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Overview of Advanced Control Strategies for Electric Machines

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Abstract: Control strategies play a key role for operation of electric machines, which would directly affect the whole system performance. In fact, different control strategies have been executed and explored for electric machines, which bring great impacts to industrial development and human society. This paper investigates and discusses the advantages control strategies for electric machines, including the field oriented control (FOC), direct torque control (DTC), finite control set model predictive control (FCS-MPC), sensorless control, and fault tolerant control (FTC). The corresponding control principles, control targets, fundamental approaches, advanced approaches, methodologies, merits and shortcomings are revealed and analyzed in detail.

Keywords: Electric machine, permanent-magnet (PM) machine, AC machine, control strategy, advanced control, field oriented control (FOC), direct torque control (DTC), finite control set model predictive control (FCS-MPC), sensorless control, and fault tolerant control (FTC).

1 Introduction

Electric machines play a key role of electromechanical energy conversion, which significantly promote the development of modern industry. In recent years, the concepts of more electricity and full electricity are presented for various applications, such as electric vehicle (EV), electric ship propulsion (ESP), aircrafts, robotics, space exploration, and so on, which can provide an efficient, convenient, and reliable way for energy utilization. So, electric machines and corresponding control strategies still propel the development of human society.

The control strategies play a significantly active role for operation of electric machines, which should achieve most of the following characteristics.

- Wide suitability for different types of electric machines without large modification.
- High versatility for various applications without substantial change.
- Mature topologies for extension in different occasions.
- Flexible and readily integration of electric circuits for algorithm performance.
- High robust and reliability for machine operating performance.
- High efficiency for machine operation.
- Low power loss for machine control.
- Rapid convergence for calculation.
- Wide speed controllability for machine operation.
- Fast response of machine control within limited computational time.
- High intermittent overload operating capability for machine control.
- Easy propagation to different platforms for machine operation.
- Sensitive reaction to control signals.
- Easy implementation for practical application.
- Reasonable cost for hardware implementation.

The rest of the paper is organized as follows: Section 2 presents an investigation of FOC for electric machines regarding the fundamental and advanced FOC strategies. Then, the DTC is surveyed and analyzed in Section 3. Section 4 discusses the FCS-MPC for electric machine operation. After that, sensorless control is introduced in detail in Section 5. Section 6 presents the FTC for machine faulty operation. Finally, a conclusion is drawn by listing the key advantages of control strategies for machine operation.

2 Field oriented control

FOC is first proposed by F. Blasehke in 1971, which is widely applied for AC motor control. In general, there are two main vector control strategies for motor control, namely the direct field oriented control and the indirect field oriented control. For the direct FOC, the feedback signals of flux magnitude and angle are directly calculated by using voltage or current models. This method is sensitive to the parameter variations and shows a poor performance in low speed region. The indirect FOC is more commonly used for motor control, since it has a wider speed range and high-speed operation by flux field-weakening control.

2.1 Electric machine with FOC

FOC is favored in many types of electric machines due to its good performance at a wide speed range. The application of FOC includes the induction machine[1-3], PMSM[4-5], flux-switching machine[6], and new magnetic-geared machine[7]. Moreover, the FOC has been investigated for multiphase machines[8-9].

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2.2 Fundamental FOC

The basic principle of FOC is the decoupling among the stator current components, magnetizing flux and torque, based on which the torque and flux can be controlled independently. First, the three-phase time and speed dependent system is transformed into a synchronous time-invariant system. In this way, the AC motor can be controlled in a similar manner as a DC motor. In addition, it is worthy to mention that the torque component is aligned with the q coordinate and the flux component is aligned with the d coordinate. A simple operation is to assume i_d=0. The diagram of FOC based on i_d=0 operation is depicted in Fig.1. However, the disadvantage of this method is the low current utilization and narrow speed range.

2.3 Advanced FOC

Some advanced FOC methods have been investigated for specific motor operations, including the maximum torque per ampere (MTPA) operation, field weakening operation, and advanced controller operation.

2.3.1 MTPA operation

The MTPA operation is favored in the control of interior-PM synchronous motor(IPMSM) drive since it is capable of achieving the optimal efficiency by controlling the current vector at specific load conditions[10-11]. Actually, the key of MTPA is to solve the optimum rotor position θ_{MTPA}. So, the maximum value of T_{em} can be obtained by assuming.

$$\frac{\partial T_{\mathrm{em}}}{\partial \theta}=\frac{3}{2}P_{\mathrm{n}}I_{\mathrm{s}}[\psi_{\mathrm{f}}\cos\theta+(L_d-L_q)I_{\mathrm{s}}\cos 2\theta]=0 \tag{1}$$

The relation between i_d and i_q can be expressed as

$$i_d+\frac{(L_d-L_q)(i_d^2-i_q^2)}{\psi_{\mathrm{f}}}=0 \tag{2}$$

The MTPA curve is a hyperbolic curve and can be depicted mathematically in Fig.2 and physically in Fig.3.

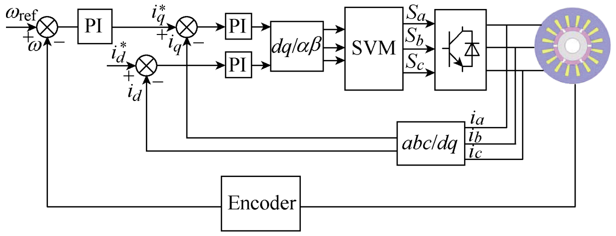

Fig.1 Diagram of indirect FOC, i_d=0 operation

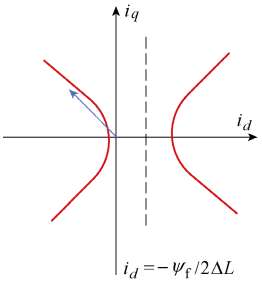

Fig.2 MTPA depicted mathematically

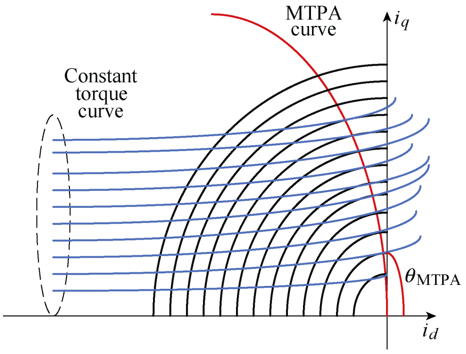

Fig.3 MTPA depicted physically

However, the inherent parameter nonlinearity of IPMSM possesses a great challenge for the practical implementation of MTPA operation. To overcome the effects of nonlinearity caused by magnetic saturation and cross-coupling, different methodologies have been presented and investigated. First, taking into account the d and q axis inductances as the current functions are considered in [12], and employing lookup tables of the numerical analysis of electromagnetic field is presented in [13-14]. In addition, the MTPA operation by injecting high-frequency current signal into the motor is presented in [15-16], which is based on the principle of the extreme seeking control. Actually, it is worthy to mention that the IPMSM has less copper loss in constant load condition due to no rotor copper loss. Moreover, the current utilization efficiency of MPTA is higher compared with i_d=0 operation. This is due to the smaller stator current required for a specific load.

2.3.2 Field weakening operation

Field weakening operation is well known of its capability to extend the rotor speed range, as in literature of [17-18]. The relation between the speed and the DC link voltage is expressed as

$$\omega=\frac{V_{\max}}{\sqrt{(L_q i_q)^2+(L_d i_d+\psi_{\mathrm{f}})^2}} \tag{3}$$

$$\left(\frac{i_q}{L_d/L_q}\right)^2+\left(i_d+\frac{\psi_{\mathrm{f}}}{L_d}\right)^2\leqslant\left(\frac{V_{\max}}{\omega L_d}\right)^2 \tag{4}$$

Fig.4 describes the speed change in MTPA mode and field weakening mode. In OB section, the motor is running in MTPA mode, where the stator voltage

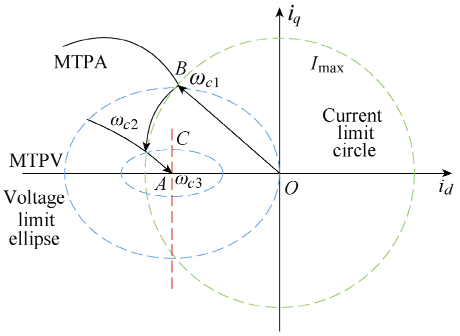

Fig.4 Linear field weakening control area of IPMSM

reaches the upper limit when the speed reaches ω_{c1}. In BC section, the motor is running in field weakening mode, where both i_d and i_q decrease. Thus, the speed increases. The diagram of FOC based on the voltage detection field weakening is depicted in Fig.5.

Unfortunately, the torque and excitation components are still coupled during the voltage detection for field weakening operation. To solve this problem, other field weakening methods, such as $1/\omega_m$ method[19], model-based method[20], and lookup table method[21], are presented.

2.3.3 Advanced controller operation

For FOC control, the time-variability motor system has a negative effect on control performance since a simple PI regulator is significantly affected by the variation of parameters and other uncertainties. Therefore, other advanced controllers, such as sliding mode controller, neural network PI controller[22], and adaptive fuzzy controller[23], are also presented to improve the control performance.

3 Direct torque control

Compared with FOC, DTC directly controls the torque and stator flux linkage without current control loops. In general, there are several DTC schemes, including the sliding mode DTC[24], deadbeat DTC[25], and switching-table DTC[26-27]. The most well-known DTC scheme is the switching-table DTC, where two-hysteresis comparators and a switching table are employed to generate the voltage command. As well, DTC offers the benefits of fast dynamic response and simple algorithm.

3.1 Electric machine with DTC

DTC was initially introduced for induction machines[28-29], and then extended for PMSM[30], or multiphase induction machine[31]. A robust direct torque control in the field weakening region for a synchronous reluctance drive is studied in [32]. A fault-tolerant DTC with arbitrary two opened phases for a six-phase PMSM is investigated in [33], where modified variables are employed.

3.2 Fundamental DTC

For fundamental DTC[29], a switching table is defined as shown in Fig.6 and Table 1, which is with the changing trends of active voltage source inverter (VSI) vectors. First, the voltage vector can be selected from the switching table according to the output of torque and the flux hysteresis comparators. The corresponding diagram of a fundamental DTC is depicted in Fig.7. Also, it is worthwhile mentioning that the switching table DTC is free of system parameter variation since both the switching table and the hysteresis comparators are independent of model parameters. Moreover, fast dynamic response can be achieved in DTC inherently since there is only one active vector employed in one control cycle. However, it can be seen from Fig.6 that the magnitudes of six vectors are equal and the angles among them are fixed. Therefore, it is difficult to adjust the output vectors, and the undesired ripples of the flux and torque are inevitable. Another drawback of conventional DTC is that it has the variable switching frequency and poor performance at low speeds. To solve the problems of the high ripples of the torque and flux and the variable switching frequency, improved DTC methods have been proposed by researchers.

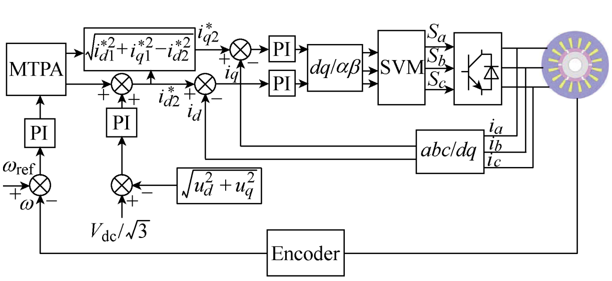

Fig.5 Diagram of FOC based on field weakening

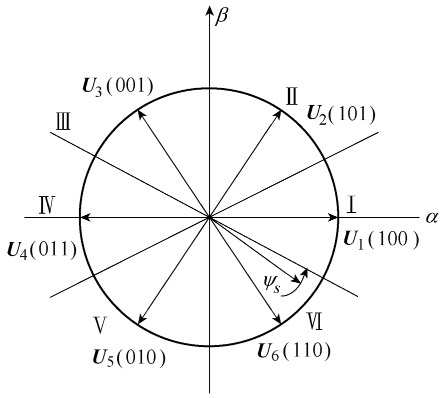

Fig.6 Voltage vectors and sections

Table 1 Switching table of fundamental DTC

ψ_s	T_e	I	II	III	IV	V	VI
	1	U_2	U_3	U_4	U_5	U_6	U_1
1	0	U_7	U_0	U_7	U_0	U_7	U_0
	−1	U_6	U_1	U_2	U_3	U_4	U_5
	1	U_3	U_4	U_5	U_6	U_1	U_2
−1	0	U_0	U_7	U_0	U_7	U_0	U_7
	−1	U_5	U_6	U_1	U_2	U_3	U_4

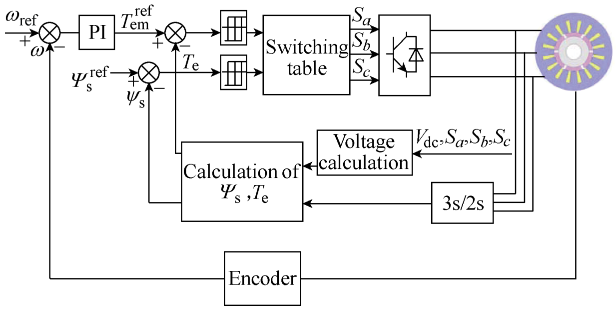

Fig.7 Diagram of fundamental DTC

3.3 Advanced DTC

3.3.1 DTC based on discrete space vector modulation

A DTC based on discrete space vector based was proposed in [34], where one period is divided into three equal intervals and in each interval only one voltage vector is applied. Using this method, 37 candidate voltage vectors are obtained. Furthermore, an improved DTC based on discrete vector was investigated in [35], where an RMS torque ripple equation is derived using instantaneous torque equations. By this mean, minimum torque-ripple and constant switching frequency are achieved. In addition, to better adjust the magnitude of the output vector, duty cycle modulation algorithms can be found in [36-37]. Also, a vector evaluation factor table based DTC was presented in [38], where six active vectors can be expanded to $3N_d$ vectors with duty cycle, and also, a two-step selection algorithm is established based on a cost function to select two vectors with duty cycle sequentially.

3.3.2 DTC based on space vector modulation

To deal with the torque and flux ripple as well as the variable switching frequency, the space vector pulse-width modulation (SVPWM) was integrated with DTC[39-43]. Compared with the conventional DTC, PI regulators and SVPWM are utilized instead of adopting the switching table and hysteresis comparators. The diagram of SVPWM based DTC is depicted in Fig.8. It can be found that the flux and torque ripple as well as the constant switching frequency can be reduced by using this method.

3.3.3 DTC combined with predictive control

Recently, the idea of combing predictive control and DTC can be found in [44-45], where the hysteresis comparators are replaced by a cost function. The voltage vectors are evaluated through the cost function and the one that produces the least torque and flux magnitude error is applied in the next instant. In the meantime, the Kalman filter is adopted for accurate flux estimation in [46]. This method possesses the merits of high flexibility of including system nonlinearities and constraints in the optimization procedure, as well as the reduction of flux and torque ripple.

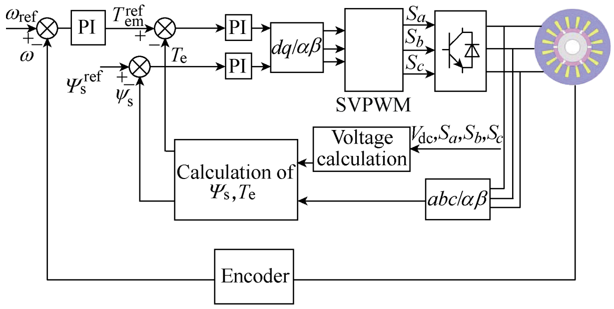

Fig.8 Diagram of DTC based on SVPWM

4 Finite control set model predictive control

In recent years, finite control set model predictive control (FCS-MPC) has received more attention in research. FCS-MPC offers the advantages of the intuitive implementation and the fast dynamic response. Furthermore, it is capable of incorporating nonlinearities and constraints in a straightforward manner. But, the FCS-MPC suffers from heavier computational burden compared to other control strategies. Currently, FCS-MPC approaches have been studied in literature for motor drives, thanks to the development of microprocessors.

4.1 Electric machine with FCS-MPC

FCS-MPC has been implemented for various machine types. A nine-phase flux-switching permanent-magnet motor with model predictive current control was evaluated in [47]. Also, FCS-MPC has been applied to induction motors[48-51], synchronous reluctance motor[52-53], switched reluctance motor[54], and PMSM[55-61]. These implementations show good control performances.

4.2 Fundamental MPC

FCS-MPC identifies a control concept which predicts the future system states by taking into account the discrete nature of the power converter. Actually, starting from an actual sampling instant, a constant number of future states are predicted, which is called prediction horizon. Then, the results of the prediction are evaluated by a cost function, which provides the criterion for selecting the appropriate control action. Fig.9 describes a fundamental FCS-MPC diagram. In general, there are three different control methods with different corresponding constraints, namely, the model predictive current control, model predictive torque control and model predictive flux control. Accordingly, the cost function can be described as

$$g_1 = \left[i_d^*(k+1) - i_d(k+1)\right]^2 + \left[i_q^*(k+1) - i_q(k+1)\right]^2 \tag{5}$$

$$g_2 = \left[T_{\text{e}}^*(k+1) - T_{\text{e}}(k+1)\right]^2 + k\left[\psi_{\text{s}}^*(k+1) - \psi(k+1)\right]^2 \tag{6}$$

The above constraints i_d, i_q, T_{e}, ψ_{s} can be expressed in the form of switching states. Therefore, each switching state is evaluated through the cost function and the one that minimizes the cost function is applied in the next instant. However, there would be too many switching states to be evaluated when the converter is multilevel or multiphase, which results in heavy computational burden.

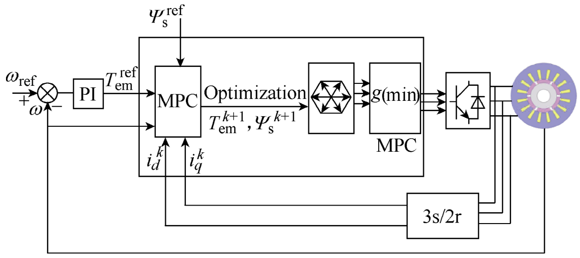

Fig.9 Diagram of FCS-MPC

Moreover, the weighting factor between torque and flux is difficult to be fine-tuned. Also, the computational delay will cause prediction error. Therefore, researchers have taken interests in this area to improve the fundamental FCS-MPC to solve the above problems.

4.3 Advanced FCS-MPC

4.3.1 FCS-MPC with computation time reduced

The computation time increases as the number of prediction voltage vectors increases. Therefore, for multiphase[47] or multilevel[62] converters fed motors, the computation time is significantly longer. A DTC-based FCS-MPC is investigated in [63], where a switching table is established according to the torque error and flux position. Using this method, only two voltage vectors need to be evaluated and the computation time is significantly reduced. The control diagram is shown in Fig.10.

Moreover, a two-vectors-based and a single- vector-based FCS-MPC were presented in [64-65], where the computational complexity is significantly reduced.

4.3.2 FCS-MPC with weighting factor avoided

Apart from the heavy computational burden, the conventional FCS-MPTC also suffers from weighting factor tuning due to the different units of torque and stator flux. A multi-objective approach is proposed in [66] to avoid the weighting factor calculation, where the selected voltage vector allows a minimization of all the objective functions. In the meantime, in [67], the weighting factor is eliminated by converting the torque and flux magnitude references into an equivalent reference vector of stator flux.

4.3.3 FCS-MPC with computation delay effect eliminated

In practical implementation of FCS-MPC, there is a one step delay between the determination of voltage vector and the applied voltage vectors caused by computational time. A valid solution was introduced in [67-68]. Fig.11 shows a two-step prediction method of FCS-MPC. In the meantime, the cost function can be written as:

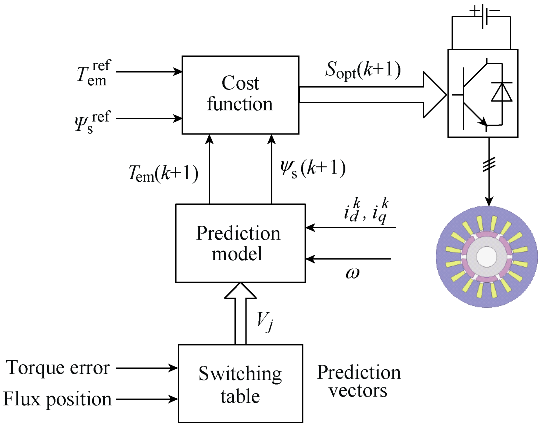

Fig.10 Diagram of improved FCS-MPC with computation time reduced

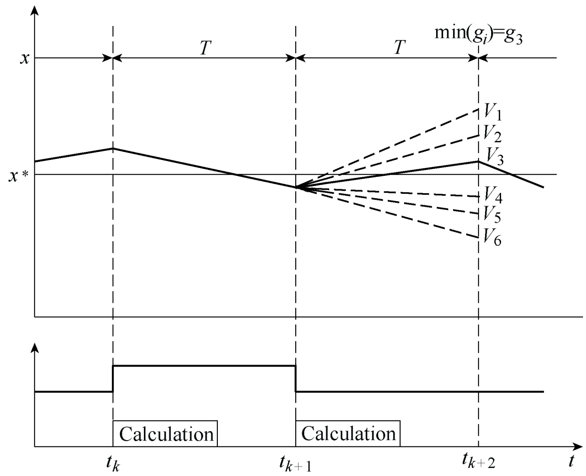

Fig.11 FCS-MPC with delay and compensation considered

$$g_1' = \left[i_d^*(k+2) - i_d(k+2)\right]^2 + \left[i_q^*(k+2) - i_q(k+2)\right]^2 \quad (7)$$

$$g_2' = \left[T_e^*(k+1) - T_e(k+1)\right]^2 + k\left[\psi_s^*(k+1) - \psi(k+1)\right]^2 \quad (8)$$

5 Sensorless control

Motor drives controlled without position sensors have emerged as a mature technology and have been extensively employed in industry. Sensorless control possesses the definitive advantage of lower cost, reduced hardware complexity and less maintenance requirements. The existing sensorless control methods can generally be classified into two types, namely with and without signal injection. The back-EMF based sensing sensorless control without signal injection is employed in medium and high speed range. While in zero and low speed region, high frequency signal injection is required to achieve sensorless control. The basic sensorless control methods are summarized in Fig.12.

5.1 Medium-high speed range sensorless control

The existing sensorless control methods in medium and high speed range are mainly based on the back-EMF model of the machine[69-71]. Updated electrical parameters, such as the stator resistances and dq-axis inductances, are required in this method, which are used to estimate the speed and rotor position. Unfortunately, the variation of the parameters causes the error in the back-EMF estimation and results in the incorrect positional information[72-73]. To improve the sensorless

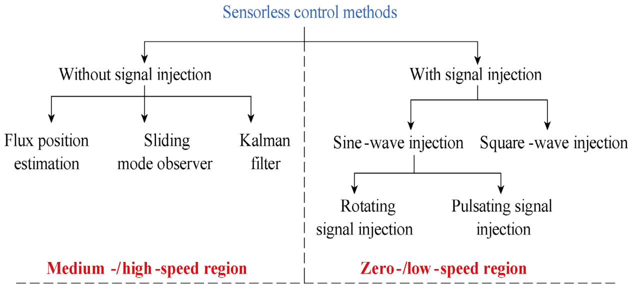

Fig.12 Sensorless control methods

control performance, advanced control methods such as the extended Kalman filter[74-75] and sliding mode control[76-77], are introduced. Moreover, the online estimation algorithm using the model reference adaptive system and the recursive least square to identify the parameters is investigated in [78-79]. However, phase shift error caused by observer and pulsating error caused by flux distortion and inverter non-linearity are introduced in these methods.

5.2 Zero-low speed range sensorless control

Since the back-EMF is proportional to the rotor speed, the EMF-based methods are invalid in zero and low speed regions. To overcome this problem, signal injection, including discrete voltage pulses[80], PWM[81] and continuous carrier-voltage[82], are introduced to achieve the efficient sensorless control at zero and low speed range. Accordingly, the control diagram of sensorless control using signal injection is depicted in Fig.13. In general, the carrier signal injection methods can be classified into rotating injection in the stationary reference frame[83-84] and pulsating injection in the estimated synchronous reference frame[85-86]. However, the position estimation accuracy may be affected by the phase shift of zero-sequence voltage, which is caused by the machine saliency in rotating injection method[87]. Meanwhile, in pulsating injection, the phase shift effect due to machine saliency can be further eliminated[88].

5.3 Full speed range sensorless control

In order to achieve sensorless control in full speed range, the model-based estimation method and signal injection method are combined in [89-91]. The diagram of the sensorless control in whole speed range is described in Fig.14. However, the coupling between the fundamental and HF components will deteriorate the sensorless position estimation since the HF component affects the observer accuracy of the back-EMF model-based method. As well, the fundamental component results in a significant transient error in HF injection method. Therefore, it is essential to decouple the fundamental and HF component in the transient operation. So, there is still much work for the full speed range sensorless control.

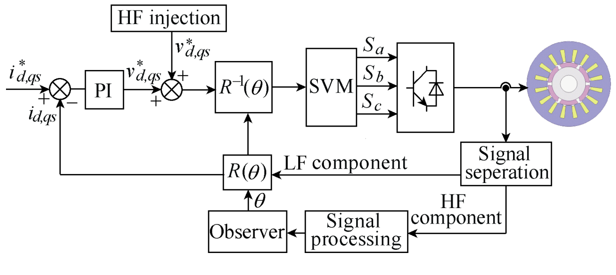

Fig.13 Diagram of sensorless control using signal injection

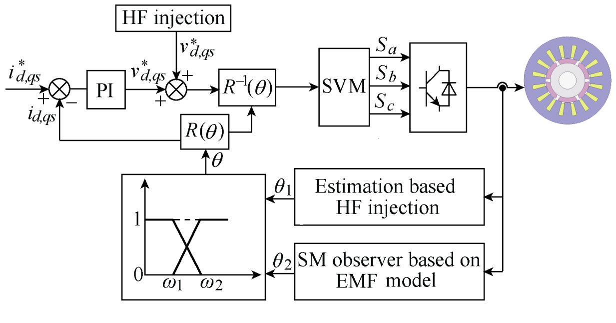

Fig.14 Diagram of combined sensorless control in full speed range

6 Fault tolerant control

Normally, FTC for electric machine operation can be classified as three types of strategies, namely the remedial BLAC operation, remedial BLDC operation, and remedial field-exited operation. These three remedial operations can provide the desired torque even under faults such as open circuit faults or short circuit faults. Actually, the electric machine operates in remedial mode to achieve the same average output torque but with large torque ripple, which enables itself to run at fault situations[92-96].

6.1 Remedial BLAC operation

The remedial BLAC operation for FTC of electric machines is to keep the electromagnetic property unchanged so long as the magnetomotive force (MMF) maintains constant. For instance, a m-phase PM motor with its currents is spatially displaced from each other by 360°/m, the MMF can be expressed by [96-97]:

$$MMF_m = MMF_1 + MMF_2 + \cdots + MMF_m \tag{9}$$

So, under the remedial BLAC operation mode with n phase open ($m-n>2$), the MMF can be reconstructed according to the healthy phase currents:

$$MMF'_m = MMF_1' + MMF_2' + \cdots + MMF'_{m-n} \tag{10}$$

In this way, the remedial average output torque can be maintained as the healthy one. This strategy is typically suitable for stator-PM machines. Also, the multiphase machines can adopt this strategy to improve its operational reliability under fault conditions.

6.2 Remedial BLDC operation

The remedial BLDC operation for FTC of electric machines is to regulate the conducting angle and amplitude of the conducting phase of a BLDC machine under the fault condition. The target is to let the healthy phases provide the enough output torque for machine operation.

For a three-phase BLDC machine under one-phase fault case, the remedial operational procedure is as follow:

- First, the faulty phase is shut down; then, the health phases are considered for reconstructed operation in BLDC mode.
- Second, the health phases will follow the same MMF for remedial operation, which will reconstruct their current conduction angles and amplitude.
- Finally, the desired average torque can be achieved with the constructed phases.
- It should be noted that during the remedial

operation, the motor will still operate in BLDC mode, but their healthy phases will follow different conduction from the normal way.

- This FOC strategy is suitable for most of BLDC machines, and especially suitable for those multiphase ones.

6.3 Remedial field-excited operation

The remedial field-excited operation for FTC of electric machines is to provide the desired output torque by strengthening the magnetic field during the fault cases[96,98]. In this way, the field windings can provide the desired magnetic field via applying a large current. Also, the original operational mode of the electric machine, namely the BLAC mode or BLDC mode, has no need to change. The key point is that the electric machines should be those with the field excitation capability, such as the PM hybrid-excited machine and the magnetless DC-excited machines.

7 Conclusion

In this paper, an overview of advanced control strategies for electric machine is presented, which reveal the following points:

- Investigate the basic principles of FOC, DTC, FCS-MPC sensorless control, and FTC.
- Discuss the application of control strategies with electric machines.
- Analyze the fundamental operations of FOC, DTC, FCS-MPC sensorless control, and FTC.
- Reveal the advanced operations of FOC, DTC, FCS-MPC sensorless control, and FTC.

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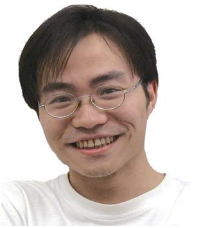

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