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Non – Regenerative IPMSM Drive Braking Scheme Based on *q* – Axis Current Component Limiting

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Abstract - **In the paper a non-regenerative braking scheme for high speed Interior Permanent Magnet Synchronous Motor (IPMSM) drive is presented. Due to price constraints, general purpose electric drives with IPMSMs are not equipped with a drive converter which allows energy recovery to the primary source. These drives are usually used for driving strictly reactive loads, in which braking mode is used only during deceleration. Therefore, in these drives it is necessary to use methods for dissipating braking energy in the motor itself and in the inverter. The paper provides theoretical analysis of various methods for non-regenerative IPMSM braking schemes, mathematical models, and the proposal of one solution suitable for use in high-speed applications based on limiting q – axis current component. Proposed solution controls recovery energy by keeping DC link voltage within given voltage margin, thus preventing unacceptable voltage rise during braking. Braking strategy is added into common IPMSM Field Oriented Control (FOC) control structure with Maximum Torque Per Ampere (MTPA) and Field Weakening (FW) algorithms. During the braking, MTPA strategy is suspended and non – regenerative braking is performed instead. In the proposed braking scheme voltage margin is also taken into account, by selecting proper *d*-axis reference current adjusted to the available voltage, so the scheme is also applicable in FW mode.**

Keywords - Interior Permanent Synchronous Motors (IPMSM); non-regenerative braking; q–axis current component limiting.

I. INTRODUCTION

In modern general purpose electrical drives, e.g. consumer drives for installation in home appliances, the overall drive price is a key factor for the motor and the drive type selection. Nowadays, high-speed Interior Permanent Magnet Synchronous Motors (IPMSMs) are often used, due to technology advancement and decrease of permanent magnets price. IPMSMs have become competitive with Induction Motors (IMs), especially in the middle performance drives, because they are, like IMs, cheap and very robust, but with significantly better energy efficiency. Additional advantage is that switch to IPMSM does not require significant research effort because IPMSM uses similar control techniques as IM, and identical power converter, mostly cheap three phase inverter with the only one current sensor in DC link.

In order to keep overall price of the drive as low as possible, IPMSM is powered by a power converter containing a low-cost, uncontrolled front - end diode rectifier, which allows only one direction of energy flow - from the primary source to the motor, as shown in Fig. 1 [1-3].

Drive topology shown in Fig. 1 has a diode rectifier (1) at its input, a capacitor (2) in DC link, a three-phase bridge inverter (4) and an IPMSM (5). The usual flow of energy is from the primary source (public network supply) to the motor and load (6). However, during the braking mode (e.g. during deceleration), as well as where the load has potential characteristic, the electric motor goes to the generator mode, converting mechanical energy into electric energy and returning it to a DC link. Since the DC link is supplied from non-controllable front end diode rectifier, energy recovery to supply source is not possible. During the braking the capacitor in the DC link charges, and eventually DC link voltage rises to unacceptable level resulting in the fault.

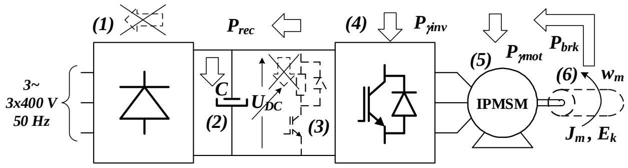

Figure 1. Power flows in IPMSM drive with front-end diode rectifier

This paper is a revised and expanded version of the paper presented at the XVI International Symposium INFOTEH-JAHORINA 2017 [17].
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In low cost consumer drives, the mechanical load has strictly reactive characteristics, and motor can turn to generating mode only when slowing down (decelerating). In this case, it is necessary only to reduce the kinetic energy of the rotating masses, without intensive braking. For this type of loads, it is not economically acceptable to use a braking resistor (3) nor to use a controllable four-quadrant input rectifier. In this case, the braking energy must be dissipated in the motor and inverter by non-regenerative braking [3-6]. This type of non-regenerative braking is the subject of this paper.

The paper is organized as follows.

In the next, second section, theoretical analysis of the non-regenerative braking principle is to be explained. After that, power flows and loss structures in IPMSM drive for motoring and generating modes will be observed. At the end of this part detailed models of DC link and IPMSM will be presented.

In the third section, usual non-regenerative braking schemes from the literature will be analyzed and discussed in detail. Their performance will be assessed, and necessary improvements will be indicated.

In the fourth section, a new approach for non-regenerative braking for high-speed IPMSM drives based on the *q*-axis current limiting will be proposed. Proposed solution will be explained in details with all approximations justified. Suggested new non-regenerative braking technique will be integrated in the common IPMSM drive control scheme, and possible operating modes will be discussed.

In the fifth section, the proposed non-regenerative braking scheme will be illustrated and justified by a computer simulation.

The sixth part of the paper is the conclusion.

II. MATHEMATICAL MODELS

In this section, the power flows in the IPMSM drive from Fig. 1 in both motor and braking mode will be discussed. Drive loss structure and mathematical models of DC link and vector controlled IPMSM in wide speed range will be also given.

A. Power Flows in IPMSM Drive

For the mechanical subsystem of the IPMSM drive shown in Fig. 1 Newton's equation of rotational motion [1] is valid:

$$J_m \frac{\mathrm{d}\omega_m}{\mathrm{d}t} = m_e - \left(m_m + k_m \omega_m\right), \qquad (1)$$

where J_m is total inertia of the drive (referred to the motor shaft), k_m is friction coefficient, ω_m is angular motor speed, m_e and m_m are motor and load torque. In general purpose drives (like in household appliances), load torque has strictly reactive characteristics, and, as friction, always has opposite direction of the speed. Thus, in normal operation, IPMSM operates only in motoring mode. However, there is accumulated kinetic energy in rotating masses W_k , which, during deceleration from speed ω_{m1} to ω_{m2} , decreases from W_{k1} to W_{k2} :

$$\Delta W_k = W_{k1} - W_{k2} = \frac{J_m}{2}\left(\omega_{m1}^2 - \omega_{m2}^2\right), \qquad (2)$$

and produces negative (generating) torque during deceleration. This braking energy is delivered to the IPMSM as braking power P_{brk}, and turns IPMSM in generating mode. This accumulated energy can be substantial, especially in the case of high speed machines due to the very high rotating speeds.

During braking (Fig. 1), braking power P_{brk} is partially dissipated in the IPMSM as motor losses $P_{\gamma mot}$, and the rest is delivered to the inverter, where some part of it is dissipated as inverter losses, $P_{\gamma inv}$. Remaining braking power is delivered to the DC link as recovery power P_{rec}, as shown in Fig 1.

Since the input diode rectifier cannot return the recovery power back to the grid, the recovery power charges the DC link capacitor and its voltage rises. Even the capacitor has some voltage tolerance, only small and short-term increase in the capacitor voltage is allowable. Once the voltage maximum is reached, further voltage rise cannot be tolerated.

To prevent further voltage rise, but still to provide some braking power, all the braking energy must be dissipated in the motor and in the drive inverter:

$$P_{brk} = P_{\gamma mot} + P_{\gamma inv} \Rightarrow P_{rec} = 0\,, \qquad (2)$$

As a result, the problem of non-regenerative braking is basically the problem of creating the proper control strategy to control motor and inverter losses which will reduce recovery power to the zero. The optimal braking solution is to maximize the motor losses, and to create the braking power always equal to those power losses.

B. IPMSM Power Flows

IPMSM loss structure is shown in Fig 2 for motoring mode (Fig. 2a) and generating mode (Fig. 2b).

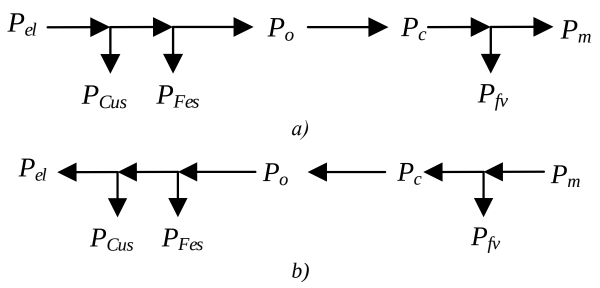

Figure 2. Power flows in IPMSM: a) motoring mode; b) generating mode

In motoring mode (Fig. 2a), electric power is delivered to the IPMSM stator winding, where stator copper losses:

$$P_{Cus} = 3R_s I_s^2\,, \qquad (3)$$

and stator iron losses are generated [7, 8]:

$$P_{Fes} \sim \left(k_h \omega_m + k_{vs}\omega_m^2\right)\Psi_s^2 = \frac{\omega_e^2 \psi_s^2}{R_c\left(\omega_e\right)}\,, \qquad (4)$$

where R_s and I_s are stator resistance and stator current, k_h and k_{vs} are hysteresis and eddy current losses coefficients, and Ψ_s is stator flux. Iron losses can be also modeled by shunt resistor $R_c(\omega_e)$ which depends on the synchronous speed ω_e [9-12].

Air gap power (rotating field power) P_o is delivered to the rotor, as shown in Fig. 2a. On the IPMSM rotor there are no copper losses since there is no field winding, and also there are no iron losses since the rotor rotates synchronously with the field. Thus, air gap power is equal to the conversion power P_c.

Finally, IPMSM output power P_m is calculated by subtracting friction and ventilation losses:

$$P_{fv} = k_m \omega_m^2 . \tag{5}$$

Power flow for IPMSM in generating (braking) mode is shown in Fig. 2b, with opposite direction compared to Fig. 2a.

Copper losses (3) depend on the square of the stator current, and the iron losses (4) depend on the squares of the stator flux and synchronous speed. Friction and ventilation losses (4) depend on the squared speed and are not controllable. From (3) and (4), it can be concluded that the IPMSM losses will be higher when stator current and flux are larger. In addition, from (4) and (5) it can be concluded that the losses are higher at higher rotating speeds.

C. Inverter and DC Link Power Flows

There are three types of losses in the inverter: commutation losses, conduction losses, and off-state losses. In order to make the losses in the inverter larger during braking, the current through inverter must be as large as possible [13].

Voltage on the capacitor C is equal to the DC link voltage U_{DC} as shown in Fig. 1. Instantaneous capacitor power, when input rectifier is blocked (during braking), is equal to the recovery power:

$$p_c = u_{DC} i_C = u_{DC} C \frac{\mathrm{d}u_{dc}}{\mathrm{d}t} = P_{rec} . \tag{6}$$

Recovery power (DC link current i_C) charges the capacitor and its voltage rises from initial value U_{DC0} to:

$$u_{DC} = \sqrt{U_{DC0}^2 + \frac{2}{C}\int_0^t P_{rec}(t)\mathrm{d}t} . \tag{7}$$

From (7) it can be concluded that average voltage on the capacitor will not change (rise) during braking only if average recovery power is equal to zero.

D. Mathematical Model of Vector Controlled IPMSM Drive

Mathematical model of IPMSM drive, with iron losses neglected is given as [2]:

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{\mathrm{d}}{\mathrm{d}t} \begin{bmatrix} \Psi_d \\ \Psi_q \end{bmatrix} + \omega_e \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \Psi_d \\ \Psi_q \end{bmatrix}, \tag{8}$$

$$\Psi_d = L_d i_d + \Psi_{PM} , \tag{9}$$

$$\Psi_q = L_q i_q , \tag{10}$$

$$m_e = \frac{3}{2} P \left(\psi_{PM} i_{sq} + \left(L_d - L_q \right) i_{sd} i_{sq} \right), \tag{11}$$

where u_d, u_q, i_d, i_q, Ψ_d and Ψ_d, are d and q components of stator voltages, currents and fluxes, while Ψ_{PM} is rotor permanent magnet flux, L_d and L_q are stator synchronous inductances, and P is pole pair number. Motor torque has synchronous and reluctance component, and electrical power is:

$$P_e = \frac{3}{2}\left(u_d i_d + u_q i_q \right). \tag{12}$$

For the speeds lower than rated, the stator current d-component i_d is adjusted to provide the maximum torque for given stator current amplitude, using Maximum Torque Per Ampere (MTPA) strategy. Since $L_d < L_q$ in IPMSMs, MTPA result for i_d current (f_d) is always negative, which provides positive reluctance torque. Since the speed regulator demands the torque by controlling the stator current amplitude i_{st} , the current q-component is calculated to achieve i_{st} for given d-component (f_q). The rest of the control scheme is typical Field Oriented Control - FOC [2].

For the speeds above rated speed, IPMSM flux must be decreased when the stator voltage rises to its maximum value:

$$\sqrt{u_d^2 + u_q^2} = U_{MAX} , \tag{13}$$

and field weakening regime is reached. High-speed IPMSMs, due to their lower price, mainly operate in field weakening, having maximum speed 3-6 times larger than rated. In field weakening regime (due to voltage limit), stator current components i_d and i_q are coupled [14-17].

III. USUAL APPROACH IN NON-REGENERATIVE BRAKING

Non-regenerative braking scheme shown in Fig. 1 is the special case of dynamic braking of IPMSM. In classical dynamic braking, recovery energy is dissipated on the braking resistor. However, in non-regenerative braking, recovery energy is dissipated into motor and inverter. Usual approach to achieve this is shown in Fig. 3.

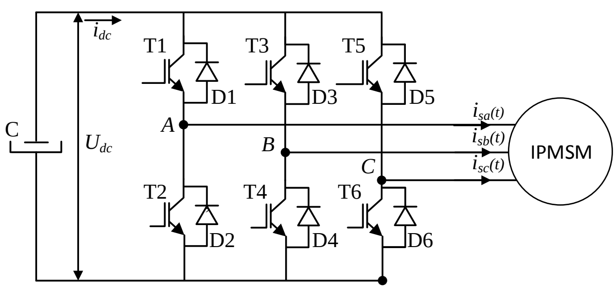

Figure 3. IPMSM during non-regenerative braking

The simplest way for braking IPMSM is to simultaneously switch on all three "lower" IGBT, namely T2, T4 and T6 in the inverter, as shown in Fig 3. This will result in short-circuiting of stator winding and create the braking power without charging the DC bus. In this regime, full short-circuit current flows through stator windings, and large braking torque is generated. However, large short-circuit current can damage or overheat the motor and inverter, and this braking principle is usually used only for emergency stopping the drive.

The more advanced braking method is to use Pulse Width Modulation (PWM) of all three lower transistors and to control the braking current through the motor windings. By this, recovery power can be adjusted to the required value. An additional advantage of this method is that the losses in the inverter are larger due to increased commutation PWM losses, which further increase braking performance.

The main drawback of this type of dynamic braking is that during the braking vector controller is suspended, and the machine is not controlled. When the braking is finished, vector control must be restored, resulting in a new transient process to recover motor flux and torque. Additionally, braking to non-zero speed in shaft-sensorless drives is almost impossible because in the shirt circuit mode speed estimators are out of the range and motor speed is unknown. This is additionally complicated in the field weakening regime which additionally influence on the stability of the flux based estimators [4].

IV. Non-Regenerative IPMSM Braking Based on q-Axis Current Control

In this Section a new non-regenerative braking control for IPMSM will be proposed. In non-regenerative braking, when the torque is negative, it is required that recovery power is equal to zero:

$$P_{rec} = 0, \tag{14}$$

or, if inverter losses are neglected, it is required that IPMSM electrical power (12) is equal to zero. From the graph of power flows in Fig 2b, Eq. (14) will be satisfied if braking power is equal to the sum of IPMSM copper and iron losses:

$$P_{Cu} + P_{Fe} = P_{brk}. \tag{15}$$

Braking power can be expressed by the torque (11) and electrical synchronous speed $\omega_e = P\omega_m$ as:

$$P_{brk} = \frac{3}{2}\left[\Psi_{PM} i_q + \left(L_d - L_q\right) i_d i_q\right]\omega_e. \tag{16}$$

By substituting copper and iron losses (3) and (4), stator fluxes (9) and (10), and braking power (16) into (15), the relation between currents i_d and i_q during non-regenerative braking is obtained:

$$\begin{aligned}&\frac{3}{2}R_s\left(i_d^2 + i_q^2\right) + \frac{\omega_e^2}{R_c}\left[(\psi_{PM} + L_d i_d)^2 + (L_q i_q)^2\right] = \\ &= \frac{3}{2}\left[\Psi_{PM} i_q + \left(L_d - L_q\right) i_d i_q\right]\omega_e\end{aligned}. \tag{17}$$

Equation (17) can be used to create non-regenerative braking strategy which is to be included into classical FOC-MTPA control strategy. During braking, it is required that:

- motor must be fully controllable during braking,
- braking current must be lower or equal to the maximum allowable current,
- voltage on the capacitor must be lower or equal to the maximum allowable DC link voltage.

Proposed braking control algorithm is added as “Braking control” block in common structure of IPMSM FOC drive with Current Regulated Voltage Source Inverter (CRVSI), as shown in Fig. 6.

For the speeds below rated, reference currents i_d and i_q are calculated by speed regulator and MTPA algorithm, while in field weakening, those currents are calculated from the speed regulator and field weakening block. In order to control non-regenerative braking, speed regulator is active, and MTPA control is suspended. Instead of MTPA, Braking Control is active. By this, speed regulator will regulate rotor speed in whole speed range, but *q*-axis stator current will be limited to the value for which recovery power is equal to zero (17), i.e. all braking power will be equal to the loss power in the IPMSM.

Stator *q*-axis component determines recovery power, and has to be limited to such value i_{qmin} which will result that all braking power is dissipated into IPMSM losses according to (15). This limit is calculated from (17) in the block „Braking control” in Fig. 6 as the solution of quadratic equation:

$$i_{q\min} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}, \tag{18}$$

where the coefficients are:

$$a = \frac{3}{2}R_s + \frac{\omega_e^2 L_q^2}{R_c}, \tag{19}$$

$$b = -\frac{3\omega_e}{2}\left[\Psi_{PM} + \left(L_d - L_q\right) i_d\right], \tag{20}$$

$$c = \frac{3}{2}R_s i_d^2 + \frac{\omega_e^2}{R_c}\left(\Psi_{PM} + L_d i_d\right)^2. \tag{21}$$

In (18)-(21) proper signs for coefficients should be chosen, in order that solution of (17) is valid for negative torque.

It should be noted that (18) is not always solvable. Namely, depending on actual *d*-axis current i_d and angular speed, discriminate of (18) can be negative. This is illustrated in Fig. 4 for several values of i_d. From Fig. 4 it is clear that for certain values of i_d and speed non-regenerative braking will not be possible, i.e. in that case some energy should be taken from the source during braking. Fig. 5 shows trajectory of *q*-axis current component limit i_{qmin} for given *d*-axis current component i_d.

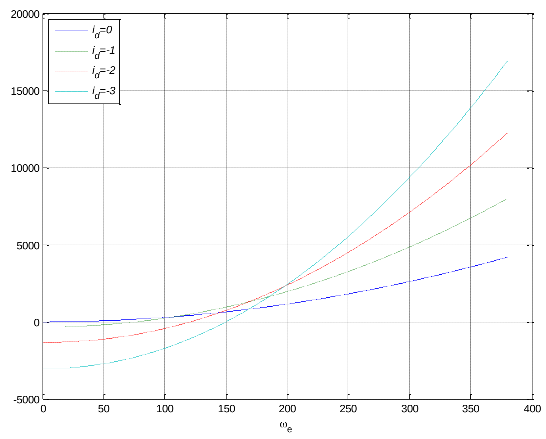

Figure 4. Discriminante of equation (18) for q-axis current component

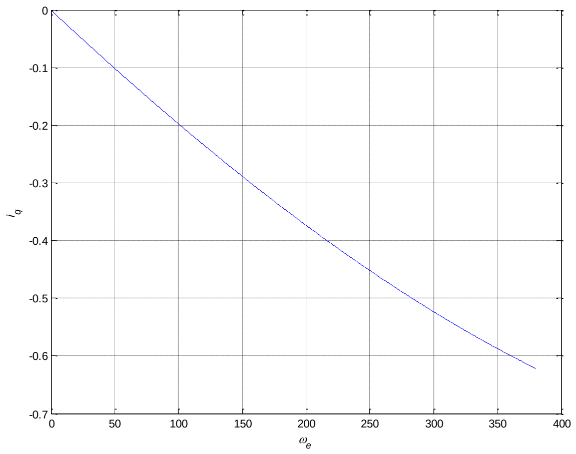

Figure 5. Trajectory of q-axis limitted current component

The braking starts when the speed reference lower than actual speed is received. The speed regulator sets large negative q-axis current reference in order to reach new speed reference. As a result, at the beginning of the braking, the DC link voltage U_{DC} rises in uncontrolled manner. When maximum allowable DC voltage value U_{DCMAX} is reached, the non-regenerative Braking control block is activated. The Braking control block starts to dynamically change the q-current limit using (18), This action keeps the negative q-current above the i_{qmin}, value, insuring that the braking power is smaller than the power losses, therefore that all will be dissipated in the IPMSM and will not reach the DC link capacitor.

In the proposed scheme in Fig. 6, the voltage limit is also taken into account, because d-axis reference current i_d in braking is adjusted to the available voltage in field weakening in the block "Field Weakening".

V. Simulation Results

Fig. 7 and Fig. 8 shows simulation results of the proposed non-regenerative braking scheme when drive decelerates from 5000 rpm to 3000 rpm. In the simulation model the voltage regulator is used instead of feed forward calculated i_q using (18). The action on this voltage limiter naturally forces the average current i_q to be equal to the i_{qlim} trajectory.

As seen from Fig. 7 DC link voltage U_{DC} oscillates between its rated and maximum allowable value U_{DCMAX}. Braking torque oscillates also, but average recovery power P_{rec} from (7) is equal to zero. Since average braking power is equal to zero, DC bus voltage is controlled to be close to its rated value.

IPMSM d- and q-axis current and voltage components during braking are shown in Fig. 8. As it can be seen, all components oscillate during the braking, but, in average q-axis component is limited to the value which will provide that average braking power is equal or smaller than the overall losses in the drive.

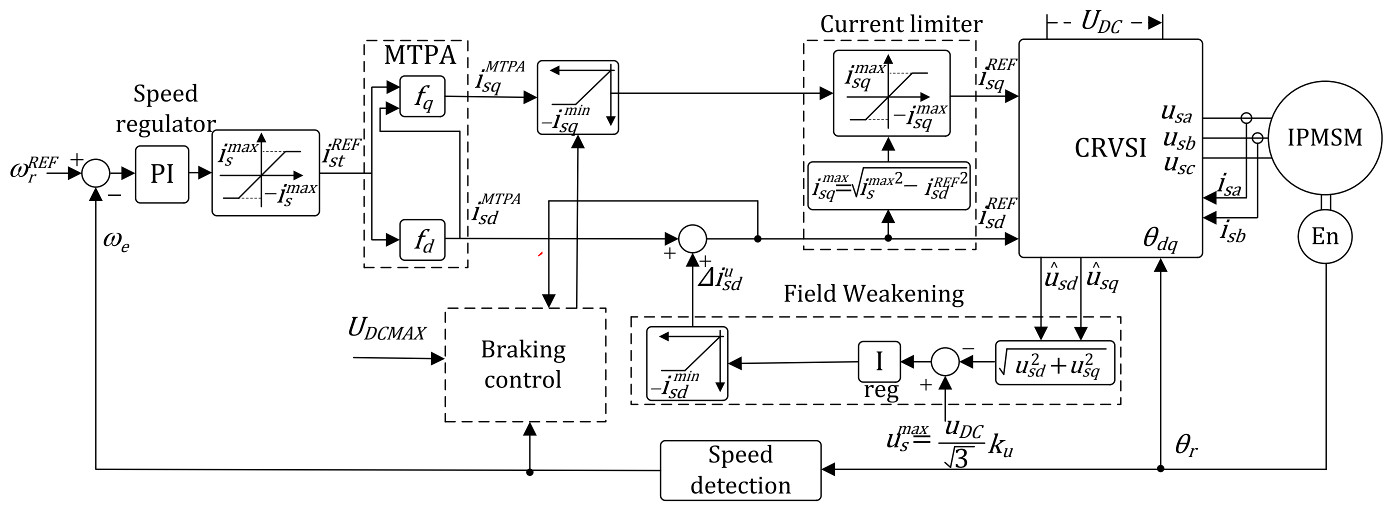

Figure 6. Block-diagram of the proposed non-regenerative IPMSM braking scheme based on q-axis current limiting

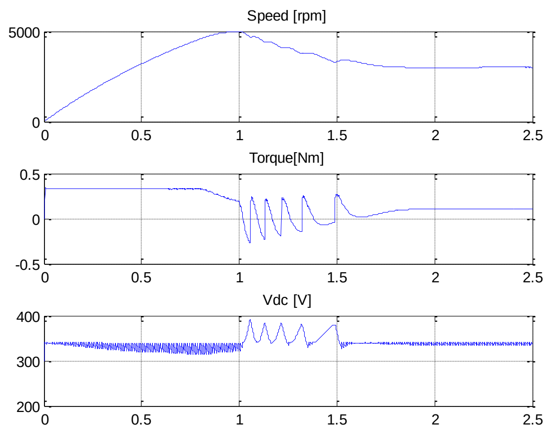

Figure 7. IPMSM speed, torque and DC bus voltage during braking

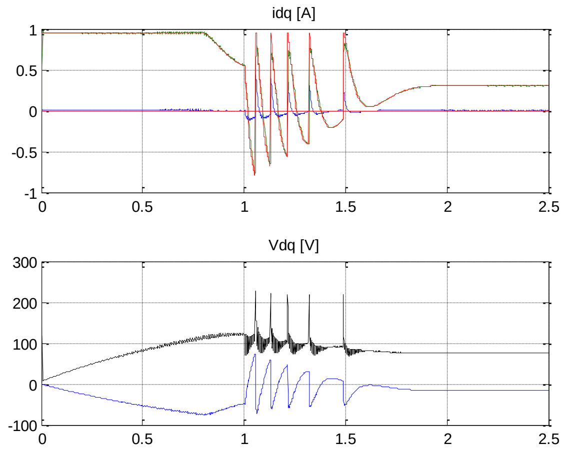

Figure 8. IPMSM *d*- and *q*-axis current and voltage components

The only problem with this solution is the consequent oscillation, due to the unstable nature of the control loop. In the future work, the voltage regulator can be replaced by the i_{qlim} trajectory, which should provide more smooth braking pattern, without wild switching between motoring and braking, as one can note from simulation results.

VI. CONCLUSION

The paper proposes a new loss-control method for non-regenerative braking of IPMSM drive based on *q*-axis current limiting. In the proposed scheme, stator current i_q is dynamically limited to the value at which the braking power is equal to the losses in the motor, and recovery power is equal to zero. By this, the rise of voltage on the capacitor in DC link is stopped, and can be limited at allowable level.

Trajectory of *q*-axis current component limit given in (18) provides non-regenerative braking for given combination of speed and *d*-axis current component. However, it cannot be calculated in all cases as shown in Fig. 4. Physically, that means that breaking power that machine receives from the load is not sufficient to cover all the losses in the machine for selected value of stator flux. In such particular combinations of *d*-axis current component and speed, a certain amount of electrical power is taken from the network during the braking.

The proposed non-regenerative braking scheme is similar to the braking approaches already used for IM. However, IPMSM braking is considerably more complicated than braking of the IM due to the permanent magnet flux and the reluctance torque.

In the proposed solution inverter and additional losses are neglected. These losses contribute to braking, so the braking of the real machine will be more efficient than in the simulation.

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