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***Abstract*—This paper presents an experimental comparative study on the performance of three different control strategies based on model predictive torque control for mono inverter dual Permanent Magnet Synchronous Machine (PMSM) system. The first control strategy uses averaged sensor information of both machines. While the second control strategy uses master/slave which takes only the machine with higher load torque into account at each instant. In the third control strategy, both machines are considered identically by using algebraic sum of cost function. The comparison is made based on five different performance indicator including integration squared error, joule loss, switching loss, total harmonic distortion and total power efficiency.**

Keywords—PMSM; Predictive; Optimal; Torque; Dual; Parallel;

I. INTRODUCTION

Like the development of modern electronic technology, aviation industrials are paying more and more attention to the concept of "More Electric Aircraft" [1] for the reason that an electric power system can provide much higher flexibility and diagnosability than a mechanical power system, such as hydraulic and pneumatic, which leads to advantages in weight and maintenance cost.

Actuator, which coverts energy (electric, hydraulic, pneumatic etc.) to mechanical motion, is key element in a control system. Among different types of electrical actuators, PMSM is the most widely used thanks to its specialties such as high power density and good dynamic performance [2]. In a regular PMSM application, an inverter and a machine together build up an actuator and the desired position, speed and torque are obtained by modulating the switching state of the inverter. But in many aeronautical actuator applications [3]; [4], such as elevator, spoiler and flap, multiple actuators are used for the same manipulating purpose. In these applications, the speed and position of each actuator are not required to be independently set thus leads to a natural consideration that trades the independence of position and speed with the weight induced by electronics and system complexity by connecting these PMSMs in parallel and using only one inverter to drive them. This type of configuration is described in Fig. 1 with two PMSMs.

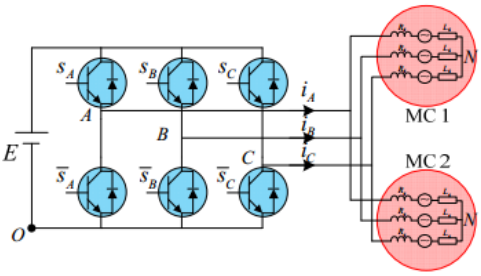

Fig. 1 A 2-level 3-phase inverter driving 2 PSMSs in parallel

Unlike induction machine, which is naturally stable thanks to the slip [5]; [6], PMSM is supposed to be subjected to a different voltage if different load torque is required. As there is only one voltage source, the torque controller must be able to find out the best compromise respecting the torque reference and ensure the stability of all the machines. Several control strategies have been proposed for this special system. [7] has proved that independent torque control for each machine is feasible if electrical angle deflection between two machines exists. In [8]; [9] average techniques are used where averaged sensor information of both machines is used so that regular current controller scheme can be applied. In [10] the Master-Slave control strategy, which choses the machine with higher torque under control and let the other one operates open loop, is introduced. In [11]-[13] optimal predictive torque control is proposed. It uses all available sensor information and predict the optimal control vector directly by minimizing a cost function.

All control strategies mentioned above have been tested in simulation or experiment but under different environment and machine parameters. As all of them use or can use predictive current control but controller configurations are not the same, it's interesting to put them under the same condition and to see how the difference in configuration impact actual performance. [14] has intended to proposed this topic but only simulation result is available. Based on this purpose, in this paper, Average Techniques, Master-Slave, and Optimal Control are introduced and their performance is compared through several indicators based on experimental results to see the advantages of them.

II. Control Schemes for Mono-Inverter Dual-PMSM System

In this part, the Model Predictive Control (MPC) is firstly defined. Then different control strategies based on Predictive Torque Control (PTC) [11] is introduced in detail. In this case only two identical machines are considered. The non-identical machines situation has been discussed in [15].

A. Three phase inverter model

A 2-level 3-phase inverter is used to feed the machine. Its mathematical model is given by (1).

$$\begin{bmatrix} V_{AN} \\ V_{BN} \\ V_{CN} \end{bmatrix} = \frac{V_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_A \\ S_B \\ S_C \end{bmatrix} \quad (1)$$

where V_{AN}, V_{BN}, V_{CN} represent the corresponding phase voltage, V_{dc} voltage of the DC bus and S_A, S_B, S_C the switching states of each phase which have the following relationship:

$$S_x = 0 \Leftrightarrow V_x = 0 \quad S_x = 1 \Leftrightarrow V_x = V_{dc} \quad (2)$$

A two levels and three legs inverter can provide $2^3 = 8$ configurations, or 8 feasible voltage vectors in α-β frame, which is stationary (Fig. 2) respect to the stator. Two of them, V_0 and V_7, correspond to the same null vectors.

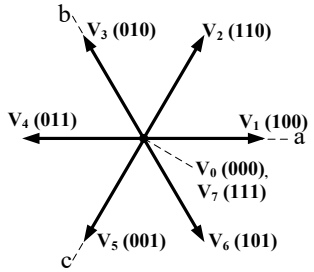

Fig. 2 Configurations of a 2-level 3-phase inverter $V_i(S_A S_B S_C)$

B. Modelling of PMSM

In this paper a non-salient pole PMSM is considered, which means the magnetic circuit operates in linear region, the electromotive force is sinusoidal and the magnetic losses and the cogging torque are negligible. Under these assumptions, defining the d axis of d-q frame synchronous with the flux, the equations of the electrical machine can be expressed as follow:

$$\begin{bmatrix} \frac{dI_d}{dt} \\ \frac{dI_q}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & \omega_e \\ -\omega_e & -\frac{R_s}{L_s} \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} + \begin{bmatrix} \frac{1}{L_s} & 0 \\ 0 & \frac{1}{L_s} \end{bmatrix} \begin{bmatrix} V_d \\ V_q \end{bmatrix} - \begin{bmatrix} 0 \\ \frac{\varphi_f \omega_e}{L_s} \end{bmatrix} \quad (3)$$

V_d, V_q: Stator Voltage.

I_d, I_q: Stator Current.

L_s: Synchronous inductance.

φ_f: Permanent magnets flux.

R_s: Stator resistance.

ω_e: Electrical speed.

Since MPC algorithm must be implemented in a digital controller, it's necessary to discretize the continuous state model. Defining T_s the interval of prediction, the discretized state model is shown below. The index k represents the samples taken in T_k.

$$\begin{bmatrix} I_d(k+1) \\ I_q(k+1) \end{bmatrix} = \begin{bmatrix} 1 - T_s\frac{R_s}{L_s} & T_s\omega_e(k) \\ -T_s\omega_e & 1 - T_s\frac{R_s}{L_s} \end{bmatrix} \begin{bmatrix} I_d(k) \\ I_q(k) \end{bmatrix} + \begin{bmatrix} \frac{T_s}{L_s} & 0 \\ 0 & \frac{T_s}{L_s} \end{bmatrix} \begin{bmatrix} V_d \\ V_q \end{bmatrix} + \begin{bmatrix} 0 \\ T_s\frac{\varphi_f\omega_e(k)}{L_s} \end{bmatrix} \quad (4)$$

with obvious notations,

$$I_{dq}(k+1) = A(\omega_e)I_{dq}(k) + BV_{dq}(k) + C(\omega_e) \quad (5)$$

and it will be assumed that the rotor speed is constant over a period T_S.

C. Cost function

The cost function represents the desired control strategy and the control is realized by optimizing this function at each instant of calculation.

For the torque control of a PMSM, the cost function is based on the electromagnetic torque and the stator flux. In order to have a homogeneous term, the predicted d-q frame currents $I_d(k+1)$, image of flux, and $I_q(k+1)$, image of torque, are used and compared to their reference. Then, the cost function is given by:

$$g = \left(I_{d\_ref}(k) - I_d(k+1)\right)^2 + \left(I_{q\_ref}(k) - I_q(k+1)\right)^2 \quad (6)$$

which has to be minimized in order to find out the best voltage vector which bring the d-q frame currents to their reference. As a smooth pole machine, I_{d_ref} is set to zero according to MTPA (Maximum Torque per Ampere) law.

D. Predictive Torque Control

Predictive Torque Control belongs to the catalog "Finite Control Set-Model Predictive Control (FCS-MPC)". During each calculation period, it predicts the currents in next-time and evaluates the resulting cost function for each of the 6 effective voltage vectors and for one of the 2 null vectors. After 7 iterations, the optimal voltage vector towards the criterion is kept. As the voltage vector corresponds to a given configuration of the inverter, modulation is not required. This method is relatively fast and simple but limited available vectors results in high current ripple and harmonic.

E. Control Schemes

1) Average Technique

As presented in [8]; [9], the configuration of this control strategy is shown in Fig. 3. Two machines are mapped into one whose sensor information (position, current) use the average value of two machines directly. As shown below:

$$\hat{\imath} = \frac{i_1 + i_2}{2} \quad (7)$$

$$\hat{\theta} = \frac{\theta_1 + \theta_2}{2} \quad (8)$$

Since there is only one control object, the cost function (6) remains unchanged.

2) Master-Slave

Fig. 4 present this configuration [10]. It separates two machines as Master and Slave. At each control instant, only the master machine is under control and let the slave machine open-loop operate. Based on stability consideration, by comparing their electrical angle, the machine with lower electrical angle which consequently has higher load torque would be chosen as the master. The cost function is kept the same as for one machine defined in (6).

3) Optimal Control

Differing with previous, as shown in Fig. 5, two machines are considered identically by defining two sub-cost function g_1 and g_1 for each machine [13]:

$$g_1 = \left(I_{d1}^1(k+1)\right)^2 + \left(I_{q1\_ref}(k) - I_{q1}(k+1)\right)^2 \quad (9)$$

$$g_2 = \left(I_{d2}(k+1)\right)^2 + \left(I_{q2\_ref}(k) - I_{q2}(k+1)\right)^2 \quad (10)$$

and the global cost function g which has to be minimized is now the algebraic sum of the two sub-criteria:

$$g = g_1 + g_2 \quad (11)$$

which intends to set the optimal state for two machines directly by choosing the optimal vector minimizing this cost function.

III. Experiment

Fig. 6 shows the experiment bench. Three PMSM are parallel placed. PMSM 1 and PMSM 2 are identical experimental machines. The machine between them is used as an external controllable load torque generator. Each of them is connected to a linear actuator ball screw driven and drives its own slide. In this experiment the slide of PMSM 1 was connected rigidly to load generator's slide.

A. Output delay consideration

For a digital control system, the output can only be updated until the start of next period [16], which means the input is sampled at k-th time instant t_k and the output is updated at t_{k+1}. In the period t_k, the predictive model must be able to estimate the system response at t_{k+2} so as to determine the output at t_{k+1}.

For this problem, paper [16] presents an iterative two steps predictive model, which is indicated below:

$$\hat{I}_{dq}(k+1) = AI_{dq}(k) + BV_{dq}(k) + C \quad (12)$$

$$\hat{I}_{dq}(k+2) = A\hat{I}_{dq}(k+1) + BV_{dq}(k+1) + C \quad (13)$$

In the first step, $\hat{I}_{dq}(k+1)$ is predicted with the voltage vector $V_{dq}(k)$ obtained in t_{k-1}. In the second step, voltage vector $V_{dq}(k+1)$ will be evaluate as described before.

The parameters of the PMSM used in the experiment are summarized in TABLE I.

During the experiment, the two machines were first put in steady state. Then, an external load torque was applied to

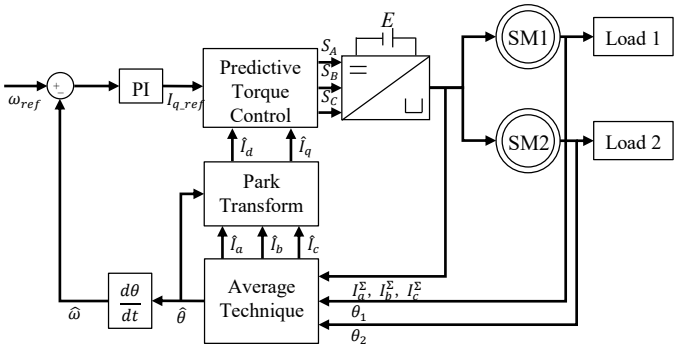

Fig. 3 Average technique with predictive torque control

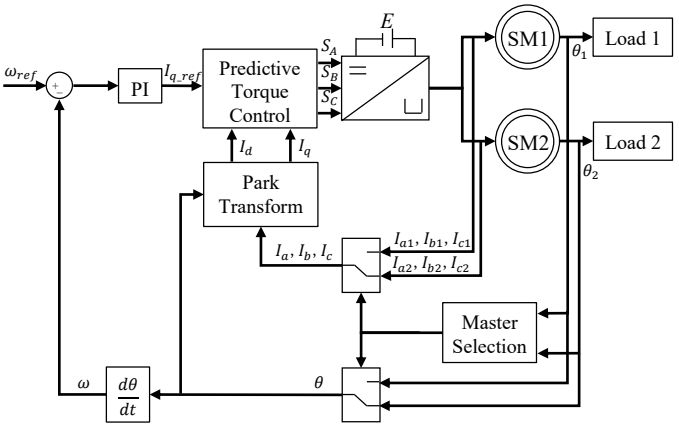

Fig. 4 Master with predictive torque control

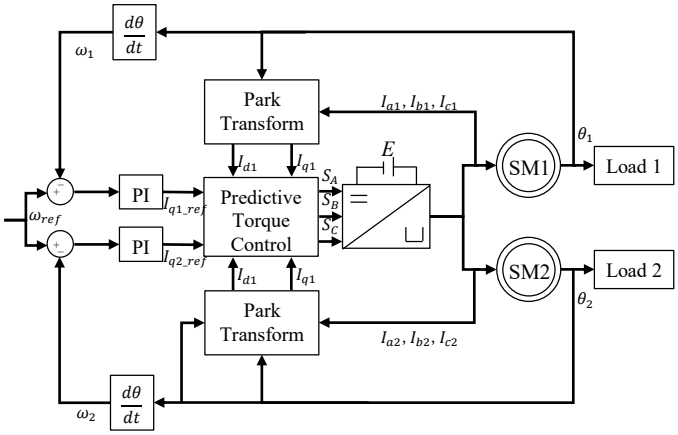

Fig. 5 Optimal predictive torque control

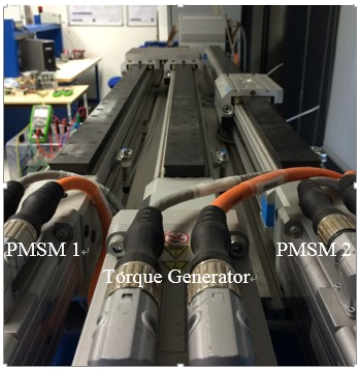

Fig. 6 The experimental bench

TABLE I
PARAMETERS OF PMSM

Symbol	Description	Value
V_{dc}	Voltage of the DC bus	30V
I_n	Nominal Current	4.3A
P_n	Nominal Power	913W
f_{dec}	Control frequency	10 kHz
R_s	Stator resistance	1.25Ω
L_s	Cyclic inductance	1.65 mH
φ_f	Amplitude of the flux due to the magnets	0.039 Wb
N_p	Number of pairs of poles	4
K_c	Torque constant	0.32 Nm/A

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ul ig. 7. For machine 2 the load torque was not applied.

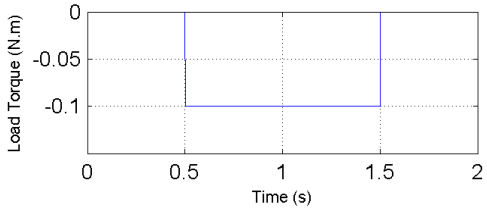

Fig. 7 Load torque applied to machine 1

The results of speed response of each control strategy are shown from Fig. 8~Fig. 10. And Fig. 11~Fig. 13 represent respectively the results of corresponding current response. The current response clearly shows Average Technique and Master-Slave can batter handle the system during load torque transient. And all control strategies can properly operate under unbalanced load torque situation.

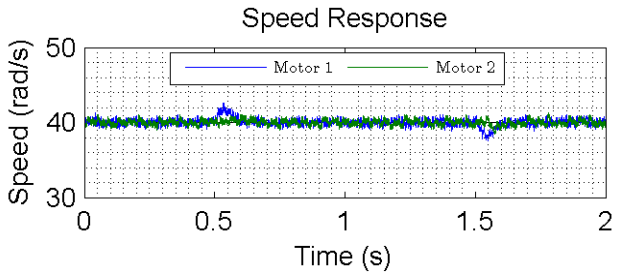

Fig. 8 Result of speed response for Average Technique with PTC

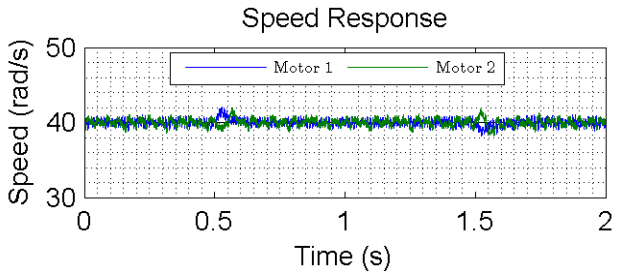

Fig. 9 Result of speed response for Master-Slave with PTC

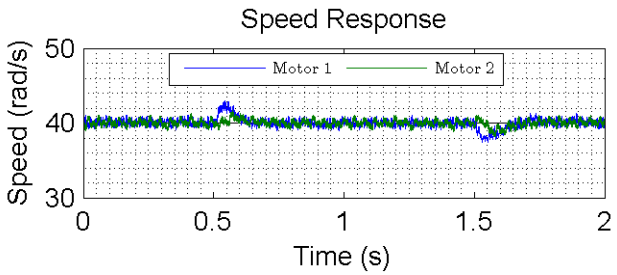

Fig. 10 Result of speed response for Optimal PTC

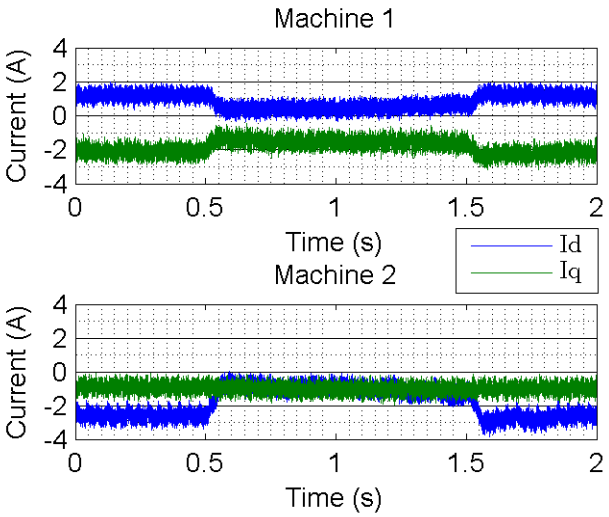

Fig. 11 Result of current response for Average Technique with PTC

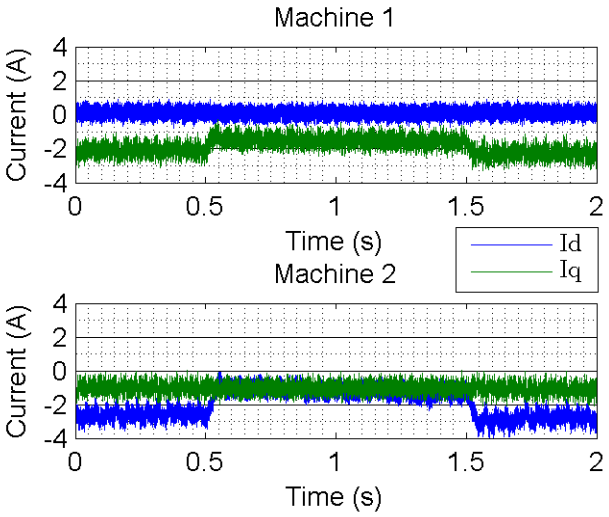

Fig. 12 Result of current response for Master-Slave with PTC

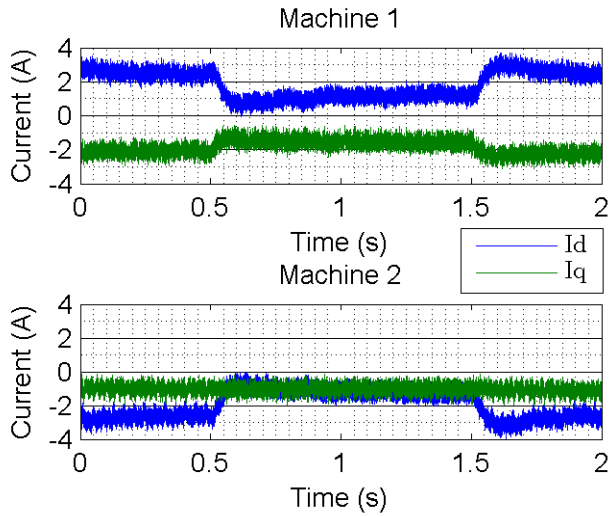

Fig. 13 Result of current response for Optimal PTC

B. Comparison of Control Law

Five performance indicators which evaluates different aspect of the candidate control strategies are employed in making the comparison.

1) Integration Squared Error (ISE) of Speed

ISE of speed response indicates the control quality of each control strategy especially during loader torque transient. It is calculated as the integration of the square error between reference and actual system response. Since the measure data are discrete, it is necessary to do the discrete integration as shown below:

$$ISE = \sum_{k=1}^{N} \left[\left(\omega_{1\_ref}(k) - \omega_1(k) \right)^2 + \left(\omega_{2\_ref}(k) - \omega_2(k) \right)^2 \right] T_S \quad (14)$$

where T_s represents the sampling period. In this case, it equal to control period (100us). And N equals to total sample number. The definition here also valid for following equations.

2) Supplementary Joule Loss

$$Joule\ Losses = \sum_{k=1}^{N} (I_{d1}(k)^2 + I_{d2}(k)^2) R_s \quad (15)$$

This indicator represents the power losses due to the d-axis currents which doesn't generate mechanical power. On the other hand it characterizes the current efficiency of each control strategy. For this special parallel connected PMSM configuration, it is not possible that I_d of both machines equal to zero if load torque or electrical angle are different [17].

3) Inverter Switching Loss

With the switching frequency increase, the state change of IGBTs used in an inverter contribute a significant amount to the total system losses. As PTC is variable switching frequency, which will vary respect to different control strategy, it worth studying the actual difference of switching loss between them. Since the switching losses only happens when IGBT change state, there is a fast way that counting their switching times directly to approximately evaluate the switching losses.

4) Total Harmonic Distortion (THD)

The Total Harmonic Distortion is a measurement of the harmonic distortion level and is defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency. This indicator characterize the power quality of electric power systems. It is calculated as:

$$THD = \frac{\sqrt{I_2 + I_3 + \cdots}}{I_{fundamental}} \times 100\% \quad (16)$$

5) Total Power Efficiency

Total power efficiency is defined as the ratio between mean mechanical power and mean input electrical power. The mechanical power can be calculated as the sum of the product between speed and torque of each machine meanwhile the electrical power is the product of DC bus current and voltage.

The total power efficiency is calculated as:

$$\eta = \sum_{k=1}^{N} \frac{N_p \varphi_f \left(I_{q1}(k)\omega_{m2}(k) + I_{q1}(k)\omega_{m2}(k) \right)}{I_{dc}(k) V_{dc}(k)} \times 100\% \quad (17)$$

All performance indicators takes the average value of five independent experiments in order to compensate the random influence. Their results are summarized in TABLE II.

TABLE II
RESULTS OF INDICATORS

Indicator	Average	Master-Slave	PTC
ISE (rad²/s)	**0.82**	0.88	1.25
Joule Loss (J)	13.26	**11.89**	22.28
THD (%)	4.76	6.39	**4.26**
Efficiency (%)	49.42	**49.58**	44.32
Switching Loss (count)	23566	23918	**23056**

The results show each control strategy owns advantages in different aspects. The performance of Average Technique and Master-Slave in control quality and system efficiency, including ISE, Joule Loss, and Efficiency, is relatively close and much better than Optimal Control. Among these three indicators, Master-Slave provides better system efficiency but not significant. And Average Technique gives higher control quality especially during load torque variation. On the other hand, Optimal Control provides lowest THD and switching loss, which both mean it generates less state changes to the inverter.

But the experiment also shows total power efficiency of the system is relatively low (< 50%). The problem is that the experimental machine has not worked under optimal condition. The power efficiency of PMSM can be defined as (18). If taking $\omega_m = 40 rad/s$, $|I_q| = 2A$, $|I_d| = 0A$ and the power efficiency of inverter is 95%, the theatrical optimal efficiency is only around 68%.

$$\frac{\omega_m \cdot N_p \varphi_f I_q}{\omega_m \cdot N_p \varphi_f I_q + R_s I^2} \times 100\% \qquad (18)$$

Considering machines are parallel connected, it's impossible that each machine works at its maximum efficiency point, or optimal point, which even decreases the total power efficiency. While lower efficiency performance of Optimal Control indicates that the optimal point of the entire system cannot be easily get through minimizing an algebraic sum of the optimal point of each machine. The future work should be in looking for an alternative way in setting the optimal point.

All performance indicator of each control law are arranged in Fig. 14 for a more intuitive understanding.

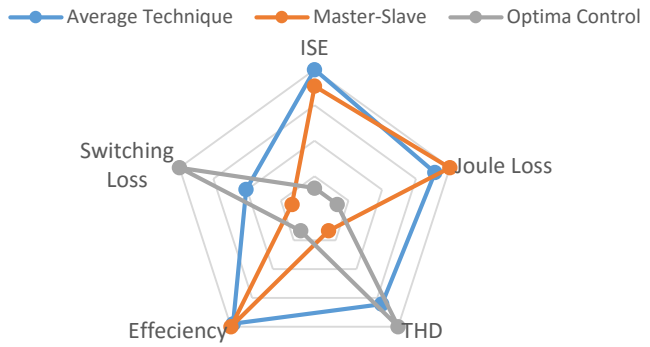

Fig. 14 Performance comparison of all control law (the best is at the border)

IV. Conclusion

The parallel connected PMSM configuration has given an alternative way to reduce the weight and volume of onboard actuator system. Three control strategies, which are based on predictive torque control but with different configuration, have been evaluated. The result proves the proper operation of the system. Moreover the performance comparison indicates that different controller configuration significantly impacts the system performance: Average Technique and Master-Slave presents relatively close performance in control quality and system efficiency and much better than Optimal Control. While Optimal Control provides lowest THD and switching loss.

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