VECTOR CONTROLLED DRIVES OF PERMANENT MAGNET SYNCHRONOUS MOTOR USING PI SPEED CONTROLLER FOR LONG CABLE APPLICATION

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Vector Controlled Drives of Permanent Magnet Synchronous Motor Using PI Speed Controller for Long Cable Application

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Abstract— **This paper present a vector controlled drives of Permanent Magnet Synchronous Motor (PMSM) by using Proportional-Integral (PI) Speed controller for long cable application. As known, long cable caused an over voltage problem at motor terminal and could be double from the pulse output voltage at inverter terminal. This caused instability of the speed performances. PI speed controller is implemented to drive a PMSM with different cables length to investigated the speed performances, load disturbances and parameter variations of the system. Hysteresis current controller is used for inner loop current control and PI controller for outer loop speed control. Simulation results are provided to show performances on different cable length driving a PMSM.**

Keywords—Proportional-Integral (PI) Controller Speed Controller, Vector Control, Permanent Magnet Synchronous Motor, Long Cable, Hysteresis Current Controller

I. INTRODUCTION

Fan drives play an important role in underground mines, 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 [1]. The main caused the winding failures due to overvoltage resonance and reflection phenomena. The problem solved with filter installed and the system show failure free with good performances and enhanced reliability [2].

The development of advanced power electronic switching operation has improved the performances of pulse-width modulated (PWM) of the adjustable speed drives (ASD). Switching frequencies of 2 to 20 kHz are common with insulated fate bipolar transistor (IGBT) technology for power levels up to 800kW. Many new and retrofit industrial 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 [3]. 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.

Variable speed drives of induction motors are generally used in many industries. One of such example is the 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 [4]. 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 [5].

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 speed response, overshoot, rise and settling time, load disturbances and parameter variation on PMSM by using PI speed controller.

II. PMSM DYNAMICS

The machine model for the PMSM on the synchronously rotating d-q reference frame can be represented as [6]:

$$V_{qs} = r_s i_{qs} + \rho\,\Psi_{qs} + \omega_r\,\Psi_{ds} \qquad (1)$$
$$V_{ds} = r_s i_{ds} + \rho\,\Psi_{ds} - \omega_r\,\Psi_{qs} \qquad (2)$$
$$\Psi_{qs} = L_{qs} i_{qs} \qquad (3)$$
$$\Psi_{ds} = L_{ds} i_{ds} + \Psi_f \qquad (4)$$
$$T_e = \left(\frac{3}{2}\right)\left(\frac{p}{2}\right)\left[\Psi_f\, i_{qs} + \left(L_{ds} - L_{qs}\right) i_{ds}\, i_{qs}\right] \qquad (5)$$
$$T_e = Jp\,\omega_r + B\omega_r + T_L \qquad (6)$$

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 for at motor stator voltage or current vector at the same time. There are two types of permanent magnet synchronous motor : the surface and inside buried. For surface PMSM, the straight axis and cross axis for the main inductance is equal ($L_d = L_q$)

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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

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

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 [7].

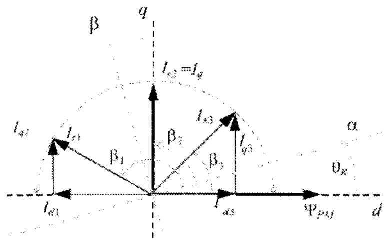

Figure 1. Different locations of the stator current vector.

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 Figure 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 $\beta = 90°$, this mode of operation gives the maximum torque per ampere of stator current and a high efficiency[7].

III. SYSTEMS DESCRIPTION

A. PMSM drives system

A speed control system of the vector controlled PMSM drive is illustrated as Figure 2. Data of the motor used are given in Table I. The rotor speed, ω_r is compared with ω_r^* and the resulted error is processed in the 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 Figure 3). Meanwhile, 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 for the voltage source inverter. Thus, by obtaining winding currents of the system, the speed response is obtained.

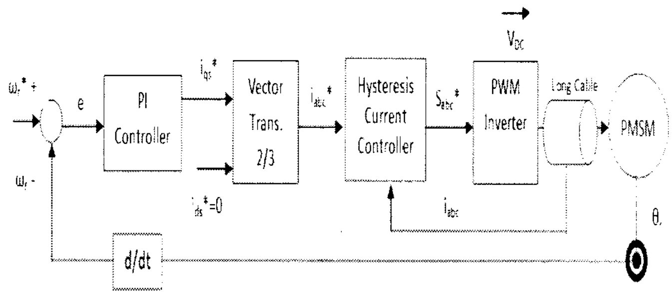

Figure 2. Configuration of PI based vector controlled PMSM drive for long cable application

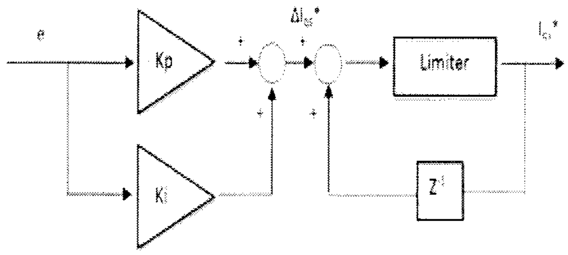

Figure 3. PI Controller with Limiter

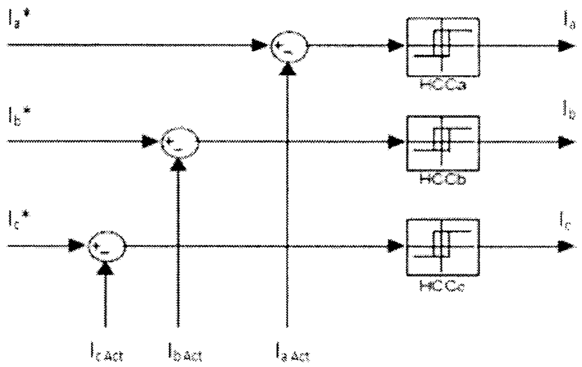

Figure 4. Hysteresis Current Control

Figure 4 shows the block diagram for hysteresis controller in order to produce the output signal. The actual phase currents (ia, ib, ic) are compared with reference phase current (ia*, ib*, ic*) using three independent comparator in hysteresis controller. The logic condition for six inverter switches is chosen by the output of the comparator [8].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. A similar procedure exists in the other legs. The reason that this is called a hysteresis controller is that the leg voltage switches to keep

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the phase current within the hysteresis band. The phase currents are, therefore, approximately sinusoidal in steady state. The smaller the hysteresis band, the more closely do the phase currents represent sine wave. Small hysteresis band, however, imply a high switching frequency, which is a practical limitation of the power device. Increased switching frequency also implies increased inverter losses.

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

B. High-frequency Cable Modeling

The cable parameter are estimated by using equations related to the geometrical configuration of the cable were found to be vastly different than actual parameter values because they do not include the frequency dependency in the calculation. Therefore, the cable parameters are estimated through experimental analysis by checking the frequency response of the power cable impedance. Two types of tests have been carried out : measurement of short circuit and open circuit impedances. [9]

The conventional 2nd order per-section model is commonly used to represent cables as shown in Figure 5 (a) [10], [11]. The advantage of 2nd-order per-section model is its simplicity. However, the disadvantage of the conventional cable model is that it doesn't represent the cable frequency-dependent phenomena such as skin and proximity effects, dielectric losses, etc. The parameters of the conventional model are also difficult to measure accurately as the cable resonant frequency depends on cable characteristics and length. An improved cable model was proposed in [9], which can represent the dielectric losses using a higher-order parallel branch as shown in Fig. 5 (b). Further improvements are proposed in this paper in order to include the skin and proximity effects. Such effects are not taken into account with the use of first-order series branch. Therefore, a high order model is proposed in Figure 5 (c). This section model combines the parallel branches as proposed in [9] and utilizes higher-order series braches to represent the skin and proximity effects.

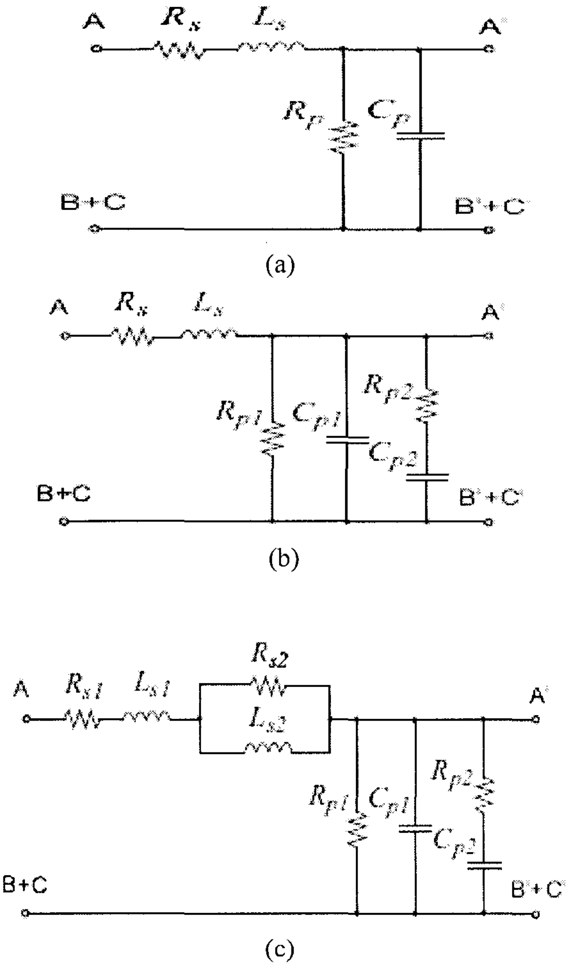

Figure 5. 2nd order per-section cable model

The parameters of the proposed cable model in Fig. 5 (c) are identified from the cable SC and OC impedances *ZSC* and *ZOC*. For the measurements of *ZSC* and *ZOC*, an HP/Agilent 4294A impedance analyzer [12] is used to evaluate the impedances in the range from 100 Hz to 10 MHz. The formulas for cable parameter calculation are given as below. [13]

$$Ls1 = L_{SC-HF} \quad (9)$$

$$Ls2 = L_{SC-LF} - L_{s1} \quad (10)$$

$$Rs1 = |Z_{SC-LF}| \cos(\theta_{SC-LF}) \quad (11)$$

$$Rs2 = |Z_{SC-HF}| \cos(\theta_{SC-HF}) - R_{s1} \quad (12)$$

$$C_{p1} = C_{OC-HF} \quad (13)$$

$$C_{p2} = C_{OC-LF} - C_{p1} \quad (14)$$

$$R_{p1} = |Z_{OC-LF}| [\cos(\theta_{OC-LF})]^{-1} \quad (15)$$

$$R_{p1//p2} = |Z_{OC-HF}| [\cos(\theta_{OC-HF})]^{-1} \quad (16)$$

$$R_{p2} = [(R_{p1//p2})^{-1} - (R_{p1})^{-1}]^{-1} \quad (17)$$

A typical power cable is used to demonstrate the effectiveness of the proposed cable model and parameter identification procedure. The cable used here is an unshielded, PVC insulated, 4-core cable with the conductor area of 1.5 mm^2. The calculated cable parameters are summarized in

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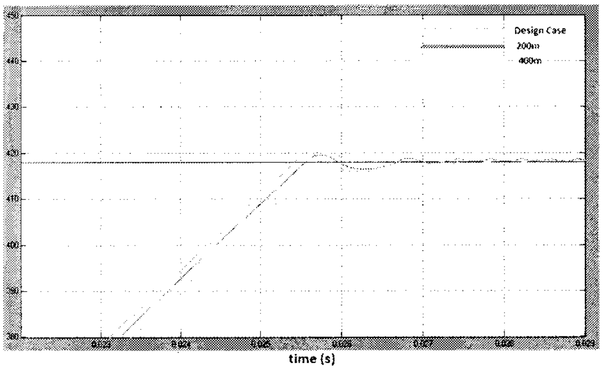
Table II. From the proposed cable model and the calculated parameters, the cable SC and OC impedances are reproduced and are superimposed with the measured characteristics, the results fitted by the proposed equivalent circuit of Figure 5 (c) are in good agreement with the measured characteristics for the actual cable segment.[13]

TABLE II. PROPOSED CABLE PER-METER PARAMETERS

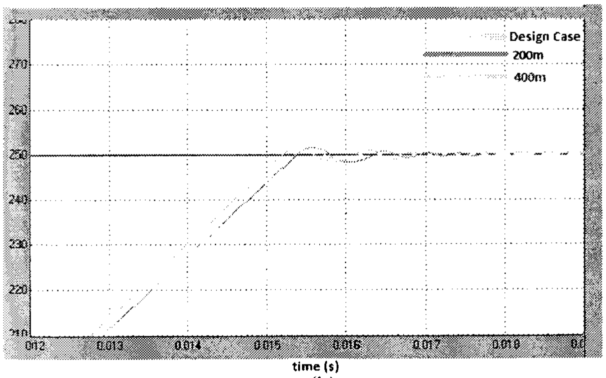
Parameter	Value
*Rs*1	21 mΩ
*Rs*2	271.2 mΩ
*Rp*1	22 MΩ
*Rp*2	100 KΩ
*Ls*1	451.8 nH
*Ls*2	89.32 nH
*Cp*1	79.6 pF
*Cp*2	34.11 pF

IV. RESULTS

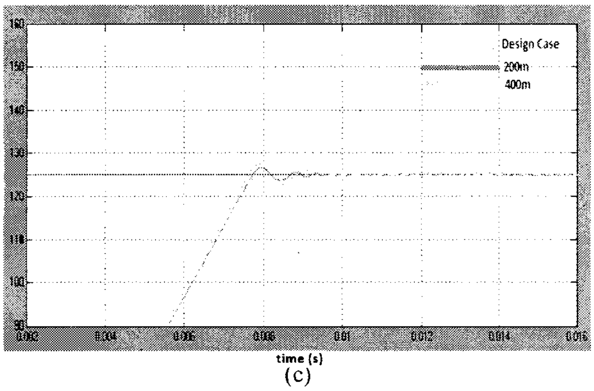
The study of vector-controlled PMSM drive with implementing Design case (1 meter), 200 meter and 400 meter cable of PI speed controller is carried out in the MATLAB (Simulink) program. All study based on rated value of the test motor model as shown in Table I and cable parameter as show in Table II. The investigations are aimed at studying the speed responses of the PI controller with implementation of different cable length connected to PMSM.



(a)



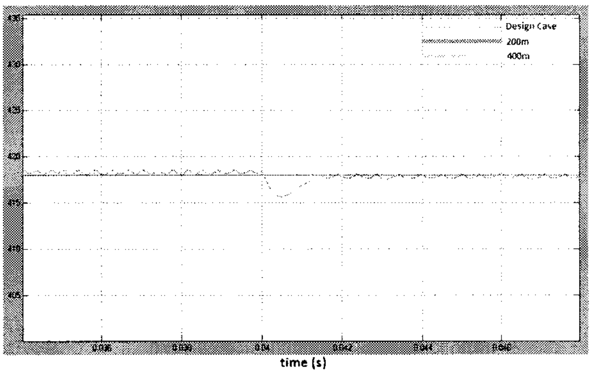
(b)



(c)

Figure 6. Comparison of speed responses obtained by different cable length during start-up for 3 different speeds : (a) at rated 418rad/s (b) at 250rad/s (c) at 125rad/s

Figure 6 presents a small overshoot of 0.4% rated speed (2rad/s) during start-up from standstill and accelerated to the speed command without load. The result show the speed response on the different cable length during start up condition, the longer of the cable length connected to motor caused rise time increased. After the responses settling down at the speed command, the system is loaded with rated load torque which is 3.6Nm at instant time, t = 0.04 sec and the results are showed in Figure 7. The speed controller reject load disturbance rapidly without overshoot and almost zero steady state error at rated speed 418rad/s. The results show speed controller reject load disturbance faster at shorter cable length and the steady state error increased when decrease speed command to 250rad/s and 125rad/s. Figure 8 can be clearly seen that shorter cable length connected to motor produces faster undershoot response compared to longer cable length.



(a)

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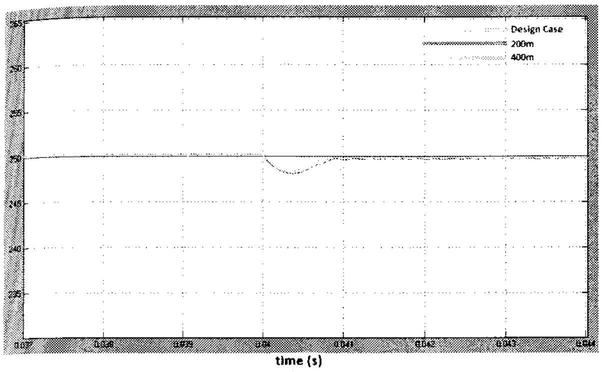
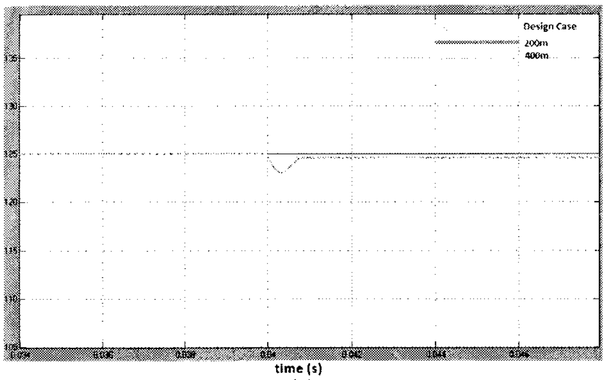


(b)



(c)

Figure 7. Comparison of speed responses to step rated load torque application obtained at different cable length for 3 different speeds : (a) at rated 418rad/s (b) at 250rad/s (c) at 125rad/s

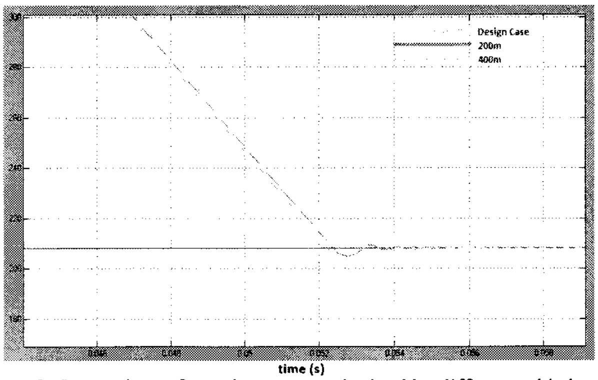


Figure 8. Comparison of speed responses obtained by different cable length during step down 50% reduction at speed command

V. CONCLUSION

This paper presents results of a vector controlled drives of PMSM using PI Speed controller for long cable application in high performance drives. 3 types of cable length : Design case (1meter), 200meter and 400meter are studied. Performance of different cable length is studied for large step speed command from standstill with rated and, load rejection transients and reverse speed command. The simulation study is realized in MATLAB environment. The comparison of speed performances over the several tests shows that longer cable connected to motor caused the speed performance degrade due to losses on long cable.

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