Harmonic Suppression in Electrical Machines Using Iterative Learning Control and Neural Networks: Startup Behavior Analysis

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Abstract

Electrical machines generate unwanted flux and current harmonics. Harmonics can be suppressed using various methods. In this paper, the harmonics are significantly reduced using Iterative Learning Control (ILC) and Neural Networks (NNs). This paper focuses on the start-up behaviour of the control system. The ILC can compensate for the harmonics well for operation at constant speed and constant current reference values. The NNs are trained with the data from the ILC and help to suppress the harmonics well even in transient operation. The simulation model is based on flux and torque maps, depending on dq-currents and the electrical angle puplished in [1].

1 Introduction

Current harmonics pose a significant challenge to the operation of permanent magnet synchronous machines (PMSMs) in both industrial and traction applications. The origin of these harmonics can be attributed to a variety of factors, including inverter behavior and inherent nonlinearities, as highlighted by [2]. Additionally, [3] emphasizes that flux harmonics within the motor itself contribute to the generation of current harmonics, which subsequently manifest as phase current harmonics.

Previous studies have explored the application of ILC in eliminating current harmonics, using methods such as a 2D-array for signal correction mapping at different speeds, as noted by [4], or a speed-independent mapping approach using a singular vector, as outlined by [5]. However, these approaches have limitations, particularly in scenarios involving rapid speed variations and the need to account for harmonics influenced by changes in torque and dq-currents.

In our recent work in [1], we introduced a novel methodology that combines the strengths of both iterative learning control (ILC) and neural networks (NNs) to adress the issue of current harmonics in permanent magnet synchronous machines (PMSMs). Building on our previous research, this paper expands its focus to comprehensively analyze the start-up behavior of the different control variations. To validate the effectiveness of our proposed approach, extensive simulations were ferformed using the MATLAB Simulink software.

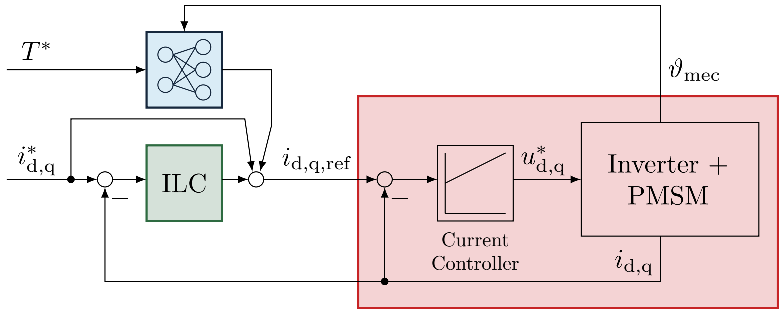

Fig. 1: Simplified block diagram of the ILC together with the NNs in the FOC, from [1]

2 Nonlinear Drive System Model

To ensure accurte results, the model used in this research incorporates the effect of saturation. Consequently, the inductances are assumed to depend on the load and, consequently, on the dq-currents [6]. This in turn leads to a non-linear relationship between the magnetic field and the current [2].

For the representation of flux and torque harmonics, both quantities are considered to be angle dependent, with the electrical rotor angle ϕ_{el} serving as the relevant parameter. In addition, the non-linearity of the motor is influenced by cross-saturation, which affects the inductances. Assumptions for simplification include the symmetry of the three phases and the absence of a connected star point in the machine, as indicated in [2]. Throughout this study, saturation is represented by the current-dependent fluxes.

In the model used, shown in [1], the angular dependence of the fluxes and the torque is considered. In conjunction with the current-dependent fluxes, the torque is also represented non-linearly. The mappings of the functions for the dq-currents and the torque are implemented by look-up tables (LUTs). These LUTs are filled with data derived from a Finite Element Method (FEM) simulation, see [1].

3 Control Architecture

The primary control framework used in this analysis is based on field-oriented control (FOC). To mitigate current harmonics, correction signals are incorporated into the dq-current setpoints using current harmonic suppression controllers, such as the ILC and NNs, as shown in Figure 1. The ILC methodology used in this research is consistent with our previous publications [1], [4], [7].

The ILC can control current harmonics at steady state operating points. To achieve better results at transient operating points, NNs are used to replace or assist the ILC. The neural networks are trained with the values stored by the ILC at steady-state operating points.

The simplified block diagram of the ILC implemented as a current harmonic suppressor, together with the current controller and the NNs, is shown in Figure 1.

The NNs were implemented in two different ways. The first variant maps the ILC directly and outputs the correction signals directly. The second variant outputs the phases and amplitudes of the Fourier analysis of the correction signal, from which the correction signal must then be calculated. The first variant requires fewer conversions, the second variant requires smaller networks. A more detailed description of the two variants can be found in [1]. To compare the different variants, torque and speed were varied and the root mean square error (RMSE) of the resulting dq-currents was calculated, see Figure 2.

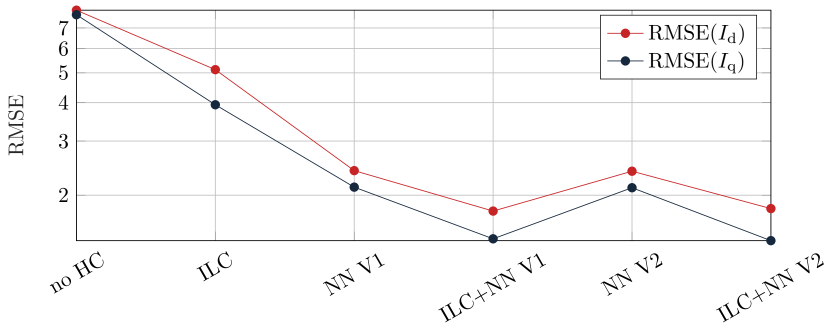

Fig. 2: RMSE for various controls: Variable speed n = 500 rpm...3000 rpm, variable torque T = -280 Nm...280 Nm, from [1]

Figure 2 shows that the NNs work better than the ILC for changing operating points, and the combination of ILC and NNs works even better. In this paper, the start-up behavior of the different methods is considered in more detail in order to include it in the selection of the most suitable variant.

4 Conclusion

This paper shows how the different current harmonic suppression variants differ in their start-up behavior. All the variants shown are generally good at suppressing current harmonics, but they differ in their ability to do so at stationary or varying operating points in different scenarios. They also differ in their implementation effort and in their initial start-up behavior. With the results of this paper, an informed decision can be made as to which of the variants is the right one for one's own application.

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