PMSM control system with open-end winding and floating bridge capacitor

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Abstract. This paper represents structure of permanent magnet synchronous motor (PMSM) control system focused to work in field weakening mode. Structurally it consists of PMSM motor with open end winding, main bridge inverter (MB) with DC voltage at one side of motor winding and floating bridge (FB) inverter with a capacitor at the other side of motor winding. Structure of control system with active and reactive power distribution for MB and FB inverter with capacitor’s voltage level control and motor’s shaft control loops is proposed. Simulation model via Matlab/Simulink and Simscape language is designed. Comparing proposed control system with field oriented PMSM vector control and “Y” motor end winding connection is provided. Obtained results shows that proposed control system helps to reach 1.4 times more maximum speed that a conventional one.

1. Introduction

Induction motors are widely used in industry because of cheap production and simple control algorithms (with ability to drive directly from the three-phase power source). There are numerous papers which describes different control strategies [1], and motor’s parameters identification methods [2]. At the same time permanent magnet synchronous motors (PMSM) have the best mass-dimensional ratio compare to other electric motor types [3]. That’s why permanent magnet electric machines are popular both in motor [4] (especially in FOC and sensorless position control systems [5,6]) and generator [7,8] modes. However, PMSM motor’s main disadvantage is rapid electromagnet torque falling in field weakening zone. In papers [9-11] field weakening PMSM control algorithms were proposed. In [12] a comparison of PMSM’s speed with different end winding connection (include OWPMSM) were provided. Obtained trends represents that OWPMSM topology has the best speed curve. Control system with OWPMSM and two independent inverters with DC sources was presented in [13]. Paper [14] describes a control algorithm of PMSM motor with open end winding, main inverter with DC power source and floating bridge inverter with electrolytic capacitor with novel hybrid PWM modulation. Results shows 2 times increasing of PMSM speed compare to conventional FOC PMSM control system.

This paper describes OWPMSM control system with Main bridge (MB) inverter powered by DC voltage source at one side of motor stator winding and Floating bridge (FB) inverter with a capacitor connected to the other side of motor winding. Control system include PI control loop for speed, d, q axis currents and for voltage level of floating capacitor.
2. Mathematical model equations of PMSM motor

PMSM motor equations for d and q axis can be described by following equations:

\[
\begin{bmatrix}
V_q \\
V_d
\end{bmatrix} = \begin{bmatrix}
R_s + \rho L_q & \omega_r L_d \\
-\omega_r L_q & R_s + \rho L_d
\end{bmatrix} \begin{bmatrix}
i_q \\
i_d
\end{bmatrix} + \begin{bmatrix}
\omega_r \lambda_f \\
\rho \lambda_f
\end{bmatrix}
\]

where \(V_d\) – d-axis voltage; \(V_q\) – q-axis voltage; \(R_s\) – stator resistance; \(L_d\) – d-axis inductance; \(L_q\) – q-axis inductance; \(\omega_r\) – rotor speed; \(\lambda_f\) – permanent magnets flux linkage; \(\rho\) – derivation operator; \(i_d\) – d-axis current; \(i_q\) – q-axis current.

Equation for electromagnetic, and mechanical torques are following:

\[
T_e = \frac{3}{2}(P)(\lambda_d i_q - \lambda_q i_d)
\]

\[
T_e = T_L + B \omega_m + J \frac{d\omega_m}{dt}
\]

where \(P\) – PMSM pole pairs number; \(\lambda_d\) – d-axis flux linkage; \(\lambda_q\) – q-axis flux linkage, \(T_L\) – rotor shaft load; \(B\) – friction coefficient \(\omega_m\) – rotor’s mechanical speed; \(J\) – rotor’s inertia;

Peak motor’s current can be found by:

\[
I_m = \sqrt{i_d^2 + i_q^2}
\]

3. Open-and winding PMSM motor control strategy

Figure 1 represents OWPMSM control system structure. Power side of proposed system consists of two two-level inverters, DC voltage source and floating capacitor.

\[\text{Figure 1. OWPMAS control system.}\]

\[\text{Figure 2. OWPMAS vector diagram}\]

\[\text{«V}_{\text{dqm}}\text{ to } V_{d1}, V_{d2}\rangle\] is the main block to form control voltage in rotating dq reference frame for MB and FB inverters. The equations for this block are following:

\[
v_{q1} = v_{q1a} + v_{Qcap}
\]

\[
v_{d1} = v_{d1a} + v_{Dcap}
\]

\[
v_{q2} = v_{q1} - v_{qm} + v_{Qcap}
\]

\[
v_{d2} = v_{d1} - v_{dm} + v_{Dcap}
\]

where \(v_{q1}, v_{d1}\) – control signals for MB inverter in d, q reference frame; \(v_{q2}, v_{d2}\) – control signals for FB inverter in dq reference frame; \(v_{q1a}, v_{d1a}\) active voltage vectors for MF inverter; \(v_{Qcap}, v_{Dcap}\) –
capacitor voltage control vectors; $v_{qm}, v_{dm}$ – d, q voltage output after speed and d, q axis PI regulators. These parameters can be described as:

\[
\begin{align*}
v_{q1a} &= \frac{2P_{D}i_q}{3l_m} \\
v_{d1a} &= \frac{2P_{D}i_d}{3l_m} \\
v_{Qcap} &= \frac{2P_{DFB}i_q}{3l_m} \\
v_{Dcap} &= \frac{2P_{DFB}i_d}{3l_m} \\
v_{q1} &= v_{q1a} + v_{Qcap} \\
v_{d1} &= v_{d1a} + v_{Dcap} \\
v_{q2} &= v_{q1} - v_{qm} + v_{Qcap} \\
v_{d2} &= v_{d1} - v_{dm} + v_{Dcap} \\
P_{D} &= \frac{3}{2}(v_{qm}i_q + v_{dm}i_d)
\end{align*}
\]

where $P_{D}$ – required power for main bridge inverter; $P_{DFB}$ – required power for floating bridge inverter; $i_q, i_d$– stator currents after Park transformation; $v_{q1}, v_{d1}$ – control signals for MB inverter in d, q reference frame; $v_{q2}, v_{d2}$ – control signals for FB inverter in dq reference frame.

D-axis setpoint sets to 0 when motor runs at nominal speed, and changes to (18) in field weakening zone.

\[
i_{d, \text{ref}} = \sqrt{l_m^2 - l_q^2}
\]

MB inverter aimed to generate only active power vector, while FB inverter produces only reactive one. Vector diagram of described above process (according to [16]) showed on figure 2.

4. MATLAB control system simulation

Simulation were provided by MATLAB/Simulink software. Proposed model does not include, voltage fluctuations, drops and asymmetrical components [17,18]. It consists of two blocks: Motor and inverters energy blocks “Motor_And_Load” and control algorithm block “Controller_algorithm”. Detailed representation of this blocks showed on Figure 3 and 4. “Controller_algorithm” block works by following steps: Speed setpoint “Velocity_Command” compares with measured shaft speed and the results goes to the PI regulator input. Output signal after Speed PI regulator sends to “Main” block where forms $v_{qm}, v_{dm}$ signals. $i_q, i_d$ stator current feedback signals and $\theta$ rotor angle are also “Main” block inputs.
Figure 3. Main view of «Controller_algorithm» subsystem.

LPF is low pass filter block. From “Main” subsystem output signals sends to “Vqm to Vd1q1, Vd2q2” block, where, according to (5)-(18) equations block forms outputs for MB and FB inverters.

Figure 4. «Motor_And_Load» subsystem main view.

“VdqVab” is reverse Park transformation block for MB and FB inverter.
“Motor_And_Load” subsystem is energy part of model. Voltage form signals from “Controller_algorithm” block goes to vector PWM forming subsystem. Vector PWM block output forms control signal for inverters semiconductor gates for MB and FB accordingly. OWPMSM is custom motor model block, written by Simscape language according to (1)-(4) equations.

Proposed model was compared with conventional field-oriented vector control system for PMSM with “Y” end winding connection.
Model parameters are following: FOC PMSM model was supplied by 310 VDC power source. Proposed OWPMSM motor’s power was 160VDC power source connected to MB inverter and 5000
nano-farad capacitor connected to the FB inverter. Both models’ reaction on speed setpoint presented on figures 5,6. Electric motor parameters presented on Table 1.

| Motor type                        | Salient pole PMSM motor |
|-----------------------------------|--------------------------|
| Nominal voltage                   | 310V                     |
| Nominal current                   | 15A                      |
| Nominal speed                     | 150 rad/sec              |
| Pole pairs number                 | 4                        |
| Q-axis inductance                 | 0.01557 H                |
| D-axis inductance                 | 0.01557 H                |
| Flux linkage                       | 0.2667 Wb                |
| Stator phase resistance           | 1.1 Ohm                  |
| Inertia                           | 0.005066 kg·m²           |
| Friction coefficient              | 0                        |

5. Conclusion

OWPMSM has the following working algorithm: at the beginning, capacitor battery is charging, afterwards, MB is configured to generate only active component of the voltage vector, while FB is generating only reactive one.

Speed setpoint was intentionally set to value, which is much more than nominal motor’s value in order to determine its maximum operating speed. FOC PMSM model reached only 160 rad/sec speed (according to figure 5) while proposed OWPMSM control system reached 200 rad/sec speed, which is 1.4 times more than conventional control system can reach. Both models were simulated under 2 Nm load. Figures 5, 6 represents simulation results of proposed and conventional models. Figure 5 shows motor’s speed and capacitor voltage level during simulation.
Figure 5. OWPMSM control system simulation results.

Figure 6. FOC PMSM simulation results.
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