Flux-Weakening Strategies for a Five-Phase PM Synchronous Machine

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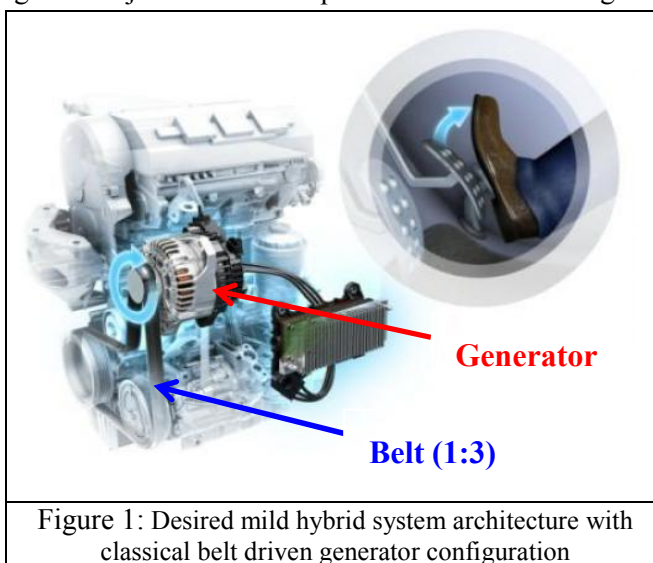E-mail : Li.LU-3@etudiants.ensam.eu

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MHYGALE ADEME

The study of this paper is included in the the project MHYGALE proposed by Valeo, which is is to develop a hybridization solution called "Mild" (mild hydride) affordable for the greatest number with a significant impact on worldwide CO_2 emissions. This solution, based on a high-power electric machine driven by belt, offers start / stop, regenerative braking and torque assist. This booster torque allows motors highly "downsized" to maintain equivalent performance with current engines, thereby making the generalization for an additional acceptable.

Abstract

In order to get a low cost mild hybrid system, a global objective is to keep the actual thermal engine architecture as in Figure 1. As consequence, the current clawpole synchronous automotive generator must be replaced by a new more powerful electrical machine but with the same large speed range [0 -18000 rpm]. In the project, a power of 15 kW and a DC bus voltage of 60V have been chosen to provide a regenerative breaking at minimum cost. With this payload (250A for the DC bus current), a five-phase machine appears to be interesting because MOSFET transistors of the voltage source inverter (VSI) have not to be used in parallel configuration (only two rated 150A transistors per leg for the VSI). As the speed range is large, a flux weakening must be applied. As the five-phase drives [16] have more degrees of freedom than three-phase ones [13], different flux weakening strategies can be considered. The aim of this paper is to compare one of them.

Figure 1: Desired mild hybrid system architecture with classical belt driven generator configuration

Keywords

Flux weakening, Five-Phase PM Synchronous Machine(Five-Phase PMSM), Maximum Torque Per Ampere(MTPA), base speed, back-EMF

I. Model of a Five-Phase PM Synchronous Machine(Five-Phase PMSM)

In order to deduce a control structure for a five-phase machine, a modelling that points out the degrees of freedom will be presented.

1. Multisystem of a Five-Phase PM Synchronous Machine

A five-phase PM synchronous machine can be split into three fictitious machines according to families back-EMF(back-electromotive force) harmonics using Concordia transformation [1][2]. In detail, the back-EMF harmonics corresponding in each fictitious machine: main machine (MM), secondary machine(SM) and homopolar machine (HM) are in Table 1. Each equivalent machine is characterised by its inductance (resp. Lh , Lm and Ls), resistance (resp. Rh , Rm and Rs), and back-EMF (resp. $\vec{e}_{hm}$, $\vec{e}_{mm}$ and $\vec{e}_{sm}$). Thus the MM (the SM and the HM) produces Tmm (Tsm and Thm) torque mainly thanks to the first harmonic (third harmonic, fifth harmonic) of the back-EMF [3][4]. An Energetic Macroscopic Representation (EMR) [4] is given in Figure 2. This synthetic graphic representation is used to deduce systematically the control structure of the 5-phase machine. It then appears that it is sufficient to implement two usual vector control algorithms already developed for 3-phase machines [3]. In EMR [4], the electrical coupling (two interleaved orange squares) takes into account the 5-leg VSI [15] and the generalised Concordia transformation. The mechanical coupling (two interleaved orange triangles) simply means that the total torque is the sum of the two 2-phase machine and a 1-phase machine torque contributions (MM, SM and HM).

Table 1 : Distribution of the EMF harmonics in the fictitious machines for a Five-Phase PM Synchronous

| Homopolar Machine(HM)	Main Machine(MM)	Secondary Machine(SM)
$5.10, \ldots, 5h$	$1, 9, 11, \ldots, 5h \pm 1$	$3, 7, 13, \ldots, 5h \pm 2$

2. Control structure of a Five-Phase PM Synchronous Machine in flux-weakening

HM can only create torque pulsations because it is a one-phase machine. So we assume that in our case machines are star-coupled without neutral output: the current in HM is zero. Then we have only two fictitious machines given in Figure 2 called MM and SM that can be defluxed. Three possible combinations of flux weakening can be defined:
a) Flux weakening in MM
b) Flux weakening in SM
c) Flux weakening in MM and SM
d) In this paper, the flux weakening in MM will be done.

II. Flux weakening control strategies

In order to define the flux weakening criterions, two electrical constraints are introduced: DC bus voltage v_{bus} and maximum thermal current $I_{max\_thermal}$. With these two limits, flux weakening sequences can be distinguished. In the next paragraphs, only one case is given with experimental results: the flux weakening control is applied in MM and Maximum Torque Per Ampere(MTPA) control is kept in SM.

Figure 2 :Multi-machine Energetic Macroscopic Representation of a 5-phase machine
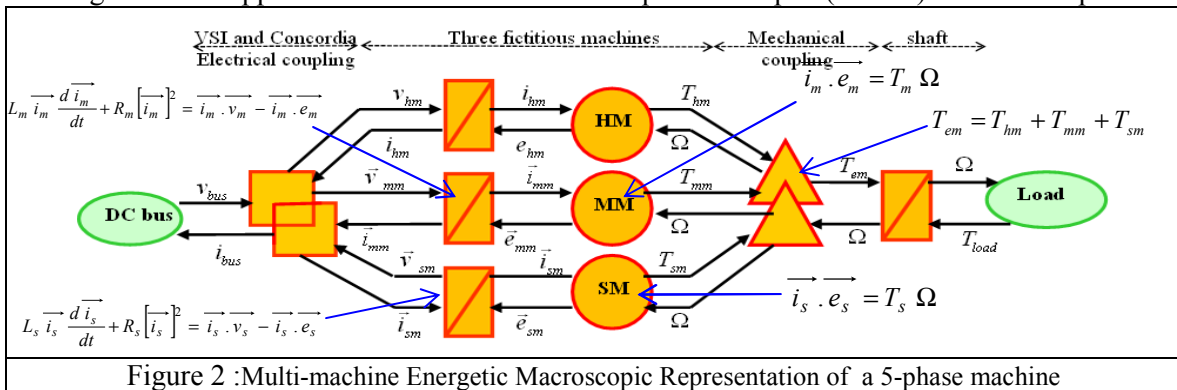
1. MTPA(Maximum Torque Per Ampere)

1.1 Review of the control structure

As far as the stator voltages do not saturate the DC-bus voltage [7]and the stator currents do not exceed $I_{max\_thermal}$ the maximum thermal current, then MTPA control is used. In a five-phase machine the MTPA control consists in ensuring collinearity between the current vector $\vec{i}$ and the back-EMF vector [3][5].

Moreover, when only harmonics 1, 3 and 5 are considered for the back-EMF, the previous MTPA strategy is equivalent to the classical MTPA strategy developed for three-phase machines. So we have only to apply MTPA strategy for SM and MM machines (Figure 7).

1.2 Impact of ratio between 3rd and 1st harmonic of back-EMF

It is well kown [1] that for 3-phase wye-coupled machine, it is possible to optimize by a ratio 115 % the 'use' of the DC-bus voltage [11][12] by injection of third harmonic component in the voltage reference [10]. For a 5-phase machine, the third harmonic is the main harmonic of the SM machine. As consequence the injection of a third harmonic of voltage will have also an impact on the torque if the emf has a third harmonic component E_3 [8][9].

In Figure 3 it is possible to see this impact of the ratio E_3/E_1, considering a range between 0 % and 50 % on the achievable maximum speed that can be obtained for the maximum torque without saturation of the VSI. After this speed, also called the base speed, the torque must be weakened if the speed must be increased. This base speed obtained with a ratio equal to zero between the third and first harmonic of emf is taken as reference speed in the paper.

We observe that we can have a higher base spped than 1.15 in a range of E_3/E_1 ratio between 0.16 and 0.26. From the E_3/E_1 ratio equals 0.35, we have a base speed lower than 1. In other words, if one wants a larger base rate in this machine, it is better to have the E_3/E_1 ratio between 0.16 and 0.26.
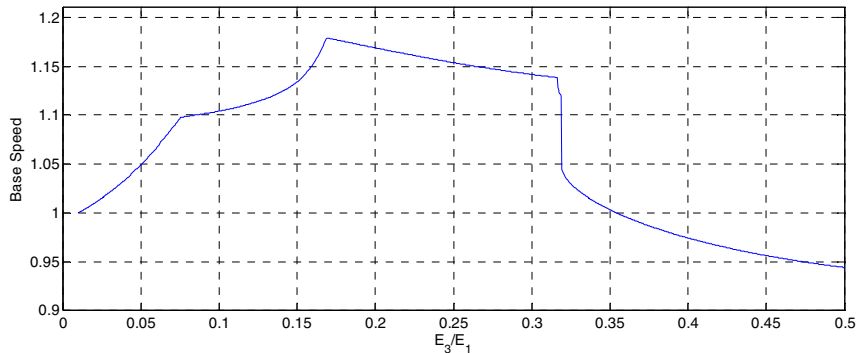

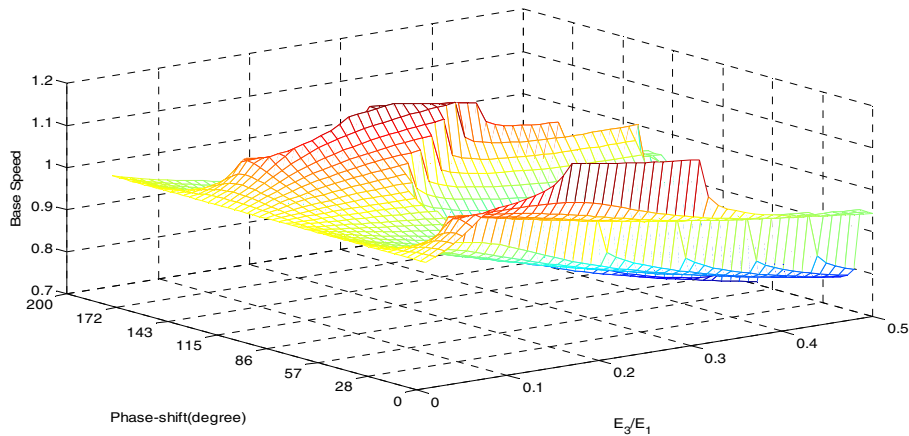Figure 3 : Base speed according to E_3/E_1

Figure 4 : Base speed according to E_3/E_1 and phase-shift

In fact, it is not only the ratio E_3/E_1 that impacts on the base speed but also the phase-shift ψ between the first and the third harmonic. The previous results have been given for a phase-shift equal to zero (look at Figure 3). In Figure 4, the results are given with both ψ and E_3/E_1.

It is observed that near the phase-shift equals zero and 115 degree in a range of ratio E_3/E_1 between 0.16 and 0.26, we have a base speed greater than 1.18. In other words, the base speed in this machine is greater if phase-shift and ratio of E_3/E_1 are in these two areas.

In conclusion, it appears that for given inductance values the best couple of values is $(E_3/E_1, \psi)=(0.2, 0)$ and $(E_3/E_1, \psi)=(0.2, 115)$. The improvement is then equal to 18 % in comparison with a 5-phase sinusoidal of back-EMF.

1.3 Impact of the fifth harmonic of back-EMF

The harmonic that plays the same role for a 5-phase machine than the third harmonic for a 3-phase machine is the fifth harmonic. Nevertheless, as it is studied in [1], its impact is less important.

In order to confirm the point for the value of the base speed, we have considered a ratio E_5/E_1 between 0 % and 20 % for the optimal point previously determined considering the ratio E_3/E_1 equals 0.2.

We find in Figure 5 that the base speed stays at 1.06 in a range of ratio E_5/E_1 between 0.02 and 0.18, and close to the ratio 0185 the base speed reaches the maximum 1.15.

In Figure 6 we can see that the impact of phase-shift ψ between the first and the fifth harmonic has almost no influence on the base speed. It's still the ratio E5/ E1 dominating the evolution of base speed.
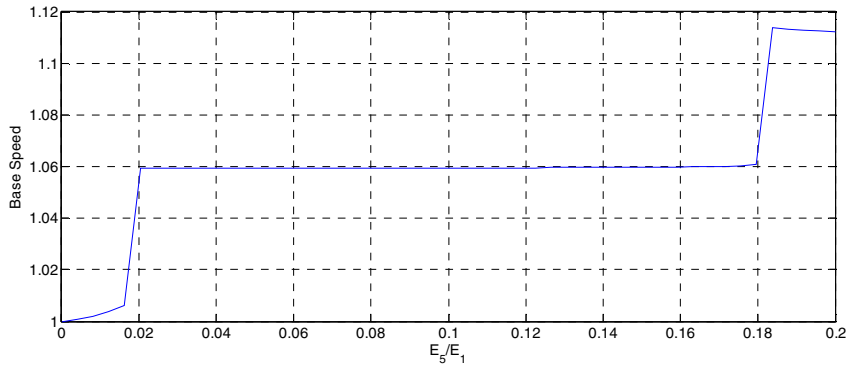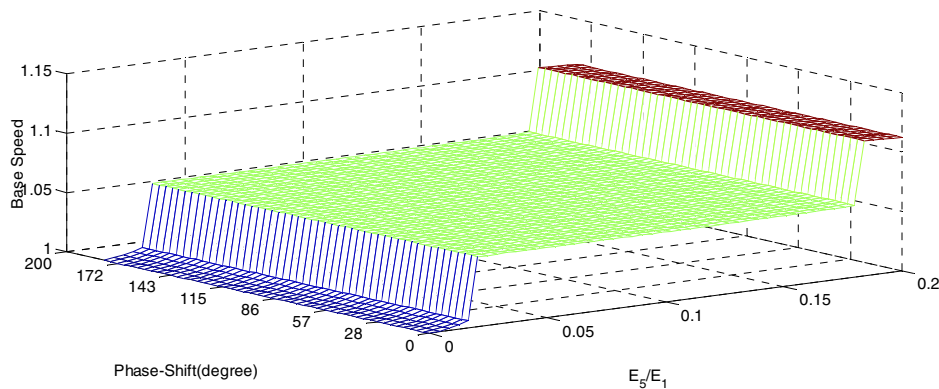

Figure 5 : Base speed according to E_5/E_1

Figure 6 : Base speed according to E_3/E_1 and phase-shift

B_v>0 : The stator voltages are unsaturated at level of DC bus voltage v_{bus}	
B_v=0 : The stator voltages are saturated at level of DC bus voltage v_{bus}	
B_i>0 : The stator currents are unsaturated at level of maximum thermal current $I_{max\_thermal}$	
B_i=0 : The stator currents are saturated at level of maximum thermal current $I_{max\_thermal}$	
	Figure 7: Stateflow of particular flux weakening strategies in of a Five-Phase PM Synchronous Machine

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2. Flux Weakening strategy of Limited Voltage(FWLV)

This strategy is applied in the case given in Figure 7 when the stator voltages saturate at v_{bus} DC bus voltage value and stator currents are below $I_{max\_thermal}$ thermal current [5][6]. In detail, in the Park reference frame associated with MM [6], the direct axis current i_d is used to decrease the magnetic flux along the direct axis of MM. The quadrature axis current i_q keeps the same value to maintain not only machine's performance but also algorithm continuity [14][17].

3. Flux Weakening strategy of Limited Current(FWLC)

This strategy is used in the case given in Figure 7 when the stator currents saturate at thermal current $I_{max\_thermal}$ [5][6]. The necessary value of the direct axis current i_d is applied and then

$$i_q = \sqrt{I_{max\_thermal}^2 - i_d^2} \quad .$$

4. Simulation and Experimental results of flux weakening control

The strategies described in paragraphs II 1,0 and 3 has been applied in simulation and on an experimental drive. Simulation results are given in Figure 8 and experimental results are given in Figure 9.
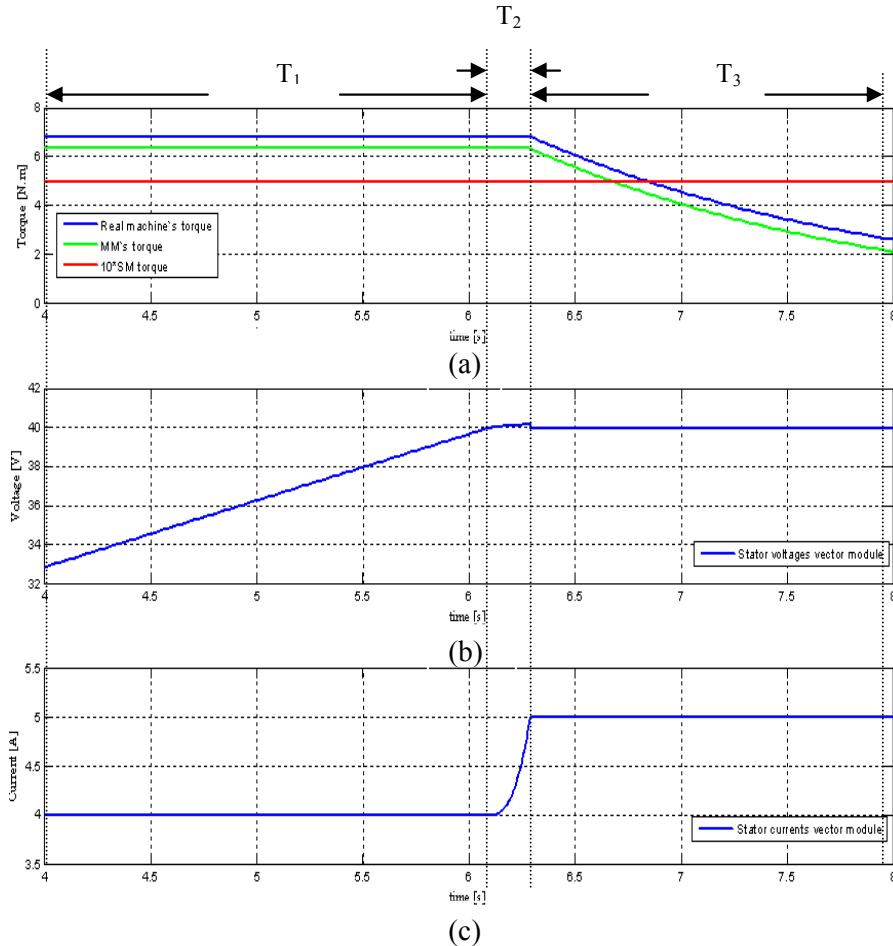

Figure 8: Simulation results of a five-phase drive. (a) Torques in real machine, MM and SM. (b) Stator voltages vector module. (c) Stator currents vector module.

According to the voltage limit given in Figure 8 (b) and current limit given in Figure 8 (c), We can see the evolution of magnetic torque given in Figure 8 (a). In detail, the MTPA control is applied during the period T1 when there is neither voltage saturation nor current saturation. During the period T2, the FWLV is applied: the voltage is maximum, current is increasing and torque is constant. During the period T3, the FWLC is applied: the current is maximum, the flux decreases thoroughly, and the total torque falls to a lower scale.

The optimal on-line control technique has been implemented on a wye-connected four-pole five-phase DC Brushless machine with trapezoidal EMF supplied by a 5-leg Voltage Source Inverter (VSI). The

load torque is generated by a magnetic powder brake associated with an inertial load. A torquemeter SCAIME DR2513 is installed between the motor and the load in order to measure the mechanical torque. Figure 10 gives a snapshot of the experimental test-bed.

We observe that there is a very good correspondence between simulation (Figure 8) and experiment(Figure 9). We found also three cases of operation (Figure 7) in these two figures.
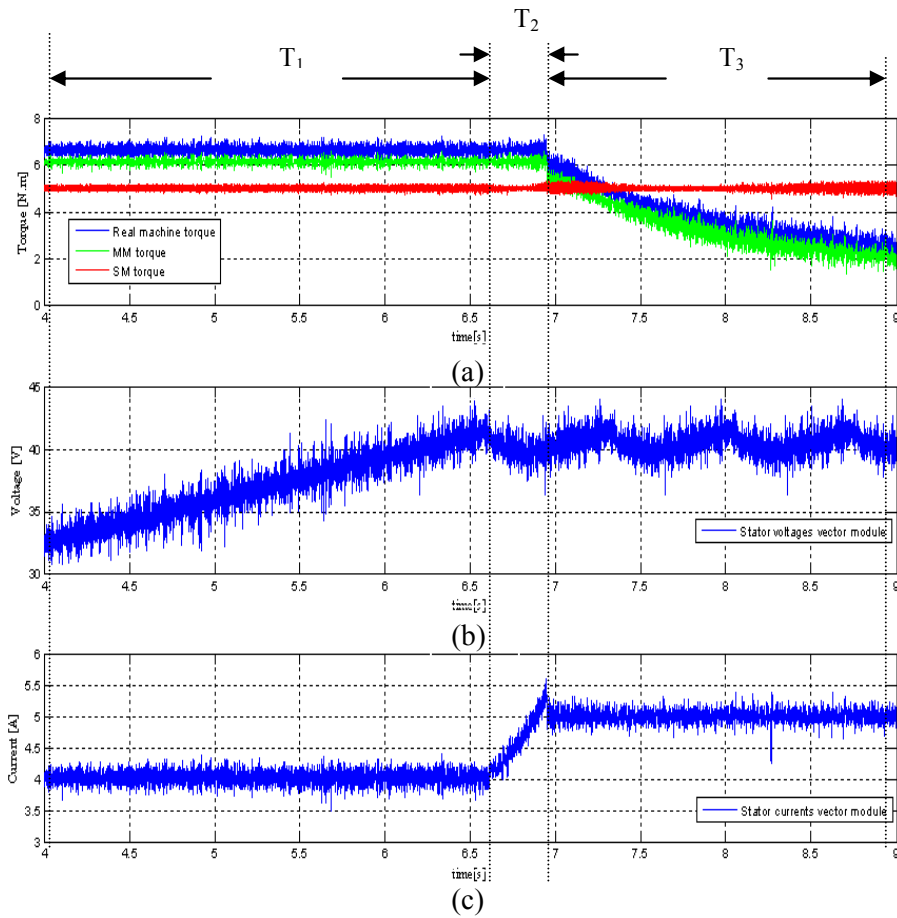

Figure 9: Experimental results of a five-phase drive. (a) Torques in real machine, MM and SM. (b) Stator voltages vector module. (c) Stator currents vector module.
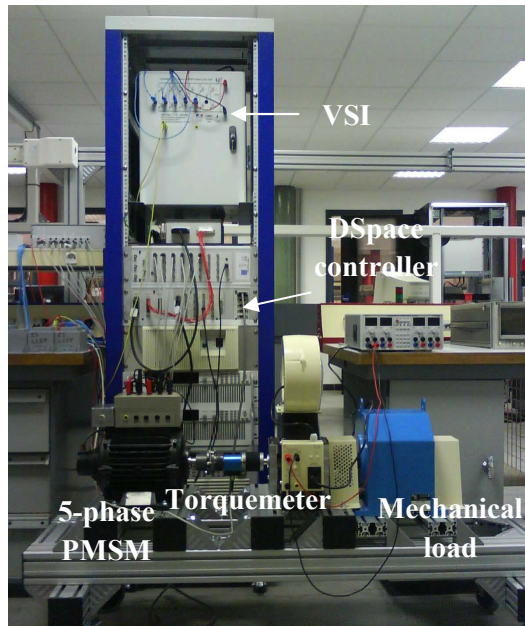

Figure 10: Snapshot of the experimental test-bed.

III. CONCLUSION

In this paper, we studied the influences on the variation of ratio and angle shift between different harmonics of emf. We found the optimal values for each case. The flux-weakening on different machines are introduced fictitious. The flux-weakening on MM is detailed into three strategies according to two electrical constraints: the DC-bus and the maximum thermal current. The results in simulation and in experiment are compared and we obtained good correspondence.

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