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Flux-Weakening Strategy for High Speed PMSM for Vehicle Application

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Abstract— High speed Permanent Magnet Synchronous Motors (PMSM) are used in electrical vehicles because of their strong power density. The high speed implies a big electromotive force and requires flux-weakening. Usual control algorithms do flux-weakening by adding negative I_d current when the required voltage by the current regulation exceeds the maximum voltage depending on the battery. If the magnet can be totally defluxed then it is better to use a Maximum Torque Per Volt (MTPV) strategy. Furthermore there is no speed regulation in the control and the driver gives a torque reference that has to be limited to the reachable operating points; the battery power limit has to be taken into account in addition to the voltage and current limits. The d-q current reference are calculated to minimize the total current magnitude required to reach the reference torque. This paper presents a salient pole PMSM control that calculates the minimum magnitude current references to obtain the reference torque while respecting the voltage, current and power limits with a flux-weakening strategy and including MTPV operation in a unified algorithm. The effectiveness of the proposed method is observed through simulations.

Keywords—Flux-weakening, vector control, maximum torque per volt, torque speed characteristic, high speed permanent magnet synchronous motor.

I. INTRODUCTION

Electrical vehicles are the future of automobile because they are environmental friendly, have low noise, and because electrical motors have better efficiency than thermal motors, and electricity energy is cheaper than fuel energy. Electrical traction requires motors to have a high torque at low speed and a wide speed range of constant power. The Permanent Magnet Synchronous Motor (PMSM) is commonly used because it is the electrical motor that has the best power density and efficiency [1] and so is well adapt for embedded applications. The volume and mass of a PMSM is proportional to its torque. For congestion, mass and price reasons a smaller, lighter and with less magnets motor is chosen. It has less torque but the same power by operating at higher speed and by adapting the gear the desired torque speed characteristic of electrical traction is retrieved.

The motor is supplied by a battery trough a three phase inverter. The control is performed in the Park d-q-frame. The torque reference from the driver's pedal is used to calculate the d-q current references that are regulated by two polynomial

discrete corrector with a decoupling strategy and the consideration of delays [2]. A Power Width Modulation (PWM) strategy enables to generate the duty cycles for the inverters phases. When the speed increases so does the electromotive force of the machine, and because of the limit voltage of the battery, from a certain speed it is necessary to reduce the magnet flux perceived by the stator windings by imposing negative I_d current that will generate a flux opposite to the magnet flux. It is called flux- weakening.

The literature presents several flux-weakening control strategies [3 to 24] with [3,4,5] that are state of the arts of flux-weakening techniques. We suggest to classify these strategies in the following way: analytical direct calculation method [6,7], direct open loop algorithm with experimental LUT [8,9,10,11], Single Current Regulator (SCR) method [12,13,14,4], torque and flux control method with Look Up Tables (LUT) [15,16], Unified Direct Flux Vector Control (UDFVC) in the stator flux frame [17,18], and Vector Current Control (VCC) [15, 19 to 25]. This last method is divided into: regulation on the voltage magnitude [19,20,21,22,15], regulation on the voltage error [15,23,4], regulation on the current error [15,24], regulation on the duty cycle [15,25]. If the magnet can be totally defluxed, i.e. the critical point is within the current limit then a Maximum Torque Per Volt strategy (MTPV) is required for flux-weakening [4 to 7, 12 to 14, 17 and 26 to 30]. Analytical direct open loop calculation method [7,26,27], direct open loop experimental LUT [28,4,5,6,7], SCR method [12,13,14] and UDFVC [17] enables to do MTPV-flux-weakening. [29,30] uses VCC strategy associated with MTPV but requires algorithm switching. The open loop method with direct calculation from the motor equations is very sensitive to parameters variation and is also long to calculate in real time controls with torque references for salient poles motors. LUT in open loop or Torque and Flux Control (TFC) in closed loop is convenient for taking into account the magnetic saturation of inductances but depend on the motor and previous experimental sets have to be carried out. The SCR avoids in voltage saturation operation the competition between the classic d-axis and q-axis regulators but the method requires to switch to another control algorithm in low speed operation. The UDFVC is compatible for all alternative current machines however the use of a flux observer is necessary and the maximum load torque has to be find experimentally which makes the method dependent on the

motor. The classic flux-weakening is the VCC method. Nevertheless in the current error regulation the Low Pass Filter (LPF) impacts the control dynamic performances. The voltage error regulation and the duty cycles regulation also uses LPF with the same issues. They are also over modulation strategies enabling to increase the maximum voltage available at the expense of additional current harmonics. Lastly the voltage norm regulation is the conventional approach that needs a voltage maximum reference depending on the battery and the PWM used and allowing also to over modulate. The control developed in this paper is based on that approach.

The reachable operating points are dependent on the maximum current and voltage and on the power of the battery. In § II these limits are discussed and plotted in the torque speed frame. The previous mentioned flux-weakening strategies usually don't take into account the power limit and only consider the current and voltage limit. In this paper is presented an algorithm to calculate the current references in the d-q frame for salient-poles and smooth poles PMSM that respect the different limitations and includes the MTPV area operation in a same unified algorithm. The performance of the algorithm is observed through simulations.

II. ACHIEVABLE OPERATING POINTS

A. PMSM model and electric limits

The PMSM's electrical model equations are presented for the voltage in (1) and (2) and for the torque in (3).

$$V_d = R \cdot I_d + L_d \frac{dI_d}{dt} - \omega \cdot L_q \cdot I_q \quad (1)$$

$$V_q = R \cdot I_q + L_q \frac{dI_q}{dt} + \omega \cdot L_q \cdot I_q + \omega \cdot \phi_f \quad (2)$$

$$T = \frac{3}{2} \cdot p \cdot (\phi_f \cdot I_q + (L_d - L_q) I_d I_q) \quad (3)$$

Where V_d , V_q and I_d , I_q are respectively the voltage and currents in the d-q frame, L_d and L_q the d-axis and q-axis armature winding inductances, p the number of pair of poles, ω the electrical rotor angle velocity, R the resistance of the armature winding, Φ_f the flux linkage of the permanent magnet, T the electromagnetic torque.

The maximum current I_{max} (4) is the more constraining current limit between the nominal current of the motor, the nominal current of the inverter and the maximum current that can deliver the battery (brought back on an equivalent motor current).

$$\sqrt{I_d^2 + I_q^2} \leq I_{max} \quad (4)$$

The maximum voltage (5) depends on the voltage limit of the battery and the pulse width modulation used; here a space vector modulation (6).

$$\sqrt{V_d^2 + V_q^2} \leq V_{max} \quad (5)$$

$$V_{max} = \frac{V_{DC}}{\sqrt{3}} \quad (6)$$

Where V_{DC} is the voltage of the battery.

At high speed the resistance is usually negligible in (1) and (2). Thus the voltage limit can be written in steady state as (7).

$$\sqrt{(\omega L_q I_q)^2 + (\omega L_d I_d + \omega \phi_f)^2} \leq V_{max} \quad (7)$$

B. Torque Speed characteristic in electrical traction.

A reduced size salient poles PMSM is used for performing the experiments and the simulations. The parameters are displayed in Table 1. The vehicle application requires to have high torque at low speed and a wide speed range at constant power. On Fig. 1 is shown the maximum torque achievable according to the speed and in nominal operation for different control strategies. For Fig. 1 a smooth poles PMSM similar to Table. 1 but with L_d equal to L_q is used.

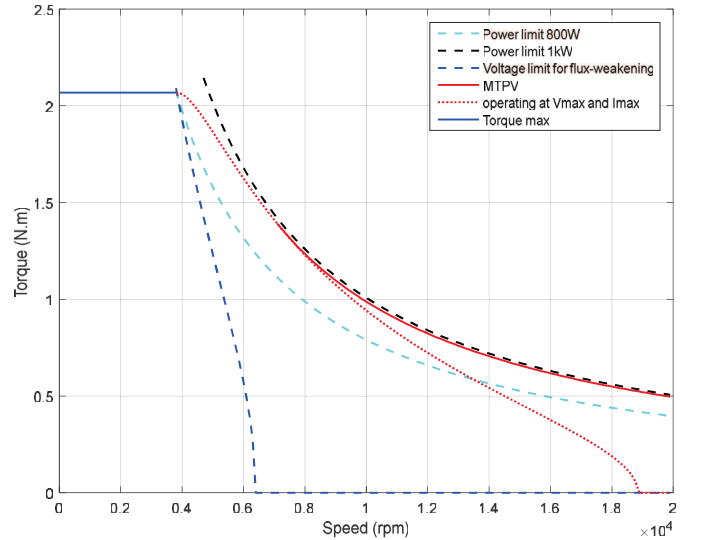


Fig. 1. Torque-speed characteristics of the smooth pole PMSM from Table 1.

TABLE I. IPMSM PARAMETERS

Reduced size salient pole PMSM parameters	
R	0.97 Ω
L_d	4.73 mH
L_q	5.77 mH
Φ_f	0.0345 Wb
p, number of pair of poles	5
I_{max}	8 A
V_{DC}	200 V
Power battery 1	1400 W
Power battery 2	1000 W
Close smooth pole PMSM used in some further simulations of the paper	
$L_d (=L_q)$	5.77 mH
Power battery 1bis	1000 W
Power battery 2bis	800 W

On Fig. 1 is plotted in blue-solid-line the maximum torque at low speed that is given by the maximum torque per ampere strategy with maximum current (8) and (9). The voltage limit is not yet reached, thus the operating points below this torque limit are imposed by the control with a strategy that minimizes the current required for the reference torque in order to reduce the losses. If this strategy is maintained when the speed increases then when the voltage limit is reached it gives the blue-dashed-line torque limit explicit in (12), and flux-weakening will need to be done to reach operating points at further speed. It is noticed that depending on the sizing of the inverter the current limit, and thus the torque limit, can be lower at speed near zero in steady state but that case is not addressed in this paper. The MTPA expression in the torque-speed frame is (3) with (8) and (9), with the torque reference that is represented by its equivalent current norm I_{norm} .

$$I_d = \frac{\phi_f - \sqrt{\phi_f^2 + 8(L_d - L_q)^2 I_{norm}^2}}{-4(L_d - L_q)} \quad (8)$$

$$I_q = \sqrt{I_{norm}^2 - I_d^2} \quad (9)$$

Where I_{norm} is the total current magnitude and depends on the torque reference or the output of the speed regulation if one is used. It is notice that for a smooth poles PMSM the classic MTPA current references (10) and (11) are obtained.

$$I_d = 0 \quad (10)$$

$$I_q = I_{norm} \quad (11)$$

The expression of the voltage limit in the torque-speed frame without flux-weakening for a smooth pole PMSM is (3) with (10) and (12). For a salient poles PMSM the MTPA strategy already adds some I_d current and so the expression of the torque depending on the speed and the voltage limit is (3) with I_d solution of (22) and I_q respecting (7).

$$I_q = \sqrt{\left(\frac{V_{max}}{L_q \omega}\right)^2 - \left(\frac{\phi_f}{L_q}\right)^2} \quad (12)$$

On Fig. 1 is plotted in red-dotted-line the maximum torque that can be achieved if the voltage limit and the current limit are reached, explicit in (13), (14) and (15). When the speed increases the electromotive force becomes more restrictive for the voltage. To respect the voltage limit the flux perceived by the stator winding has to be reduced. To do so a negative I_d current is applied that creates a flux opposite to the magnet flux, it is the flux-weakening. It can be noticed that the operating points below this torque limit are imposed by the controller with a classic flux-weakening algorithm (e.g. VCC) that will follow the intersection between the current limit and the voltage limit. It can also be notices that the torque-speed characteristic is not really a constant power limit if only the current and voltage limits defined in (4) and (7) are considered,

especially in the ‘‘top right corner’’ where the torque is high and the voltage limit is just reached. The classic power limit is more a battery limit or a mechanical requirement than a motor electric limit.

For a smooth poles PMSM:

$$I_d = \frac{V_{max}^2 - \omega^2 \phi_f^2 - L_q^2 \omega^2 I_{max}^2}{2L_d \omega^2 \phi_f} \quad (13)$$

For a salient poles PMSM:

$$I_d = \frac{L_d \phi_f}{L_d^2 - L_q^2} + \frac{\sqrt{L_d^2 \phi_f^2 - (L_d^2 - L_q^2)(\phi_f^2 + L_q^2 I_{max}^2 - \frac{V_{max}^2}{\omega^2})}}{L_d^2 - L_q^2} \quad (14)$$

And:

$$I_q = \sqrt{I_{max}^2 - I_d^2} \quad (15)$$

On Fig. 1 is plotted in red-solid-line the Maximum Torque achievable Per Volt (MTPV) explicit in (16) and (17). This requires that the magnet can be totally defluxed. It is possible if the critical point is within the current limit. In that case this strategy is the one that gives the highest torque at high speed. The control strategy in § III presents a way to include MTPV in a flux weakening method. Notice that in such case the speed is theoretically not limited by the electrical limits. The MTPV expression in the torque-speed frame is (3) with (16) and (17).

$$I_d = \frac{\left(\frac{V_q}{\omega} - \phi_f\right)}{L_d} \quad (16)$$

$$I_q = -\frac{V_d}{L_q \omega} \quad (17)$$

Where:

$$V_q = \frac{\phi_f - \sqrt{\phi_f^2 + V_{max}^2 \left(\frac{L_d - L_q}{L_q \omega}\right)^2}}{-4\left(\frac{L_d - L_q}{L_q \omega}\right)} \quad (18)$$

$$V_d = -\sqrt{V_{max}^2 - V_q^2} \quad (19)$$

It is noticed that for a non-salient poles PMSM the MTPV references become (20) and (21).

limitation that can be calculated by solving (22). To summarize if the motor is at salient pole and that the reference is a torque reference or that the power battery limit is constraining then (22) has to be solved, otherwise (8) can be used as in [31].

If it is possible to inject an I_d current that creates a flux that totally counters the magnet flux then it frees all the voltage (c.f. (1) and (2)) for generating torque and to follow the MTPV trajectory (16) and (17). This improvement of the control strategy is usually not taken into account in classic controls because it is useful to increase the torque only at very high speed and requires to totally flux-weaken the magnet. In the control MTPV strategy is translated by the modification of the torque limitation in Fig. 2 Bloc 1, and by creating a variable saturation in the I_d flux-weakening saturation. The Bloc 3 in Fig. 2 limits the I_d reference current by the more constraining limit between the maximal current (4) that is constant and the I_d current required by the MTPV strategy (11) that shortens to the critical point ($I_d = -\Phi_f/L_d$) when the speed increases [31].

The I_q current reference is calculated in Bloc 4 Fig. 2 using (3) with the knowledge of the I_d reference after flux-weakening and the torque limited reference. This Bloc 4 also ensures that the final d-q current reference respects the current limit.

IV. SIMULATION RESULTS

The performance of the method is observed through a simulation. The parameter used are shown in Table 1. The torque reference is 1.90N.m and so less than the maximum torque of 2.13N.m at low speed, to see the effect of flux-weakening while operating under the current limit, and then operating in both current and voltage limitations, when the speed increases and more negative I_d current is required.

Fig. 3 shows the current reference trajectory in the I_d - I_q frame. In blue the current limit (4) that is a circle centered on the origin of the frame and of radius the norm of the maximum current. In green the voltage limit (7) that is an ellipse centered on the critical point with its size that decreases when the speed increases. In blue-circles the desired current reference

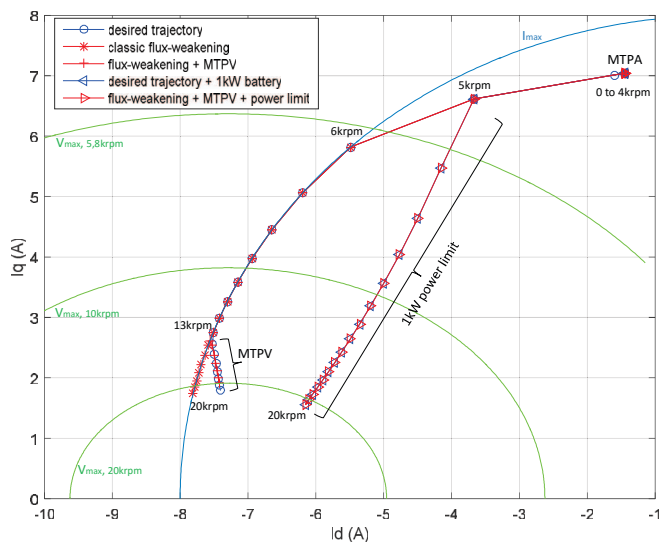


Fig. 3. I_q - I_d scheme of the currents references trajectories.

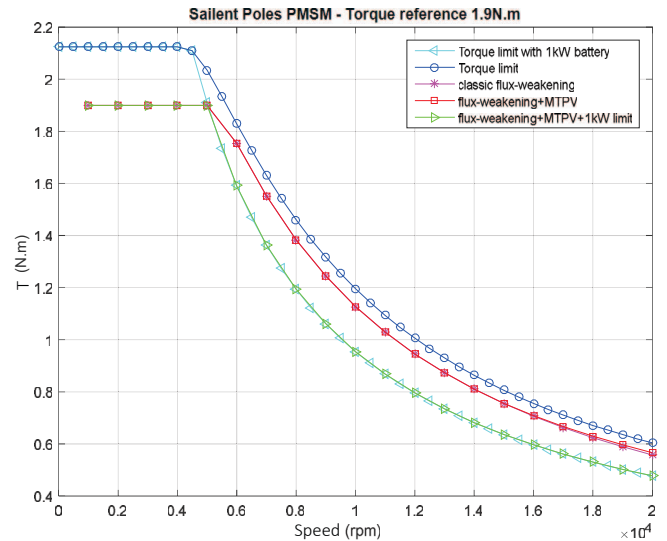


Fig. 4 Torque obtained in steady state depending on the speed with a reference of 1.9N.m for the salient-poles PMSM form Table 1.

trajectory in steady-state for an evolution of the speed calculated analytically. These references respect the limitation while generating the required torque with minimal magnitude current at the given speed. The same in blue-triangles but with a 1kW power battery that gives a power limit more constraining than the current and voltage limit. In red-stars the current reference given by a classic flux weakening algorithm that only takes into account the current and voltage limit and does not include a MTPV strategy in the control. It is notice that the current references generated by this algorithm are oversized at high speed and do not respect the battery power limit. In red-crosses the current reference calculated by the flux-weakening control presented in § III, and the same in red-triangles for a battery power limit of 1kW. One can notice that this algorithm follows the desired current reference trajectory whatever the speed and the constraining limitations. In

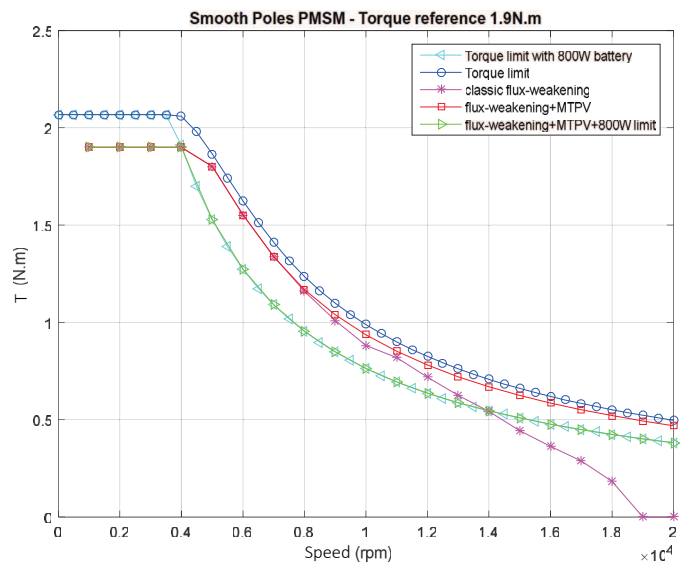


Fig. 5 Torque obtained in steady state depending on the speed with a reference of 1.9N.m for the smooth-poles PMSM form Table 1.

particular the cases when operating in MTPV area or power limit are validated.

On Fig. 4 and Fig. 5 are shown the torque achieved in steady state for different speeds with a reference torque of 1.90N.m smaller than the max torque a low speed. Fig. 4 is for the salient PMSM of Table 1 and Fig. 5 is for a smooth pole PMSM equivalent to the motor Table 1 but with L_d equal to L_q . In blue-circles the torque reference limitation depending on the speed from § II and in cyan-triangles the same with a power limit of 1kW for Fig. 4 and 800W for Fig. 5. In red-squares the electrical torque generated with the control in Part III, and the same in green-triangle but with a smaller battery with a more constraining power (1kW for Fig. 4, and 800W for Fig. 5). It is noticed that the power limit is respected if more constraining than the other limits. In magenta-stars the torque generated with classic flux-weakening when operating in both current and voltage limit. It is notice that MTPV strategy improves performances at high speed because it is not necessary to over-flux-weaken. It is especially visible on Fig. 5 for the smooth pole motor. For the salient poles motor the effect of the MTPV strategy is less visible because the I_d negative current for flux-weakening also contributes to generate torque. Nevertheless if it operates a higher speed the torque difference would be bigger between flux-weakening strategy with MTPV and the classic flux-weakening strategy. Finally the torque error observed in flux-weakening operating between the torque limit and the torque generated is due to the motor resistance that is neglected for the calculation of the theoretical torque limits a high speed and that is still impactful with the small scaled motor used in this paper.

The Fig. 6 shows the time simulation results for a torque reference of 1.9N.m for the salient poles PMSM with a 1400W battery. The evolution of the d-q-current reference from the flux-weakening strategy, the d-q-current, the electrical torque, motor speed, the voltage norm and the current norm vs. time are displayed. One can recognize the passage of the operating point between the MinCPT area, the flux-weakening with only voltage saturation, the flux-weakening with both saturation and the MTPV area when the speed increases.

V. CONCLUSION

High speed PMSM are used in electrical vehicles because they are lighter, smaller, and cheaper than other classic PMSM. This paper presents a control algorithm in the d-q frame that enables to drive these machines whatever their speed and that ensures that the reference operating points respect de voltage limit, the current limit and the battery power limit. The reference torque is saturated by a mask that takes into account the different limitations. The flux-weakening is carried out by a regulation on the reference voltage given by the current regulation and ensures that it doesn't go over the voltage limit. If the critical point is within the current limitation then the MTPV strategy is required to maximize the torque achievable at high speed with minimal current and respecting the voltage limit. The MPTV is taken into account in the control by modifying the current limit at high speed with the current required for MTPV and so without needing to switch between algorithms. Finally the performance of the proposed control is observed trough simulations.

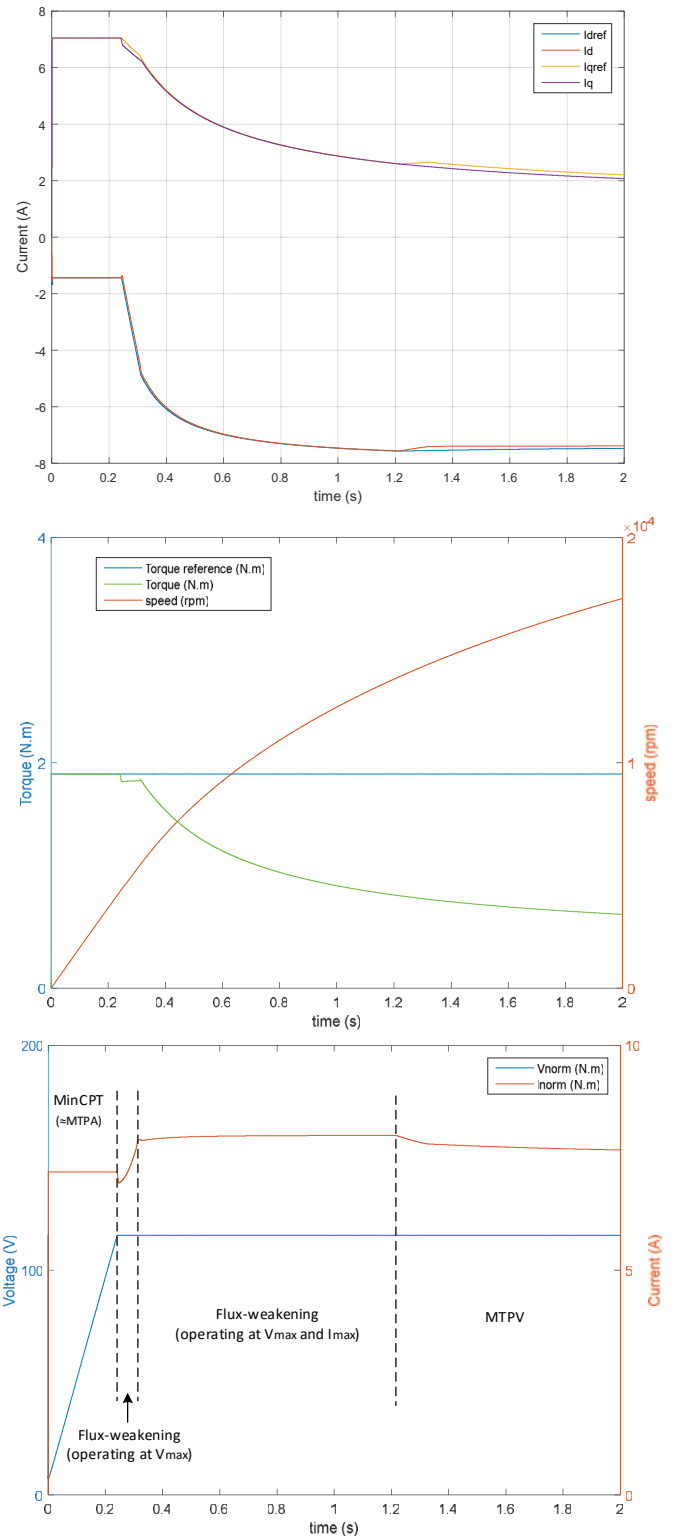


Fig. 6 Time simulation for the salient pole PMSM with a Torque reference of 1.9 N.m. The evolution of the d-q-current reference, the d-q-current, the torque, speed, the voltage norm and the current norm vs. time are displayed.

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