A Novel Method for Inverter Faults Detection and Diagnosis in PMSM Drives of HEVs based on Discrete Wavelet Transform

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***Abstract*—The paper proposes a novel method, based on wavelet decomposition, for detection and diagnosis of faults (switch short-circuits and switch open-circuits) in the driving systems with Field Oriented Controlled Permanent Magnet Synchronous Motors (PMSM) of Hybrid Electric Vehicles. The fault behaviour of the analyzed system was simulated by Matlab/SIMULINK R2010a. The stator currents during transients were analysed up to the sixth level detail wavelet decomposition by Symlet2 wavelet. The results prove that the proposed fault diagnosis system have very good capabilities.**

***Index Terms*—Discrete Wavelet Transforms, Wavelet Packets, Fault Diagnosis, Electric Vehicles, Permanent Magnet Motors.**

I. Introduction

The growing interest in Electric Vehicles (EV) comes from the early 1990s, induced by rising fuel prices, high economic dependence between nations and strong climate impact due to several pollutant emissions from the traditional transport.

PMSM drives become a very attractive option for various industrial applications because of their good efficiency, high power density, efficient heat dissipation; simple control concept [1-8]. This type of drive is preferred also for special areas such as aerospace and automotive applications, where high reliability is a very important aspect [9-10]. Using PMSM as traction motor for Hybrid Electrical Vehicles becomes one of the most important applications of PSMS [11-12]

In the vehicle propulsion control, fault detection and diagnosis are very important for both the reliability of the drive system and the proper operation of the vehicle after a fault. In the last years, the fault diagnosis has been developed, by using intelligent techniques for monitoring power systems and for giving real-time information in fault states [13-15].

Fault detection and diagnosis for PMSM drives are a complex task since the wide variations in the operating conditions of power electronics switches and the performance dependence of many constraints. For obtaining a solution in terms of the time–frequency localization, this requires strong and sophisticated investigation methods [16-17].

The detection and diagnosis of faults can be made by analyzing the spectrum of the stator currents and detecting some specific high frequency components of the fault currents. The spectrum analysis can be performed by Fast Fourier Transform (FFT) or by Discrete Wavelet Transform (DWT).

The main superiority of DWT over FFT is that the size of the analysis window varies proportionally to the frequency. [15,18]. Other advantage of DWT is obtaining simultaneously a good localization of the signal in both time and frequency domains. Consequently, DWT can operate effectively in terms of frequency localization [19].

The DWT decomposes transients into a series of wavelet components, which are useful for detecting, identifying and localizing the sources of transients. The power system transients are analyzed and vital embedded information is extracted [18].

In this paper, a novel DWT based method for detection and diagnosis of faults in a three-phase power inverter feeding a PMSM with Field Oriented Control (FOC) is presented. Two kinds of fault i.e. switch short-circuits and switch open-circuits can be detected and the state of the inverter can be diagnosed by detecting the position of the fault switch. These results proof that the proposed fault detection and diagnosis method has very good capabilities.

II. PMSM Drives Used in HEVs

Many propulsion drive systems (induction motor drive, permanent magnet synchronous motor drive, brushless DC motor drive and switched reluctance motor drive) have been developed for HEVs and are nowadays used for EV and HEV applications by several automotive manufacturers, such as Toyota, Honda, Nissan, Renault, Mercedes [20].

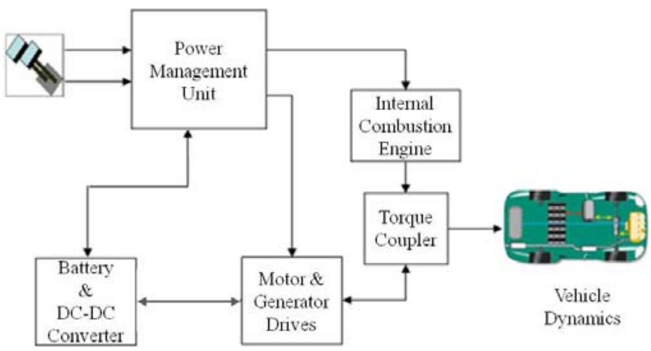

Figure 1. Block diagram of a Hybrid Electric Vehicle using PMSM drive.

Fig.1 shows the block diagram of a HEV propelled by a PMSM and an Internal Combustion Engine (ICE). The Torque Coupler transmits the power from the ICE and from the PMSM to the propulsion system. The Power Management Unit provides the control of the electrical and

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mechanical power between blocks. The architecture of HEV is a parallel one: if any fault in the electric propulsion system occurs, the vehicle propulsion is not interrupted.

As mentioned before, compared to other electric motors, PMSM offers the advantage of a simple control concept. However, it has a limited field in weakening operation, which is required in vehicle applications since the PMs restrict the extended speed range. But the speed range may be extended up to four times over the base speed by an adequate control of the power converter [20, 21].

PMSM control strategies can be classified into scalar control and vector control. The scalar control is the simplest AC motor drive method for changing the voltage proportionally to the frequency, but it is used only for a low speed range of the motor [22]. The vector control needs to know the rotor position and usually uses an encoder for this purpose. There are also sensorless control algorithms that estimate the rotor position without encoders [22, 24]. The DSP Vector Control is used in PMSM drives when speed control and position control are required. In Field Oriented Control (FOC), the stator current is vector controlled on basis of a synchronous *d-q* frame (Fig. 2) [23].

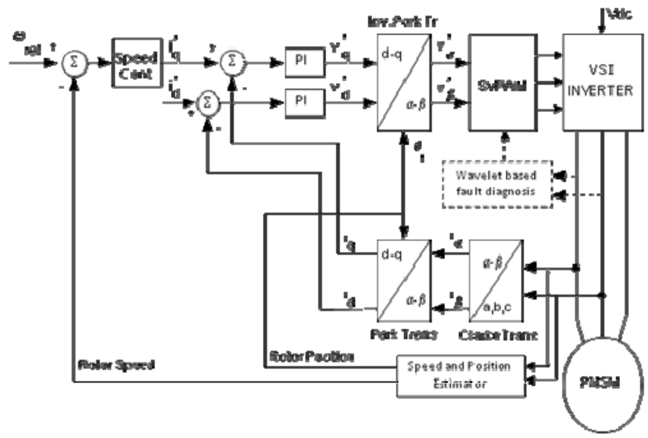


Figure 2. Sensorless Field Oriented Control System of PMSM, chosen for implementing the proposed fault detection and diagnosis method.

In FOC, the *a-b-c* to α-β system transformation (Clarke) and α-β to *d-q* system transformation (Park) are widely used, allowing the reducing the 3 phase analysis to a 2 phase one. Therefore the d-axis stator current directly controls the flux-linkage and the *q*-axis stator current controls the torque. PMSM flux and torque control are similar to those of the separately excited DC Motor. Since the flux linkage due to the rotor magnets is constant, the torque is directly proportional to the *q* axis stator current. FOC technique allows an independent control of flux and torque. Therefore, good dynamic performances can be achieved.

For modelling the behaviour of the PMSM, following simplifying hypotheses have been assumed [22, 25]: the magnetic saturation is neglected although it can be taken into account by changing of some parameters; the back emf is sinusoidal; eddy currents and hysteresis losses are neglected. The model of the PMSM in *d-q* coordinates are described by the following set of equations, which was used for the Matlab/SIMULINK simulation:

$$\frac{\mathrm{d}i_d}{\mathrm{d}t} = \frac{1}{L_d}\left(v_d - R_s\, i_d + \omega_s\, L_q\, i_q\right) \tag{1}$$

$$\frac{\mathrm{d}i_q}{\mathrm{d}t} = \frac{1}{L_q}\left(v_q - R_s\, i_q + \omega_s\, L_d\, i_d - \omega_s\, \Psi_m\right) \tag{2}$$

$$\frac{\mathrm{d}\omega_s}{\mathrm{d}t} = \frac{1}{J}\left(T_e - B\,\omega_s - T_l\right) \tag{3}$$

$$\frac{\mathrm{d}\vartheta_s}{\mathrm{d}t} = \omega_s \tag{4}$$

$$T_e = \frac{3}{2}\, p\left[\Psi_m\, i_q + \left(L_d - L_q\right) i_d\, i_q\right] \tag{5}$$

In Eqs (5) the following notations have been used:

v_d, v_q, i_d, i_q, L_d, L_q - stator voltages, currents, and inductances, respectively;

R_s - stator resistance;

Ψ_m - rotor flux linkage;

T_e, T_l – electromagnetic and load torque, respectively;

ϑ_s- stator angle relative to the *d-q* reference system;

ω_s - synchronous angular speed.

The rotor flux linkage Ψ_m revolves at rotor speed and is positioned away from a stationary reference by the rotor angular position given by

$$\vartheta_r = \int \omega_r\, \mathrm{d}t \tag{6}$$

The expression of the *d*-axis magnetic flux Ψ_d is

$$\Psi_d = L_d\, i_d + \Psi_m \tag{7}$$

If the d-axis stator current id is forced to be zero, then

$$\Psi_d = \Psi_m \tag{8}$$

$$T_e = \frac{3}{2}\, p\, \Psi_m\, i_q \tag{9}$$

III. Faults in PSMS Drive Systems of HEVs

Several failures can occur in the PMSM drive, the drive performance and reliability can be severely affected [10]. Generally, these faults can be divided into three classes: breakdowns in the motor, breakdowns in the drive chains and failures in the inverter [26].

In HEV, approximately a half of the propulsion process depends on the regular operation of the electric traction motor. The early detection of electric machine faults prevents the propagation of faults. Therefore, a proper maintenance of the electric drive has to be performed and it can reduce the costs of repairs [27].

The industry's requirements on electric motors in critical applications frequently cause very costly shutdowns due to switch failures in inverter. Therefore, fault detection, diagnosis and the monitoring of functioning conditions have been studied to prevent costly interruptions due to motor faults [1]. In the case of HEVs and of other electric motor applications, if the electric machine is continuously monitored, motor faults and accidents can prevent severe damage.

In the HEV traction drive system, PMSM is almost fed by voltage source inverters (VSI), and if one or more of the power switches of the inverter fail, critical damages can occur either in the inverter or in the motor. Therefore, a switch fault diagnosis has been developed, by using intelligent techniques, to monitor power systems and to give instant information in fault states [18, 19].

In a VSI used for driving the PMSM, different fault types can occur, but the most common failures are the single switch open-circuit fault and the short-circuit fault [17, 18].

Short-circuits are the most serious class of faults in power electronics converters. If a single switch is short-circuited, its phase leg is directly connected to the DC bus and the gate signal of the other switch in the same inverter branch has to be immediately turned off to prevent a more dangerous failure. These kinds of failures can be relatively easy identified by using several diagnosis methods. In a faulty PMSM drive system, when current signal and electromagnetic torque signal are considered, short-circuit switch faults produce high pulsating torque and current oscillations, and a significant threat of rotor demagnetization occurs.

Open-circuits are the other serious class of faults in power electronics converters. If a single switch is open-circuited, its phase-leg is not connected to the DC bus or to the motor and the phases are delivered power can be not high enough.

Although numerous fault detection and diagnosis methods are suggested using complex software and hardware [27-32], but there was only a basic implementation. For the generalized real time monitoring it is necessary to reduce strongly the computational complexity. For a generalized implementation, which is the case in vehicles, it needs also a solution with reduced price of the used hardware.

In the following chapter the inverter switch faults, more precisely open circuit faults and short circuit faults in IGBTs will be investigated. Therefore, stator current analysis has been implemented to provide a practical solution for continuous monitoring and for quasi-instantaneously fault detection. The current signal of an inverter which feeds electric motors in a vehicle is readily available for control, investigation and protection purposes but, for automotive applications, the most attractive method is one without extra sensors. Thus, such a method is proposed and implemented.

IV. Fault Diagnosis of Electric Motors in HEVs

A real time monitoring system is vital equipment for HEVs. In the vehicle, early warnings and monitoring systems should be developed for critical failures in the vehicle such as ignition, battery, electric motor and drives failures, oil and gasoline levels, brakes, etc. If a problem or failure is detected, then the protection system should be activated by the vehicle management or driver.

The health monitoring of electric traction motor and its drive system in the energy conversion system of HEVs is becoming a critical issue that needs to be solved. Condition monitoring and fault detection of electric motors in HEVs are quite vital for protection, control, safety and cost-effective maintenance. The operating conditions of the electric machine are to be monitored, for diagnosing any failure as early as possible. The lifetime of the electric machine can be prolonged by performing maintenance works before a catastrophic failure occurs.

There are various studies based on the application of FFT and DWT methods to detect and classify the faults in power systems [33] and in AC motor drive systems [34-40]. In [33], DWT has been applied to a typical three phase inverter to detect open-circuit faults in IGBT inverter. In [34], a FFT method for detecting and diagnosing the sensor faults by processing the currents of the PMSM acting the HEV is presented. In [36], the DWT method for the current analysis in the Induction Motor is used.

There are few studies to detect and classify the inverter faults in drive systems. In [26], by combining the slope calculation of the current-vector trajectory, faulty transistors that were simultaneously opened were detected and located.

The FFT method was also used for inverter fault detection. In [28], the feasibility of detecting bearing faults using a spectrum of a single phase stator current in the induction machine was investigated. In [29], the motor current signature analysis which utilizes results from the FFT spectral analysis of the stator current is used.

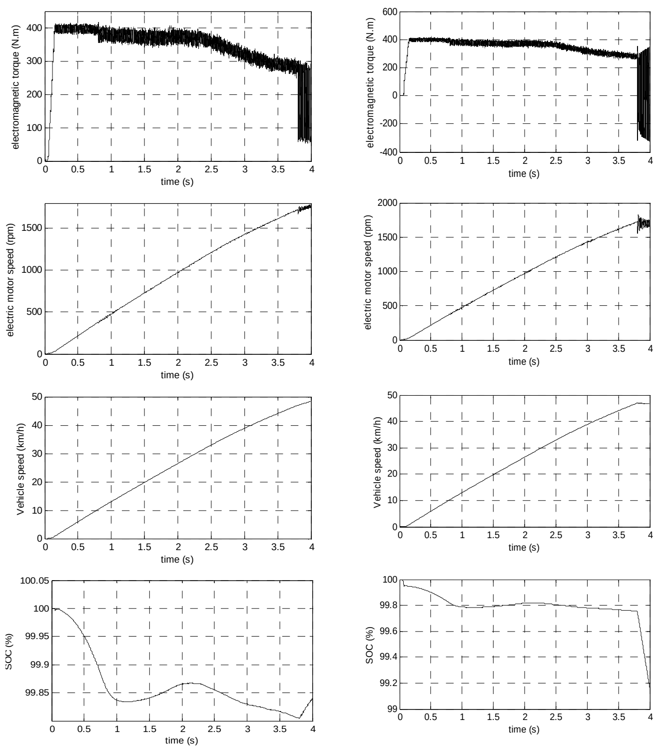
The developed analysis techniques of AC motor control can be used also in the PMSM [23]. Therefore, the fault diagnostic method should support critical functions of the control system and provide cost-effective maintenance [27].

The solution should enhance the reliability of the power train of the HEV. Once the fault diagnostic system makes any kind of severe electric motor fault decision, the vehicle must not stop its duty even there is a malfunction.

In the following chapter a novel method for Inverter Faults Detection and Diagnosis in PMSM Drives of Hybrid Electrical Vehicles based on the processing the stator currents by DWT is proposed.

V. The Proposed DWT-Based Inverter Switch Fault Detection

A simple real-time fault diagnosis system using the DWT method for processing the stator currents is proposed. The major advantage of the proposed method is that it doesn't require an additional sensor or hardware, it is robust and reliable. In Fig. 3 few faulty operation signals in HEV, (electromagnetic torque, motor speed, vehicle speed and SOC, respectively) obtained by Matlab/SIMULINK were presented.



(*a*) (*b*)

Figure 3. Faulty operation: short-circuit (*a*) and open-circuit (*b*) signals in HEV, electromagnetic torque, motor speed, vehicle speed and SOC, respectively.

The Matlab/SIMULINK R2010a software was used to perform the DWT of the resulting signals.

When a short-circuit fault occurs in a power switch of the inverter, stator currents show unstable oscillation, as shown in Fig. 4a for a time interval from t=0 to t=4 s. (only for the a-phase current). A fault in IGBT1 occurs at 3.8 s in simulation, and therefore, current in all three phases are affected. When DWT is performed on the a-phase current for each faulty, it can be seen in Fig. 4b that variation within the decomposition coefficient of the current signals contains useful fault signatures as it will be presented bellow.

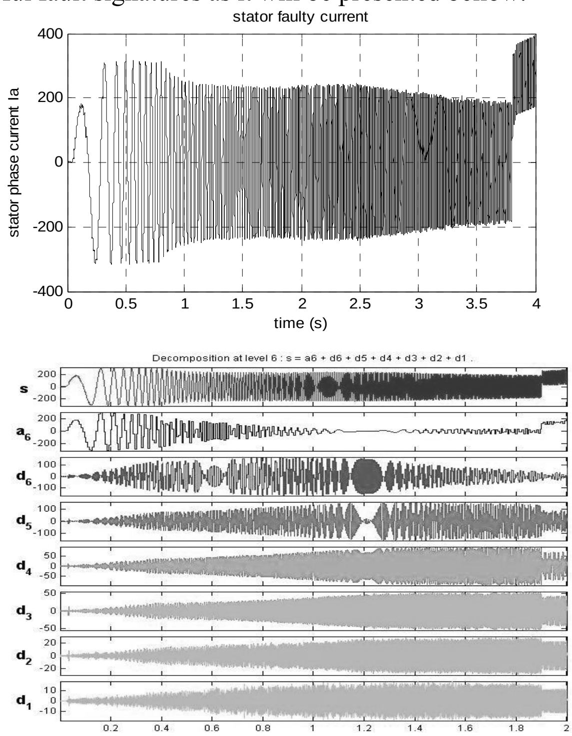


Figure 4. Stator phase current (i_a) and Symlet2 wavelet level six decomposition in IGBT1 short-circuit faulty.

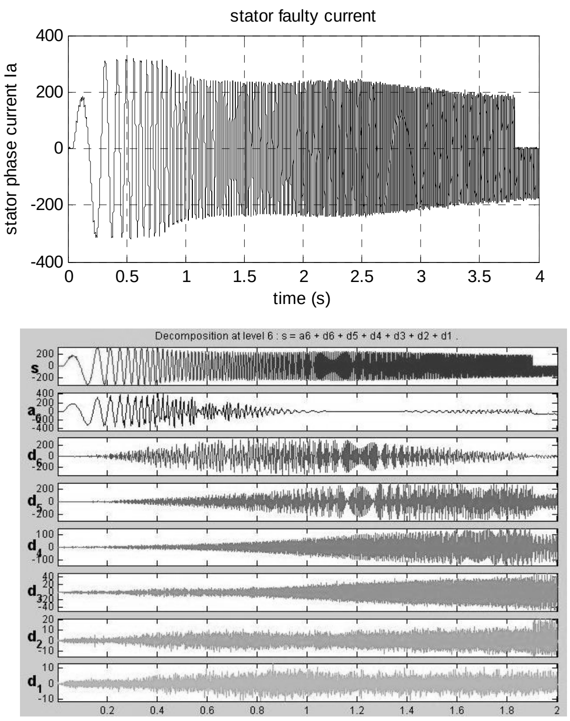


Figure 5. Stator phase current (i_a) and Symlet2 wavelet six level decomposition in IGBT1 open-circuit faulty In the *x*-axis is the data number, expressed in ten thousands (2→20 000 data).

When a open-circuit fault occurs in a power switch of the inverter, stator currents show unstable oscillation, as shown in Fig. 5a for a time interval from *t*=0 to *t*=4 s. (only for the a-phase current). A fault in IGBT1 occurs at 3.8 s in simulation, and therefore, current in all three phases are affected. When DWT is performed on the a-phase current for each faulty, it can be seen in Fig. 5b that variation within the decomposition coefficients of the current signals contains useful fault signatures.

In Table I and Table III, the mean energy values of the i_a stator phase current obtained by DWT in the case of the short-circuit fault and in the case of open-circuit fault of every IGBT, respectively, were presented.

The sharp signal variations can be regarded as feature of the fault. The switch faults in power inverter were analysed using the six level approximations. In time domain analysis, the faulty system can be easily discriminated from a healthy one. In fact, detailed levels, such as d5, d6 and a6 are distinguishable. Furthermore, the comparison of the various levels of the details and approximations in both healthy and faulty operating conditions demonstrate that whereas the signal increases in certain frequency area, it decreases in another region.

TABLE I. THE i_a STATOR PHASE CURRENTS DWT MEAN ENERGY VALUES (SHORT-CIRCUIT)

		a6	d1	d2	d3	d4	d5	d6	*E*
i_a	*Normal*	38,3693	0,0181	0,0378	0,3858	4,6356	26,1221	30,4312	10,2718
	$IGBT_1$	44,9365	0,0158	0,0334	0,3334	3,9276	22,7979	27,9553	9,1772
	$IGBT_2$	39,4365	0,0182	0,0396	0,3798	4,3113	24,9534	30,8612	10,2939
	$IGBT_3$	39,8490	0,0172	0,0364	0,3642	4,2754	24,9396	30,5183	10,0252
	$IGBT_4$	38,0384	0,0180	0,0407	0,3987	4,4807	26,5262	30,5973	10,1769
	$IGBT_5$	41,0385	0,0169	0,0356	0,3558	4,2011	24,4386	29,9135	10,3269
	$IGBT_6$	38,0357	0,0181	0,0401	0,3860	4,4970	26,8100	30,6131	10,3274

TABLE II. THE i_a STATOR PHASE CURRENT DWT MEAN ENERGY ERROR (SHORT-CIRCUIT)

i_a	e_{a6}	e_{d1}	e_{d2}	e_{d3}	e_{d4}	e_{d5}	e_{d6}	e_E
$IGBT_1$	-6,5672	0,0023	0,0044	0,0524	0,7080	3,3242	2,4759	1,0946
$IGBT_2$	-1,0672	-0,0001	-0,0018	0,0060	0,3243	1,1687	-0,4300	-0,0221
$IGBT_3$	-1,4797	0,0009	0,0014	0,0216	0,3602	1,1825	-0,0871	0,2466
$IGBT_4$	0,3309	0,0001	-0,0029	-0,0129	0,1549	-0,4041	-0,1661	0,0949
$IGBT_5$	-2,6692	0,0012	0,0022	0,0300	0,4345	1,6835	0,5177	-0,0551
$IGBT_6$	0,3336	0,0000	-0,0023	-0,0002	0,1386	-0,6879	-0,1819	-0,0556

Table II and Table IV list the error values of the mean energy values obtained by Symlet2 wavelet at sixth-level decomposition for both short-circuit and open-circuit faulty in every IGBT, respectively. Furthermore, from Table I and Table II it can be observed that the stator *a*-phase current values are different in no-fault and faulty conditions, respectively. It is to distinguish that the *E*, a6, d5 and d6 coefficient values are different in fault situations for every IGBT.

TABLE III. THE i_a STATOR PHASE CURRENTS DWT MEAN ENERGY VALUES (OPEN-CIRCUIT)

		a6	d1	d2	d3	d4	d5	d6	E
i_a	*Normal*	38,3693	0,0181	0,0378	0,3858	4,6356	26,1221	30,4312	10,2718
	$IGBT_1$	39,4775	0,0180	0,0397	0,3801	4,3017	24,9912	30,7916	10,0871
	$IGBT_2$	44,5816	0,0158	0,0334	0,3339	3,9413	22,9752	28,1187	9,2364
	$IGBT_3$	37,9017	0,0181	0,0403	0,3991	4,4941	26,5002	30,6465	10,1830
	$IGBT_4$	38,1120	0,0172	0,0364	0,3619	4,2858	24,7855	30,4012	9,9813
	$IGBT_5$	37,6104	0,0182	0,0402	0,3883	4,5027	25,8066	30,6334	10,2316
	$IGBT_6$	40,5200	0,0171	0,0361	0,3602	4,2326	24,6478	30,1862	10,3133

These values enable us to identify the faulty phase and the faulty power switch (by analysing the stator dc offset current polarity).

TABLE IV. THE i_a STATOR PHASE CURRENT DWT MEAN ENERGY ERROR (OPEN-CIRCUIT)

i_a	e_{a6}	e_{d1}	e_{d2}	e_{d3}	e_{d4}	e_{d5}	e_{d6}	e_E
$IGBT_1$	-1,1082	0,0001	-0,0019	0,0057	0,3339	1,1309	-0,3604	0,1847
$IGBT_2$	-6,2123	0,0023	0,0044	0,0519	0,6943	3,1469	2,3125	1,0354
$IGBT_3$	0,4676	0,0000	-0,0025	-0,0133	0,1415	-0,3781	-0,2153	0,0888
$IGBT_4$	0,2573	0,0009	0,0014	0,0239	0,3498	1,3366	0,0300	0,2905
$IGBT_5$	0,7589	-0,0001	-0,0024	-0,0025	0,1329	0,3155	-0,2022	0,0402
$IGBT_6$	-2,1507	0,0010	0,0017	0,0256	0,4030	1,4743	0,2450	-0,0415

All these can be represented as a fault diagnosis table, such as Table V, which contains data for both faults, the short-circuit fault and the open-circuit fault. It is to distinguish that the values of error coefficients e_E, e_{a6}, e_{d5} and e_{d6} are different in fault situations for every IGBT. For determining the faulty switch, it is enough to know the polarity of these coefficients.

TABLE V. FAULTY INVERTER SWITCH DIAGNOSIS

e_{a6}	e_{d5}	e_{d6}	e_E	value	Faulty Switch	e_{a6}	e_{d5}	e_{d6}	e_E	value
0	1	1	1	7	IGBT 1	0	1	0	1	5
0	1	0	0	4	IGBT 2	0	1	1	1	7
0	1	0	1	5	IGBT 3	1	0	0	1	9
1	0	0	1	9	IGBT 4	1	1	1	1	15
0	1	1	0	6	IGBT 5	1	1	0	1	13
1	0	0	0	8	IGBT 6	0	1	1	0	6

VI. CONCLUSIONS

In this paper, a novel DWT based method for detection and diagnosis of faults in a three-phase power inverter feeding a PMSM with Field Oriented Control (FOC) was presented. By this new and original method, two faults i.e. switch short-circuit and switch open-circuit have been detected and the state of the inverter was diagnosed by detecting the position of the fault switch. These results proof that the new fault detection and diagnosis method has very good capabilities.

The analyses of electrical transients arising during the switch short-circuit faults and the open-circuit faults in the three phase power inverter were made by using the DWT decomposition. In order to differentiate between no-fault and faulty states, the energy coefficient and the decomposition coefficients of the current signals were calculated. The wavelet components and the obtained coefficients were used for detecting, identifying and localizing the sources of transients. The obtained results show that the proposed fault detection and diagnosis system has very good capabilities

The DWT method offers a better compromise in terms of frequency localization as other methods since it offers a better decomposition of transients. Hence, this method is very useful for analyzing power system transients.

Our next studies will concentrate to setting up of a corresponding hardware design.

APPENDIX A: PARAMETERS OF THE PMSM

Parameter	Symbol	Rated Value
Number of poles pairs	p	4
Stator resistance	R_s	0.0065 Ω
q-axis inductance	L_q	2.05 mH
d-axis inductance	L_d	1.6 mH
Magnetic Flux linkage	Ψ_m	0.175 Wb
Inertia	J	0.089 kg·m^2
Frictional coefficient	B_m	0.005 N·m·s

APPENDIX B: PARAMETERS OF THE VEHICLE

Vehicle Model Parameters	Rated Value
Vehicle mass	1325 kg
Horizontal distance from centre to front axis	1,4 m
Horizontal distance from centre to rear axis	1,6 m
Centre of gravity height from ground	0,5 m
Frontal area	3 m^2
Drag coefficient	0,4

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