

OPEN LOOP TORQUE CONTROL BASED ON LOOK-UP TABLES TO ANALYSE THE POWER LOSSES OF THE INTERIOR PERMANENT MAGNET SYNCHRONOUS MOTOR FOR ELECTRIC VEHICLE APPLICATION

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The Interior Permanent Magnet Motor (IPMSM) gained a vast interest in the automotive industry, due to its high efficiency, high power, and torque density. However, to reach its highest performance, it requires an effective control method that guarantees optimum energy utilization at different speed levels. The IPMSM control technique used to be applied by an open-loop torque control. For the sake of this paper, a virtual dynamo-meter is developed using MATLAB/Simulink to test a look-up table based flux weakening strategy against the zero d-axis current control technique. Both techniques were compared in terms of accuracy, IPMSM losses, and the complexity of implementation.

Keywords: IPMSM, Virtual dynamo-meter, Electric Vehicle, Flux weakening, Look-up table

1. Introduction

Permanent magnet synchronous motors (PMSM) became a preferred option in the automotive industry due to high efficiency and high power to weight ratio [1]. High efficiency is necessary for EVs since it is directly related to the travel distance per charge, battery size, and vehicle cost [2]. The high power factor is a desirable attribute for a higher efficiency, and this is an interesting feature of the IPMSM because of the presence of the reluctance torque. The use of the reluctance torque is related to the increase in the power factor [3], and that is what makes the IPMSM the best choice for EV applications rather than a surface mounted configuration (SPMSM). Drive control is required to set the requested torque with high precision and accuracy, and this will ease the integration of IPMSM into the vehicle's powertrain.

Accuracy has always been the target of designing high-performance controllers for EVs. Due to space, weight and cost reasons, the torque is not

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measured, and the torque control is realized in an open-loop structure with an inner closed-loop current controller [3]. In a field-oriented control scheme, an operation point selection strategy is essential to choose the appropriate current set points to generate the requested torque with high precision and optimal efficiency [3]. The main torque control strategies for IPMSM are the maximum efficiency, maximum torque per ampere (MTPA), I_d equal zero, unity power factor, constant mutual flux linkages [4], and Maximum torque per voltage (MTPV). Permanent magnet machines are often considered due to their high torque-per-ampere characteristics and potential for long field-weakened operation [5].

The MTPA control strategy, known for several decades, provides maximum torque for a given current. This, in turn, minimizes copper losses for a given torque [4]. The losses in an IPMSM consist of the mechanical loss, copper loss, iron loss, and stray loss. The mechanical loss is dependent on the rotor speed, but not controllable. The controllable losses are copper and iron losses [2]. However, iron and stray losses have a strong dependence on motor speed. Since MTPA is independent of the frequency ω , it does not reflect iron or stray loss. It can be interpreted as the copper loss minimizing solution [2]. Note that the MTPA control is not feasible in the field weakening region due to the voltage limit [6]. In the field-weakened mode of operation, the optimal current commands to the machine become a function not only of torque requested and speed but also of battery voltage and machine temperature [5].

The benefit of field weakening control can be seen from the perspective of torque production [6]. In practice, the optimal current commands are found experimentally and stored as a current command in a lookup table. The experimental method searches for I_d and I_q current pair of the minimum magnitude for each electric torque (T_e) and rotor speed (ω_r) pair, measured using a dynamo-meter system, or estimated off-line from FEA data (look-up table)[6],[7]. These look-up tables can be utilized in open-loop torque control algorithms, and are verified to achieve high torque control accuracy and are suitable for torque control of PMSM in automotive applications [7]. However, this approach requires costly and time-consuming measurements to construct the look-up tables [2]. On the other hand, the model-based design helps engineers to perform more testing by simulating a virtual dynamo-meter in Matlab/Simulink to reduce the hardware testing and overall development time [8].

2. PMSM Model

IPMSM model in dq frame with simplified loss representation [4] is given in Fig. 1, where I_d and I_q torque-generating currents, respectively. I_{dc} and I_{qc} are q -axis and d -axis core loss currents. I_{qs} and I_{ds} are d -axis and q -axis currents, V_{ds} and

V_{qs} are d and q -axis stator voltages respectively. R_s and R_c are stator and core loss resistors. L_d and L_q models the q -axis and d -axis self-inductances, λ_{af} is the magnet flux linkage and ω_r is the rotor electrical speed.

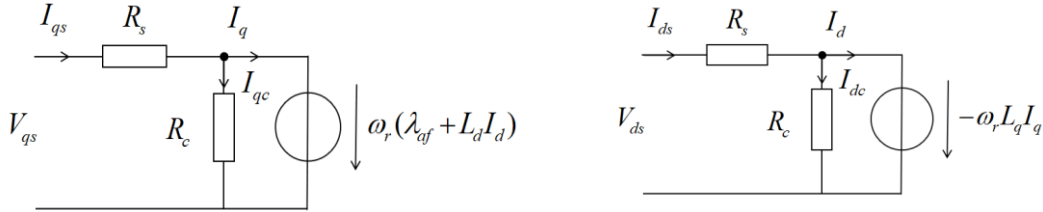


Fig. 1. q-axis and d- axis steady state model in rotor reference frame including stator and core losses resistances.

2.1 Loss model and electrical equations of IPMSM

The motor power loss was calculated by implementing (5) and (6). However, there are other ways to estimate IPMSM losses by subtracting the motor mechanical power and the inverter losses from the input power at the DC -link [2]. The Iron loss is modelled by equivalent resistance R_c in parallel to the induced voltage [3] as shown in Fig. 1.

$$\begin{bmatrix} I_{qs} \\ I_{ds} \end{bmatrix} = \begin{bmatrix} I & \frac{L_d \omega_r}{R_c} \\ -\frac{L_q \omega_r}{R_c} & I \end{bmatrix} \begin{bmatrix} I_q \\ I_d \end{bmatrix} + \begin{bmatrix} \frac{\lambda_{af} \omega_r}{R_c} \\ 0 \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} V_{qs} \\ V_{ds} \end{bmatrix} = \begin{bmatrix} R_s & \omega_r L_d \left(1 + \frac{R_s}{R_c}\right) \\ -\omega_r L_q \left(1 + \frac{R_s}{R_c}\right) & R_s \end{bmatrix} \begin{bmatrix} I_q \\ I_d \end{bmatrix} + \begin{bmatrix} \omega_r \lambda_{af} \left(1 + \frac{R_s}{R_c}\right) \\ 0 \end{bmatrix} \quad (2)$$

The torque T_e equation is given by (3):

$$T_e = \frac{3}{4} P (\lambda_{af} I_q + (L_d - L_q) I_d I_q) \quad (3)$$

Where T_e and P are the torque and number of rotor poles respectively. The copper loss is given by (4):

$$P_{copper} = 1.5 R_s (I_{qs}^2 + I_{ds}^2) \quad (4)$$

The main losses of the IPMSM are the copper loss that developed by the stator coil and core or Iron loss that accounts for hysteresis and eddy current losses. The net core loss P_c and the total losses P_t can be written as follows:

$$P_c = \frac{1.5\omega_r^2 (L_q I_q)^2}{R_c} + \frac{1.5\omega_r^2 (\lambda_{af} + L_d I_d)^2}{R_c} = \frac{1.5}{R_c} \omega_r^2 \lambda_m^2 \quad (5)$$

$$P_t = 1.5R_s (I_{qs}^2 + I_{ds}^2) + \frac{1.5}{R_c} \omega_r^2 [(L_q I_q)^2 + (\lambda_{af} + L_d I_d)^2] \quad (6)$$

Where λ_m is the air-gap flux linkages.

3. Open loop torque control structure

In this section, different current control techniques have been implemented, and compared in terms of power losses of IPMSM, such as the zero d -axis current and flux weakening strategy based on look-up tables.

3.1 Zero d -axis current control technique

This vector control technique works by maintaining the d -axis current at zero, which makes the torque proportional to the q -axis current [4]. The current controller is made up of a PI controller. When we set the I_d current to zero in (3), equations (7) is obtained:

$$I_q = T_e \left(\frac{3}{4} P \lambda_{cf} \right)^{-1} \quad (7)$$

In this control mode, the torque generation is realized by controlling I_q . Therefore, the control system is easy to implement, and high-performance torque control can be achieved [10]. The Fig. 2 shows the drive system configuration for torque control of IPMSM, in this system the block converts the torque command into I_q current reference according to equation (7).

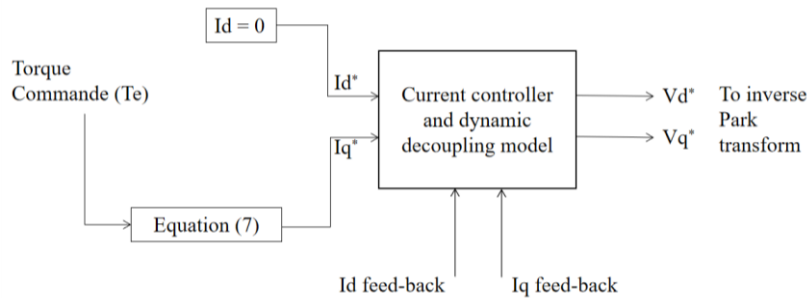


Fig. 1. Current controller implementation for $I_d = 0$ technique.

3.2 Look-up table based control strategy

The schematic diagram in the Fig. 3 describes the flux weakening control strategy. It shows different operating regions (MTPA, MTPV). The I_d and I_q tables have been generated from finite element analysis data by [9] using a Model-based calibration toolbox (MBC). The controller provides the minimum magnitude of I_d and I_q currents to the closed-loop current controller after it receives the torque request from the virtual dynamo-meter, and the speed feedback of the IPMSM to be compared to the rated speed. The controller provides understanding of the behaviour of the machine below and above base speed regions.

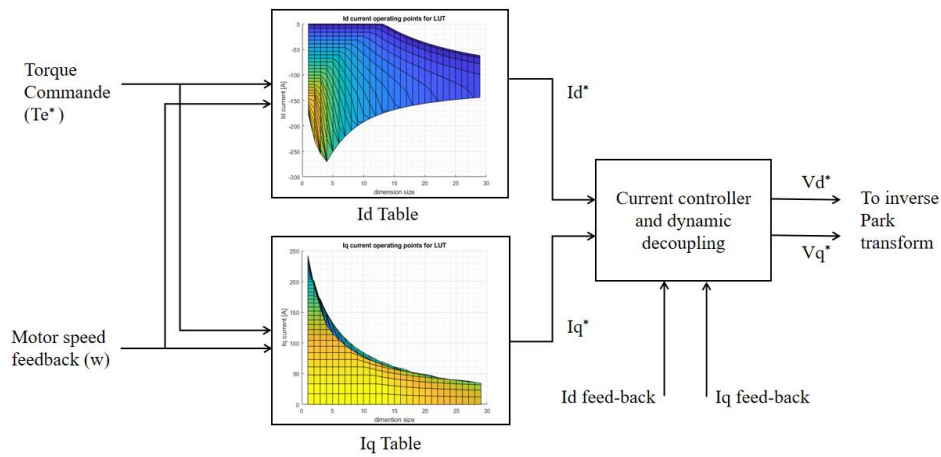


Fig. 2. Implementation of open loop torque control look-up table based flux weakening strategy for IPMSM.

In IPMSM drives, the amplitudes of the stator current and the voltage vector are limited by the rated current of the insulated gate bipolar transistor (IGBT) and the DC-link voltage, respectively [10]. As the torque and speed increase, resources of the inverter are utilized to the maximum, i.e., either current, voltage, or both are utilized maximally. Hence, the loss minimizing solution is obtained either inside of the voltage and current constraints or on the current/voltage limit boundary [1] (see Fig. 4). For example, one section of the optimal operation boundary is known as the maximum torque per ampere (MTPA) curve. To calculate this curve, we can use Model-Based Calibration Toolbox to set up a DoE (design of experiment) which lets us sweep the current operation points along a current circle and monitor the torque until the maximum torque point is reached. Similar approaches can be used for calculating the maximum current and maximum torque per volt (MTPV) boundaries [8]. In Fig. 4 the operation points enveloped in the (I_d , I_q) plane depicts the different trajectories taken by the controller, which provides the best

operating points to ensure the minimum losses during different speed levels. Using Model-Based Calibration Toolbox (MBC) is used to set the maximum torque per ampere (MTPA) curve as the objective, then the maximum phase current i_{max} and voltage v_{max} are set as constraints as shown in (8) and (9), and finally we run the optimisation [8] to generate the current operating points envelop as shown in Fig. 4.

$$v_d^2 + v_q^2 \leq v_{max}^2 \quad (8)$$

$$i_d^2 + i_q^2 \leq i_{max}^2 \quad (9)$$

The machine is limited by the maximum current magnitude in the constant-torque region [5]. The MTPA strategy presents one of these solutions, it assumes that the overall electrical losses are mainly ohmic losses caused by the winding resistors and therefore the torque is generated with minimal current magnitude [3].

However, the machine operates with maximum torque per ampere while it does not reach its voltage constraint (constant torque region). The appropriate operating points are found on the MTPA trajectory from point A to B (see Fig. 4) [7]. If the requested torque is feasible, but cannot be realized on the MTPA trajectory, appropriate operation points are found on the respective flux weakening curve between B and C. For very-low torque request (or in a constant power region) the operating points can be found on the MTPV trajectory between C and D. Finally, for very high speed, the operating points are found in the deep flux weakening region from D and E.

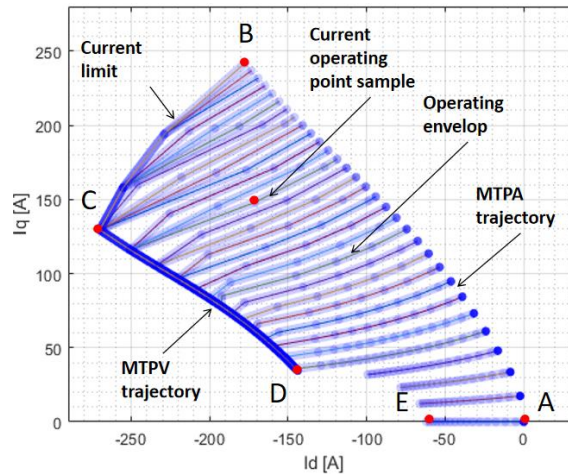


Fig. 3. Plot of current envelop in the (i_d , i_q) plane.

4. Results

A computer-based dynamo-meter was developed using Matlab/Simulink to test an open-loop torque control for a look-up table based flux weakening strategy, and a zero d -axis current controller to investigate the motor losses, and behaviour of the IPMSM during motoring and generating modes (below and above base speed regions). Fig. 5 shows the torque request and the dynamo-meter speed reference. Initially, the machine operated at zero RPM, and it gradually increased to 1000 RPM. Next, the dynamo-meter speed maintains at a constant value from 0.3s to 0.6s. Afterwards, the motor speed increased up to 1800 RPM and remained at this level until the end of the test. During speed changes, a torque command is applied to test the IPMSM model during motoring and generating modes. Negative and positive torque requests are applied to simulate the vehicle's accelerator pedal during acceleration and deceleration periods.

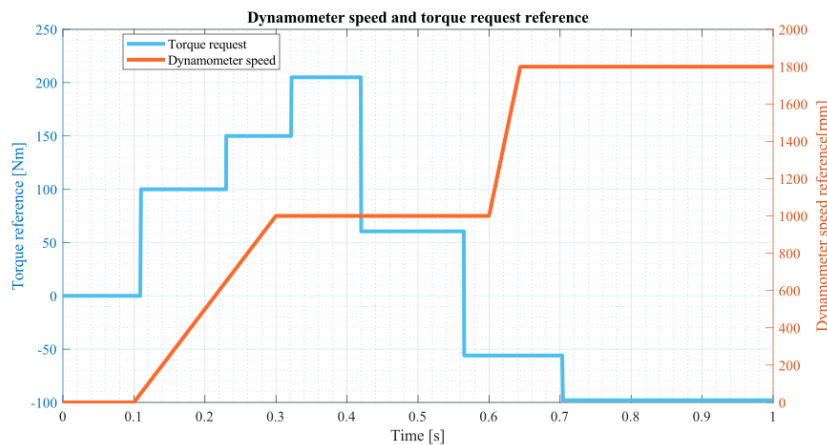


Fig. 5. The speed applied by the dynamo-meter test-bench and the torque request for testing the motor during motoring and generating modes below and above base speed.

Fig. 6 shows the IPMSM torque response for a period of 1 s. The torque response of the flux-weakening control strategy followed the torque reference applied by the dynamo-meter below and above base speed. On the contrary, the $I_d = 0$ (see Fig. 6) control strategy does not follow the torque request at the flux-weakening region from 0.7s to 1s where the motor speed is 1800 RPM. This is explained due to the stator's voltage limit at high speeds.

Fig. 7 shows the phase current of the IPMSM for flux weakening and the $I_d = 0$ technique. It can be observed from the figures that the current delivered

by the inverter for the $I_d = 0$ strategy was higher than the current absorbed by the IPMSM in the case of the look-up table based technique, especially at the high-speed region when the motor controller stops following the dynamo-meter torque request. The phase current exceeded 150A in case of $I_d = 0$ at high torque command, whereas in the case of the flux weakening, the current is greater or equal to 100A at high torque command request. On the other hand, the phase current reached high values that almost equal twice to the current phase achieved by the flux weakening controller.

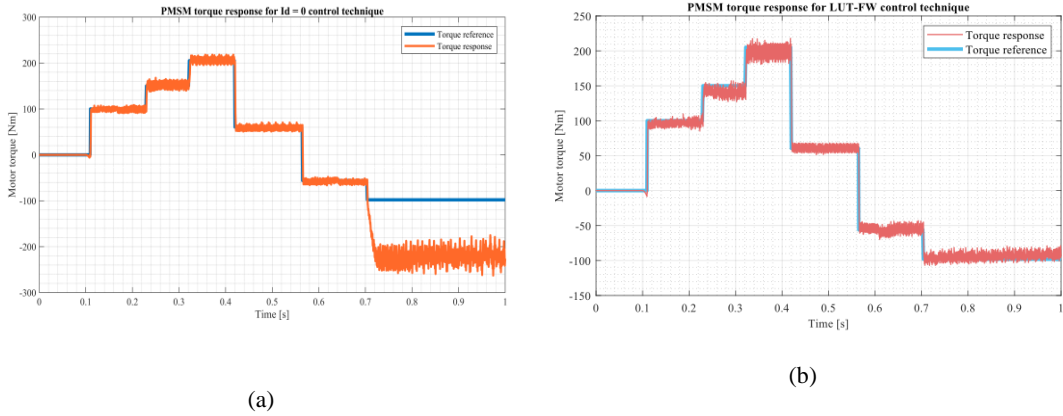


Fig. 6. The torque response for (a) zero I_d strategy and (b) look-up table flux weakening control during motoring and generating modes.

The overall IPMSM losses for $I_d = 0$ and flux weakening control techniques are depicted in Fig. 8, the latter, is calculated based on the copper and core losses formula (4),(5), and (6). We can observe that the losses in the case of I_d equal zero are greater than the FW-LUT strategy. The green line represents the speed applied by the dynamo-meter, and along with that speed, the IPMSM kept the losses at a lower level in the case of the FW-LUT technique. On the other hand, the $I_d = 0$ strategy did not perform well during transition periods and at the high-speed level.

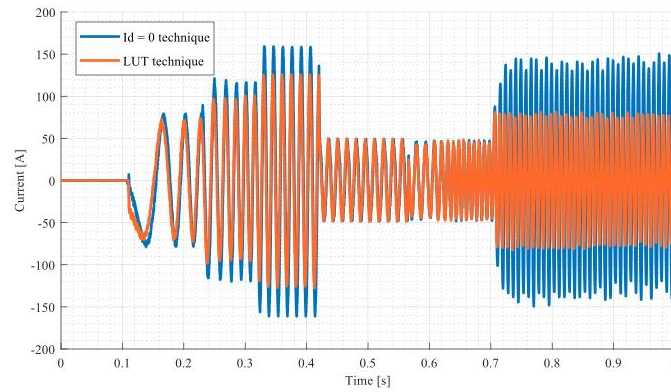


Fig. 7. Phase current for $I_d = 0$ and flux weakening strategy based on look-up tables (LUT).

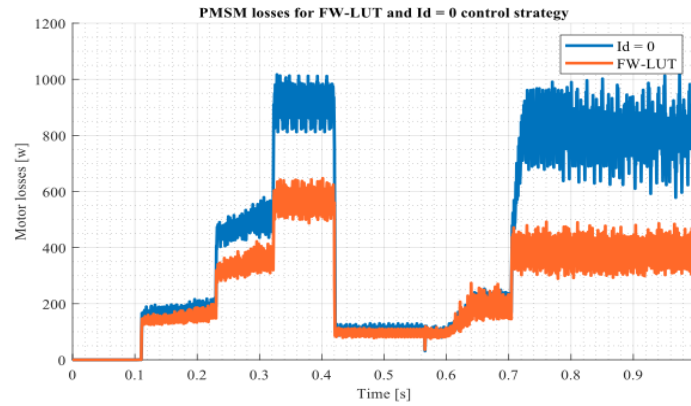


Fig. 8. IPMSM losses for flux weakening and $I_d = 0$ controller strategy.

I_d and I_q currents followed the exact current references generated by look-up tables. It is worth mentioning that the I_q current for the control technique ($I_d = 0$) is much higher than the FW-LUT strategy. During motoring mode, when we apply a positive torque, the I_d current takes a negative value, and positive values in generating mode (see Fig. 9).

The iron and copper losses were compared for both control techniques in Fig. 10. We notice that the loss is high for both strategies during high torque requests, and also during the transition periods. Nonetheless, it tends to be higher in the case of the I_d equal zero control strategy. When a negative torque request is applied at the high-speed region, the copper losses increase by a factor of 3 compared to the FW-LUT. The iron loss (Fig. 11) is less than the copper loss below base speed, especially in the FW-LUT control strategy. However, The copper loss takes a large part of the total loss at the low-speed region, despite the control technique, especially in the FW-LUT control technique.

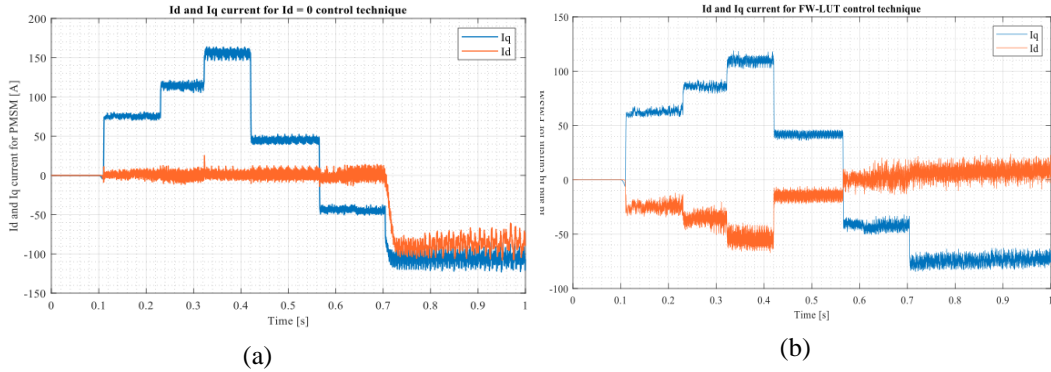


Fig. 9. Id and Iq response for (a) Id= 0 and (b) flux weakening strategy for different torque request levels.

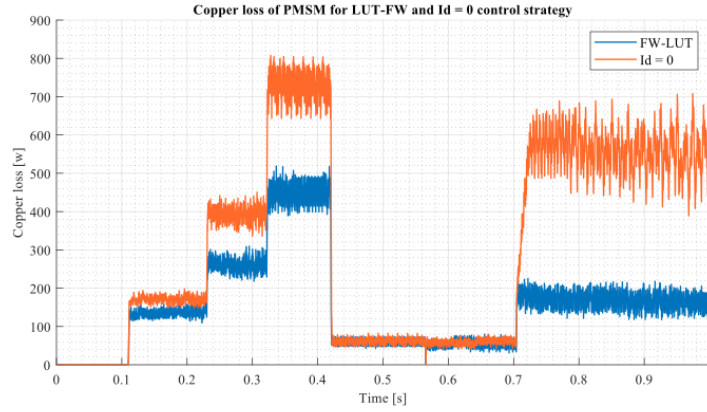


Fig.10. Copper loss comparison between zero d-axis and flux-weakening look up table based strategy amid motoring and generating modes.

5. Discussion

In this study, we developed a computer-based dynamo-meter using Matlab/Simulink. Different speed levels were applied by this dynamo-meter to investigate the IPMSM performance, through the analysis of the iron and copper losses under various torque requests. The Finite element analysis data published by [9] was used for flux-weakening control strategy, and the optimized look-up tables were generated using Model-Based Calibration (MBC) toolbox from Mathworks, the latter is then compared to zero *d-axis* current control technique.

The maximum torque per ampere (MTPA) is a current minimizing control technique for a given torque. It is a copper loss minimizing control [6]. The copper loss is related directly to the I_d and I_q current magnitude provided by the look-up tables. Since it is optimized by setting the MTPA as an objective in

MBC toolbox, we see that the copper loss, in this case is lesser than the losses produced by the motor in case of the $I_d = 0$ strategy, especially when the motor lost its control and the phase current reached a high level. At this level, the I_d current is no longer equal to zero, that is why the copper loss is increased in this part of the simulation.

With the increase of torque, I_d also increases in the negative direction during acceleration to weaken the air gap flux. Otherwise, the torque would drop rapidly due to the voltage limit. In other words, field weakening is a high-speed solution within the voltage boundary [6]. The iron loss is higher during deceleration since the speed decreases rapidly [2]. For the deceleration period, when a negative torque request is applied, the d -axis current decreases to minimize the copper loss high-speed, when the q -axis current converges to the negative values. It can be seen that losses at low torque are almost equal for both controlling techniques. In terms of design, the higher phase current requires a large and expensive inverter, and that's what happened to the current in the case of zero d -axis technique which is why this technique is considered as a below base speed strategy [4]. Therefore, we don't find this technique implemented in the automotive industry.

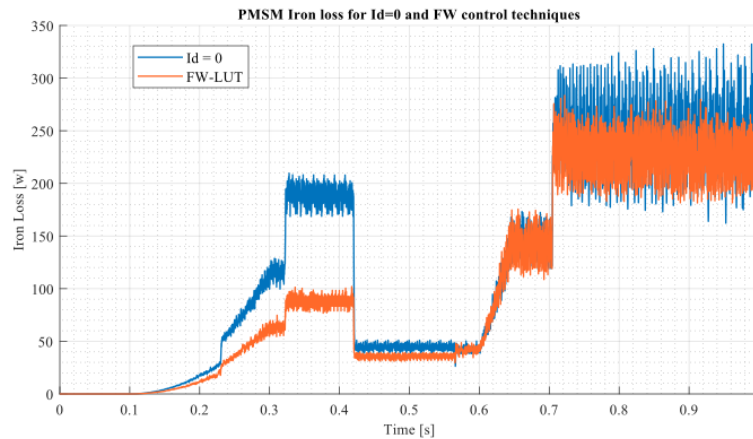


Fig. 11. Iron loss response of IPMSM for $I_d = 0$ and flux-weakening look-up table based strategy for below and above base speed regions.

6. Conclusions

The look-up tables flux weakening technique has been implemented and compared to zero d -axis current control technique, a well-known technique in

the industry application. In the first testing method, the simulation has shown that the torque response followed the reference applied by the dynamo-meter at different torque requests and speed regions when the other controller suffers at high-speed demand. In terms of efficiency, the IPMSM copper loss for the flux weakening strategy is less than in the zero I_d controller, especially at high speed when the motor loses its control. On the other hand, the iron loss is almost equal for both techniques at the high-speed region, but it is not the case at low speed, where the losses are higher in the case of zero d -axis current controller.

Reducing the losses of the IPMSM during motoring and generating modes especially at high speeds, will help in increasing the vehicle performance and extend its range. Therefore, the lookup table control technique could be an a loss minimising or an optimisation solution to address this issue. The proposed technique can be implemented in real-time to estimate the energy consumption of the FPGA-based high-level electric vehicle model, which provides accurate result during SIL, HIL and RCP testing.

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