Effective Formulation of the DTC Strategy for Convergence and Stability Analysis The IPM Motor Drive Case Study

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Outline

1. Introduction
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3. IPM motor drive case study
4. Simulation results
5. Experimental results

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Introduction

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Direct Torque Control technique

The Direct Torque Control **DTC** is the control technique that defines the three–phase voltages source inverter state on the basis of the torque and flux errors, without current control loops.

DTC has two variants:

1. Finite Control Set, if the selection of the voltage vector is performed among the six active inverter spatial vectors ($\bar{U}_1 \cdots \bar{U}_6$) and the two null spatial vectors ($\bar{U}_0$ and $\bar{U}_7$)
2. Continuous Control Set, if voltage vectors of any phase angle are available (thanks to a PWM voltage control).

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Direct Torque Control technique

DTC Formulation

A novel formulation of the DTC base principle is presented that can be an effective tool for understanding and comparing implementation variants but also for studying convergence and stability issues.

IPM application

An IPM synchronous motor drive controlled by a Finite Control Set DTC is assumed as case study for exemplifying the proposes approach of analysis.

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DTC new formulation

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Mathematical formulation

New complex variable

The DTC is a technique based on the control of:

- torque m
- module of flux vector $|\lambda|$

A new complex variable $\bar{z}$ can be introduced:

$$\bar{z} = \frac{m}{M_N} + j\frac{|\lambda|}{\Lambda_N}$$

where M_N and Λ_N are the torque and flux nominal values.

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Mathematical formulation

Error

For a given reference torque m^* and reference flux $|\lambda|^*$, it is possible to define the error $\bar{\varepsilon}$ as:

$$\begin{aligned} \bar{\varepsilon} &= \bar{z}^* - \bar{z} = \frac{m^* - m}{M_N} + j\frac{|\lambda|^* - |\lambda|}{\Lambda_N} \\ &= \varepsilon_m + j\varepsilon_{|\lambda|} \\ |\bar{\varepsilon}| &= \sqrt{\varepsilon_m^2 + \varepsilon_{|\lambda|}^2} \end{aligned}$$

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Mathematical formulation

Target of the control

The target of the control is to maintain the actual vector $\bar{z}$ very close to the reference $\bar{z}^*$.

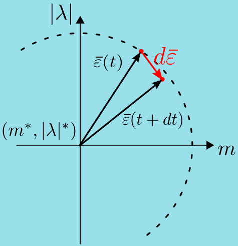
$$|\bar{\varepsilon}| \leq E_{max}$$

where E_{max} is a prefixed value.
In the case in which the inequality is satisfied the control continues applying the same voltage vector.

Adopted strategy

Right case

When $\bar{\varepsilon} \geq E_{max}$ an action has to be taken to reduce $|\bar{\varepsilon}|$ choosing the new vector voltage in order to obtain $\bar{\varepsilon}$ in the next step.



In this case the applied voltage is correctly selected.

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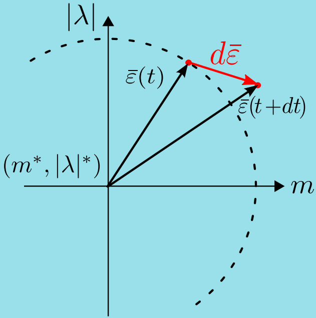
Adopted strategy

Wrong case

On the contrary, in this case the voltage selection is wrong.



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Adopted strategy

Wrong case

Control convergence condition is that the selected $\bar{U}$ has to meet $\frac{d|\bar{\varepsilon}|}{dt} \leq 0$.

In the case of Finite Control Set the possible voltage are chosen among the six inverter spatial vectors ($\bar{U}_1 \ldots \bar{U}_6$) and the two null spatial vectors ($\bar{U}_0$ and $\bar{U}_7$).

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Convergence condition

$$\frac{d|\bar{\varepsilon}|}{dt} = \frac{d\sqrt{\varepsilon_m^2 + \varepsilon_{|\lambda|}^2}}{dt} = \frac{\varepsilon_m \dot{\varepsilon}_m + \varepsilon_{|\lambda|}\dot{\varepsilon}_{|\lambda|}}{\sqrt{\varepsilon_m^2 + \varepsilon_{|\lambda|}^2}}$$

Then equivalent convergence conditions are:

$$\Delta = \varepsilon_m \dot{\varepsilon}_m + \varepsilon_{|\lambda|}\dot{\varepsilon}_{|\lambda|} \leq 0$$

$$\Delta = \varepsilon_m \left(-\frac{\dot{m}}{M_N}\right) + \varepsilon_{|\lambda|}\left(-\frac{|\dot{\lambda}|}{\Lambda_N}\right) \leq 0$$

Convergence condition

Prediction nature of DTC

$$\Delta = \varepsilon_m \left(-\frac{\dot{m}}{M_N} \right) + \varepsilon_{|\lambda|} \left(-\frac{|\dot{\lambda}|}{\Lambda_N} \right) \leq 0$$

Prediction nature of DTC is evident from the last equations as the control is decided by the future (of course predicted) error (or feedback) derivatives.

IPM motor drive case study

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Control features

- Equations are expressed in discrete form being the control implemented in discrete time.
- Last sampling time index is k
- The chosen $\bar{U}(k)$ will be imposed at instant $k+1$
- Then a $1-$ *step* prediction of currents and other quantities must be done.
- The time–line is moved at the instant $k+1$ because of the inverter delay.

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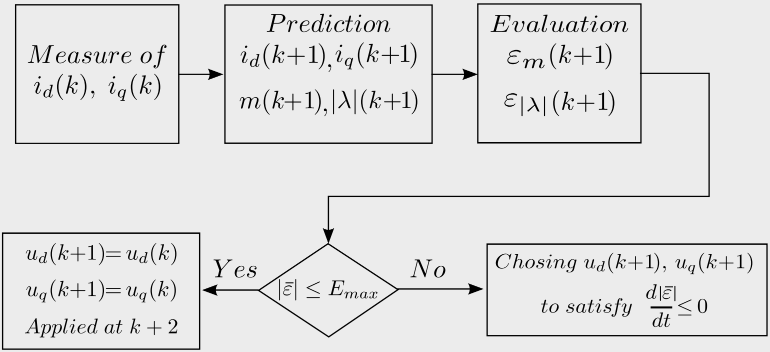
Control algorithm



If the error is inside the limit, then no action is taken and the voltage vector of the previously step is maintained. Otherwise, if the error exceeds the limit, the new voltage vector is chosen in order to bring back the error inside the limit.

Torque and flux equation

The two controlled variable are the torque and the stator flux module that can be expressed as:

$$m(k+1) = \frac{3}{2} p \Lambda_{mg} i_q(k+1) + \frac{3}{2} p (L_d - L_q) i_d(k+1) i_q(k+1)$$

$$|\lambda(k+1)| = \sqrt{\lambda_d(k+1)^2 + \lambda_q(k+1)^2}$$

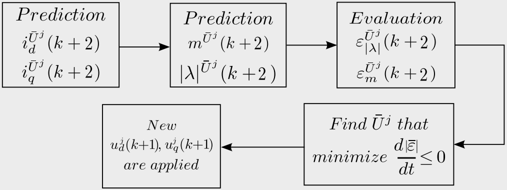
$$\lambda_d(k+1) = L_d i_d(k+1) + \Lambda_{mg}$$

$$\lambda_q(k+1) = L_q i_q(k+1)$$

Torque and flux can be calculated at any sampling time, starting from the measured or predicted current (i_d and i_q).

Control algorithm-Choosing of voltage vector

$\bar{U}^j$ *are the eight inverter voltage vector,* $j = 0 \dots 7$



The new voltage vector are chosen in order to minimize Δ_j, i.e. to determine its higher negative value.

$$\Delta_j = \varepsilon_m^{\bar{U}^j}\left(-\frac{\dot{m}^j}{M_N}\right) + \varepsilon_{|\lambda|}^{\bar{U}^j}\left(-\frac{|\dot{\lambda}|^j}{\Lambda_N}\right) \leq 0$$

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Control algorithm

Prediction of currents

The currents are predicted considering the voltage balance equations:

$$i_d^{\bar{U}^j}(k+2) = T_s \frac{di_d}{dt}(k+1) + i_d(k+1)$$

$$= T_s \left(\frac{u_d^j(k+1)}{L_d} - \frac{R}{L_d} i_d(k+1) + \omega_{me} \frac{L_q}{L_d} i_q(k+1) \right) + i_d(k+1)$$

$$i_q^{\bar{U}^j}(k+2) = T_s \frac{di_q}{dt}(k+1) + i_q(k+1)$$

$$= T_s \left(\frac{u_q^j(k+1)}{L_q} - \frac{R}{L_q} i_q(k+1) - \frac{\omega_{me}}{L_q} (L_d i_d(k+1) + \Lambda_{mg}) \right) + i_q(k+1)$$

$m^j(k+2)$ and $|\lambda|^j(k+1)$ are predicted from $i_d^j(k+2)$ and $i_q^j(k+1)$.

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Control algorithm

Key points of the control:

- No switching table is required by this approach.
- To reduce the switching frequency it is possible to implement a switch state graph with the law that only one inverter leg can be switched.
- Electrical machine model must be well known.

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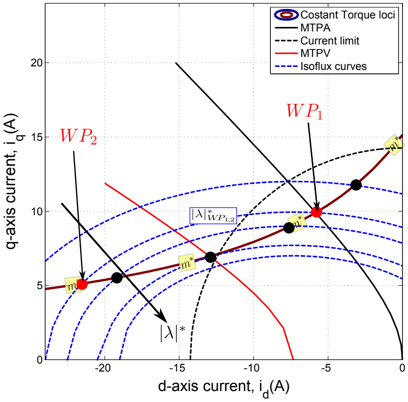
d– and *q*–axis current plane

- The machine working pont is defined by a chosen m^* and $|\lambda|^*$.
- Fixed the reference values, there are two possible Working Points (WP) given by the intersections between the constant torque and constant flux curves.



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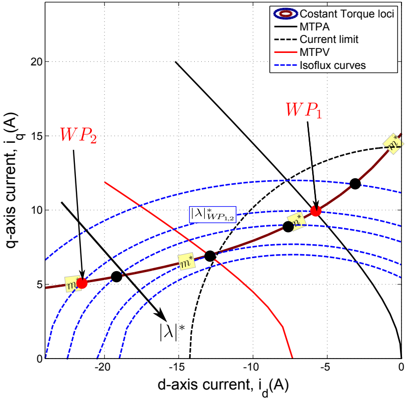
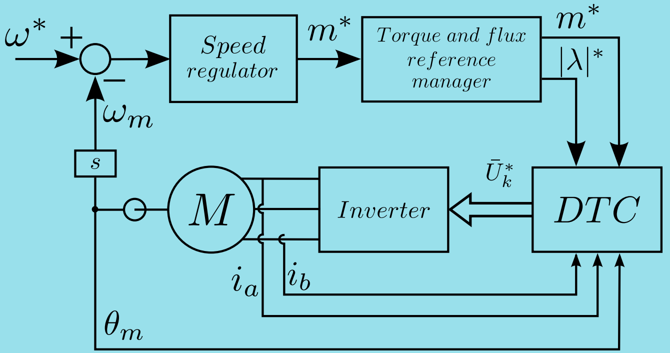
d– and *q*–axis current plane

- The presence of two WP is a drawback of the control strategies.
- The machine could be operated in one or the other point indiscriminately.
- WP_1 is along the MTPA trajectory. Coordination between torque and flux references is needed, in order to work on MTPA locus.



Simulation results

Simulation scheme



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Simulation features

- The motor has been simulated taking into account its non–linear magnetic characteristics.
- The actual torque–flux relationships extracted by experimental results are used.
- The DTC is designed assuming linear magnetic characteristics.

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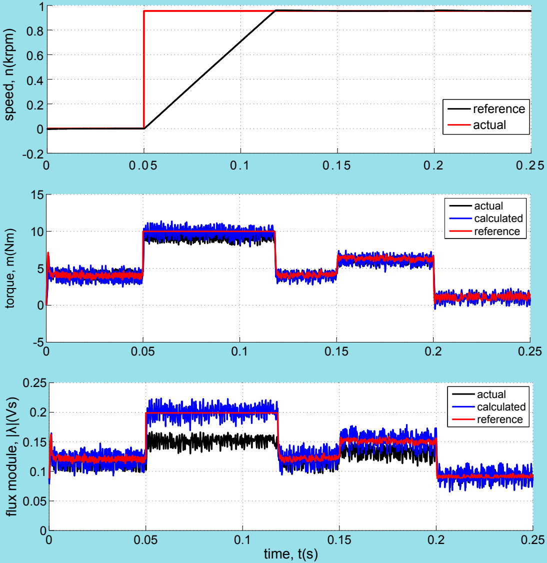
Speed reference step



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Speed reference step

- The speed presents an oscillation around the reference value of 0.3 *rpm*.
- The actual torque and flux presents an error, respect to the reference value, due to the linear model used in the DTC control.
- Flux reference value is chosen from torque reference in order to control the machine along the MTPA trajectory.

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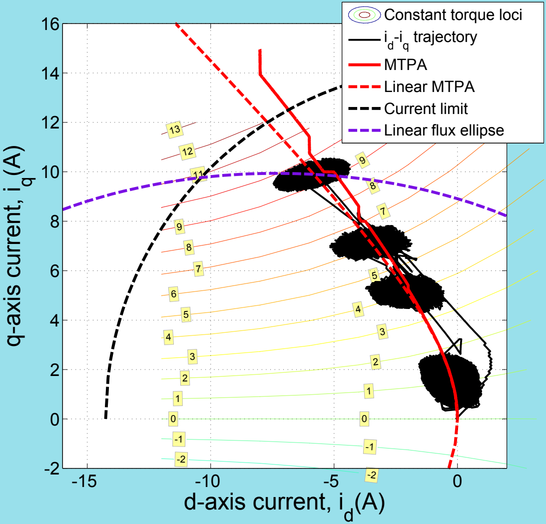
Speed reference step



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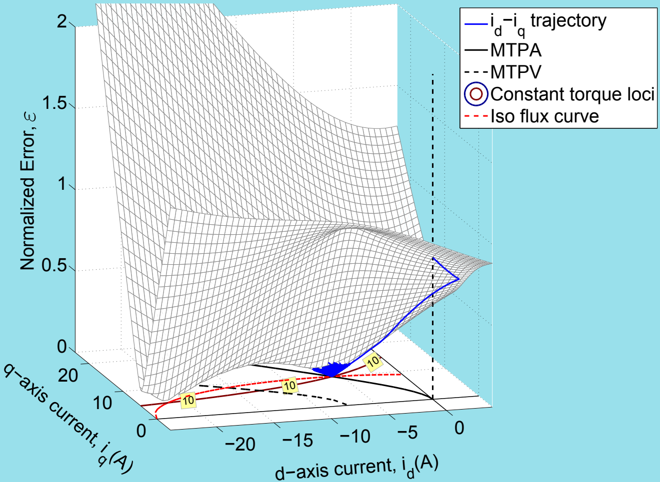
Two stable points

The error $|\bar{\varepsilon}|$ is plotted for a given m^* and $|\lambda|^*$, in the plane i_d–i_q.



Experimental results

Test bench

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Test bench

IPM machine

- ✓ Some tests have been carried out in order to confirm the mathematical analysis.
- ✓ The test bench is equipped with a master motor that can be speed or torque controlled by an industrial inverter.
- ✓ The machine under test is an IPM motor with 12–slot and 10–pole.
- ✓ The IPM motor is controlled by means of a laboratory inverter coupled to a *dSpace 1104* control board.

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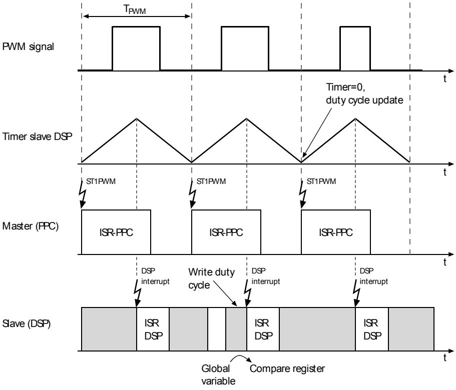
Delay on the duty–cycles updating

- Firmware is implemented in the *dSpace 1104*.
- New duty–cycle value are calculated inside the ISR on the master PPC.
- ISR is trigged by the PWM interrupt.
- Master transfers the new values to the slave, that store theme in a global variables.



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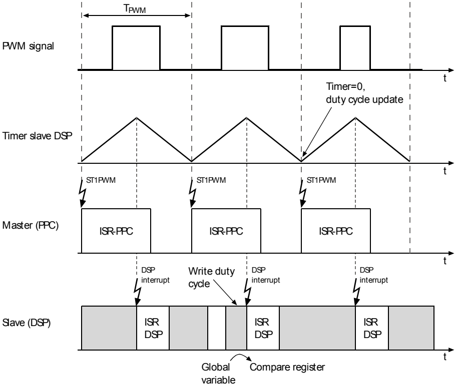
Delay on the duty–cycles updating

- At $T_{PWM}/2$ slave copied the values of global variables into the PWM compare register unit.
- Duty cycle is updated for the next PWM period if the new values are stored before $T_{PWM}/2$.
- Otherwise, the duty cycles are updated in the second next PWM period.



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Delay on the duty–cycle updating

✓ The DTC control code required a lot of computation time and then the new values of duty–cycles are updated after two PWM periods.

✓ The control must be modified.

✓ The currents must be predicted, with a prediction of two steps.

✓ From them all the other quantities can be predicted.

✓ Finally the error $\bar{\varepsilon}$ is evaluated.

✓ From it, when necessary, the new duty–cycle values are evaluated in according to the algorithm previously described.

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Experimental results

Tests with 1–step and 2–steps prediction

Tests with 1–step and 2–steps prediction

- Effects of error prediction have been investigated at first.
- The machine is dragged at constant speed of about 400 *rpm*.
- The reference torque is equal to 5 *Nm* and the reference flux is equal to 0.1337 *Vs*.
- Results with and without currents prediction will be shown.

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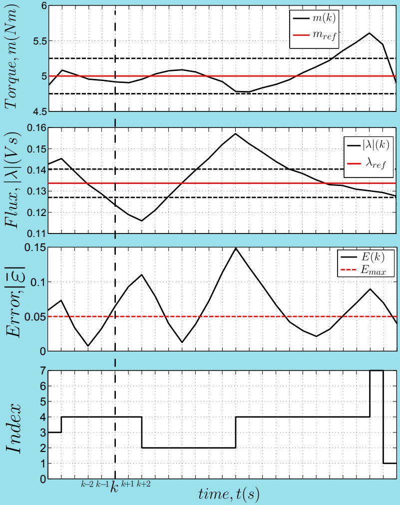
Tests with $1 - step$ and $2 - steps$ prediction

Tests with $1 - step$ prediction

- At instant k error $\bar{\varepsilon}$ is higher than E_{max}.
- New voltage vector, able to cause a negative error derivative, is chosen.
- Such vector is applied at instant $k+2$.
- The error starts to decrease only at the instant $k+2$.



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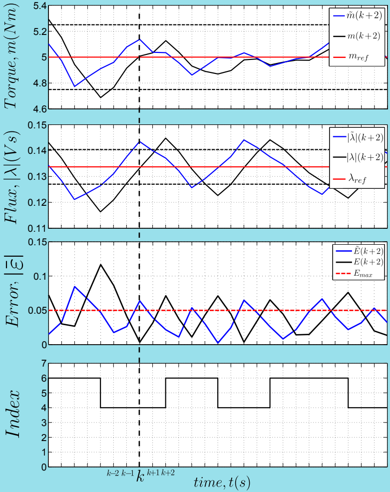
Tests with 1 − *step* and 2 − *steps* prediction

Tests with 2 − *steps* prediction

- Currents $\tilde{i}_d(k+2)$ and $\tilde{i}_q(k+2)$ are predicted.
- Blue curves are for predicted quantities while black is for the actual ones.
- One can realize that predictions anticipate the actual variables by two steps with a good accuracy.
- Discrepancies are mainly due to parameter mismatch and model inaccuracy.



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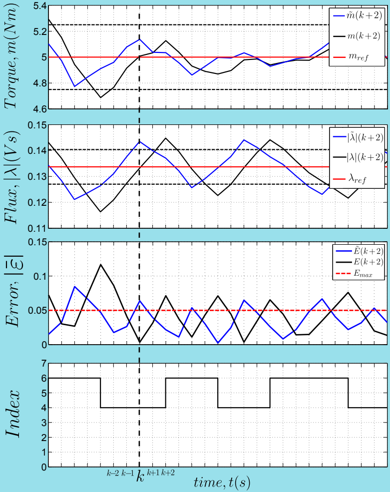
Tests with $1-$ *step* and $2-$ *steps* prediction

Tests with $2-$ *steps* prediction

- At instant k the predicted error exceeds the limit E_{max} while the actual error is well inside the limit.
- Therefore a new voltage vector is calculated that will be applied at time $k+2$.
- At instant $k+2$ actual error has just overcame the limit and is forced to come back.
- Error exceeds the limit only for a single sampling time, provided that prediction is performed accurately.



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Experimental results

Tests with PWM vectors graph and control performance

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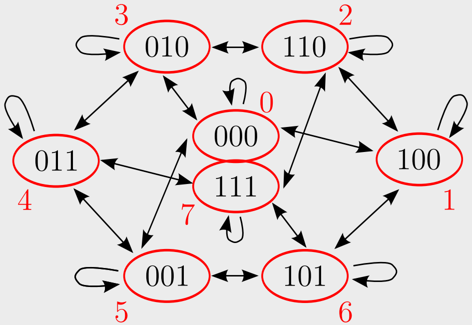
Tests with PWM vectors graph and control performance

A switch state graph can be adopted for limiting number of inverter switch commutation.



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Tests with PWM vectors graph and control performance

Performance comparison

Comparison of control performance with and without prediction, with and without switch state graph are performed.
Error and number of phase–*a* commutation in 1 *s* at steady–state operation are taken into account.

	With pred. without graph	With pred. with graph	Without pred. without graph	Without pred. with graph
Average Error	0.0568	0.0605	0.0878	0.091
♯ commutation phase a	3093	2323	2200	2007

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Experimental results

Speed control with 2–step prediction

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Speed control with $2 - steps$ prediction

Features of control

- Reference speed step from $400\ rpm$ to $-400\ rpm$
- Nominal torque equal to $7\ Nm$
- Nominal flux equal to about $0.17\ Vs$.

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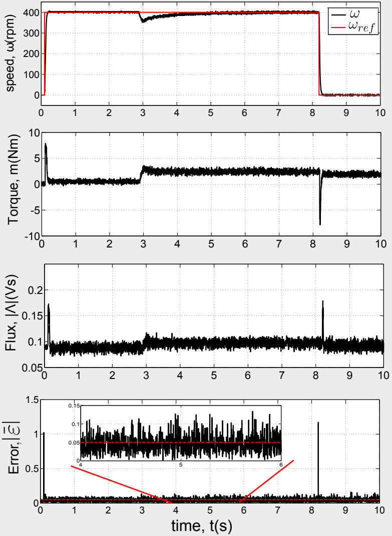
Speed control with 2 − *steps* prediction



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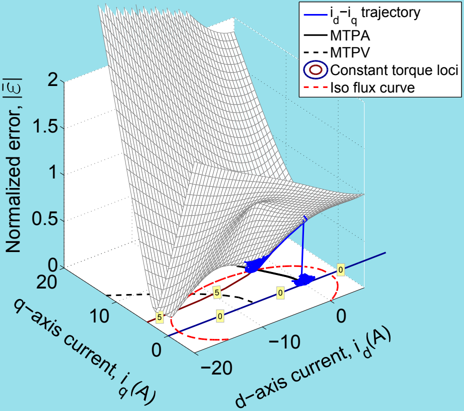
Speed control with 2 – *steps* prediction

DTC performance in response to torque step

- Current trajectory in the i_d–i_q plane.
- $|\bar{\varepsilon}|$ surface calculated for given step torque and flux reference.



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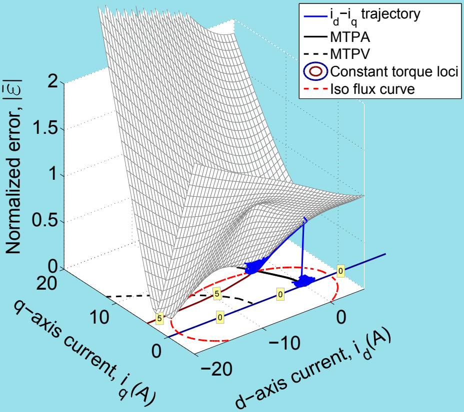
Speed control with 2 − *steps* prediction

DTC performance in response to torque step

- Initially the trajectory current remains around the plane origin.
- When the reference step occurs, the operating point move to the error surface and slides towards the nearest hollow.
- This is a stable operating point that guaranties a null error on the MTPA locus.



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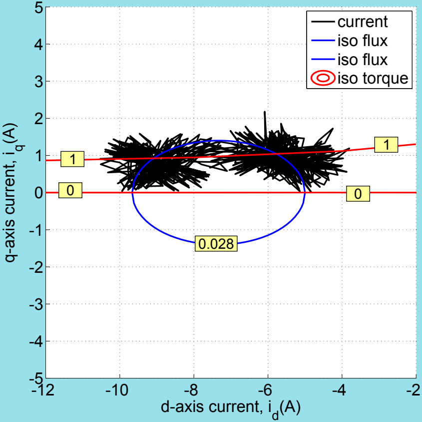
Control trouble due to the double stable points

i_d–i_q trajectory

- By reducing the flux level with a given torque, the two intersection points approach each–other.
- The operation point could jump casually from one of the two hollows to the other.



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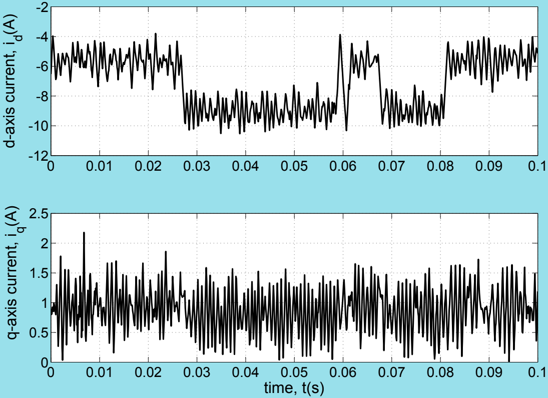
Control trouble due to the double stable points



One can note that the currents i_d and i_q assume two different values casually.

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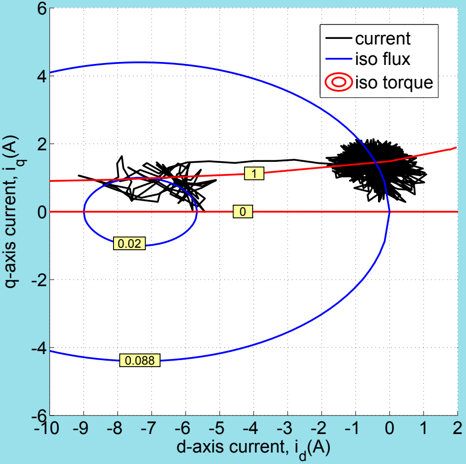
Control trouble due to the double stable points

Wright operating point

- Increasing the flux level again, the two minima of the error surface distance themselves and the operating point remains trapped in one of the two.
- In this case the operating point moves towards lower currents on the MTPA locus.



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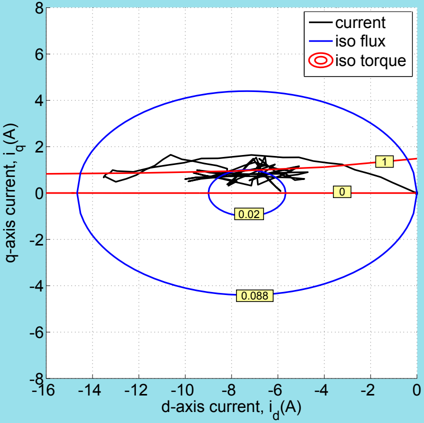
Control trouble due to the double stable points

Bad operating point

- On the contrary, in this case the operating point moves towards higher currents on the right side of MTPV locus.
- This cause the intervention of the current protection of the drive and the currents go to zero.



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Thank you for your attention

Appendix index

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Electrical Parameter

Parameter	Symbol	Value	Unit
Pair–pole	p	5	
Slot number	sl	12	
Phase resistance	R	0.063	Ω
d–axis inductance	L_d	0.012	H
q–axis inductance	L_q	0.020	H
Residual flux linkage	Λ_{mg}	0.088	Vs
Nominal voltage	U_N	80	V