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Research Article

# Fault diagnosis and fault-tolerant finite control set-model predictive control of a multiphase voltage-source inverter supplying BLDC motor

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ABSTRACT

Due to its fault tolerance, a multiphase brushless direct current (BLDC) motor can meet high reliability demand for application in electric vehicles. The voltage-source inverter (VSI) supplying the motor is subjected to open circuit faults. Therefore, it is necessary to design a fault-tolerant (FT) control algorithm with an embedded fault diagnosis (FD) block. In this paper, finite control set-model predictive control (FCS-MPC) is developed to implement the fault-tolerant control algorithm of a five-phase BLDC motor. The developed control method is fast, simple, and flexible. A FD method based on available information from the control block is proposed; this method is simple, robust to common transients in motor and able to localize multiple open circuit faults. The proposed FD and FT control algorithm are embedded in a five-phase BLDC motor drive. In order to validate the theory presented, simulation and experimental results are conducted on a five-phase two-level VSI supplying a five-phase BLDC motor.



## 1. Introduction

Due to their FT capabilities, the five-phase BLDC motor drives are suitable candidates in applications demanding high reliability such as automotive industry [1–5]. These motors can be operated continuously after missing up to two phases. Applications such as chemical industry, aerospace, electric ship propulsion and electric vehicles [1,6,7] are the most important one among others. N-phase motors are supplied by an N-phase inverter. On the other side, different fault types may occur in inverter. According to the statistics, 38% of all faults occurring in motor drives are related to the power switches [8]. Therefore, to maintain the continuous operation of a BLDC motor drive, a FD scheme should be used to detect faults in the inverter.

In order to operate a FT motor drive, fast FD and isolation of the faulty components in the power converter are of paramount importance. Different FD methods have been investigated in literature. Fault types in the power converter can be divided into the open switch and short circuit faults. The open circuit faults are less destructive; the primary effect of such faults is the reduction of the drive performance. However, if this fault is not detected, secondary faults may occur. On the other side, the short circuit faults are indeed destructive; following these faults, the drive should be shut down immediately. However, if it is detected fast enough, typically less than 10 μs in case of an IGBT, the drive shutdown can be avoided. The fault types, and FD methods in VSIs have been comprehensively studied in [9].

In a multiphase motor drive, it is necessary to develop a FT control algorithm with embedded FD scheme. The FT algorithm is able to set the reference currents under both healthy and faulty mode. It should be noted that the reference current in a multiphase machine consists of the fundamental components as harmonics; for example in case of a five-phase BLDC motor, the reference currents are non-sinusoidal and unbalanced under faulty mode [10]. The focus of this paper is on the design of the inner controller in the FOC algorithm. The advantages of the proposed FT FCS-MPC against the conventional control methods are explained in the following.

There are several methods to implement the inner controller; the proportional-integral (PI), proportional resonance (PR), and predictive deadbeat are the most important one among others.

Regarding PI controller for application in a five-phase BLDC motor, the controller in synchronous reference frame (SRF) should set both DC and oscillatory components. It is well known that the bandwidth of the PI controller is limited to dc-components [11]; this causes the steady state error. In order to make all components

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in SRF to dc components, the positive and negative sequence components of the current should be separately controlled. This implies a high computational load. Despite of the high computation load, the PI control is a simple standard method in industrial applications.

The DB controller is another method to set the reference currents. In this method, the mathematical model of the motor-drive is used to calculate the reference voltages in SRF so that the reference currents are followed. It is known that the accuracy of the motor parameters is subjected to uncertainty and motor operating point [12]. This means that the controller performance depends on the model accuracy. To avoid this drawback, authors use complex algorithms such as extended Kalman filter to compensate the model inaccuracy [12]. This can result in a high computational cost.

Regarding PR controller, it can maintain the reference currents in the stationary reference frame accurately. The drawback of this method in motor drive application is the tuning effort. This is mainly due to the variable frequency of the motor in an electric vehicle.

According to the FCS-MPC theory, the calculations can be done directly in abcde reference frame; so extra transformation is not necessary in this method. On the other side, it has a high band width; this means that it can set both fundamental and harmonic components in the reference current, accurately. At the same time it is simple. Moreover, different constraints can be easily implemented in this method. Therefore, authors use this method for FT control implementation in this paper. There is the lack of research on developing this control method for application multiphase BLDC motor drives. The flexibility, simple implementation, and fast dynamic response of the FCS-MPC to implement the FT control algorithm are explored in this paper.

The FD in the power converter is the complementary part of the FT control algorithm. Different open circuit FD methods in VSIs have been presented in literature. The FD methods are classified in three categories such as: model based methods, reference based methods, and signal based methods [13].

Considering the model based FD methods, the load response to the input signal is predicted by using the load mathematical model. After that, difference between the estimated and measured signal is used to define an FD index [14,15].

Regarding the reference based FD method, difference between the real signal and reference signal is used to define the FD index [16]. Application of this method is limited to a system with the closed loop control.

Regarding the signal based FD methods, output voltages or currents of the power converters are measured. After that, by using a signal processing technique, the FD index is calculated [17–19].

The FD and FT FCS-MPC of the five-phase BLDC motor in stationary reference frame have been presented in [20]. In this paper, a simple open transistor FD method is presented by using the converter current signal and a signal available in the control method. This method is fast, simple and flexible. It can be used in two-level multiphase VSIs. Both the open switch and open phase faults can be detected by using this method.

Two contributions are presented in this paper. In the first part, the FT FCS-MPC is developed for application in a five-phase BLDC motor drive. In the second part, a simple FD scheme is presented; this scheme can detect, localize and isolate the open circuit faults in the power converter feeding a five-phase BLDC motor drive.

Remaining parts of this paper are organized as follows: the FT control algorithm for the system under study is presented in Section 2. The proposed FD method is explained in Section 3. Simulation results are provided in Section 4. The sensitivity analysis and comparison of the proposed FT control method with classic methods is explained in Section 5. To validate the theory, the experimental results are provided on a five-phase BLDC motor drive in Section 6. The conclusions are presented in Section 7.

## 2. Fault-tolerant control and analysis

With emerging high performance digital signal processors such as DSPs and FPGAs, despite of its high computational cost the MPC has been an attractive control method for researchers and industry during recent years. Due to its flexibility, it can be applied to control the power electronics converters. Main advantage of this control method is high dynamic performance. The MPC methods can be classified into two groups. In the first category, reference voltage waveform is predicted from the system mathematical model. After that, the reference signal is applied to the conventional pulse width modulators to produce the reference waveforms. This method is known as dead beat MPC [21]. In the second category, from the system mathematical model, the current waveform is predicted by using all possible switching vectors of the power converter. After that, a cost function is calculated. The state vector which has the minimum cost is chosen as the optimal vector and applied to the power converter during the next switching period. This method is known as FCS-MPC in literature [22]. Using this control method, there is always a steady state error [23]; this error is more relevant at lower switching frequency and small phase current. The focus of this paper is on FCS-MPC methods.

The FCS-MPC is a flexible; it can be used as an alternative for the inner control loop of the power converters in any application such as motor drives, grid connected converters, dc–dc converters, power quality conditioners, etc. Depending on the application, the cost function can be designed based on the required control objectives; this is due to its flexibility. A review on the applications of the power converter controlled by FCS-MPC was demonstrated in [22]; a comparison with the traditional methods based on PWM was shown. A review on state of the art emerging FCS-MPC in power electronics is shown in [22,24,25].

### 2.1. Model of the five-phase BLDC motor drive

In this paper, a five-phase converter supplying a BLDC motor is considered as the case study. The considered system is shown in Fig. 1. The five-phase motor drive is a FT system; it can tolerate up to two faulty phases. In the following, the mathematical model is discussed.

A five-phase BLDC motor connected to a VSI can be modeled under healthy operational mode as [26]

$$\dot{x} = Ax + Bu, \quad x = [i_a\ i_b\ i_c\ i_d\ i_e]$$

$$u = [v_a - e_a\ v_b - e_b\ v_c - e_c\ v_d - e_d\ \ v_e - e_e]^T + v_x[11111]^T$$

$$A = -R/L, \ \ B = -1/L$$

$$R = \begin{bmatrix} r_a & 0 & 0 & 0 & 0 \\ 0 & r_b & 0 & 0 & 0 \\ 0 & 0 & r_c & 0 & 0 \\ 0 & 0 & 0 & r_d & 0 \\ 0 & 0 & 0 & 0 & r_e \end{bmatrix}, \quad L = \begin{bmatrix} l_a & m_1 & m_2 & m_2 & m_1 \\ m_1 & l_b & m_1 & m_2 & m_2 \\ m_2 & m_1 & l_c & m_1 & m_2 \\ m_2 & m_2 & m_1 & l_d & m_1 \\ m_1 & m_2 & m_2 & m_1 & l_e \end{bmatrix} \tag{1}$$

where $i$ is the phase current, $v$ is the voltage of each phase, $r$ is the phase equivalent resistance, $l$ is the phase self-inductance, $m_1$ is the mutual inductance between two adjacent phases, $m_2$ is the mutual inductance between two nonadjacent phases, $e$ is the back EMF in each phase of the motor, and $v_x$ is the neutral voltage. The