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Magnet Design Based on Transient Behavior of an IPMSM in Event of Malfunction

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***Abstract* -- This paper deals with the approach of analyzing the magnet design based on transient behavior of an IPMSM during switching processes in the event of malfunction for automotive applications. Depending on the maximal current increase during the transient process the needed percentage of Dysprosium for the magnet design is conducted. Switching off strategy is introduced for both Voltage-Source- and Current-Source-Inverter for automotive application. Both inverters are compared concerning the transient current increase and respectively the Dy-content for the magnet design.**

***Index Terms*—IPMSM, short-circuit analysis, Voltage-Source-Inverter, Current-Source-Inverter, magnet design, Dysprosium, demagnetization**

I. NOMENCLATURE

i_u, i_v, i_w	Phase current
u_{uv}, u_{vw}, u_{wu}	Line-to-line voltage
T	Torque
J	Polarization
H	Magnetic field strength
H_{KP}	Magnetic field strength at knee-point
B_r	Remanence flux densitiy

II. INTRODUCTION

In order to meet requirements of reducing emissions and air pollution, development of electrified propulsion solutions is proceeding rapidly. Several highway-capable and series-producible models such as smart ed, Mitsubishi i-MiEV, Nissan Leaf have been introduced to the market. The structure of the electrical power train of a battery electric vehicle includes an electrical machine as traction motor, a DC/AC inverter, optionally with a DC/DC converter, a battery as energy storage and an additional on-board-charger. Due to the fact that the energy storage device is a battery, which is inherently a voltage source, a voltage source inverter (VSI) is exclusively used as the DC/AC inverter for all BEVs existing on the market so far. Depending on the dc-link energy storage components, inverter topologies can be basically grouped into two main categories: voltage-source and current-source topologies [2]. While the VSIs use dc capacitors in the dc-link circuits, the current source inverters (CSIs) employ dc inductors in the dc-link circuits. In recent years research works on using a CSI for electric vehicles have been studied in [1], [2], [3].

The widespread electrical machine is the Interior Permanent Magnet Synchronous Motor (IPMSM) because of its high starting torque and its wide constant-power speed range, due to the high energy content of rare earth materials such as neodymium-iron-boron (Nd-Fe-B) [4].

Despite of the high power density of IPMSM alternative applications. The main reason behind the pressure is due to the increase of the rare earth material costs, which are multiplied during the period between 2011 and 2012. The increase is mainly caused by the monopolistic role of China. Have a closer look at the price development it is noticeable, that the increase of the absolute price of light rare earth materials such as Nd are far below the price of heavy rare earth materials such as Dysprosium (Dy). Fig. 1 shows the price development of Dy and Nd. Although the material requirements of Dy in an IPMSM is only about 7%, it causes about 65% of the entire permanent material costs and hence determines primarily the costs of an IPMSM.

a) Dysprosium (Dy)

b) Neodymium (Nd)

Fig. 1. Material costs of the rare earth materials of a) Dy and b) Nd from March 2011 till July 2012 in €/kg [8].

Dy is a rare earth element used to increase the coercive force which affects the stability against temperature and external fields. While Nd is used as the basic rare earth material to produce magnetic flux, Dy is combined in the alloy in order to achieve demagnetizing stability, which is needed in the event of a malfunction. Therefore, a closer look at the transient behavior of the IPMSM in malfunction must be taken at.

In order to reduce and control the torque within the electrical machine in the event of a malfunction, the electrical machine must be

1) disconnected from the energy storage
2) switched off by the inverter.

In order to do so, two methods are basically used to lead the electrical machine to the following modes:

- an active short-circuit mode

Especially the high transient increase of the current component in the d-axis is critical. If it is high enough, the permanent magnets of the IPMSM can irreversibly be demagnetized. That is why it is necessary to combine the basic rare earth magnets with materials such as Dy in the alloy.

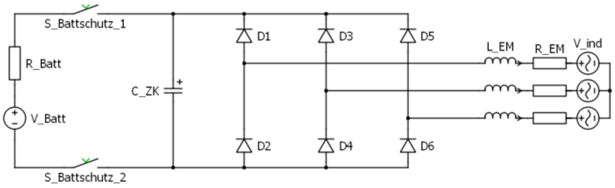
We will discuss the approach of analyzing the transient current increase while switching off an IPMSM. Simulation results for both types of inverters: VSI and CSI are introduced. Depending on the current increase an analysis of the needed percentage of Dy for the magnet design of an IPMSM is conducted.

III. METHODS OF SWITCHING OFF AN IPMSM

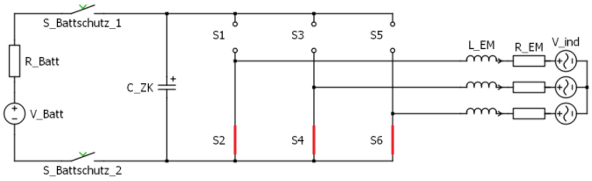
A. *VSI*

In case of an IPMSM with a VSI two methods according to the state of the art are described as following:

- Strategy I VSI: to switch the electrical machine to a disconnected mode of operation in which all switches of the VSI are open, as illustrated in Fig. 2a),
- Strategy II VSI: to switch into the active short-circuit mode in which the high-side switches are open and the low-side switches are turned on to the ground, as illustrated in Fig. 2b).



a) Strategy I VSI



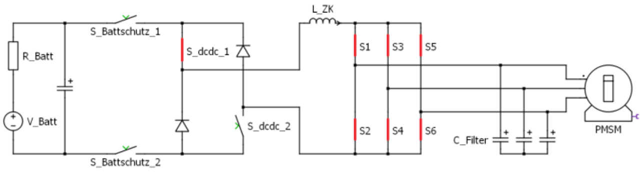
b) Strategy II VSI

Fig. 2. Two different methods of switching off an IPMSM using VSI in the event of a malfunction a) disconnected mode b) active short-circuit mode.

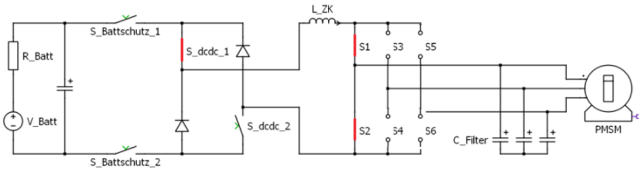
B. *CSI*

Using a CSI for automotive application a DC/DC-converter must be integrated according to [5], [6]. The only approach of switching off the electrical machine by CSI is studied in [7]. According to [7] the following two methods can be used to switch off an IPMSM:

- Strategy I CSI: to active the short circuit by turning on all six switches of the CSI and one switch of the BUCK-inverter, as shown in Fig. 3a),
- Strategy II CSI: to turn on both the top and button switches of one phase of the CSI and one switch of the BUCK-inverter, as shown in Fig. 3b).



a) Strategy I CSI



b) Strategy II CSI

Fig. 3. Two different methods of switching off an IPMSM using CSI in the event of a malfunction a) disconnected mode b) active short-circuit mode.

IV. TRANSIENT CURRENT INCREASE DURING THE SWITCHING OFF PROCESS

A. *Simulation Model*

In order to simulate the transient behavior of the IPMSM during the switching off process a Finite-Element-Analysis (FEA)-based simulation model of the electrical machine is connected to a switching circuit. The calculation is conducted by a transient solver. An IPMSM applied as a traction motor is chosen for the simulation. Fig.4 illustrates the detailed cross section of the machine. The key data of the simulated IPMSM is shown in Table I.

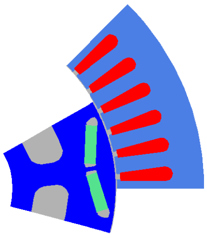


Fig. 4. Detail of the cross section of the simulated IPMSM.

Two switching circuits are built each for VSI and CSI. The windings of the IPMSM are connected to a current source in each phase. The switches of the circuit are implemented as resistors with the value of either zero (switching on) or infinite (switching off). Beginning from one steady-state operation point the switching strategies are induced by changing the parameters of the correspondent resistors at the switching point.

TABLE I
KEY DATA OF THE SIMULATED IPMSM

No. of Slots	48
No. of Polepairs	4
DC Voltage	300V
Max. Torque	330Nm
Max. Power	120kW

The characteristic operation point, which is chosen for the simulation, is the corner point in generator mode with a torque of 330Nm and a rated speed of 3500rpm. This operation point is known as the one with the highest current

B. *Simulated Results for VSI*

In order to protect the battery in the event of malfunction the relays between the battery and the inverter must be opened at the switching point. The magnetic energy stored in the inductance of the motor is fed into the dc link capacitor. Therefore the dc link voltage increases. When steady state is reached, line-to-line voltages of the electrical machine become equal to the level of the back electromotive force (EMF). The simulated results of the transient phase currents, line-to-line voltages and torque of the IPMSM are shown in Fig. 5.

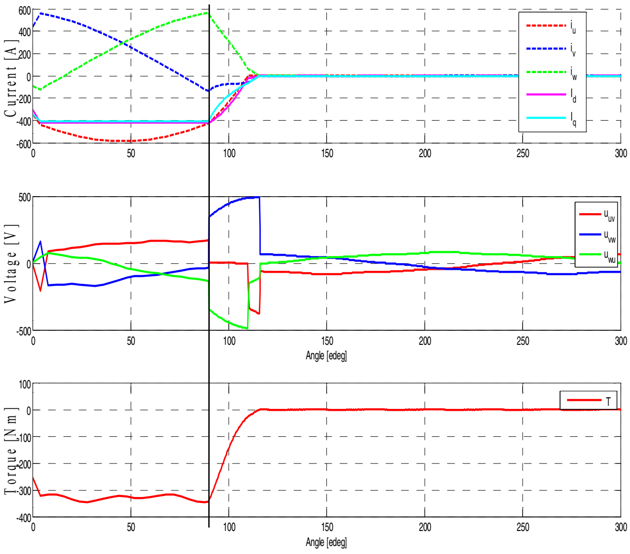


Fig. 5. Strategy I VSI @ T=330Nm, n=3500rpm: simulated results of the transient phase currents, line-to-line voltages and torque.

Since the back EMF increases proportional with the speed of the electrical machine, Strategy I VSI only can be used in the low speed working area. As soon as the back EMF becomes higher than the maximum blocking voltage of the power electronics, the inverter can be damaged by the transient voltage increase by switching off the IPMSM using Strategy I VSI. In this case Strategy II VSI must be implemented.

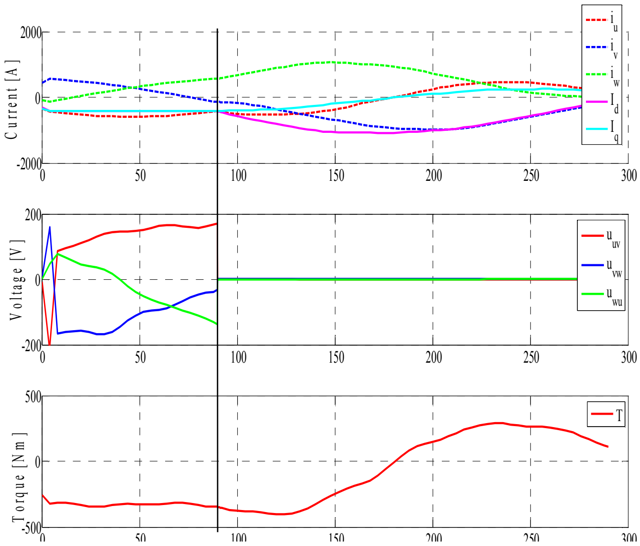


Fig. 6. Strategy II VSI @ T=330Nm, n=3500rpm: simulated results of the transient phase currents, line-to-line voltages and torque.

The simulated results using Strategy II VSI are shown in Fig. 6. After leading into the active short-circuit mode in which the high-side switches are open and the low-side switches are turned on to the ground, the line-to-line voltage drops down to zero. High transient currents occur and end in the stationary short-circuit state. The maximum current in d-axis generates a magnetic field acting opposite to the permanent magnet and defines the coercive force of the magnet material respectively the Dy content, which will be detailed explained in Section V.

C. *Simulated Results for CSI*

Equivalent to Strategy I VSI the Strategy I CSI causes high line-to-line voltage which is critical for the power electronics of the inverter. The simulated results of the transient phase currents, line-to-line voltages and the torque are shown in Fig. 7.

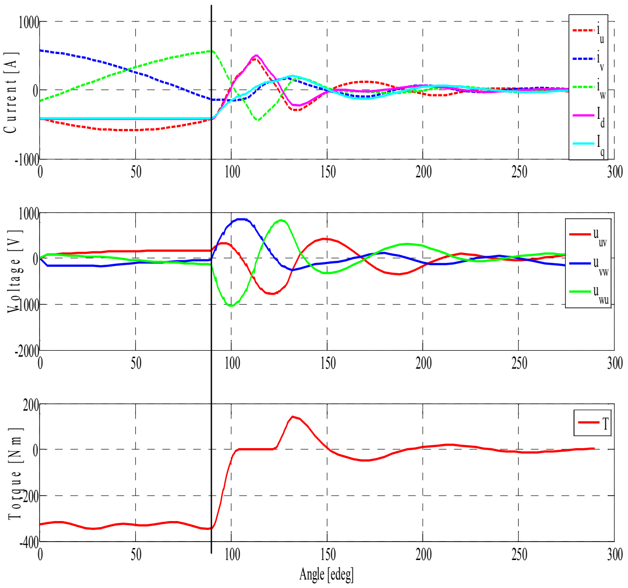


Fig. 7. Strategy I CSI @ T=330Nm, n=3500rpm: simulated results of the transient phase currents, line-to-line voltages and torque.

Also in this case Strategy II CSI must be implemented to keep the line-to-line voltages at an uncritical level. A transient increase of the d-axis current can be observed in Fig. 8. as well.

Compared to the maximum d-axis current shown in Fig. 6, the maximum d-axis current during the switching off process using CSI is lower than using VSI, which will positively affect the needed Dy-content.

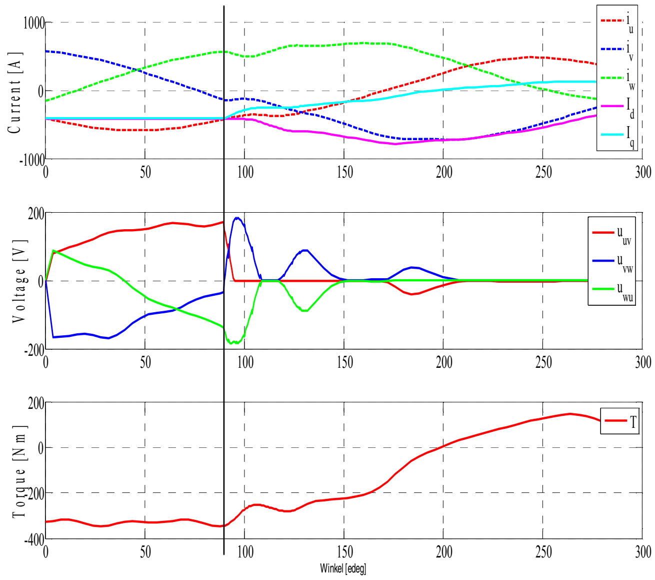


Fig. 8. Strategy II CSI @ T=330Nm, n=3500rpm: simulated results of the transient phase currents, line-to-line voltages and torque.

V. MAGNET DESIGN

A. Demagnetization Stability Based on Dy-Content

Fig. 9 shows the JH-curves (polarization versus magnetic field) of 3 permanent magnet materials with different coercive force depending on the Dy-content. 180°C is the considered temperature as it is the maximum rotor temperature of the chosen motor design. The irreversible demagnetization starts at the marked knee-point when an irreversible degradation of 5% in the magnetic flux occurs. The higher the content of Dy, the higher the magnetic field strength H_{KP} can be achieved at the knee-point. At the same time, the remanence B_r is reduced as the percentage of Nd decreases respectively, which reduces the energy-content of the magnet.

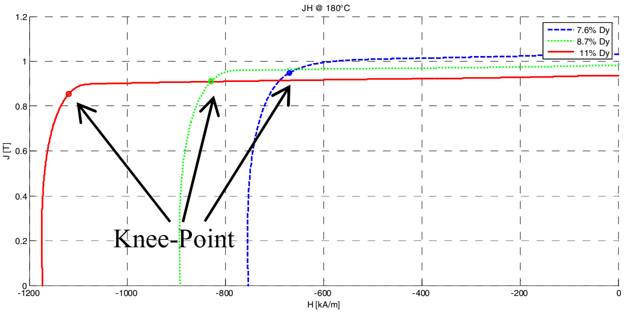


Fig.9. Magnetic field strength at the knee-point with different Dy-content.

In the event of malfunction a demagnetization field is caused. This demagnetization field is not evenly distributed all over the magnet's area. The most critical demagnetization field occurs at the edges of the permanent magnet facing the air gap, as illustrated in Fig. 10. For the magnet design it is important to ensure that not more than a certain percentage of the entire magnet area is penetrated by the demagnetizing field.

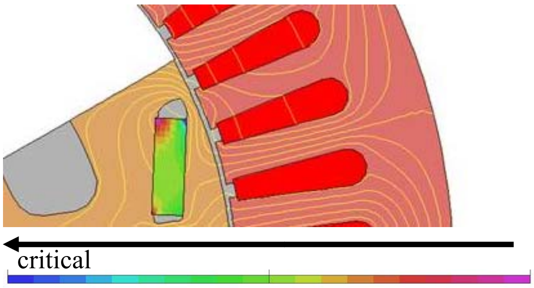


Fig.10. Example of one detailed aspect of the demagnetization fields in the permanent magnet.

Nevertheless, one main goal during the magnet design process is to reduce the content of Dy because of its high costs and the fact of reducing the flux B_r. Fig. 11 shows the correlation of magnetic field strength of the knee-point depending on the Dy-content at the temperature of 180°C.

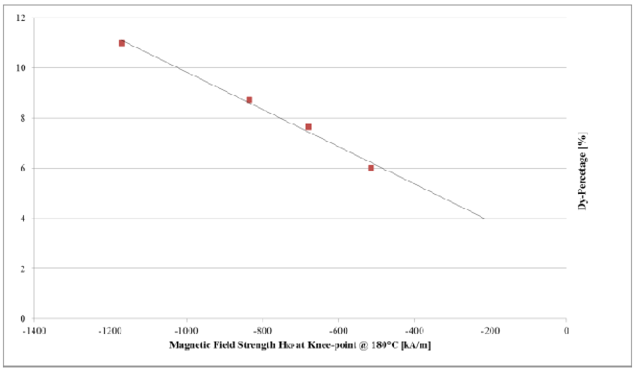


Fig.11. Correlation of coercive force depending on the Dy-content at the temperature of 180°C.

B. Dy-Content Based on Transient Behavior

Fig. 12 shows the required magnetic field strength of the knee-point as a result of FEA-simulations depending on the maximal d-axis current cause by the switching off process.

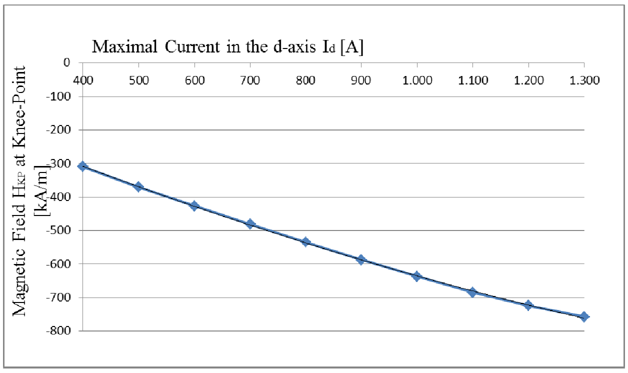


Fig.12. Required magnetic field strength of the knee-point depending on the maximal d-axis current generated during the switching off process.

With the aid of Fig. 11 the needed Dy-content to protect the permanent magnet from demagnetizing can be estimated. The needed Dy-content based on the maximum transient current in d-axis and respectively the magnetic field using VSI and CSI is compared in Table II. For both types of inverters Strategy II is considered as the save switching off strategy, as discussed in Section IV.

TABLE II
COMPARISON BETWEEN VSI AND CSI CONCERNING TRANSIENT CURRENT INCREASE, MAGNETIC FIELD STRENGTH AND THE DY-PERCENTAGE

	Strategy II VSI	Strategy II CSI
Max. transient current in d-axis I_d	1089 A	782 A
Required magnetic field strength of knee-point H_{KP}	-675 kA/m	-527 kA/m
Dy-Content	7.4 %	6.3 %

The comparison in Table II leads to the result that when compared to VSI 1.1% of Dy can be reduced by using CSI because of the less caused transient current increase in d-axis during the switching off process. With an assumed amount of 2 kg permanent magnet of the simulated IPMSM 22g Dy can be reduced. This leads to a cost reduction of 33€ with an assumed Dy cost of 1500€/kg.

VI. CONCLUSIONS

This paper studies the approach to design the permanent magnet of an IPMSM for automotive application based on the analysis of the transient current increase in the event of a malfunction. Dysprosium (Dy) is used to protect the permanent magnet from demagnetization caused by the transient current increase. Different methods of switching off an IPMSM are introduced for both types of inverters: Voltage-Source- (VSI) and Current-Source-Inverter (CSI). Simulation results based on Finite-Element-Analysis are used to calculate the coercive force influenced by the content of Dy. Transient current increase while the switching off process is simulated as well. Depending on the current increase an analysis of the needed percentage of Dy and the magnet design of an IPMSM is conducted. A comparison between CSI and VSI including the reduced amount of Dy is presented as the final result of this paper.

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VIII. BIOGRAPHIES

Sicong von Malottki (nee Liu) was born in China, on July 30, 1985. She studied Electrical Engineering and Information Technology at RWTH Aachen University and received her degree of Dipl.-Ing in 2010. Currently she works as a Ph.D. student of Institute of Electrical Machines (IEM) supervised by Prof. Hameyer in cooperation with Daimler AG. Her research focuses on electrical machines, converters and drive systems for automotive application.

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Andreas Wanke was born in Merseburg, Germany, on April 3, 1986. From 2005 to 2011 he studied Mechatronics at the Dresden University of Technology and graduated with the degree of Dipl.-Ing. Since 2011 he works in the research and development department of Daimler AG. His working experiences include simulation and testing of electrical machines in terms of system performance evaluation and acoustic behavior in automotive use.

Kay Hameyer (M96-SM99) received the M.Sc. degree in electrical engineering from the University of Hannover, Hannover, Germany, and the Ph.D. degree from the University of Technology Berlin, Berlin, Germany. After his university studies, he was with Robert Bosch GmbH, Stuttgart, Germany, as a Design Engineer for permanent-magnet servo motors and board net components for vehicles. Until February 2004, he was a Full Professor of numerical field computations and electrical machines at the Katholieke Universiteit Leuven, Belgium. He is currently a Full Professor, the Director of the Institute of Electrical Machines at RWTH Aachen University, Aachen, Germany, where he has been the Dean of the Faculty of Electrical Engineering and Information Technology from 2007 until 2009. His research interests include numerical field computation and simulation, design of electrical machines, particularly permanent-magnet excited machines and induction machines, and numerical optimization strategies.