A Method to Switch off an IPMSM by a Current-Source-Inverter in the Event of a Malfunction in a Battery Electric Vehicle

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Keywords

Current Source Inverter (CSI), Fault handling strategy, Permanent magnet motor, Electric vehicle, Converter machine interactions

Abstract

This paper presents a method to switch off an IPMSM by using a Current-Source-Inverter in the event of a malfunction in a Battery Electric Vehicle. The analysis includes transient currents, voltages and the torque development during the switching off process. The investigated method based on a voltage observer is able to minimize undesirable side effects caused by high transient currents and voltages.

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 converter, 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 converter for all BEVs existing on the market so far. The widespread electrical machine is the Interior Permanent Magnet Synchronous Motor (IPMSM) because of its high starting torque and its wide constant-power speed area, due to the high energy content of rare earth materials such as neodymium-iron-borron (Nd-Fe-B) and samarium-colbalt (Sm-Co) [1].

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 investigated in [2], [3], [4], [5]. The investigations so far mainly include topics of control and performance of the CSI integrated in an electric vehicle.

In the event of a malfunction the electrical machine must be 1) disconnected from the energy storage and 2) switched off by the inverter. During this process high transient currents and voltages may be generated by using different strategies. The problem is especially critical at high speed because a high back EMF is inducted in the IPMSM. That is why it is especially important to choose the right strategy in order not to damage the rest of the system components.

The common method of switching off the electrical machine is to actively conduct the short circuit mode of the VSI by turning on either all three low-side or the high-side switches. However, in both cases a transient short-circuit current is generated which is high enough to degauss the permanent magnets of the IPMSM.

In [6] a method of switching off the electrical machine by a VSI is invented to minimize the undesirable side effects. The introduced strategy is to first switch the electrical machine to a disconnected mode of operation in which all switches of the VSI are open and then to switch into the short-circuit mode in which the high-side switches are open and the low-side switches are turned on to the ground.

However, while considering the integration of CSI as the DC/AC-converter for BEV, investigation for the same purpose must be done. The results presented in this paper are concerning the methods, how an IPMSM can be disconnected from the battery and switched off by a CSI in case of system malfunction without causing transient undesirable side effects. Based on the results of this paper, a comparison to a BEV system to VSI and the impact of the switching off strategy on the design of an IPMSM are conducted and presented in [9].

This paper proposes analysis of the short circuit effect on the IPMSM performance during the event of malfunction. Simulation model of the electrical system including battery, electrical machine, CSI is built in Plecs. The control and modulation part is implemented in MATLAB/Simulink environment. The performance of IPMSM under short circuit operation is analyzed including the transient currents, voltages and the torque development. A method containing a voltage-observer based control to switch off the IPMSM is developed in order to avoid undesirable side effects caused by high transient currents and voltages during the switching off process.

CSI with BUCK-converter for a BEV

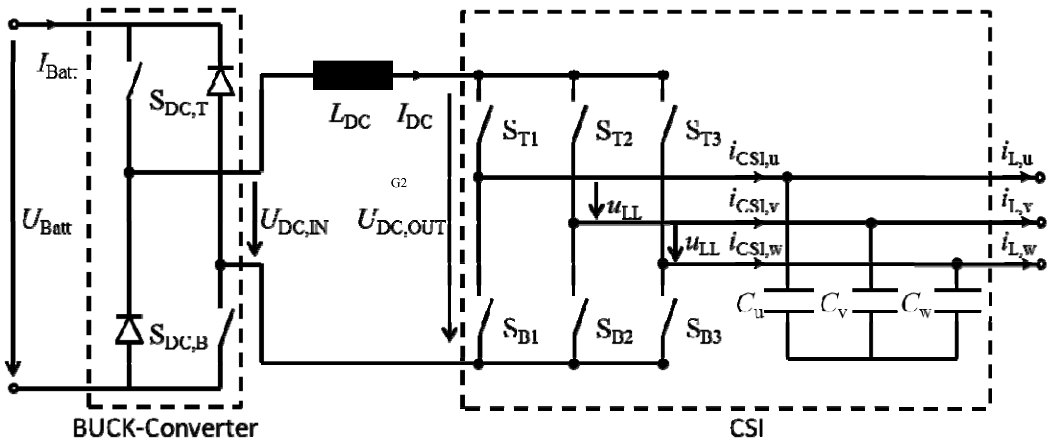

Fig. 1: Proposed structure of CSI with an integrated BUCK-Converter for BEV application.

The proposed structure of CSI with an integrated buck-boost-converter for BEV application is shown in Fig. 1. As mentioned before CSI is used as AC/DC-converter as an alternative to VSI according to the current state of technology. The proposed topology includes an asymmetrical half bridge as BUCK-converter, mainly because of the following reasons:

- Because of the fact that the dc link current of the CSI must be positive, it is only possible to provide the generator mode to charge the battery during recuperation by reversing the polarity of the input voltage of the CSI. This can be done with the BUCK-converter.
- In order to archive high power density the control method for loss minimal operation of an IPMSM is used for automotive application [1]. Based on a given reference torque T* and the flux limit the reference current components I^*_d and I^*_q are chosen for each operation point. As investigated in [7] and [8], in order to achieve good harmonic performance the dc link current must be equal or higher in comparison to the peak value of the phase currents of the electric machine. The decoupling between the battery current and the dc link current can be achieved by the BUCK-converter.
- While a VSI operating as a buck-converter, a CSI has the advantage of boosting its output voltages. This function is detailed described in [2]. In order to operate the electrical machine above the voltage

limit which exists while using a VSI, the dc link current must be increased. This can only be achieved by using an additional BUCK-converter.

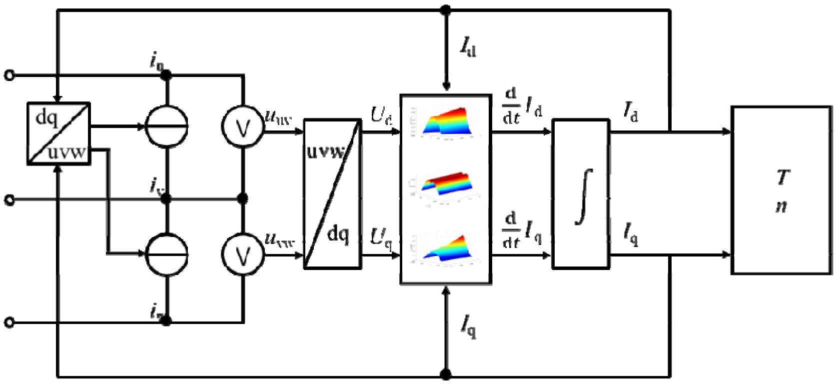

Fig. 2: Structure of the IPMSM model with implemented LUT of its FEM-calculated inductances in d- and q-axis and permanent magnet flux.

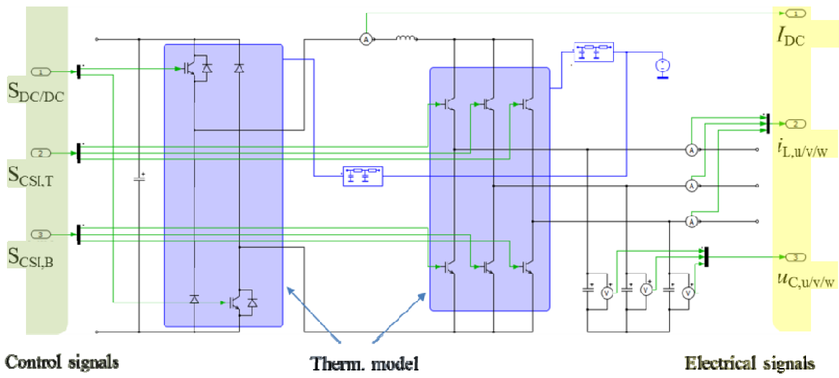

Fig. 3: Thermal model of the proposed DC/AC-converter structure of the CSI and the buck-converter.

Based on the above described structure a simulation model is implemented in MATLAB/Simulink with a Plecs Blockset integrated environment. While the battery is simplified to an ideal voltage source and its inner resistance, the model of the IPMSM is built with Look Up Tables (LUT) of its inductances and its permanent magnet flux, which are calculated from with Finite-Element-Modell in dependence of the current components, as shown in Fig 2. A thermal model of the proposed DC/AC-converter structure of the CSI and the buck-converter is built and illustrated in Fig. 3. The optimum control strategy for IPMSM explained in [1] is implemented in the simulation model. The following purposes can be fulfilled with the simulation:

1. Steady-state and transient analysis to proof the control, modulation strategy
2. Simulation of transient operation modes of the system.

Two Basic Strategies of the Switch off Process

Beginning from a steady-state mode the switching off process is led in by turning on and off the correspondent semiconductor devices. In case of a CSI there are basically two different strategies to switch off the electrical machine.

Strategy I

One possibility of switching off the electrical machine is to active the short circuit by turning on all six switches of the CSI and one switch of the BUCK-converter as shown in Fig. 4. The gates $S_{Batt,1}$ and $S_{Batt,2}$ in Fig. 1 are switched off to disconnect the battery from the rest of the system.

From the working point with a mechanical speed of n=4000 rpm and a reference torque of T=70 Nm the active short circuit is led in with the simulation model. The simulation results of the transient mode are shown in Fig. 4.

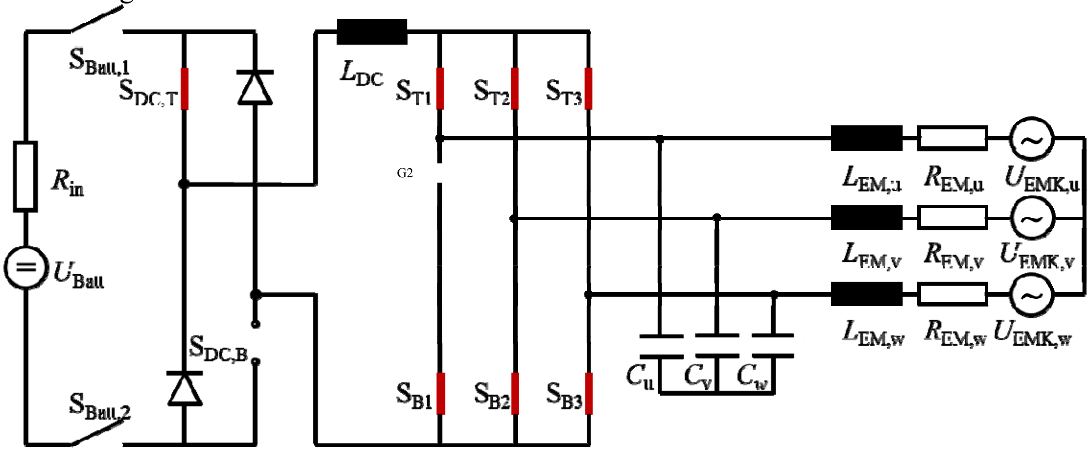

Fig. 4: Strategy I to switch off the IPMSM by a CSI with a BUCK-converter integrated.

With this strategy low transient voltages are generated. This way the semiconductor devices can be protected. The drawback of this strategy is the high transient current generated in the electrical machine during the entire process. In Fig. 5 b) the green area marks the uncritical area of the current. The red area marks the level of currents which is high enough to damage the magnets in IPMSM.

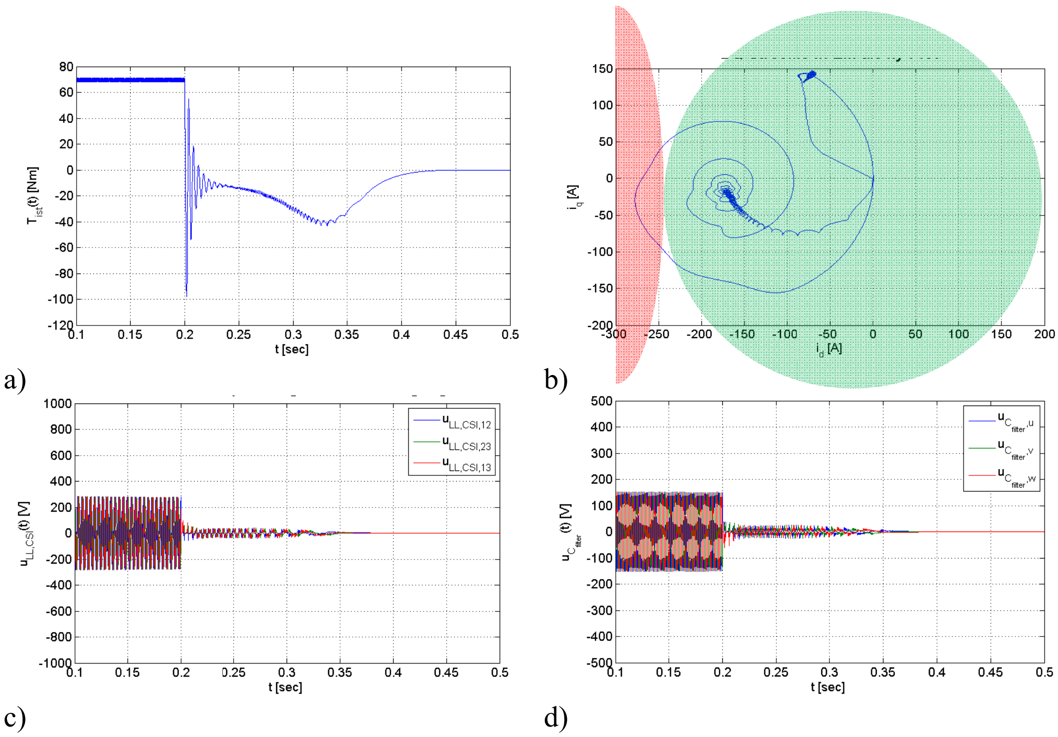

Fig. 5: Simulation results after switching off the IPMSM by implementing strategy I, starting from the steady-state working point @ T=70 Nm and n=4000 rpm. a) torque, b) current components I*d, I*q c) three phase line-to-line voltages d) voltages of the filter capacitors.

Strategy II

The second possibility is to turn on both the top and button switches of one phase of the CSI and one switch of the BUCK-converter, as shown in Fig. 6. Also in this case the gates $S_{Batt,1}$ and $S_{Batt,2}$ are switched off to disconnect the battery from the rest of the system.

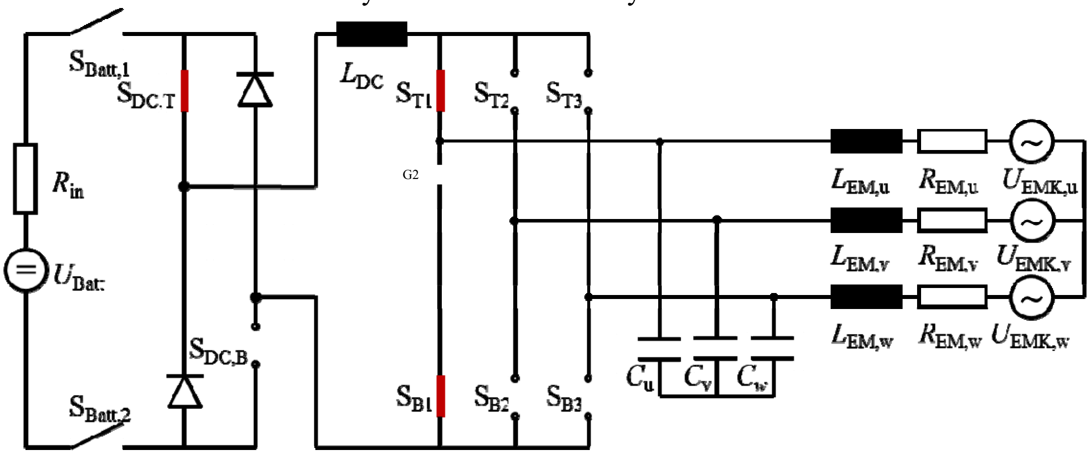

Fig. 6: Strategy II to switch off the IPMSM by a CSI with a BUCK-converter integrated.

Simulation results are presented in Fig. 7. Although low transient current is generated while switching the electrical machine with this strategy, the transient line-to-line voltages become very high, which is critical and can damage the semiconductor devices.

As shown with the simulation results, both strategies have their advantages and disadvantages. While high transient current are generated in the electrical machine by using the first strategy which may degauss the permanent magnets of the IPMSM, high transient line-to-line voltages are generated by implementing the second strategy. The high voltages are critical because they are high enough to damage the semiconductor devices with a blocking voltage of 650 V.

Proposed Method

Starting from a steady-state working point very high line-to-line voltages are generated because of the high back EMF in the IPMSM, if strategy II is chosen to switch off the electrical machine. By using strategy I the transient currents become critical, not directly after turning on the six switches, but during the process until steady-state. No overvoltage is generated of the filter capacitors, hence the line-to-line voltages of IPMSM is not critical by using strategy I.

The proposed method combines both strategies by first leading in to strategy I, in order to avoid the high transient voltages and to protect the semiconductor devices. By disconnecting the battery from the BUCK-converter and turning on all six switches of the CSI, a B6-bridge is built. The IPMSM is switched to a disconnected mode of operation. The output currents of CSI become zero, the three phase currents are commutating into the filter capacitors. Hence the line-to-line voltages at the electrical machine increase. After a calculated time period strategy II should be led in, in order to avoid the high transient currents caused by the process of strategy I. By opening two bridge legs, switching to strategy II, the point of time becomes very important. On the one hand, if it is too early, the line-to-line voltages are still high enough to damage the semiconductor devices. On the other hand, if the point of time is too late, the transient current may become high enough to damage the IPMSM. That is why the proposed method uses an observer based control to online calculate the line-to-line voltage. Based on the criterions the switches are changed from strategy I to II during the switching off process.

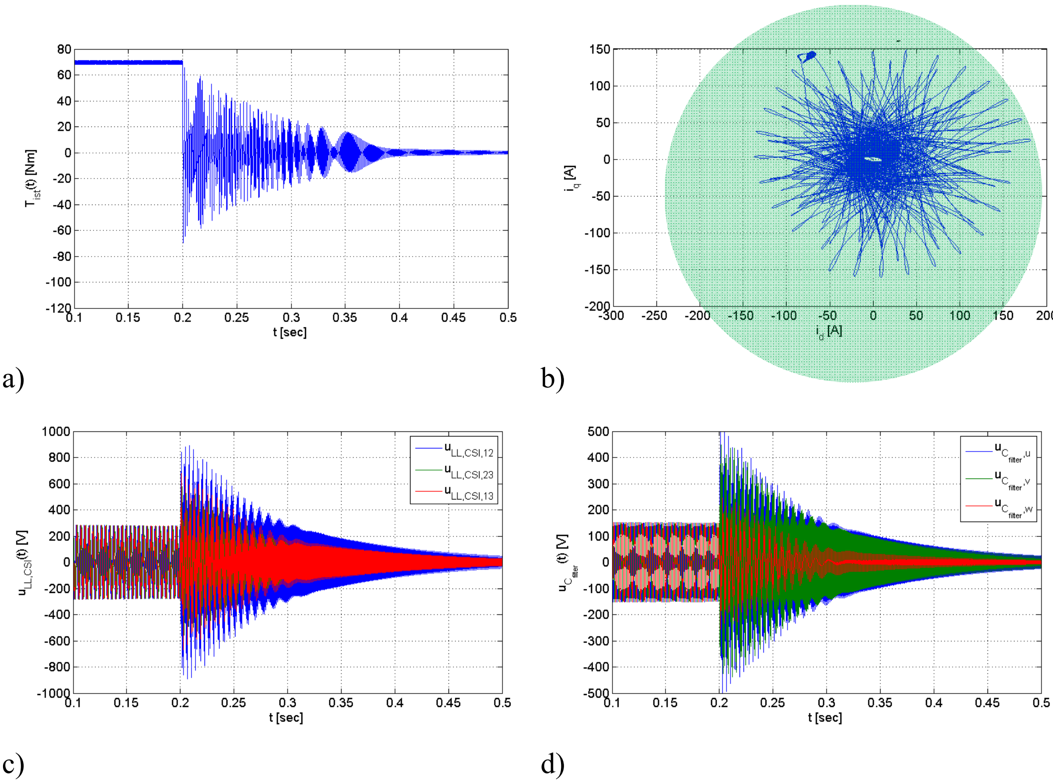

Fig. 7: Simulation results after switching off the IPMSM by implementing strategy II, starting from the steady-state working point @ T=70 Nm and n=4000 rpm. a) torque, b) current components I^*_d, I^*_q c) three phase line-to-line voltages d) voltages of the filter capacitors.

$$u_{\mathrm{C,Peak1}} = u_{\mathrm{C}}(t_S) + \frac{1}{C_{\mathrm{Fi}}} * \int_{t_S}^{t_S+\frac{t_0}{4}} i_{\mathrm{C}}(t)\ dt = u_{\mathrm{C}}(t_S) + \frac{1}{C_{\mathrm{Fi}}} * \int_{0}^{\frac{t_0}{4}} \hat{I} * \cos(\omega t)\ dt = u_{\mathrm{C}}(t_S) + \frac{\hat{I}}{C_{\mathrm{Fi}}} * \int_{0}^{\frac{t_0}{4}} \cos\left(\frac{2\pi}{t_0} t\right) dt$$

$$= u_{\mathrm{C}}(t_S) + \frac{\hat{I}}{C_{\mathrm{Fi}}} * \left[\sin\left(\frac{2\pi}{t_0} t\right) * \frac{t_0}{2\pi}\right]_0^{\frac{t_0}{4}} = u_{\mathrm{C}}(t_S) + \frac{\hat{I}}{C_{\mathrm{Fi}}} * \frac{t_0}{2\pi} \sin\left(\frac{\pi}{2}\right)$$

$$= u_{\mathrm{C}}(t_S) + \hat{I} * \sqrt{\frac{L_{\mathrm{EM}}}{C_{\mathrm{Fi}}}} \qquad (1)$$

$$u_{\mathrm{C,Peak}} = \left| u_{\mathrm{C}}(t_{\mathrm{S}}) + \hat{I} * \sqrt{\frac{L_{\mathrm{EM}}}{C_{\mathrm{Fi}}}} \right| + \left| \hat{U}_{\mathrm{ind}}(t_{\mathrm{S}}) \right| \tag{2}$$

The calculation of the filter capacitor voltages in consideration of the commutating process by switching the CSI according to strategy I is shown in (1). The total peak value of the transient filter capacitor voltages also include the back EMF of the IPMSM during the switching off process. Hence the online calculation of the filter capacitor voltages becomes the description of (2). As long as the transient voltages from the online calculation is higher than the blocking voltage of the IGBTs, strategy I is activated. The switching mode of CSI can be changed to strategy II, if the online calculated voltages of the filter capacitors and the IPMSM become lower than the defined criterions shown in (3).

$$\begin{aligned} u_{\mathrm{C,Peak,max}} &= max\{u_{\mathrm{C1,Peak}}, u_{\mathrm{C2,Peak}}, u_{\mathrm{C3,Peak}}\} \overset{!}{<} u_{\mathrm{C,lim}} \\ u_{\mathrm{LL,Peak}} &= max\{ |u_{\mathrm{C,1}} - u_{\mathrm{C,2}}|, |u_{\mathrm{C,2}} - u_{\mathrm{C,3}}|, |u_{\mathrm{C,1}} - u_{\mathrm{C,3}}| \} \overset{!}{<} u_{\mathrm{LL,lim}} \end{aligned} \tag{3}$$

Starting from the same steady-state working point of T=70 Nm, n=4000 rpm simulation results using the proposed method are shown in Fig. 8-10. The criterion of $u_{LL,lim}$=650 V is defined for the simulation. As estimated with the online voltage observation the line-to-line voltages is smaller than the maximal allowed value after switching from strategy I to strategy II. The transient currents during the entire process stay below the critical levels as well.

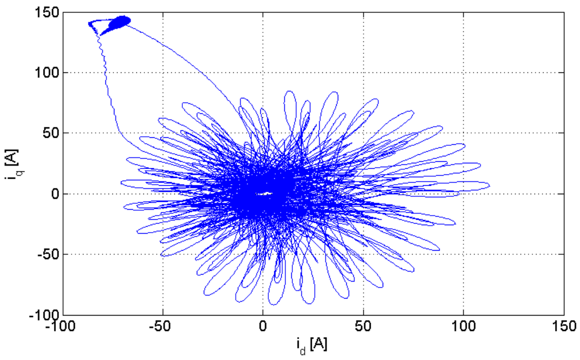

Fig. 8: Simulation results of the current components I_d and I_q after switching off the IPMSM by first leading in to strategy I and switched to strategy II using the proposed method of an online observing of the filter capacitor voltages. Starting from the steady-state working point @ T=70 Nm and n=4000 rpm.

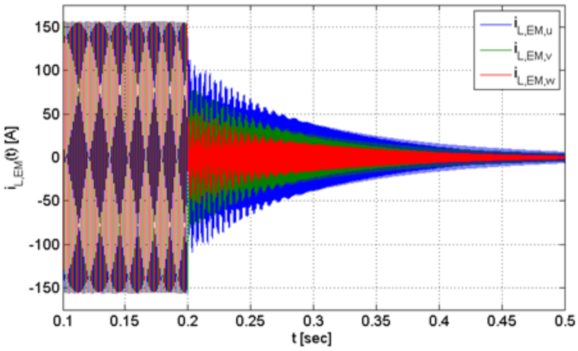

Fig. 9: Simulation results of the phase currents in IPMSM after switching off the IPMSM by first leading in to strategy I and switched to strategy II using the proposed method of an online observing of the filter capacitor voltages. Starting from the steady-state working point @ T=70 Nm and n=4000 rpm.

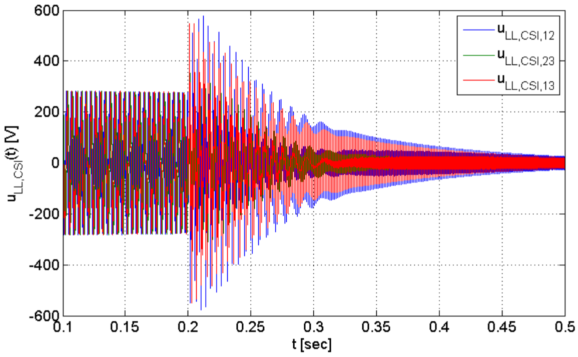

Fig. 10: Simulation results of the line-to-line voltages after switching off the IPMSM by first leading in to strategy I and switched to strategy II using the proposed method of an online observing of the filter capacitor voltages. Starting from the steady-state working point @ T=70 Nm and n=4000 rpm.

Conclusion

This paper deals with the transient process of switching off an IPMSM by a CSI in the event of malfunction in a BEV system. Analysis of the short circuit effect on the IPMSM performance has been done with implemented simulation model of the electrical system including battery, electrical machine, CSI and its control. The performance of IPMSM under short circuit operation is analyzed including the transient currents, voltages and the torque development. A method containing a voltage observer based control to switch off the IPMSM is developed in order to avoid undesirable side effects caused by high transient currents and voltages during the switching off process.

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