Safe Turn-off Strategy for Electric Drives in Automotive Applications

Corresponding author: Aravind Ramesh Chandran, Aalto University, Helsinki

Personal Address: Isarstraße 6, 91052, Erlangen, Germany
Email: aravind.rameshchandran@aalto.fi Phone: +4917630008276
Martin D. Hennen, Robert Bosch Gmbh, Stuttgart
Antero Arkkio and Anouar Belahcen, Aalto University, Helsinki

Abstract—This paper proposes a strategy to safely turn off an electric drive system in case of a fault without destroying the power module and the electric machine. Classic turn-off strategies like Active Short Circuit (ASC) and Freewheeling (FW) are adopted as state of the art for electric vehicle applications. However, these methods cause either high currents in the machine or over-voltage in the DC-link capacitor, the system should be designed to withstand these unwanted effects making them more expensive. The novel method proposed in this study mitigates both over-voltage and over-currents, thereby achieving a smooth transition from torque control to a safe state. The proposed method can be implemented almost cost neutral with respect to the state of the art methods. In this method, voltage-vectors are identified with respect to the position of the current-vector, which can either charge or discharge the DC-link capacitor hence keeping both the DC-link voltage and stator-currents to a safe value. The proposed strategy is analysed through simulations with a combined inverter and machine model. The simulation model includes skin-effect loss models which are essential for the accurate calculation of the DC-link voltage. Measurements were done on an electric drive system to validate the strategy.

Index Terms—E-mobility, Electric Traction system, Over-voltage protection, DC-link capacitor, Power-Electronics, Induction Machines.

Special Issue on Novel Hybrid and Electric Powertrain Architectures

NOMENCLATURE

K_r Skin effect correction factor for Rotor resistance
K_x Skin effect correction factor for Rotor inductance
L_M Main Inductance
P_cond Power module conduction losses
P_switch Power module switching losses
R_ac Skin effect correction factor for Rotor resistance
R_Rt Rotor winding resistance
R_S Stator winding resistance
s_i Switching phase vector for phase x = a,b,c
u_α Stator phase voltage in alpha axis
u_β Stator phase voltage in beta axis
U_pc Collector emitter voltage of the IGBT
u_de DC-link voltage
u_d Phase voltage in direct axis
U_fw Forward voltage of the diode
u_q Phase voltage in quadrature axis
u_s Stator voltage space vector
u_sn Stator phase voltage (referred to the star point) x = a,b,c

I. INTRODUCTION

The automobile industry throughout the world has been pushing for the electric propelled traction system in favor of the conventional internal combustion engines. The race for dominance in the electric mobility market has been highest ever than before, every automobile maker and suppliers have been urged to develop better electric drive systems which are more robust and power dense. One of the most critical factors in designing an electric drive system in an automotive system is safety. Adhering to the high safety standards will require the system to turn-off from the active state to a final state with as minimum stress on the components. In the event of a fault in an electric drive system or in an event where the electric drive system needs to be manually turned off, the system will go to a safe state. During the safe state the energy exchange between the battery and the electric machine is interrupted, so that no unwanted torque is generated which would harm the driver or the passenger in the vehicle. Safe states are requested either as a reaction from a fault which needs to be executed within a specified time, or it can also be a reaction to an explicit request from the vehicle control unit which requests the motor controller to shut down. In prior
art there are mainly two classical safe state strategies. The first method is Active short circuit (ASC), which refers to actively short circuiting the windings of the machine using the inverter. [1] shows that in the event of a single phase fault in the electric machine, short circuiting the three phases would reduce the post fault currents and torque in the electric machine. The second method is to turn off the gate supply of the inverter switches so that the machine behaves like an uncontrolled generator [2] and [3]. This safe state is referred to as Freewheeling (FW) in this paper, since the current would still continue to freewheel through the diodes till zero crossing. This second method generates lower post fault stator currents and torque in the machine compared to the short circuiting method, but generates a high over-voltage on the DC-link side. The impact on the DC-link capacitor for an induction machine drive are investigated in [4]. In [5] both the short circuit and the open circuit strategies are compared and evaluated in case of a single phase open circuit fault in the electric machine. [6] proposes a hybrid approach by varying the switching signals between FW and ASC. The selection of the safe state depends on the operating point of the electric machine and the type of electric machine used. A detailed explanation of these safe states is explained in Section II. The abrupt transition to any of the mentioned safe states would always result in either a transient over-current in the electric machine or a transient voltage peak in the DC-link capacitor. Alternatively if the request for safe state transition is not time critical, there are so called soft turn-off strategies which uses the main micro-controller of the inverter to slowly transition to either Active short circuit or Freewheeling. For example, if the turn-off is predetermined or expected, the phase currents can be controlled down to zero and then safely turned off to a safe state. There are also different variations of soft turn-offs especially soft-ASC where the reference \( U_d \) and \( U_q \) values can be ramped down to zero, which is a form of Active Short Circuit. These methods are patented and can be found in [7].

Discharging the DC-link capacitor voltage by controlling the operating mode of the electric machine has also been discussed in [8]. Such soft transition techniques still require the main micro-controller of the inverter remain functional.

This paper proposes a new safe state transition technique that employs specific voltage vectors depending on the current space vector, which transfers the inductive energy from the machine inductance to the DC-link capacitor or vice-versa. This energy transfer is accomplished in a manner that neither DC-link voltage nor the phase currents never crosses any values that would damage the system. This technique would be implemented on a hardware close CPLD (Complex programmable logical device) which is more robust and fast to respond than the main micro-controller. A similar idea had already been discussed in [9] for a permanent magnet machine, and this paper extends this idea of using charging and discharging vectors to turn off an 90 kW induction machine drive in case of an fault. Some of the major differences and similarities to the article [9] has been listed below.

- [9] and this paper, both are trying to solve the same problem of over-voltage in the DC-link capacitor during an uncontrolled generation scenario. [9] is aiming to solve the problem for an electric drive with a permanent magnet synchronous machine, while in this paper induction machine is in focus. The difference in the considered electric machine also changes where the energy is consumed during the strategy, for [9] the energy transferred from the DC-link capacitor is burned in the stator windings of the permanent magnet machine. In this paper the rotor windings are the primary consumer of energy transferred from the DC-link capacitor.
- In this paper the proposed method not only stops the DC-link voltage from rising any further, but it has also the ability to discharge the DC-link voltage to a value of less than 60 V with a time of around 100ms (also seen in the measurements See Fig. 20). The reason is mostly in an induction machine the rotor flux linkage slowly dies out as the current also dies out in both the stator and rotor of the machine. While in [9] the primary goal was to halt the rising DC-link voltage but not to decrease it below 60 V.
- In both [9] and this paper the idea of using the charging and discharging vectors are the same. The patterns or the distribution in which they are used are different, the voltage vectors are optimized for an induction machine.

The strategy in detail, and the hardware implementation are explained in Section III and IV respectively.

II. CLASSICAL SAFE STATE DURING UNCONTROLLED GENERATION

Fig. 1 shows a schematic of a three phase electric drive system consisting of an electric machine, three phase inverter, DC-link capacitor and the battery. The three phase inverter provides the necessary voltage to the electric machine, to achieve the desired torque. There is also a relay or a connector between the DC link capacitor and the battery as shown in the figure. In case of a system failure like over-voltage or over-current in the DC side, this connector is opened and the battery is isolated from the inverter machine side. The battery disconnection unit is usually activated in the event of a crash, in this scenario the DC-link capacitor voltage is supposed to decrease to a safe value of 60V within 5s to avoid
any electrical shock risks as described in the United Nation Vehicle Regulation ECE R94 [10]. If the machine is in the regenerating mode, the current $i_{pm}$ would flow entirely into the DC-link capacitor. This creates a condition of uncontrolled DC-link voltage rise; the typical rate of voltage rise for the 90 kW induction machine considered in this paper is around 2 $V/\mu s$. By the time the main micro-controller realizes that there is an over-voltage in the DC link capacitor, the voltage in the DC-link capacitor would have already crossed the threshold and damaged the inverter. In this scenario the only alternative reaction possible is to either go into ASC or FW, this action is usually implemented on a CPLD chip which acts swiftly and commands the inverter to go into the safe state.

### A. Active short Circuit: ASC

Active short circuit (ASC) refers to the intentional action of shorting the input phases of an electric machine to reach a desired safe state. Fig. 2 shows the simulation result for a 90 kW induction machine during ASC. In the simulation the electric machine is initially ($t<0.3$) in a generating operating point (1000 rpm -100 Nm) with stator current of 300 A (rms). At $t=0.3$ sec the battery is disconnected creating a condition of uncontrolled generation, hence making the DC-link voltage to rise. A threshold of 355V is set for the DC-link voltage after which ASC is triggered. ASC is achieved by commanding either the upper three or lower three IGBTs to be turned on, making a short circuit between the phases of the machine. This creates high transient currents in the machine and would eventually settle down to zero, as soon as the flux in the rotor of the induction motor decays. Nevertheless the DC link voltage remains constant after the threshold and is isolated from the electric machine. The maximum transient peak current during ASC for the simulated operating point is 1390 A, this current increases with operating points with higher torque. The high stator current would destroy the inverter, and hence ASC is not the preferred safe state for induction machines.

### B. Freewheeling: FW

Fig. 3 shows the simulation of a induction machine drive when a transition from normal torque control to freewheeling occurs. As in the case of active short circuit, the electric machine is initially ($t<0.3$) in a generating operating mode. At $t = 0.3$ sec, the battery is disconnected creating a condition of uncontrolled generation, hence making the DC-link voltage to rise. A threshold of 355V is set for the DC-link voltage after which FW is triggered. All the switches of the inverter are turned off, this forces the current to flow back to the DC-link capacitor through the freewheeling diodes, until the current commutate at zero crossing. Detailed analysis are done in the paper [4].

Another alternative strategy is to directly turn-off all the switches in the inverter during a fault. When all the switches in the inverter are turned-off the currents in the machine continues to flow back to the DC-link capacitor through the freewheeling diodes, until the current commutate at zero crossing. Detailed analysis are done in the paper [4].

Using ASC to turn-off the system prevents any transient voltage peaks in the DC-link capacitor, however, it causes high currents to flow through the phases (Fig. 2), demanding high current-rating of the switching devices. FW can avoid these high currents but leads to a high transient voltage peak in the system (Fig. 3). However, the amplitude of this transient peak can be reduced by using a big DC-link capacitor or...
by choosing a high voltage rating switching device that can withstand the transient peak. Such over-dimensioning to cover these side-effects will lead to higher cost of the system.

Almost all the disadvantages from ASC and FW can be solved using soft transitioning strategies provided that the motive is to shutdown the system slowly and time is not a critical factor. An uncontrolled generation scenario with battery relay open creates a rising voltage with a slew rate of slope 2 V/μs. If an action must be taken before the inverter is damaged, a faster response is required from the controller. In this scenario the only alternative reaction possible today is to either go into ASC or FW, this action is usually implemented on a CPLD chip which acts swiftly and commands the Inverter to go into the post-fault state. In case the primary supply to the main controller fails, the CPLD chip and the gate driver circuits are provided with a redundant power supply that could still run during a fault situation. A new turn off strategy is proposed in this paper which can also be triggered from a CPLD, but with no over-current or over-voltage.

III. DESCRIPTION OF THE PROPOSED STRATEGY

At any given operating point of an electric machine, there is always some energy stored in the inductance of the machine. This energy can be manipulated to charge or discharge the energy in the DC link capacitor. In order to understand this, lets start with the basic equations of an induction machine.

A. Mathematical Model for an Induction Machine

The relationship between the stator phase currents and the applied voltage from the inverter can be explained by starting with the space vector model for an induction machine. An IRTF (Ideal rotating transformer) model derived for an induction machine in the stator reference frame is taken as basis for our analysis ([11]). The equations are explained with the following variables -

- \( u_s \) is the stator voltage vector.
- \( i_s \) and \( i_R \): are the stator current and rotor current vector.
- \( R_S \) and \( R_R \): are the stator winding resistance and rotor resistance respectively.
- \( \psi_s, \psi_M \) and \( \psi_R \): are the stator flux linkage, main flux linkage and the rotor flux linkage respectively.
- \( L_{\sigma S} \) and \( L_{\sigma R} \) are the stator leakage inductance and rotor leakage inductance respectively.
- \( L_M \) is the main inductance of the machine.
- \( i_\mu \) is the magnetizing current of the machine.

The voltage equations on the stator side are as follows -

\[
u_s = R_S i_s + \frac{d\psi_s}{dt}, \quad \psi_s = \psi_M + L_{\sigma S} i_s \tag{1}\]

The main flux linkage formulations based on the magnetizing current is as follows -

\[
i_\mu = \frac{\psi_M}{L_M} = i_s - i_R \tag{2}\]

The voltage equations on the rotor side is as follows -

\[
0 = -R_R i_R + \frac{d\psi_R}{dt} - j\omega_m \psi_R, \quad \psi_R = \psi_M - L_{\sigma R} i_R \tag{3}\]

Expanding the value of \( \psi_R \) in Eqn. 3

\[
\frac{d\psi_M}{dt} = R_R i_R + L_{\sigma R} \frac{di_R}{dt} + j\omega_m (\psi_M - L_{\sigma R} i_R) \tag{4}\]

Substituting the value of \( \psi_M \) from Eqn. 3 onto Eqn. 1 -

\[
u_s = R_S i_s + R_R i_R + L_{\sigma S} \frac{di_s}{dt} + L_{\sigma S} \frac{di_R}{dt} + j\omega_m \psi_M \tag{5}\]

Substituting the value of \( i_R \) from Eqn. 2 onto Eqn. 5 -

\[
u_s = R_S i_s + R_R i_R + (L_{\sigma R} + L_{\sigma S}) \frac{di_s}{dt} + j\omega_m \psi_M \tag{6}\]

Due to a high rotor time constant, the main flux linkage can be assumed to be constant \( \frac{di_s}{dt} \sim 0 \). Substituting in Eqn. 6

\[
u_s = R_S i_s + R_R i_R + L_{\sigma R} \frac{di_s}{dt} + j\omega_m \psi_M \tag{7}\]

The stator voltage is supplied from a standard three-phase inverter, the inverter can supply 6 nonzero voltage vectors and 2 zero vectors. The voltage vector is defined by the switching vector or switching state, this can be denoted using the gate status of the three bridges of the inverter. The switching state can be written as

\[
x = [S_a, S_b, S_c] \tag{8}\]

Where \( x \in [0, 1, 2, 3, 4, 5, 6] \), the phase voltages (referred to the star point) can be written as follows (taken from [12]).

\[
\begin{bmatrix}
 u_{an} \\
 u_{bn} \\
 u_{cn}
\end{bmatrix}
= \begin{bmatrix}
 2 & -1 & -1 \\
 -3 & 1 & -1 \\
 -1 & 2 & -1
\end{bmatrix}
\begin{bmatrix}
 S_a \\
 S_b \\
 S_c
\end{bmatrix} \tag{9}
\]

Assume a switching state \( S_1 = [100] \), as per Eqn. 9, the phase voltage can be written as

\[
u_{an} = \frac{2u_{dc}}{3}, \quad u_{bn} = -\frac{u_{dc}}{3}, \quad u_{cn} = -\frac{u_{dc}}{3}
\]

\[
\begin{bmatrix}
 u_\alpha \\
 u_\beta
\end{bmatrix}
= \begin{bmatrix}
 2 & -\frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \\
 0 & -\frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}}
\end{bmatrix}
\begin{bmatrix}
 u_{an} \\
 u_{bn} \\
 u_{cn}
\end{bmatrix} \tag{10}
\]

Using Eqn. 10, three-phase voltages are converted to the alpha beta axis, and from there the stator space vector is calculated.

\[
u_\alpha = \frac{2u_{dc}}{3}, \quad u_\beta = 0
\]

\[
u_s = u_\alpha + ju_\beta = \frac{2u_{dc}}{3}
\]

Applying \( u_s \) in equation 8

\[
\frac{di_a}{dt} = \frac{2u_{dc}}{3} - R_S i_s - R_R i_R + j\omega_m \psi_R \tag{11}
\]

Depending on the selected switching state of the inverter the stator current can be increased or decreased.
B. Mathematical Analysis - Impact of stator currents on the DC-link voltage

When the battery is disconnected, the impact of the current \( i_{pm} \) (show in Fig. 1) on the DC-link capacitor is very high, since there is no battery. The direction and amplitude of \( i_{pm} \) determines the rate at which the DC-link capacitor can charge or discharge. The dependency of \( i_{pm} \) on \( U_{dc} \) can be calculated using the expression.

\[
u_{dc} = u_{dc}^{init} + \frac{1}{C} \int i_{pm} dt \quad (12)
\]

The current \( i_{pm} \) is the current coming out of the power module or inverter on the DC side, this value depends on the switching vector and the position of the current vector at that instant. The current \( i_{pm} \) is calculated by applying a dot product of both the switching vector and the current vector.

\[
i_{pm} = \begin{bmatrix} S_a & 0 & 0 \\ 0 & S_b & 0 \\ 0 & 0 & S_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (13)
\]

Where \([S_a \ S_b \ S_c]\) represents the switching vector, and \([i_a \ i_b \ i_c]\) are the phase currents at that particular instant. For example, assume a switching vector \( SV = [1 \ 0 \ 1] \), which means in the first bridge and the third bridge the top IGBT is turned on, while on the second the lower IGBT is turned on. Assume an arbitrary stator current vector with phase currents of \( I_a = 100 \ A \ \ I_b = -75 \ A \ \ I_c = -25 \ A \). \( i_{pm} \) can be calculated as the following.

\[
i_{pm} = i_a * 1 + i_b * 0 + i_c * 1 = 100 * 1 + -75 * 0 + -25 * 1 = 75A
\]

hence creating a positive value of \( i_{pm} \). Consider another current vector with \( I_a = -100 \ A \ \ I_b = 75 \ A \ \ I_c = 25 \ A \), \( i_{pm} \) can be now calculated as -

\[
i_{pm} = i_a * 1 + i_b * 0 + i_c * 1 = -100 * 1 + 75 * 0 + 25 * 0 = -75A
\]

By choosing the correct switching vector based on the angle of the current vector, \( i_{pm} \) can be chosen to be either positive or negative. These characteristics can be used to manipulate the voltage across the DC-link capacitor.

Two vertically opposite current vectors are chosen, along with six possible non-zero voltage vectors of the inverter. The current \( i_{pm} \) is calculated using Eqn. 13 for each of the current voltage vector combination, the evaluated \( i_{pm} \) applied on Eqn. 12 gives the DC-link voltage rise or fall with respect to time (calculated for 10 \( \mu s \)). Fig. 4 and Fig. 5 shows the effect of different voltage vectors on the DC-link voltage for the two chosen current vectors respectively. On the left side are all the possible non-zero voltage vector possible for a three-phase inverter, and also shown is one of the chosen current vector in a phasor diagram. On the right is the calculated DC-link voltage change with respect to time for each of the chosen voltage vector. In both Fig. 4 and 5 (on the left), depicted is also a hypothetical zero charging line drawn perpendicular to the current vector, this line cuts the space vector plane into 2 regions. The first region which contains the chosen current vector, while the second region which does not contain the current vector. It can be observed from the right side of the figures that any voltage vector located in region 1 (containing the current vector) discharges the capacitor, while the rest of the voltage vectors lying on region 2 charges the capacitor, any voltage vector exactly on the zero charging line neither charges nor discharges the DC-link capacitor. For e.g. in Fig. 4, it can be observed that the voltage vectors \( SV = [100], [110], [101] \) discharges the DC-link capacitor, while the remaining voltage vectors charges the capacitor. In Fig. 5, since the chosen current vector is vertically opposite, hence the behaviour of the voltage vectors are also vice-versa than the first current vector. This is the foundation of the strategy and based on this theory further development and analysis of the method are explained.

C. Charging and Discharging vectors

Fig. 6 shows the equivalent circuit of the three phases of an electric machine with currents flowing at a particular time instant. Here \( L_{dc} \) represents the leakage inductance and \( u_i \) represents the back emf in the machine. For a given current direction or vector (Here \( i_a : +ve, \ i_b : -ve, \ i_c : -ve \)), there are always sets of voltage vectors which can charge or discharge
Fig. 5. Impact of current vector on the DC-link voltage - left: Current Vector 2 + all possible non-zero voltage vectors Right : DC-link voltage with respect to time for all possible non-zero voltage vectors applied

the capacitor. In Fig. 6, the inductance in the machine acts as a temporary current source which draws or pumps energy into the capacitor momentarily. The capacitor connected on the left side of the electric machine, where phase A is connected to $+U_{dc}/2$, while phase B and phase C is connected to $-U_{dc}/2$, this signifies a voltage vector of : $[1 \ 0 \ 0]$. The capacitor on the right side of the electric machine, where phase A is connected to $-U_{dc}/2$, while phase B and phase C is connected to $+U_{dc}/2$, this signifies a voltage vector $[0 \ 1 \ 1]$. The voltage vector configuration on the right side would charge the DC-link capacitor, while the configuration on the left side would discharge the DC-link capacitor. Since the inductance of the phase windings resists any change in the currents, $L\frac{di}{dt}$ forces the currents to flow towards or away from the capacitor, and also charge or discharge the capacitor. The currents in the electric machine would behave inversely to the DC-link voltage, that means discharging the capacitor, would mean an increase in the stator currents and also vice-versa. The exchange of energies between the electric machine and the DC-link capacitor can be described by the energy equation (16).

![Fig. 6. Charging and discharging the capacitor](image)

$$\Delta E_{cap} = \Delta E_{indLeak} + E_{shaft} - E_{res} \quad (16)$$

- $E_{cap}$: Energy stored in the capacitor
- $E_{indLeak}$: Energy stored in the leakage inductance
- $E_{shaft}$: Energy received or send depending on whether it is (mot\(\rightarrow\)gen)
- $E_{res}$: Energy dissipated as ohmic losses in the machine using a three-phase inverter shown in Fig. 1. 8 different voltage vectors can be applied to the machine. For each angle of the stator current ($i_{sttr}$) a voltage vector either with a positive or negative energy can be chosen, which then would charge or discharge the DC-link capacitor.

D. Charging and Discharging vectors on the phasor diagram

Fig. 7. Charging and Discharging vectors

Fig. 7 shows the current vector $i_{sttr}$ and the back-emf $u_i$ of an induction machine in the phasor diagram at the moment when the machine is operating in the generating mode. Also shown are the 6 possible non-zero voltage vectors (1 – 6)
in the $\alpha - \beta$ axis. The space vector area has been classified depending upon two different criteria.

- Operating point of the machine (Motoring\Generating)
  At this particular instant the back-emf of the machine $u_s$ lies at the $\beta$ axis, making the $\alpha - \beta$ axis coincide with the d-q axis. Therefore, the 1st and 2nd quadrants (rectangular brown area) represent the motoring region and the 3rd and 4th quadrant (rectangular blue area) represent the generating region.

- Charging and Discharging region - The area can also be classified into regions where the instantaneous power output from the inverter (Eq. 17) is either positive or negative depending on the position of the current vector. The green semi-circular region in Fig. 7 has a positive power output of the inverter, while the red semi-circular region has a negative power output. A positive power output means that the inverter is drawing energy from the DC side, that is the energy flow is from the DC link capacitor to the machine side, and vice-versa for negative power. Hence, any voltage vector selected on the positive power output region will discharge the capacitor, while the vectors selected on the red semi-circular region will charge the capacitor.

$$P_{inv} = u_s i_s$$  \hspace{1cm} (17)

The uncontrolled rise of DC link voltage during generating can be stopped by applying alternating discharging (DV) and charging (CV) vectors. Alternating DV and CV voltage vectors would make sure that both the DC-link voltage and stator currents are in the safe limits. The charging vector is chosen from the red semi-circular region, while the discharging vector is chosen from the green semi-circular region. Simulations showed that a stable combination of charging and discharging vector is voltage vector 3 and 6, with respect to the current vector $i_{inv}$ as shown in Fig. 7. All the other voltage vectors combination would change the amplitude and angle of the current vector very fast and it becomes more difficult to contain the current amplitude inside the band where it is safe for the device to operate. More details about the simulations are in subsection IV-C. The thumb rule used in this paper to identify the discharging vector is to find the voltage vector leading the current in the same sector, and the charging vector would be vertically opposite to the discharging vector. Applying these vectors sequentially for a finite number of steps will make the current vector rotate in the vector plane. This behaviour will cause the machine to oscillate between the motoring and generating region, hence dissipating the energy as mechanical output in the shaft and resistive losses in the phase windings. This strategy is termed as safe turn-off in this paper.

IV. IMPLEMENTATION

The strategy is tested on an induction motor drive for an electric vehicle. The electric drive unit consists of the housing with the three-phase inverter and the main micro-controller responsible for the functions of the electric drive, like torque control. The drive unit also has a CPLD chip (Complex Programmable Logic Device), which is a smaller controller with limited memory. The CPLD has a faster clock frequency, than the main controller, which makes it quicker to respond. Most of the fault detection checks and the fault reactions are programmed in the CPLD, and they talk directly to the gate driver of the power module. A fast reaction from the hardware is required, when the electric drive system is in a state of uncontrolled generation, so that the DC-link capacitor and the power module is not damaged. Hence, the strategy was programmed on a Complex Programmable Logic Device (CPLD) which reacts faster than the main micro-controller.

A. Current Vector Identification

![Current Vector Identification Diagram](Image)

For the proposed safe turn-off to work, it is essential that the position of the current vector is calculated correctly. The vector identification must be simple and robust. The method described here compares the instantaneous values of currents in three of the phases and estimates the current vector location inside a sector. Three comparators were used as shown in Fig. 8. The inputs to each of the comparators are connected to consecutive current sensors and gives the signals shown in Eq. (18).

$$si_1 = (i_1 > i_2)$$  \hspace{1cm} (18a)
$$si_2 = (i_2 > i_3)$$  \hspace{1cm} (18b)
$$si_3 = (i_3 > i_1)$$  \hspace{1cm} (18c)
$$si = [si_1 \ si_2 \ si_3]$$  \hspace{1cm} (18d)

Where $si_1, si_2$ and $si_3$ denote the output of the comparators shown in Fig. 8. $i_1, i_2$ and $i_3$ denote the instantaneous value of stator currents measured using current sensors. The expression $si$ in (18d) gives the location information of the current sector on the space vector plane. Consider Fig. (9), if $si = [1 0 0]$ then the location of the current vector will...
be in the sector highlighted red in the figure. Using this information an approximate position of the current vector can be calculated and hence calculate the correct charging and discharging vectors.

![Current sector identification](image)

Fig. 9. Current sector identification

### B. Fault reaction algorithm

A voltage-divider circuit combined with a comparator is used to create an over-voltage detection mechanism, this creates an over-voltage flag for the DC-link voltage. Whenever the DC-link voltage is above the threshold, a flag is sent to the CPLD to commence the start of the strategy. The over-voltage flag along with the output from the current comparators to estimate the current vector location serve as an input to the CPLD. The discharging and charging vectors are then calculated from the current vector location. As described in section III-C, the discharging vector is the voltage vector leading the current in the same sector, and the charging vector would be vertically opposite to the discharging vector. The identified vectors are then applied sequentially for a finite number of PWM periods. A PWM period consists of a discharging period and a charging period, a ratio $\frac{DV}{CV}$ is calculated which determines if the overall voltage gradient is positive or negative in the DC-link capacitor. When switching frequency in the inverter is 10kHz, the length of 1 time period is $100\mu s$. If the ratio $\frac{DV}{CV}$ is 80:20, in the first $80\mu s$ discharging voltage vector is applied and for the last $20\mu s$ charging vector is applied. Using this ratio as a control parameter and the feedback from the over-voltage flag, the DC-link voltage is controlled to a constant value.

![Fault reaction algorithm](image)

Fig. 10. Safe turn-off during battery disconnection: Proposed Algorithm

The safe turn-off strategy is split into 2 stages. In the first stage and the second stage, the ratio $\frac{DV}{CV}$ is chosen so that, the DC-link voltage gradient is negative and positive respectively. When the controller receives an over-voltage flag, stage 1 is initiated for a finite number of PWM periods ($n_1$). During stage 1, The dc-link voltage decreases to a value smaller than the voltage threshold. After $n_1$ number of PWM periods, stage 2 is initiated and continued until there is an over-voltage flag or $n_2$ number of PWM periods. Due to a positive voltage gradient, the DC-link voltage would increase back to the value of the threshold. This discharging and charging behaviour of the strategy will maintain the voltage under the voltage limit as shown in Fig. 10. In this figure, in stage 1 the $\frac{DV}{CV}$ ratio was set to 80:20, and later in stage 2 the $\frac{DV}{CV}$ ratio was set back to 20:80. A state machine diagram is shown in Fig. 11 which explains the conditions on which the transitions between stage1, stage2 and finally to the classic safe states are performed. The proposed strategy acts like an intermediate step which helps to avoid any over-currents or
over-voltages which happens when directly going to any of the classic safe states. If there was a DC-link voltage sensor, instead of the comparator with voltage divider circuit, the DC-link voltage could be controlled with more accuracy. The idea of the two stages is to save the cost of such a sensor, which should also be reliable when the fault happens.

C. Simulation Results

Safe turn-off was simulated in a MATLAB Simulink model for a 90kW induction machine drive over the entire torque speed map. The simulation model consists of a dq model of the induction machine, a three-phase Inverter source, and a controller. The safe turn-off algorithm is programmed in the inverter module which activates when there is an over voltage fault. Using the model, the DV:CV ratio and n1 was varied and optimized for minimum stator current and DC-link over-voltage using iterative simulations. One of the best combination of possible DV:CV ratio and n1 are given in Table. I. Fig. 12 shows the output from the simulation at 1000rpm and -100Nm using the chosen ratio. In Fig.12, the battery was disconnected at \( t = 0.3 \), the DC-link voltage increases because of the uncontrolled generating mode. The safe turn-off strategy commences when the DC-link voltage reaches the threshold of 355V. The DC-link voltage charges and discharges after every PWM cycle, maintaining the voltage under the threshold as expected.

| Stage1   | Stage2   |
|----------|----------|
| DV:CV 80:20 | DV:CV 20:80 |
| \( n1 = 2 \) | \( n2 = 20 \) |

**TABLE I**

OPTIMIZED PARAMETERS FOR SAFE TURN-OFF

V. LOSS MODELING

The simulations in section IV-C are done using a dq fundamental model of the induction machine which doesn’t consider any high frequency losses in the machine, also the inverter losses in the model were also ignored. The DC link voltage calculation in the simulation model is done using the current \( i_{pm} \) going into the inverter as described in [4]. The current \( i_{pm} \) should reflect all the losses in the electric drive system, so that the DC-link voltage is calculated accurately. In this section two major losses are going to be considered so that the described simulation model is closer to the reality.

- Inverter Losses : Conduction Losses + Switching Losses
- High frequency conduction losses in the rotor bars of the induction machine

A. Inverter Losses

Not all the DC power entering the inverter ends up on the other AC side, there are losses dissipating in the IGBTs as both conduction and switching losses. These losses must be calculated and included in the simulation so that the input DC power is calculated correctly, and hence also the voltage across the capacitor. In this analysis, the losses occurring across the capacitor are neglected.

**Conduction Loss:** Depending on the direction of the current flow and the voltage vector applied, it can be determined if the current flows through the diode or the IGBT. With this information the conduction losses of each bridge can be calculated as in Eq. 19.

\[
P_{\text{cond}} = \begin{cases} 
U_{cei}, & \text{if current flows through IGBT} \\
U_{fwi}, & \text{if current flows through diode}
\end{cases} \quad (19)
\]

Both \( U_{ce} \) (Collector Emitter voltage of the IGBT) and \( U_{fw} \) (Forward voltage of the diode) are obtained from the data sheet of the switching device.

**Switching Loss:** The data sheet of the IGBT power module provides the following information about its switching characteristics:
- $E_{\text{on} \_ \text{IGBT}}$, $E_{\text{off} \_ \text{IGBT}}$: Energy consumed during turn-on and turn-off for the IGBT
- $E_{\text{off} \_ \text{diode}}$: Energy consumed during turn-off of the diode

![Diagram](image)

Fig. 13. Definition of $f_{\text{g}_r}$ and $f_{\text{g}_f}$

Fig. 13 defines two flags $f_{\text{g}_r}$ and $f_{\text{g}_f}$ which are set when the voltage output ($U_{\text{out}}$) of the bridge is either rising or falling respectively, these variables are updated throughout the simulation process and are used to calculate the switching losses. Table II explains which device is conducting during either a voltage rise or voltage fall in a single bridge of the inverter. Based on these conditions and using the information from the data sheet, the expression to calculate the switching losses have been summed up in Eq. 20.

| $U_{\text{out}}$ | $i_{\text{g}_r}$ | $i_{\text{g}_f}$ |
|-----------------|---------------|-----------------|
| Rising          | High side IGBT turned on | Low side IGBT turned off |
| Falling         | High side IGBT turned off | High side IGBT turned on |

| $P_{\text{switch}}$ | $E_{\text{on} \_ \text{IGBT}} + E_{\text{off} \_ \text{diode}}$ | $E_{\text{off} \_ \text{diode}} + E_{\text{on} \_ \text{IGBT}}$ |
|---------------------|------------------------------------------------|------------------------------------------------|
| $i_{\text{g}_r} > 0$ | $f_{\text{g}_r}$ | $f_{\text{g}_f}$, if $i_{\text{g}_r} > 0$ |
| $i_{\text{g}_r} < 0$ | $f_{\text{g}_r}$ | $f_{\text{g}_f}$, if $i_{\text{g}_r} < 0$ |

Eq. 22 calculates the depth where the current will flow depending on the frequency of the applied currents on the rotor bars. In [14] a parameter $\xi = h/\delta$ is defined, where $h$ is the height of the rotor bar and $\delta$ is the skin depth. This factor is used to calculate the frequency dependence of the rotor resistance and rotor inductance, and is shown in 23.

$$\delta = \sqrt{\frac{\rho}{\pi f \mu_0}} \quad (22)$$

In Eq. 23 both $K_r$ and $K_x$ are the correction factors depending on the frequency which is multiplied with the dc values of $R_r$ and $L_r$. Figure 15 shows the increase in rotor bar resistance and the decrease in the rotor leakage inductance with frequency. This change in the parameter needs to be incorporated into the dq model in time domain so that the high frequency losses are correctly calculated. Eq. 24 shows the frequency dependent resistance and inductance derived from the DC values using the correction factors.

$$R_{ac} = K_r R_{dc} \quad (24a)$$

$$L_{ac} = K_x L_{dc} \quad (24b)$$

B. High Frequency losses in the rotor

Fig. 14 shows the FFT of the stator currents during safe turn-off. During STO the currents are no longer normal sinusoidal signals, instead they consist of higher order harmonics (1 kHz and above) which are well beyond the fundamental frequency of the stator currents. This creates high frequency losses in the machine, which are mainly high copper losses in the rotor due to deep bar effects or skin effect in the rotor slots. Due to the higher current harmonics seen in Fig. 14, it can be assumed that the stator flux directly interacts with the rotor bar with a slip equal to 1, this will induce high frequency currents in the rotor bars. These high frequency currents in the rotor bar will force the current to flow only through a small portion of the bar (skin effect), this increases the effective resistance of the rotor bar and also the losses. This frequency dependent characteristics of the rotor resistance needs to be in-cooperated into the simulation model, so that the high frequency conduction losses can be accurately estimated.

$$K_r = \xi \left( \frac{\sin(2\xi) + \sin(2\xi)}{\cosh(2\xi) - \cos(2\xi)} \right) \quad (23a)$$

$$K_x = \xi \left( \frac{\sin(2\xi) - \sin(2\xi)}{\cosh(2\xi) - \cos(2\xi)} \right) \quad (23b)$$

$\xi$ is defined, where $h$ is the height of the rotor bar and $\delta$ is the skin depth. This factor is used to calculate the frequency dependence of the rotor resistance and rotor inductance, and is shown in 23.

C. RL-ladder circuit

The next step is to achieve a frequency dependent rotor resistance time domain model, which is simple enough to yield reasonable simulation times. The impedance-frequency characteristics of rotor conductor can be modelled using
This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TTE.2021.3104461, IEEE Transactions on Transportation Electrification

Fig. 15. Rotor bar resistance and reactance correction factors

simple networks of resistances and inductances as explained in [17]. There are several publications which use this method to simulate the dynamic model of induction machine with skin effect ([18],[16],[15]). In this paper the frequency dependent resistance is modelled by using an R-L lattice circuit as illustrated in the dissertation in [13]. The rotor bar can be assumed to be divided into different sections as shown in Fig. 16 and each section can be represented as a resistance along with a leakage inductance in the RL-ladder circuit. This allows to have non-uniform current density in a single rotor bar. Since the current density is higher at the top of the bar, it makes more sense that the height of the section is smallest at the top of the rotor bar and slowly increasing to the bottom. Fig. 16 shows the RL-ladder circuit which replaces $R_{r}$ (rotor resistance) in the dq equivalent circuit used in the simulation model. This RL-ladder circuit makes the lower frequency components to flow through the farthest resistance, while the high frequency components will flow through the nearer resistances. The values of resistances and inductances in the ladder circuit must be tuned to match the real frequency dependent rotor bar resistance. The total resistance and reactance of the ladder circuit is calculated by representing the circuit using state space equations. Followed by this, the RL-ladder circuit is transformed into the Laplace domain, through which the frequency dependent resistance and reactance of the circuit can be calculated. The step-by-step procedure is explained in [13] and won’t be explained further in this paper. The final model impedance of the ladder circuit can be written as in Eq. 25.

$$\dot{X} = AX + BU \quad (25a)$$
$$y = CX + DU \quad (25b)$$

$$Z(s) = \frac{1}{C(SI - A)^{-1}B + D} \quad (25c)$$

With $S = 2\pi f$

$$Z(jw) = R_{t} + jX_{t} \quad (26)$$

Where $R_{t}$ and $X_{t}$ are the frequency dependent total resistance and reactance of the ladder circuit. Each RL group in the ladder circuit (Fig. 16 : $R_{i}, L_{i}$) can be represented as a section in the rotor bar with its own resistance and inductance written as in Eq. 27.

$$R_{i} = \frac{\rho l}{d_{i}w_{k}} \quad (27a)$$
$$L_{i} = \mu_{0}d_{i}^{2}w_{k} \quad (27b)$$

$$\sum_{i=1}^{5} d_{i} = h \quad (28)$$

In Eq. 27 $w_{k}$ denotes the width of the slot and $d_{i}$ represents the height of the ith section of the rotor bar. This resistance and inductance represent one RL group in the ladder network. A total of 5 layer or RL group ladder networks is considered in the model to include the skin effect losses. A parameter search is performed on the RL ladder network by keeping the frequency dependent characteristics of $R_{ac}, L_{ac}$ from Eq. 24 as reference. The optimum parameters for the ladder circuit are searched which holds the criteria in Eq. 28, these criteria makes sure that the total height of the rotor bar remains constant. An optimization run in MATLAB is performed using fminsearch which minimizes the normalized objective function mentioned in Eq. 29.

$$\varepsilon_{r} = \left( \frac{R_{ac} - R_{t}}{R_{ac}} \right)^{2} \quad (29a)$$
$$\varepsilon_{l} = \left( \frac{L_{ac} - L_{t}}{L_{ac}} \right)^{2} \quad (29b)$$

Fig. 17 shows the result from the optimization algorithm, the RL ladder circuit has the expected frequency dependent resistance characteristics. This optimized RL-ladder circuit is replaced in the dq circuit for rotor resistance $R_{r}$ of the induction machine. This new model would be used to compare with the measurements done in Section. VI.
VI. MEASUREMENTS AND ANALYSIS

A. Measurement setup

The measurement setup consists of a 90kW induction machine coupled to a load machine, the inverter unit, battery emulator and a mechanical disconnect unit between the battery and the inverter unit. The inverter unit consists of the power module, gate drive circuits, micro-controller unit, DC-link capacitor and also the bus-bars on both the AC and DC side. The specification of the measurement setup are shown in Table III. The measurement setup is shown in Fig. 18, the inverter casing is open to tap out gate signals to the inverter. The micro-controller unit is responsible for the main functionality of the system like torque control of the system. The safe turn-off strategy has been programmed in a CPLD, which is a programmable logic device and can function immediately on start-up. All the commands which are time critical are done here. Three comparators to determine the phase current sector have been added to the inverter unit and this output was connected to the CPLD. The output from the CPLD interacts directly with the gate driver of the IGBT of the inverter. The DC-link voltage was set to 180 V and the voltage threshold for the commencement of the strategy was set to 356V, this provides a buffer for the inverter to operate under a safe operating voltage. The PWM duty cycle during safe turn-off has been chosen with a DV/CV ratio of 20/80 (Positive gradient) in stage1 with n1=6, and DV/CV ratio of 30/7 in stage2 (Positive gradient). The ratio is chosen so that the capacitor does more charging than discharging and hence an overall positive gradient of voltage is expected. The DC voltage was provided by a battery emulator which provides the voltage for the system. A mechanical switch was connected in between the battery and DC-link capacitor which is used as the disconnect unit. Measurements were done for different operating points and the results were compared with simulation results.

![Fig. 17. Optimization of the RL ladder parameters to fit the analytical expression](image)

![Fig. 18. Measurement Setup](image)

| Nominal DC-link Voltage | 350V |
|-------------------------|------|
| Nominal Phase Current   | 380 A (rms) |
| Rated Power             | 90 kW |
| Switching Frequency     | 10 kHz |
| Modulation technique    | SVPWM |
| Coolant Flow            | 10 lpm |

**TABLE III**

SPECIFICATION OF THE MEASUREMENT SYSTEM

B. Analysis and Discussion

Fig. 19 shows the comparison between measurement and the simulation of the operating point at 1000rpm -100Nm with no loss model (skin effect in the rotor bar + Inverter losses excluded). At t=0.28, the battery is disconnected, creating a condition of uncontrolled generation in the DC-link capacitor. In the simulation model, the DC-link voltage is rising up after it reaches the threshold of 356V because of a chosen positive gradient ratio selection for DV:CV, While the DC-link voltage in the measurement is falling down after the voltage reaches the threshold. In Fig. 20 the same comparison is made with the measurements, but now the simulation model with the extra losses (Extra copper loss due to skin effect + Inverter losses) is used. The comparison in Fig. 20 shows that the simulation and measurement matches very well, and prove that the calculation of the extra losses in the inverter and the high frequency losses in the rotor bar is vital for accurate simulation of the DC link voltage. The characteristic exponentially decaying dc link voltage in the simulation proves that skin effect is one of the major reasons behind this behaviour. Higher frequency of stator current increases the high frequency losses in the induction machine and hence skin...
effect acts like a positive reinforcement for the safe turn-off strategy. The important takeaway from the above comparison is that the energy exchange between the DC-link capacitor and the inductance of the machine is comparatively less than the energy dissipated in the rotor windings of the induction machine. This is the reason why a positive gradient $DV:CV$ ratio still creates a drop in the DC-link voltage. Fig. 21 shows the torque characteristics during safe turn off at 1000 rpm -100 Nm, no unwanted or dangerous torques are produced at this operating point. Fig. 22 shows the comparison between results from the loss inclusive simulation model and measurements at 3000 rpm and -100 Nm. The safe turn off strategy has been successfully validated using measurements. Experimental comparison with active short circuit measurements for the same operating points were not carried out, as the currents are too high (simulated in section II-A : 1390A) and it could potentially damage the inverter. The peak currents at the same operating point in the measurement for safe turn off strategy is way smaller than shown in measurements in both the operating points. Measurements for FW are also done in the paper [4] with the induction machine, in FW a DC-link transient voltage peak is inevitable and always higher than the DC-link voltage during safe turn off. Results in Table. IV shows the comparison between the turn off strategies ASC, FW and the
proposed safe turn off strategy @1000 rpm -100 Nm. With the proposed strategy the post fault currents are smaller than the ASC current of 1380A, also the DC link voltage always stays inside the threshold of 356V which is smaller than the DC link voltage peak in FW. Fig. 23 shows the various steps that was followed in this publication to develop the strategy. This workflow will evolve once different power class machines and inverter are analysed and setup as part of future works.

VII. CONCLUSION

A method to safely turn off an electric drive without a transient peak in the DC link capacitor and low stator currents has been proposed. In this method, the energy between the inductance of the machine and the DC-link capacitor are transferred by applying charging and discharging voltage vectors based on the location of the current vector. During the strategy the frequency of the stator currents were observed to be very high compared to the fundamental, this increases the skin effect in the rotor bars of the machine and correspondingly more resistance in the rotor bar. This higher rotor resistance increases the energy dissipation, and hence quickly discharging the DC-link capacitor faster. The strategy was tested using a simulation model in MATLAB simulink. The major losses, like the inverter losses and the rotor ohmic losses, were incorporated into the simulation model. The algorithm was realized in a CPLD which can directly control the gate driver of the IGBTs in a standard three-phase inverter and the measurements were done with an induction machine drive. The results showed no transient peak in the DC link capacitor and less stator currents, hence validating the strategy. Using this turn-off method in an electric drive system, causes less stress on the DC-link capacitor, IGBTs and the electric machine. Hence, requiring a smaller DC-link capacitor, IGBTs with lower voltage rating and electric machine with lower current rating, thereby reducing the cost of the overall system.

TABLE IV

| ASC (Simulations) | FW (Simulations) | STO (Measurements) |
|-------------------|------------------|--------------------|
| Peak $i_{thm}$ = 1390 A | $\Delta U_{dc}$ = 30 V | Peak $i_{ rated}$ = 603 A |
| No transient DC-link voltage Peaks, but high stator current overshoots | Transient DC-link voltage Peaks with no stator current overshoots | No stator current overshoots and transient DC-link voltage Peaks |
| Higher currents leads to torque overshoots | No current overshoots and hence no torque overshoots | Small ringing effect in the torque as seen in Fig. 21 |
| Can be implemented in a CPLD without any current vector location | Can be implemented in a CPLD without any current vector location | Can be implemented in a CPLD with current location information using comparators |

REFERENCES

[1] B. A. Welchko, T. M. Jahns, W. L. Soong and J. M. Nagashima, “IPM synchronous machine drive response to symmetrical and asymmetrical short circuit faults,” in IEEE Transactions on Energy Conversion, vol. 18, no. 2, pp. 291-298, June 2003.

Step1: Set up a system simulation model with the machine equations specified in Section III-A using the electric machine parameters in question. Also, set up the DC-link voltage calculation using the equations in Section III-B to consider the effect of the current $i_{pm}$ on $U_{dc}$.

Step2: In the system simulation model, add models for inverter losses based on the power module used as described in Section V-A. The machine model in step 1 must be adapted with a ladder circuit to include skin effect which is mentioned in the Section V-C.

Step3: Calculate the max DC-link voltage that the inverter can handle using data sheets of the power modules. Design a voltage-divider circuit combined with a comparator which would set a flag when the threshold voltage is reached. Prepare also the three comparators (Section IV-A) in hardware with which the location of the current sector can be identified.

Step4: Simulate the uncontrolled generation scenario with the battery disconnected and apply the strategy safe turn-off strategy in simulation. Use n1,n2 and the charging discharging ratio values as specified in the measurement (Section VI). These parameters can only be taken as an initial guess and fine tune the parameters to find the value which yields a stable DC link voltage discharge.

Step5: Once the algorithm is proven stable in simulations, implement the strategy in hardware and do measurements to validate the simulations.

[2] T. M. Jahns and V. Caliskan, "Uncontrolled generator operation of interior PM synchronous machines following high-speed inverter shutdown,” in IEEE Transactions on Industry Applications, vol. 35, no. 6, pp. 1347-1357, Nov.-Dec. 1999.

[3] Chong-Zhi Liaw, W. L. Soong, B. A. Welchko and N. Ertugrul, "Uncontrolled generation in interior permanent-magnet Machines," in IEEE Transactions on Industry Applications, vol. 41, no. 4, pp. 945-954, July-Aug. 2005.

[4] Aravind Ramesh Chandran, M. Hennen and A. Arkkio, "Analytical investigation of DC link overvoltages during freewheeling for inverters in EV,” 2016 IEEE Transportation Electrification Conference and Expo (ITEC), Dearborn, MI, 2016, pp. 1-6.

[5] B. A. Welchko, T. M. Jahns and S. Hiti, "IPM synchronous machine drive response to a single-phase open circuit fault," APEC 2001. Sixteenth Annual IEEE Applied Power Electronics Conference and Exposition (Cat. No.01CH37181), Anaheim, CA, USA, 2001, pp. 421-427 vol.1.

[6] K. Lu, Y. Zhu , Z. Wu, and M. Xiao, "Suppression of Current Fluctuations and the Brake Torque for PMSM Shutoff in Electric Vehicles,” Mathematical Problems in Engineering - Hindawi Volume 2019, https://doi.org/10.1155/2019/5026316

[7] M. Merkel, T. Merkel, G. Plapp, A. König, L. Xie, "Vorrichtung und Verfahren zum Betreiben einer elektrischen Maschine,” Deutsches Patent und Markenamt, 102013226564, Jun. 25, 2015

[8] Z. Ke, J. Zhang and M. W. Degner, "DC bus capacitor discharge of permanent magnet synchronous machine drive systems for hybrid electric vehicles,” 2016 IEEE Applied Power Electronics Conference and Exposition (APEC), Long Beach, CA, 2016, pp. 241-246. doi: 10.1109/APEC.2016.7467879

[9] J. i. Itoh, W. Aoki, G. T. Chiang and A. Toba, "Suppression method of rising DC voltage for the hyst cycle sequence of an inverter in the motor regeneration,” 2013 IEEE Energy Conversion Congress and Exposition,
[10] J. Itoh, W. Aoki, G. T. Chiang and A. Toba, "United Nation Economic Commission for Europe Vehicle Regulation", No.94 (ECE R94), Uniform provisions concerning the approval of vehicles with regard to the protection of the occupants in the event of a frontal collision, Rev. 2, Annex 11, Aug. 2013

[11] De Doncker, R., Pulle, W.J. and Veltman, A. (2011) Advanced Electrical Drives. London: Springer

[12] Stefanos N. Manias, 6 - Inverters (DC–AC Converters), (2017) Power Electronics and Motor Drive Systems. Academic Press, Pages 271-500, ISBN 9780128117989, https://doi.org/10.1016/B978-0-12-811798-9.00006-8.

[13] O. I. Okoro "Dynamic and Thermal Modelling of Induction Machine with Non-Linear Effects," PhD thesis, Kassel University, 2002

[14] Alger, P. L "The nature of induction machines", Gordon and Breach, London, 1965

[15] E. A. Klingshirn and H. E. Jordan, "Simulation of Polyphase Induction Machines with Deep Rotor Bars," in IEEE Transactions on Power Apparatus and Systems, vol. PAS-89, no. 6, pp. 1038-1043, July 1970.

[16] D. Lin and P. Zhou, “An improved dynamic model for the simulation of three-phase induction motors with deep rotor bars,” 2008 International Conference on Electrical Machines and Systems, Wuhan, 2008, pp. 3810-3814.

[17] D. S. Babb and J. E. Williams, "Network analysis of A-C machine conductors," in Transactions of the American Institute of Electrical Engineers, vol. 70, no. 2, pp. 2001-2005, July 1951. doi: 10.1109/T-AIEE.1951.5060665

[18] W. Levy, C. F. Landy and M. D. McCulloch, “Improved models for the simulation of deep bar induction motors,” in IEEE Transactions on Energy Conversion, vol. 5, no. 2, pp. 393-400, Jun 1990. doi: 10.1109/60.107238