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CONSEQUENCE OF STATOR AND ROTOR INUNDATION ON SENSOR LESS ROTOR LOCUS DETECTION MACHINE DESIGN

[1]A.RAVEENDRA, [2]M.PRINCE, [3]K. MALLIKARJUNA

[1,2& 3]Professor, Department of Mechancial Engineering, Malla Reddy Engineering College (Autonomous), Maisammaguda(H), Gundlapochampally Village, Secunderabad, Telangana State - 500100

Abstract

This paper deals with self-sensing-oriented optimization of synchronous reluctance machines. This kind of machine isamong the most challenging to control without the position sensorat low speed. In fact, typical position estimations adopt high-frequency voltage injection which heavily relies on the intrinsicmachine saliency. However, both at low and high currents, such asaliency is not guaranteed due to the presence of the iron ribs andto the saturation of the iron material, respectively. Furthermore,the estimation algorithm could also become unstable due to theabsence of convergence points. The aim of the paper is to tacklethis issue, embedding proper sensor less-control cap.

Introduction

Synchronous reluctance machines (SyRM) represent anattractive alternative to induction and PM motors in manyapplications. One of the advantages is their intrinsic saliencywhich allows for sensorless position estimation at low speedsusing high-frequency (HF) voltage injection [1]–[3].However, iron cross-saturation reduces the effectiveness ofthis position estimation algorithm creating an estimation error[4]–[6]. The typical solution for this problem is to add acompensation angle or equivalently tilt the high-frequencyvoltage vector to correct the estimated position [7], [8]. Incase of heavily saturated machine this kind of strategy is notenough, though. In fact, the algorithm could even not converge.This aspect has been analyzed in [9], [10], where different kindof compensations were proposed to extend the self-sensingfeasibility torque range. Even though these compensationtechniques proved to be effective, they require additional effortfor the implementation and also some information about themachine magnetic behaviour.

Several papers in the past tried to enhance the self-sensingcapability of interior permanent magnet (IPM) motors [5],[11], [12], focusing on avoiding that the Maximum TorquePer Ampere (MTPA) trajectory crosses the point where thecurrent error signal is zero. Despite that, few or no research isavailable for SyRM, where the convergence issue is differentin nature. In this paper, the non-convergence issue is tackledfrom early electromagnetic design phase, trying to embedthe solution into a complete optimization of the motor. Thesensorlesstechnique considered hereafter is the injection ofhigh-frequency pulsating voltage along the estimated d-

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axis

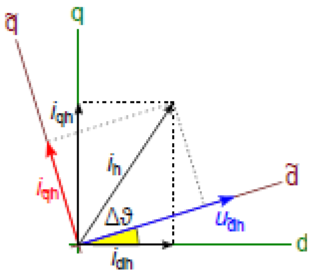

Fig. 1: Estimation error and current error signal.

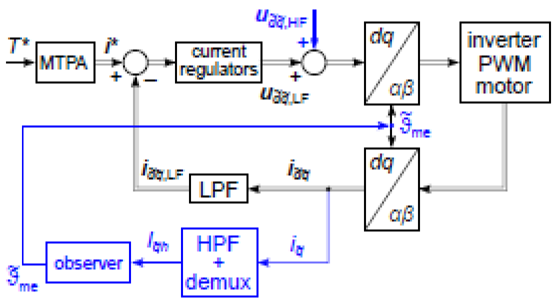

Fig. 2: Control scheme of the electric drive with high-frequency signal injection for rotor position estimation.

Proposed method

This kind of machine isamong the most challenging to control without the position sensorat low speed. In fact, typical position estimations adopt high-frequency voltage injection which heavily relies on the intrinsicmachine saliency. However, both at low and high currents, such asaliency is not guaranteed due to the presence of the iron ribs andto the saturation of the iron material, respectively.

Methodology

Example of a typical optimization

The specifications and the constraints of the machine underanalysis are reported in Table I. In particular, the requirementis to obtain about 90Nm with the highest possible efficiencywithin the given dimensions. At first, also the stator geometryis a constraint, and its data is also reported in Table I.A state-of-the-art optimization coupled to finite elementanalysis (FEA) has been performed in order to assess the feasibilityof the design and to get the overall machine performance.The main objectives for synchronous reluctance machines areaverage torque and torque ripple. Since most of the losses arelocated in the stator and in this optimization the stator is keptthe same, the efficiency depends only upon the average torque.

The objectives plane is reported in Fig. 3. Every dotrepresents a simulated individual. Each evaluation took about

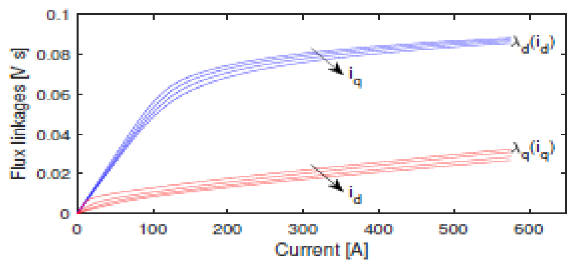

Fig. 4: Flux linkages as functions of the two axes currents.

that for this machine the last achievable torque level withoutany compensation is at about 45Nm (49% of the rated one).Since □q˜d˜(_ϑ) stays always negative when convergenceproblems appear (see Fig. 6), the convergence region can alsobe found in the whole (id, iq) plane for every working pointlooking at the maximum value of the □q˜d˜ waveform: if thisvalue is higher than zero, then there is a zero-crossing andtherefore the estimating algorithm converges. Thus, the contourmax □q˜d˜= 0 delimits the unfeasible region. In Fig. 8 it can beobserved that such a region is quite wide. he cause of thisissue is the presence

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of harmonics in both ℓ_ and ℓdq alongthe current circles.

The presence of a second order harmonic isevident (in the figure only a semi-period is shown). The errorsignal can be computed substituting ℓ_ and ℓdq harmonics intothe numerator of (5). Defining ϑi the angle starting from thed-axis, the error angle _ϑ is defined through .

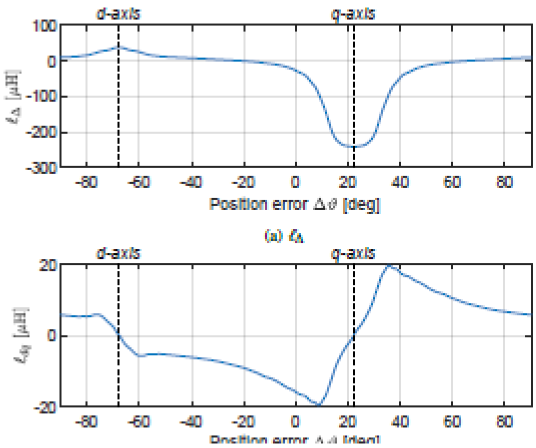

Fig. 9: ℓ_ and ℓdq as functions of position estimation error at rated current

A. First self-sensing-oriented optimizationIn this optimization there were three objectives: torqueripple, efficiency and cross-saturation differential inductance.The parameters (degrees of freedom) were the three fluxbarrierangles, the magnetic insulation ratio, the stator splitratio, the stator tooth width and slot height.The results of the first optimization are reported in Fig. 10.It can be observed that the cross-saturation differential inductanceℓ_ is proportional to the efficiency. So the higher the efficiency,the higher ℓdq. Such a quantity strongly depends on thesaturation of the machine, which is affected by the geometricalparameters (and so is the torque, thus the efficiency). Largeriron areas improve ℓdq but negatively affects the motor torqueand so the efficiency. In fact the rotor diameter decreases toleave more space for the stator yoke, and the slots shrink toobtain larger teeth. As a consequence the slot area has todecrease, and so the copper losses increase.

In this optimization the Pareto front is a 3D surface. InFig. 10 the efficiency and ℓdq are reported in the two axes,while the torque ripple is displayed through the size of themarkers: the bigger the marker, the lower the ripple. Theaverage torque is not an objective now, but it is implicitly takeninto account in the torque ripple and in the efficiency. Someindividuals on the Pareto front were selected for the complete

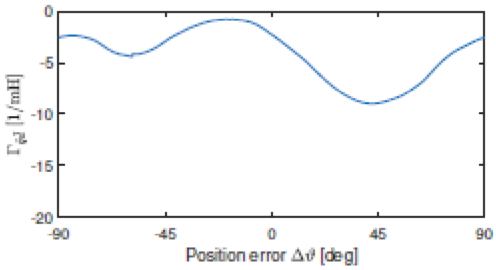

Fig. 16: □˜ q ˜d as a function of _ϑ for the base point.

course, this improvement comes at a cost: the efficiency dropsto about 91.4 %. The torque ripple has been minimized througha second optimization to a value of about 5 %. The extensionof the self-sensing range is evident also looking at Fig. 15 andcomparing it to Fig. 8. The unfeasible region now is greatlyreduced and it presents lower absolute values.

In Fig. 14 the geometry analyzed is shown and compared tothe one first studied. The differences are evident. In particularthe rotor diameter is smaller, but that does not affect the torquecapability of the machine. Overall, there is now more iron inthe stator, both in the yoke and in the teeth. As

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a result, theslot area becomes smaller, which explains the decrease in theefficiency.

Finally, Fig. 16 reports the waveform of □q˜d˜ as a functionof the estimation error for the base point. Comparing it withFig. 6, it can be noted that the behavior is improved eventhough it still does not cross the x-axis. In fact, it has lessnegative offset, and also the peak before _ϑ = 0° is morepronounced and closer to zero. This means that smaller currentand angle compensations are needed.

Conclusion

In this paper a HF-injection self-sensing-oriented optimizationscheme has been presented. A heavily saturated synchronous reluctance motor has been selected as a case study.At first, a typical optimization has been performed on the rotorof the machine. The torque range for sensorless control wasrather limited. After that, the source of the issue has been highlighted,together with the possible mitigating solutions. Thesesolutions were embedded into the optimization algorithm, intwo different ways. Even though the solution found was notable to exhibit self-sensing capability at the maximum torque,the torque range has been greatly extended to about 87% ofthe rated torque.

It has been demonstrated that the factor that affects theconverge of the observer the most is R_, which is mainlydue to the stator saturation. However, the rotor should bedesigned accordingly to guarantee a high average torque, highefficiency and low torque ripple. Finally, it has been deducedthat a better self-sensing capability comes at the cost of lowerefficiency. This fact highlights the importance of consideringHF-injection sensorless control at early design phases.

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