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# AN EFFICIENT BRAKING ALGORITHM FOR INTERIOR PERMANENT MAGNET SYNCHRONOUS MOTORS

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**Abstract:** ***This paper presents an efficient braking algorithm for a permanent magnet synchronous motor drives with a diode front end rectifier. Regenerative braking energy is dissipated in stator windings which act as a braking resistor, without adding any additional braking choppers and electronic control circuits. Application of this braking algorithm results in maximum power losses in stator windings and relatively high braking torque, all within inverter current and voltage capabilities. Also, this algorithm determines braking dynamics by regulating voltage on a DC link capacitor well bellow critical limit.***

**Key Words:** ***Braking/Permanent Magnet Synchronous Motor***

## 1. INTRODUCTION

Permanent magnet synchronous motor drives can operate in all four quadrants of torque-speed characteristics. Beside the work in motoring and generating mode, braking mode is particularly interesting for speed regulated drives. Nowadays large number of commercially available electric drives come with diode front end rectifiers (due to their low price), which have irreversible nature; hence it is not possible to drive recuperative energy back to the mains. Instead, this energy largely contributes to the raise of voltage on a DC link capacitor. A common way of solving this problem is to add switching and passive element (braking transistor and resistor) in parallel with DC link capacitor, though creating a braking chopper. Chopper maintains voltage on a DC link capacitor and dissipates regenerated braking energy. However, this device also increases drive complexity and price and decreases reliability; therefore it is worthy considering different methods for braking, which employ main motor operating features instead of using additional electronics. Holtz [1] presented and efficient braking scheme for induction motor drive with diode front end rectifier. Paper [2] deals with efficient braking methods for surface permanent magnet synchronous motors. In this paper, in order to maximize braking torque without adding any braking resistors, a braking algorithm suitable for interior permanent magnet synchronous motors that employ both permanent magnet and reluctance torque has been proposed.

## 2. EFFICIENT BRAKING CRITERIA

Braking methods within electrical motor drives can be classified into three main groups – inertial, soft and active braking.

a) Inertial, passive braking (coast down) is achieved simply by turning off the inverter. The whole braking process relies on rotor inertia, mechanical load, viscous and ventilating friction. This braking method has no practical value when being used at high motor speeds, due to very long stopping time. Also, this way of braking is recommended for low speeds only. In case of high speeds, where field weakening algorithm is used (with notoriously high direct axis currents), electromotive force can be relatively high (several kV). In case of high current trip situation, it is required from stator windings to be shorted, in order to protect stator stack. This on the other hand, interrupts braking process and makes it less efficient.

b) Soft braking (ramp down) represents a controlled deceleration of motor. With this type of braking, speed control loop normally follows linearly falling reference signal (speed ramp) and generates limited braking torque. Gradient of speed ramp is most commonly limited by raise of DC link capacitor voltage due to appearance of recuperative braking energy. The value of stator current in the case of soft braking is not necessarily the highest possible and therefore it is not possible to dissipate complete braking energy, nor give maximum braking torque. This braking method gives good results for mid and low speed ranges, but still it is not the most efficient method.

c) Active braking provides maximum braking torque, by having maximum dissipated power (losses) in motor stator windings. To achieve maximum losses in stator copper, stator current has to be highest possible, which is normally constrained by inverter capabilities. This is the most efficient and the fastest braking method which results with the shortest stopping time.

In order to get optimal torque during active braking sequence, it is pertinent to define three criteria that have to be met:

1) DC link capacitor voltage has to be limited to a maximum allowable value that prevents capacitor destruction (dielectric breakthrough).

2) Maximization of stator current within voltage and current inverter limits has to result in quickest dissipation of generated energy.

3) Braking torque has to be maximized in order to reduce motor braking (stopping) time.

## 3. ACTIVE BRAKING WITHIN VECTOR CONTROLLED IPMSM DRIVE

In case of vector controlled interior permanent magnet synchronous motor (IPMSM) drive, definition of active braking scheme is effectively a definition of reference current trajectories in d-q reference frame. Starting point for definition of these trajectories is a mathematical model of interior permanent magnet synchronous motor in d-q synchronously rotating reference frame [3]:

$$\begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} = \begin{bmatrix} R_s + sL_{sd} & -\omega_e L_{sq} \\ \omega_e L_{sd} & R_s + sL_{sq} \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_e \psi_m \end{bmatrix} \quad (1)$$

$$T_e = \frac{3}{2} p i_{sq} \left[ \psi_m + \left( L_{sd} - L_{sq} \right) i_{sd} \right] \quad (2)$$

where $v_{sd}$ and $v_{sq}$ are d and q-axis stator voltages, $i_{sd}$ and $i_{sq}$ are d and q-axis stator currents, $R_s$ is stator phase resistance, $L_{sd}$ and $L_{sq}$ are d and q-axis stator synchronous inductances, $\psi_m$ is flux linkage of rotor permanent magnets, $\omega_r$ is rotor mechanical speed, $p$ is number of rotor pole pairs, $\omega_e = p\omega_r$ is rotor electrical speed and $T_e$ is electromagnetic torque.

Power generated during braking can be defined with following expression

$$P_g = T_e \omega_r \approx \frac{3}{2} p \psi_m i_{sq} \omega_r \quad (3)$$

Reluctance component of electromagnetic torque can be neglected in this case, assuming that ZDAC (***Zero D-Axis Current***) control strategy is being used. Also, in the case of IPMSM motors, inductance $L_{sq}$ is generally greater than $L_{sd}$ resulting in negative reluctance torque for positive values of $i_{sd}$ current. Due to very high value of braking currents, stator core (iron) losses are negligible in comparison with stator copper losses ($P_{Fe} \approx 0$). The copper losses in stator windings can be expressed as

$$P_{Cu} = \frac{3}{2} R_s \left( i_{sd}^2 + i_{sq}^2 \right) \quad (4)$$

DC link capacitor voltage is highly dependant on the difference between generated and dissipated power in stator windings, and by simultaneous regulation of both powers it is possible to meet first criterion (limitation of DC link capacitor voltage). Available d and q-axis currents have to meet a power limit condition, which dictates that dissipated power (4) has to be greater or equal than regenerated (braking) power (3) ($P_{Cu} \geq P_g$):

$$i_{sd}^2 + \left( i_{sq} + \frac{p\psi_m \omega_r}{2R_s} \right)^2 \geq \left( \frac{p\psi_m \omega_r}{2R_s} \right)^2 \quad (5)$$

This curve, when represented in d-q plane has form of an ellipse with the centre in $(0, -p\psi_m\omega_r/2R_s)$. To maximize braking power, q-axis current must be maximized, whilst at the same time, both d and q-axis current must meet inverter current and voltage boundaries (second criterion). The d-axis and q-axis voltages $v_{sd}$ and $v_{sq}$ are limited by the maximum available output voltage of the inverter $V_{smax}$. Since maximum available inverter voltage is a function of instantaneous DC bus voltage and assuming that inverter can operate also in overmodulation, voltage limit imposed through stator currents $i_{sd}$ and $i_{sq}$ can be formulated as (limiting curve is an ellipse in d-q plane with the centre in $(-\psi_m/L_{sd}, 0)$):

$$\left( \frac{L_{sd}}{L_{sq}} \right)^2 \left( i_{sd} + \frac{\psi_m}{L_{sd}} \right)^2 + i_{sq}^2 \leq \left( \frac{V_{s\max}}{p\omega_r L_{sq}} \right)^2 \quad (6)$$

In order to avoid overmodulation region, a common practice is to adopt that maximum available output voltage equals fundamental voltage harmonic (which is $2V_{dc}/\pi$ for wye and $3V_{dc}/\pi$ for delta connected stator). Current limit of inverter in d-q reference frame can be defined as:

$$\sqrt{i_{sd}^2 + i_{sq}^2} \leq I_{s\max} \quad (7)$$

where $I_{smax}$ is a peak inverter current, and the whole limiting curve represents a circle in d-q plane.

During braking from high speed, power limit and voltage limits (5) and (6) are applied simultaneously on reference values of $i_{sd}$ and $i_{sq}$ currents. The voltage boundary angular speed for which current under the voltage limit reaches that of the current limit (7), is given by

$$\omega_{rv} = \frac{V_{s\max}}{p\left( L_{sd} I_{sw\max} + \psi_m \right)} \quad (8)$$

Bellow speed $\omega_{rv}$, reference stator currents are governed by power and current limits (5) and (7). The trajectory of stator current space vector during optimized active braking is shown in Fig. 1.

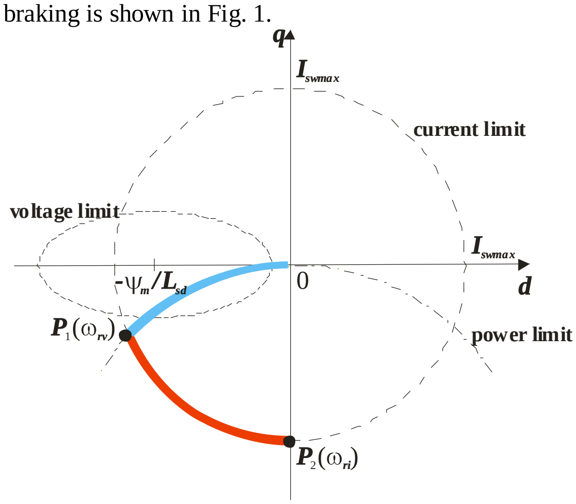


Fig. 1 ***Trajectory of stator current space vector during braking***

During operation in area limited by power and current, stator current vector is shifted towards q-axis, finally having zero direct component and maximum negative quadrature component currents ($i_{sd}$ = 0, $i_{sq}$ = $-I_{swmax}$) at rotor angular speed

$$\omega_{ri} = \frac{R_s}{p\psi_m} I_{sw\max} \qquad (9)$$

Bellow speed $\omega_{ri}$, regenerated power is lower than maximum dissipated power in stator windings. Reference current trajectories for d and q-axis currents can be derived as functions of rotor angular speed $\omega_r$ with different equations for different speed regions (defined with boundary values $\omega_{ri}$ and $\omega_{rv}$).

$$i_{sdref} = \begin{cases} -\left(\dfrac{\psi_m}{L_{sd}} + \dfrac{V_{s\max}}{pL_{sq}\omega_r}\right) & ,\omega_r > \omega_{rv} \\ -I_{sw\max}\left[1-\left(\dfrac{R_s}{p\psi_m\omega_r}\right)^2\right]^{1/2} = -\left(I_{sw\max}^2 - i_{sqref}^2\right)^{1/2} & ,\omega_{ri} < \omega_r \le \omega_{rv} \\ 0 & ,\omega_r \le \omega_{ri} \end{cases} \qquad (10)$$

$$i_{sqref} = \begin{cases} -\dfrac{R_s}{p\psi_m\omega_r}\left(\dfrac{\psi_m}{L_{sd}} + \dfrac{V_{s\max}}{pL_{sq}\omega_r}\right)^2 = -\dfrac{R_s i_{sdref}^2}{p\psi_m\omega_r} & ,\omega_r > \omega_{rv} \\ -\dfrac{R_s}{p\psi_m\omega_r} I_{sw\max}^2 & ,\omega_{ri} < \omega_r \le \omega_{rv} \\ -I_{sw\max} & ,\omega_r \le \omega_{ri} \end{cases} \qquad (11)$$

Fig. 2 shows the proposed control block topology applied during active braking in discrete z domain. Operating regions during braking are determined by the actual motor speed, which also determines which particular equation may be used to calculate reference d and q-axis currents $i_{sdref}$ and $i_{sqref}$. Reference signal $V_{dcmax}$ in voltage PI regulator serves to limit DC link capacitor voltage. If the braking power exceeds maximum system losses ($P_g > P_{Cu}$), then this regenerated power has to be reduced. Otherwise, it can significantly contribute to the raise of DC link capacitor voltage. In case of motoring, $V_{dc} < V_{dcmax}$ and consequently $\Delta i_{sqref} < 0$, which contributes to the motoring torque, having $i'_{sqref} > 0$. However, in the case of regenerative braking (having $i'_{sqref} < 0$), for $V_{dc} > V_{dcmax}$ output of voltage PI regulator gives positive corrective value $\Delta i_{sqref} > 0$ which decreases amount of braking torque.

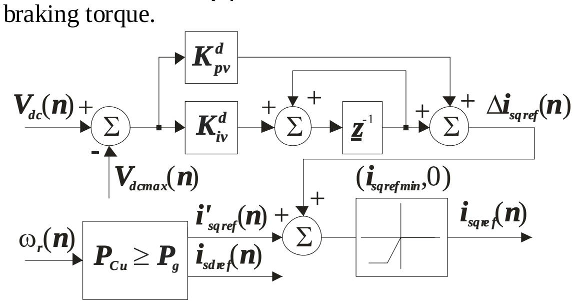


Fig. 2 ***Block-diagram of braking control system***

## 4. SIMULATION RESULTS

An extended set of simulation tests has been performed for performance investigation of proposed braking scheme. The data of the 1.1 kW IPM synchronous motor for simulation setup are collected in Table 1. Motor has rated voltage of 230Vrms and rated speed of 3500rpm. Maximum mechanical speed is 8000rpm. Maximum inverter current is 10A, whilst maximum voltage on a DC link capacitor is 500V. IPMSM drive operates at 20 kHz switching frequency, using SVPWM symmetrical switching pattern. Current regulation loop works at 10 kHz and speed regulation loop works at 500Hz. Also, PI current loop bandwidth is tuned at 500Hz and PI speed loop bandwidth is tuned at 20Hz. To improve current regulation dynamics, both magnetic decoupling and electromotive force feed forward compensations have been included in current regulation scheme.

Table 1. ***IPMSM motor data and parameters***

| Quantity | Symbol | Value |
|---|---|---|
| Torque constant | $K_t$ | 0.61 Nm/A |
| EMF constant | $K_e$ | 0.039 V/rpm |
| Viscous friction | $K_{vf}$ | 5.5E-6Nm/rpm |
| Stator resistance | $R_s$ | 2.4Ω |
| Rotor inertia | $J$ | 1.6E-5kgm$^2$ |
| Pole pairs | $p$ | 2 |
| PM flux linkage | $\psi_m$ | 0.123Wb |
| d-axis inductance | $L_{sd}$ | 5.7mH |
| q-axis inductance | $L_{sq}$ | 12.5mH |

Figure Fig. 3 shows commanded rotor speed signal $\omega_{rref}$ and actual speed $\omega_r$ during active braking sequence. In Fig. 4 it is possible to see waveforms of stator $i_{sd}$ and $i_{sq}$ currents during steady state and braking period. In steady state, $i_{sq}$ has positive value and $i_{sd}$ has zero value. During braking, $i_{sd}$ starts with a large negative value which quickly falls down to zero; meanwhile $i_{sq}$ falls from positive value (motoring torque) to negative value (braking torque).

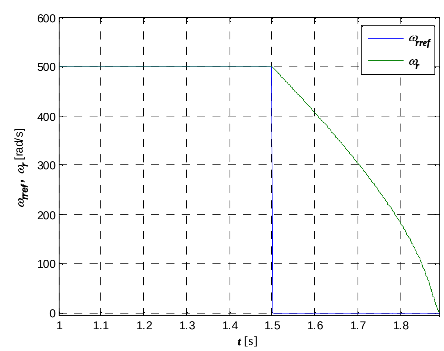


Fig. 3 ***Reference and actual motor speed during braking***

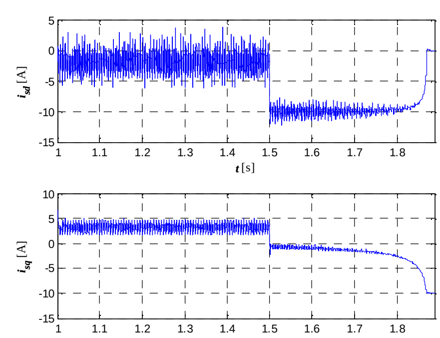


Fig. 4 ***Stator d and q-axis currents during braking***

Fig. 5 depicts traces of DC link capacitor voltage $V_{dc}$ and DC link current $I_{dc}$. Raise of $V_{dc}$ during braking is easily noticeable. However, in this case, due to relatively light load (approx. 1Nm), instantaneous value of $V_{dc}$ never crossed limiting value $V_{dcmax}$, and hence never activated voltage PI regulator. Figure Fig. 6 shows motor input (electrical power) $p_e$ which equals zero during braking interval, and also waveforms of motor electromagnetic torques (both real and estimated values $T_e$ and $T_{eest}$, respectively) which vary from 2Nm (motoring) to almost -4Nm (braking).

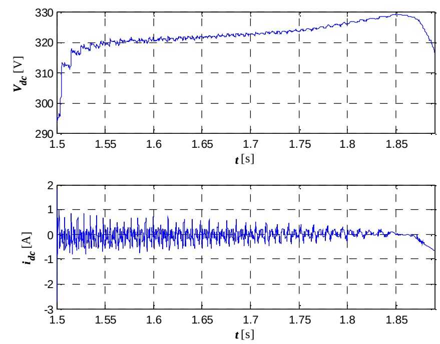


Fig. 5 ***DC link voltage and current during braking***

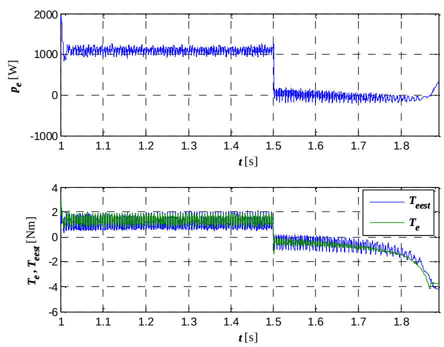


Fig. 6 ***Motor electrical power and electromagnetic torque during braking***

## 5. CONCLUSION

A braking algorithm for interior permanent magnet synchronous motor drives has been proposed. Also, different operating modes within the inverter voltage and current limits have been analyzed. Regenerative braking power is regulated indirectly, thru stator d and q-axis currents regulation, using pre-defined current trajectories which maximize braking torque. The whole system operates within inverter voltage and current capabilities, having DC link capacitor voltage maintained bellow critical limit by using an additional PI regulator.

## 6. REFERENCES


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