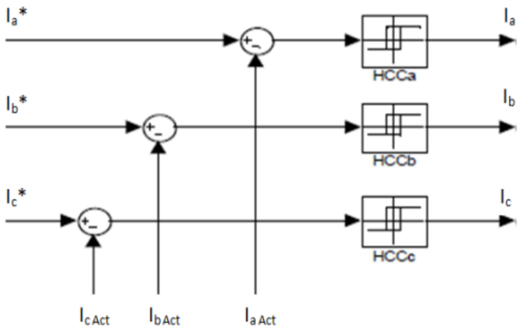


Fig 4. Hysteresis Current Control

In the Fig. 4 show the block diagram for hysteresis controller in order to produce the switching signal for inverter circuit. The actual phase currents (i_a, i_b, i_c) are compared with reference phase current (i_a*, i_b*, i_c*) using three independent comparator in hysteresis controller. The logic condition for six inverter switches is chosen by the output of the comparator. When the phase "a" current is smaller than (i*-Δi), where Δi is the hysteresis band, the output of the comparator is "1", the "a" phase will be connected with the positive track of DC link. In contrast, if the phase "a" current is bigger than (i*- Δi), the output of the comparator will become "0", and the "a" phase will connected to the negative track of DC bus. The similar procedures are applied on other legs. With the hysteresis controller, the phase current control within the hysteresis band. The phase currents are approximately sinusoidal in steady state. The smaller the hysteresis band, the more closely do the phase currents represent sine wave but implied a high switching frequency which is a practical limitation of the power device and increased inverter losses. In this experimental, ±0.1 hysteresis band are chosen.

TABLE I. PMSM TEST MOTOR

Parameter	Value
Maximum torque	10.8 Nm
Rated torque	3.6 Nm
Rated current	6.29 A
Maximum current	16 A
Rated speed	418 rad/s (4000rpm)
Inertia	0.000553 kgm^2
Stator winding resistance	2.2 Ω
Inductance	8.2 mH
Voltage Constant	57.5 Vpk/krpm
Pole pairs	2
V_{DC}	300 V

4. EXPERIMENTAL RESULTS

The experimental rig of control system for PMSM includes dSPACE DS1103 DSP board, PMSM coupled with DC generator as a dynamic load, isolated and driving circuit, personal computer (PC), current sensor, RDC, an inverter circuit and the cable used here is an unshielded, PVC insulated, 4-core cable with the conductor area of 1.5 mm^2. The dSPACE DS-1103 DSP board [25] forms the core of the closed loop system. Aside from the duties of controlling the operator interface, it perform the acquisition of the feedback signal, computes a speed signal, delivers the speed signal to the control algorithm, and executes the control algorithm to determine a control signal. A variable DC power supply is used as DC link and a DC power supply is used to supply the isolator and driving circuit with 15V DC. The PC is a Pentium (R) Dual CPU 1.19GHz with Windows XP. Fig. 5 showed the experimental rig.

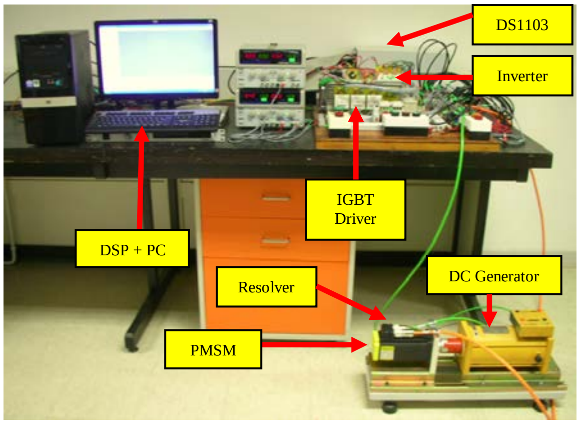


Fig 5. The Experimental Rig

The motor is 4000 r/min three-phase. It is equipped with resolver. The RDC use to convert resolver signal to the speed and angle from PMSM as feedback signal. The motor is also coupled with a DC Generator as a dynamic load. A variable resistive load is connected to the terminals of the DC generator. To achieve sudden disturbances, the dSPACE send a signal to trigger and activate a relay to switch resistive load turned ON and OFF.

The control algorithm is build within Simulink environment combined with the Real-Time Interface (RTI) provided by dSPACE and is implemented by the main processor of the DS-1103 board in real-time Fig. 6.

Control Desk is a user interface that allows the user to run simulations on different platforms such as the real-time DS1103 Controller Board, Fig. 7 expanded layout window in ControlDesk [25].

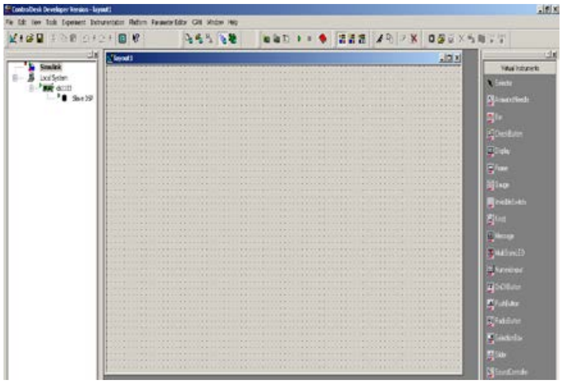


Fig 7. Expanded Layout Window In Control Desk

In the experiment, the sampling time is 10 µs. A low pass third order Butterworth filter is used for noise elimination and the passband edge is 50 rad/s.

The study of vector-controlled PMSM drive with implementing 1 meter and 15 meter cable of PI speed controller is carried out in the MATLAB (Simulink) program. All study based on rated value of the test motor model as shown in Table I. The investigations are aimed at studying the robustness of different length of cable over step response, changes in command setting with inertia variations and load disturbance are studied.

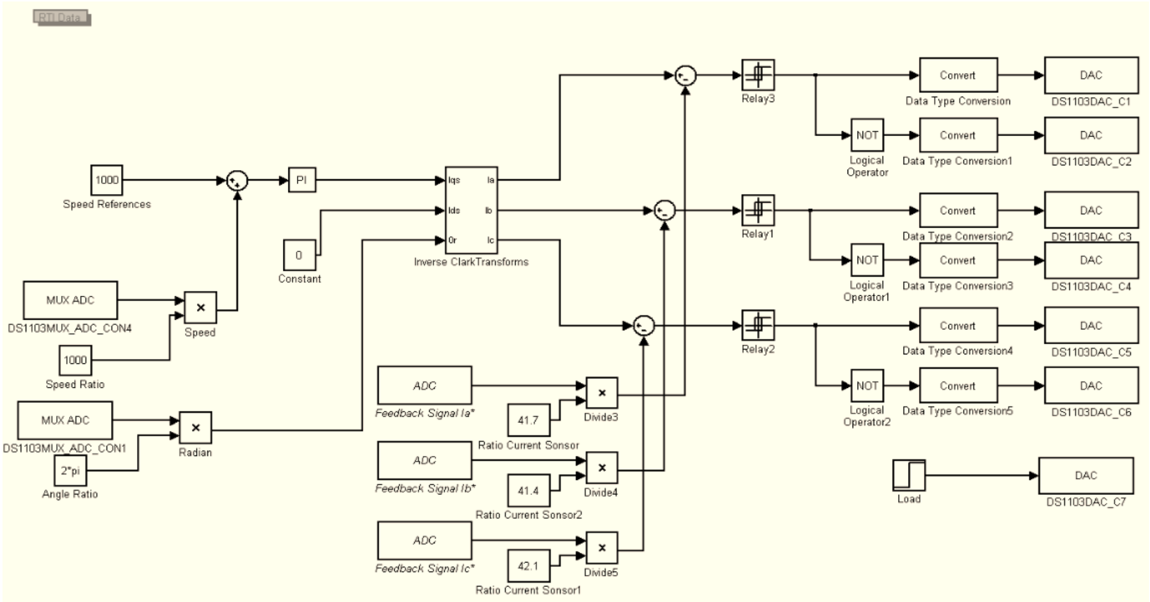
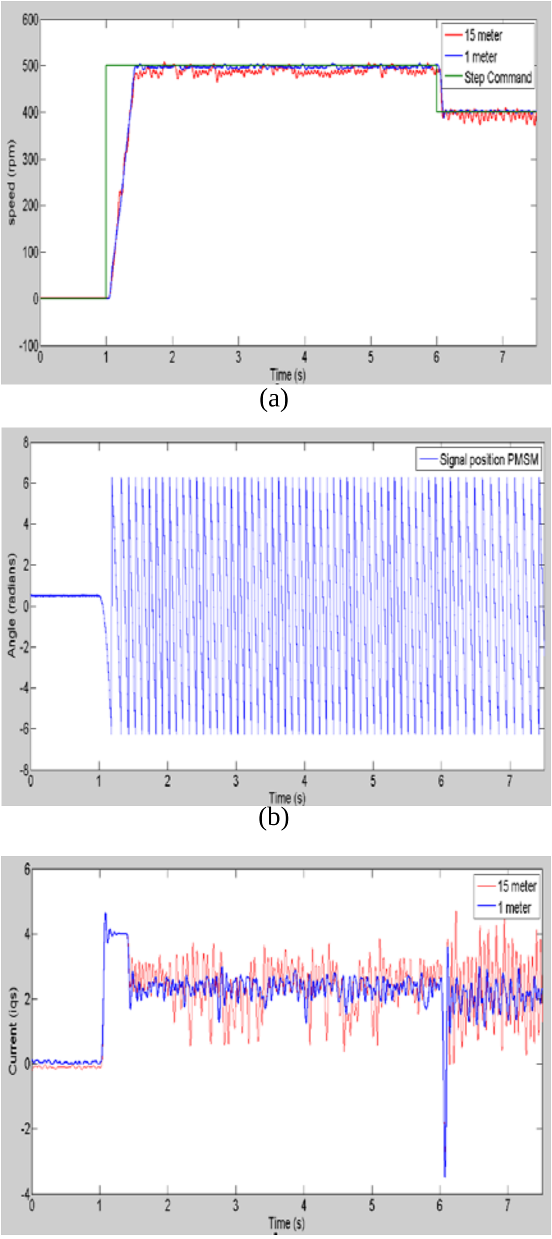


Fig 6. Real-Time Control Prototyping



(a)

(b)

(c)

Fig 8. Comparison Of Different Cable Length During Start-Up : (A) Speed Response At 500rpm (B) Current Iqs (C) Signal Position Resolver

Fig. 8 presents a speed response start-up from standstill and accelerated to the speed command without load. With Proportional (P) is 1.8 and Integral (I) is 0.1, no load start with speed command is 500rpm at t = 1s, t = 6s when the step down command to 400rpm. The result show the speed and current response on the different cable length during start up condition, the longer of the cable length connected to motor caused degrade and unstable speed response compare shorter cable.

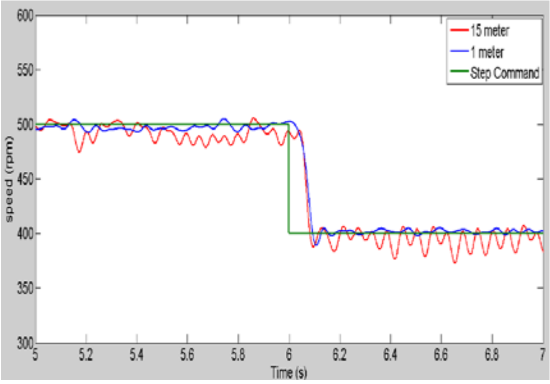


Fig 9. Comparison Of Speed Responses Obtained By Different Cable Length During Step Down 20% Reduction From Speed Command

After the responses settling down at the speed command, the system is step down 20% reduction from speed command when *t* = 6 sec and the results are showed in Fig. 9. The results show speed controller rejected step down disturbance is faster and achieved steady state at shorter cable length.

For load disturbances applied on the PMSM, the DC generator have high inertia and caused PI controller need to retuning on PI value to make sure PMSM operate at optimum performance. In this case, P is 15 and I is 0.395, the system is loaded with 0.85Nm at instant time, *t* = 1s and the results are showed in Fig. 10. The speed controller reject load disturbance rapidly without overshoot and almost zero steady state error at speed command 500rpm for PMSM connected with 1 meter cable. Unfortunately, for speed controller connected with 15 meter cable, the speed response unable to recover back to achieved zero steady state error after load disturbance applied.

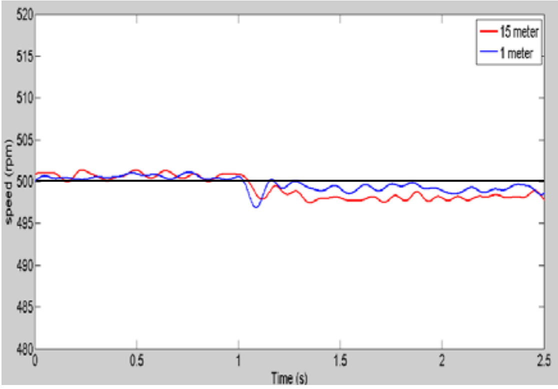


Fig 10. Load Disturbance Waveform

5. CONCLUSION

This paper presents results of a vector controlled drives of PMSM using PI Speed controller for long cable application in high performance drives. 2 types of cable length: 1meter and 15 meter are studied. Performance of different cable length is studied for step speed command from standstill with rated and, load rejection transients and step down speed command. The comparison of speed performances over the several tests shows that longer cable connected to motor caused the speed performance degrade and unstable due losses on longer cable. For future work, fuzzy logic or neural network speed controller could be used to investigate, improved and minimize the degradation of speed performance.

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