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Letter

Maximum Continuous Operation Time Control of PMSM with Compressor Loads of Air Conditioners under DC Power Supply Loss

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In this letter, a method to maximize the operation time, even in cases of longer power interruption, by minimizing the power lost by the load is developed using the Lagrange function.

Keywords: PMSM, power supply loss, continuous operation, low inertial loads

1. Introduction

The permanent magnet synchronous motors (PMSM) drive systems for the compressor of air conditioners are required to continue its operation as long as possible even when the input power source is interrupted. Because it takes long time to recover the heat cycle, once it stops. In the case of short time power interruption, a method to utilize both Filter Capacitor (FC) energy and kinetic energy was proposed to continue its operation until the power source is recover [1]. However, in the case of long time power interruption, it is preferable to continue the operation for as long as possible by minimizing the losses. In this letter, a method to maximize the operation time even in the case of the longer power interruption by minimizing the power lost by the load is derived by means of the Lagrange function.

2. Modeling

The modelling of the physical behavior including each loss is performed. The load torque of the compressor τ_L is assumed as constant regardless of the rotating speed. The load torque of the compressor is mainly determined by the conditions of discharge pressure and suction pressure of the compressor. Within a few seconds of an instantaneous power interruption, even if the rotating speed change, the discharge pressure and suction pressure do not change greatly unless the cycle conditions such as valve conditions change in the refrigerant cycle. And, d-axis current value i_d is set to 0.

When the power supply is interrupted, the overall energy E_{all} coincides with the sum of the integral of the overall losses of the whole system P_{loss} and the power transmitted from FC Energy and/or kinetic energy to the load side P_{load} as follows:

$$E_{all} = \int (P_{loss} + P_{load})dt \quad (1)$$

The equations of the losses and P_{load} are defined in (2) to (11). P_{loss} consists of the motor losses $Loss_{motor}$ and inverter losses $Loss_{inverter}$. $Loss_{motor}$ consist of copper losses $Loss_{copper}$, iron losses $Loss_{iron}$, and mechanical losses $Loss_{mech}$. $Loss_{inverter}$ consist of losses of equivalent resistance of FC $Loss_{cap}$, conduction losses $Loss_{on}$ and switching losses of switching devices $Loss_{sw}$.

$$P_{loss} = Loss_{motor} + Loss_{inverter} \quad (2)$$

$$Loss_{motor} = Loss_{copper} + Loss_{iron} + Loss_{mech} \quad (3)$$

$$Loss_{inverter} = Loss_{cap} + Loss_{on} + Loss_{sw} \quad (4)$$

$$Loss_{copper} = R_m i_q^2 \quad (5)$$

$$Loss_{iron} = K_{IL}\omega^3 \left(L_q^2 i_q^2 + \phi_f^2\right) \quad (6)$$

$$Loss_{mech} = K_{me}\omega^2 \quad (7)$$

$$Loss_{cap} = V_{fc}^2/R_d \quad (8)$$

$$Loss_{on} = K_{on}\left|i_q\right| \quad (9)$$

$$Loss_{sw} = K_{sw}\left|i_q\right| V_{fc} \quad (10)$$

$$P_{load} = \tau_L \times \omega \quad (11)$$

where R_m is stator coil resistance, i_q is q-axis current, ω is rotating speed, L_q is q-axis inductance, ϕ_f is PM flux, V_{fc} is voltage of FC, R_d is equivalent parallel resistance of FC including discharge resistor, and K_{IL}, K_{me}, K_{on}, K_{sw} are coefficients of each losses, respectively.

If V_q can be approximated as $p\omega\phi_f$, where p is number of pole pairs, (12) is obtained combined with the motion equation:

$$C_{fc}V_{fc}\frac{dV_{fc}}{dt} + J_m\omega\frac{d\omega}{dt} + \omega\tau_L = 0 \quad (12)$$

where C_{fc} is capacitance of FC, and J_m is inertial load.

3. Maximum Continuous Operation Time Control

In order to search the optimal time-FC voltage pattern $V_{fc}(t)$ which gives the longest continuous operation time, the calculus of variations is applied as the one of the optimization methods [2]. Overall energy loss E from the time $t = 0$ at the time of the power supply interruption until an arbitrary time $t = t_a$ is expressed as (13), if the loss power P is expressed as (14).

$$E = \int_0^{t_a} P dt \quad (13)$$

$$P = R_m i_q^2 + K_{IL}(p\omega)^3\left(\phi_f^2 + L_q^2 i_q^2\right) + K_{me}\omega^2 + V_{fc}^2/R_d + K_{on}\left|i_q\right| + K_{sw}\left|i_q\right| V_{fc} + \tau_L\omega \quad (14)$$

Then, the Lagrange function L can be obtained by (15) and (16).

$$L\left(V_{fc}, \dot{V}_{fc}, t\right) = P\left(V_{fc}, \dot{V}_{fc}, t\right) + \lambda\left(C_{fc}V_{fc}\frac{dV_{fc}}{dt} + J_m\omega\frac{d\omega}{dt} + \omega\tau_L\right) \quad (15)$$

$$\frac{\partial L\left(V_{fc}, \dot{V}_{fc}, t\right)}{\partial V_{fc}} - \frac{d}{dt}\left(\frac{\partial L\left(V_{fc}, \dot{V}_{fc}, t\right)}{\partial \dot{V}_{fc}}\right) = 0 \quad (16)$$

where, λ is Lagrangian multiplier.

$V_{fc}(t)$ which gives minimum loss energy in (13) can be generally obtained by solving (16). However the left side of (16) is always positive in any V_{fc} (t) as shown in (17) in this case.

$$2V_{fc}/R_d + K_{sw}\left|i_q\right| > 0 \quad (17)$$

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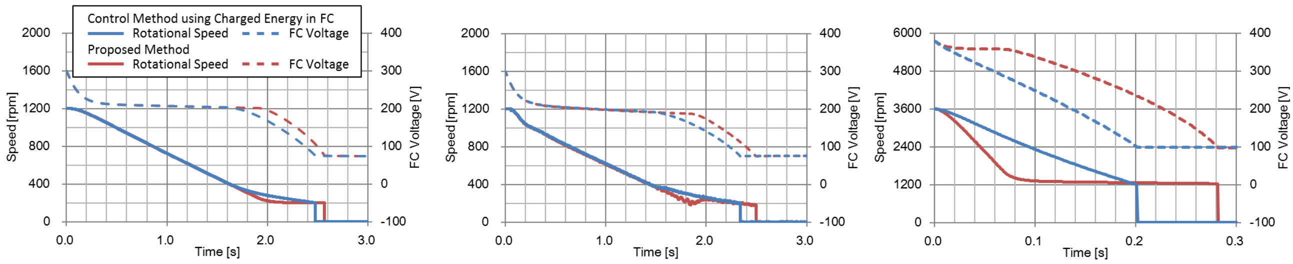

(a) (b) (c)

Fig. 1. Simulation and Experiment Results: (a) simulation results at the experiment conditions (Table 1), (b) experimental results, (c) simulation results at the compressor conditions (Table 2)

Therefore, the energy loss E in (13) is monotonically increasing or decreasing with respect to the V_{fc} (t), as far as V_{fc} (t) > 0.

According to (12), $d\omega/dt$ is zero to keep the kinetic energy maximum. In this case $\omega(t)$ is ω_0 which is given at $t = 0$ and $V_{fc}(t) = \sqrt{(V_{fc0}^2 - 2\omega_0\tau_L/C_{fc}\cdot t)}$. On the other hands, V_{fc}/dt is zero to keep the capacitor energy maximum and the kinetic energy minimum. In this case $\omega(t) = \omega_0 - \tau_L/J_m \cdot t$ according to $d\omega/dt = -\tau_L/J_m$ in (12) and $V_{fc}(t)$ is V_{fc0} which is given at $t = 0$. If the energy losses at $\omega(t) = \omega_0$ and $\omega(t) = \omega_0 - \tau_L/J_m \cdot t$ are defined as $E(\omega_0)$ and $E(\omega_0 - \tau_L/J_m \cdot t)$ respectively, $\Delta E = E(\omega_0) - E(\omega_0 - \tau_L/J_m \cdot t)$ can be obtained as (18)

$$\Delta E = \int_0^{t_a}\left[R_m i_{q0}^2 + K_{IL}\phi_f^2\left\{\omega_0^3 - \left(\omega_0 - \frac{\tau_L}{J_m}t\right)^3\right\}\right.$$
$$+K_{IL}\omega_0^3 L_q^2 i_{q0}^2 + K_{me}\left\{\omega_0^2 - \left(\omega_0 - \frac{\tau_L}{J_m}t\right)^2\right\}$$
$$\left.+K_{on}\left|i_{q0}\right| + K_{sw}\left|i_{q0}\right|\sqrt{V_{fc0}^2 - \frac{2\omega_0\tau_L}{C_{fc}}t} + \frac{\tau_L^2}{J_m}t - \frac{2\omega_0\tau_L t}{R_d C_{fc}}\right]dt$$
$$= \int_0^{t_a}\left(A + \frac{\tau_L^2}{J_m}t - \frac{2\omega_0\tau_L t}{R_d C_{fc}}\right)dt \quad \cdots\cdots (18)$$

where, i_{q0} is the q-axis current at the power interruption. Because A is always positive value, ΔE can be expressed as follows:

$$\Delta E > \int_0^{t_a}\left\{\tau_L\left(\frac{\tau_L}{J_m} - \frac{2\omega_0}{R_d C_{fc}}\right)t\right\}dt = \int_0^{t_a}(\tau_L U t)\,dt \quad \cdots\cdots (19)$$

In the compressor of residential air conditioner with 4.5 kW or less power, the inertial loads J_m is at most about 0.001 kgm^2, the maximum ω_0 is 733 rad/s (7000 rpm), the minimum R_d is 20 kΩ, and the minimum C_{fc} is almost 1000 μF. Then, if the load torque τ_L is about 0.07 Nm or more, the sign of U is positive. In the compressor, from a load torque of 0.1 Nm or more is generated due to the friction load, it could be said that U is always positive. Therefore, the losses become the lowest when $\omega(t)$ is controlled as $\omega(t) = \omega_0 - \tau_L/J_m \cdot t$.

After ω reaches the lower limit ω_{min} which is set to avoid the damage to the compressor, i_q is controlled as constant values to keep $\omega = \omega_{min}$ until V_{fc} reaches the lower limit V_{fcmin}. According to (12), if ω is kept constant as ω_{min}, discharging power of FC is constant as shown in (20).

$$C_{fc}V_{fc}\frac{dV_{fc}}{dt} = -\omega_{min}\tau_L \quad \cdots\cdots (20)$$

Thus, the higher V_{fc} enables longer operation time after ω reaches ω_{min}. For this sake, the proposed method to keep V_{fc} constant instead ω is decelerate by load torque τ_L is reasonable for longer operation.

Table 1. Specifications and control parameters of the experiment.

Symbol	Meaning	Value
ω_0	Speed before Power interruption	126 rad/s (1200rpm)
ω_{min}	Minimum Speed	21 rad/s (200rpm)
τ_L	Load Torque	1.5 Nm
C_{fc}	Capacitance of FC	1320 μF
J_m	Inertial Load	0.028 kgm^2
V_{fc0}	DC Power supply voltage	300 V
V_{fcmin}	Minimum FC voltage	75 V

Table 2. Specifications and control parameters of the compressor.

Symbol	Meaning	Value
ω_0	Speed before Power interruption	377 rad/s (3600rpm)
ω_{min}	Minimum Speed	126 rad/s (1200rpm)
τ_L	Load Torque	2.0 Nm
C_{fc}	Capacitance of FC	1020 μF
J_m	Inertial Load	0.00075 kgm^2
V_{fc0}	DC Power supply voltage	380 V
V_{fcmin}	Minimum FC voltage	100 V

4. Simulation and Experiment Results

The same loss models in the previous section is utilized in the simulation. The power supply is interrupted at 0 second. The current reference is input through first-order lag filter in order to prevent sudden change in torque [1].

The simulation results in Fig. 1(a) and the experimental results in Fig. 1(b), generally agree with each other. Thus, the simple loss model and power balance model in (12) are reasonable enough to propose the method. It is also revealed that the continuous operation time by proposed method is longer than the time of the control method using charged energy in FC. As shown in Fig. 1(c), assuming the smaller inertial load case such as Table 2, the continuous operation time by the proposed method is expected to be about 40% longer than the method using charged energy in FC.

5. Conclusion

The longest continuous operating pattern of $V_{fc}(t)$ at the power source interruption is derived theoretically by the simple loss models. The proposed method is verified by both the simulation and experimental test.

References

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