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Full Length Article

# Comparison of DC link current and stator phase current in inverter switching faults detection of PMSM drives in HEVs

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ABSTRACT

In this paper, a robust method for detection of inverter short circuit faults in field oriented control (FOC) of permanent magnet synchronous motor (PMSM) drive that is used frequently in hybrid electric vehicles (HEV) thanks to high power density and high efficiency is introduced. In the proposed method, a fault diagnostic and protection technique is developed by using discrete wavelet transform (DWT) and artificial neural network (ANN). The Symlet2 wavelet is selected to perform stator current analysis and the DWT coefficients of the motor currents are used as inputs of ANN for detecting inverter faults in PMSM drives. In HEVs, motor faults can cause permanent damage and accidents. So the early detection of PMSM drive faults in HEV will be provided by the proposed method. For implementing this method, the Matlab program is used to process DWT of signals. DC link and phase currents are compared in inverter switch faults detection and the results show that the proposed technique is very effective for fault diagnostic.



## 1. Introduction

The permanent magnet synchronous motor (PMSM) is frequently preferred for hybrid electric vehicle (HEV) propulsion thanks to its high power density and high efficiency. In a HEV application, parameters of the PMSM must be selected carefully in order to minimize losses and PMSM must operate at varying loads and speeds. However, electrical losses are minimized by control action in PMSM. The minimization of losses in the PMSM will minimize the current from the dc source [1,2].

In HEV the speed and position control of PMSM drive is required for power management, which determines when internal combustion engine or electric motor will operate, so field oriented control (FOC) which is a kind of vector control, is necessary for HEV. The other important subject is the faults of three phase inverter fed PMSM drive. The most common failures in motor drives are open-circuit faults and short-circuit faults in the inverter. If an open circuit fault happens in an IGBT switch, unstable oscillation occurs [3]. Also if there is a short circuit fault in an IGBT switch, the short circuit current signals exhibit more fluctuation than open circuit current signals. Between these faults, the most serious one is short circuit faults for PMSM drives in HEVs. Because current through IGBT increases rapidly until it saturates and also the gate signal of other switch in the same inverter leg must be turned off immediately because of connection to the DC bus so the IGBT can be destroyed and cause catastrophic failures and permanent magnet can weak if this fault is not continuously monitored and detected early [4–6]. So condition monitoring and the early detection of these faults for PMSM drives in HEVs are very important for protection, control, safety and cost-effective maintenance. By diagnosing the electric motor faults quickly, the life cycle of the electric motor in HEV can be extended [7–9].

Operating conditions of the IGBT switches used in the inverter circuit vary widely so they increase complexity of fault detection and diagnose system for PMSM drives in HEV. For this reason, detecting the faults in inverter fed AC drives has become a research topic. One of these methods is based on artificial intelligence (AI) which is not appropriate for real time analysis with its complex structure. The other developed method is based on comparison of actual and reference voltages by using extra sensors so it increases costs and complexity of the system. The standard digital signal processing based techniques such as discrete Fourier transform (DFT), fast Fourier transform (FFT) are used for condition monitoring and fault diagnostic of motors but these techniques can be implemented separately in time and frequency domains. In the standard digital signal processing techniques, fault currents

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are often non-periodic and non-stationary so performance of these techniques is limited according to the constraint on the window size. Therefore, the advanced digital signal processing based techniques such as discrete wavelet transform (DWT) is required. Because they can be applied together in time and frequency domains which extend the window size [9–14]. Sometimes according to the DWT coefficients, more than one switches in the inverter can appear faulty although one of them is faulty. So this problem can be solved by artificial neural network (ANN) since it is very efficient in the field of classification. The potential benefits of ANN extend beyond the high computation rates provided by massive parallelism of the networks. In additionally, adaptation and continuous learning are parts of an ANN. These properties are very important for nonlinear processes. Therefore, ANN is required for discriminating the healthy switches from the others.

In this study, a robust method is developed to ensure high reliability for detecting short circuit faults by using DWT and ANN. DWT the six level wavelet packet transformed coefficients of both DC link current and stator phase currents are used as inputs of ANN for detecting the failure switch which causes short circuit fault. ANN is used to classify the results. Monitoring the stator current signal of inverter fed PMSM drives is enough for protection purposes. Any other sensors are not required in the proposed PMSM drive for fault diagnosis and this is one of the most used methods for applications.

In the most of the studies, either DC link current or stator phase currents were investigated but in this study both of them are analyzed and compared with each other. The results demonstrate that the proposed method has great capabilities. Also the analyses of DC link current and stator phase currents show that they have some advantages against each other's.

## 2. Field oriented control of PMSM in hybrid electric vehicles

Nowadays PMSMs are frequently used in HEVs thanks to their structure, high efficiency and robustness. In recent years torque ripples and harmonics in PMSM have been tried to reduce. There are two popular ways for inverter control. One of them is voltage control such as space vector modulation and the other one is current control such as hysteresis and delta modulation [15,16]. Since important improvements have been made regarding the control techniques, especially the FOC with its flux/torque decoupling feature has no better alternative in PMSM drives. FOC which is preferred instead of scalar control especially in high speed range, is one of the vector control methods. The goal of FOC is to control torque variations demand in HEVs and mechanical speed. Also the aim of FOC is to regulate stator phase currents in order to prevent current spikes during transient phases [17,18]. In HEVs when both position and speed control are required for power management, vector control by DSP is implemented. The FOC is implemented successfully in order to force the motor to track the command trajectory in spite of motor load variations [19]. In this control method, stator phase currents are controlled in synchronous *d-q* frame in order to reduce torque ripple for quieter motor operation.

In FOC, two phase equivalent circuit in *d-q* frame and $\alpha$–$\beta$ frame are used instead of three phase circuit in order to analyze PMSM drives easily. For this purpose, *abc* to $\alpha\beta$ (Clarke) and $\alpha\beta$ to *dq* (Park) transformations are used widely. FOC block diagram of PMSM drives in HEV is shown in the Fig. 1. In this control method, while *d*-axis stator current controls flux linkage directly, *q*-axis stator current controls torque. For controlling the current, flux and torque, a compact and reliable motor model is required. The AC motor analysis techniques can also be used for PMSM in high performance electric vehicles [20]. Mathematical model of the PMSM with the electrical and mechanical equations in *d-q* frame is given as follows [21,22]:

$$\frac{di_d}{dt} = \frac{1}{L_d}(V_d - R_s i_d + \omega_r L_q i_q) \tag{1}$$

$$\frac{di_q}{dt} = \frac{1}{L_q}[V_q - r_s i_q - \omega_r(L_d i_d + \Psi_m)] \tag{2}$$

$$\psi_d = L_d i_d + \psi_m \tag{3}$$

$$\psi_q = L_q i_q \tag{4}$$

$$\frac{d\omega_{rm}}{dt} = \frac{1}{J}(T_e - T_L - B\omega_{rm}) \tag{5}$$

$$\omega_r = \frac{p}{2}\omega_{rm} \tag{6}$$

$$\frac{d\theta_r}{dt} = \omega_r \tag{7}$$

The electromagnetic torque $T_e$ is given by:

$$T_e = \frac{3}{2}p[\Psi_m i_q + (L_d - L_q)i_d i_q] \tag{8}$$

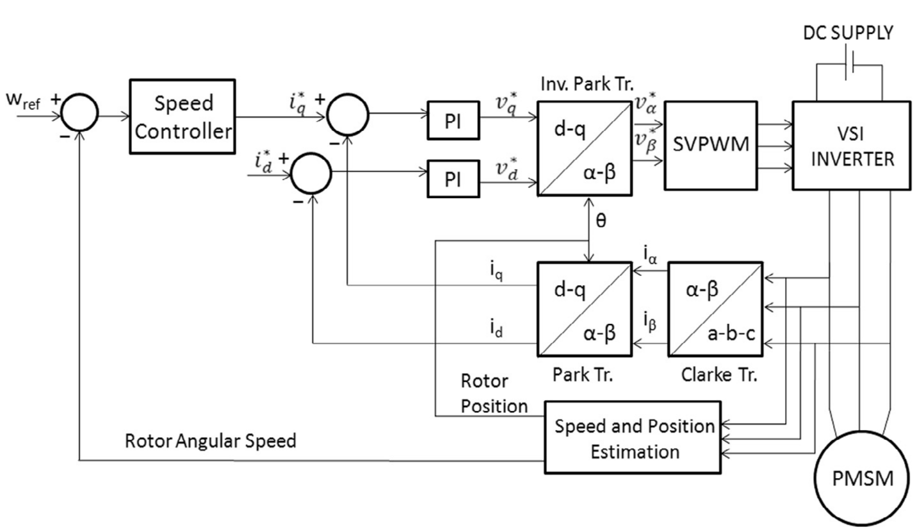


**Fig. 1.** FOC block diagram of PMSM in HEVs.

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