CLOSED-FORM SOLUTION FOR ZERO-VOLT LOOP ELECTROMAGNETIC ENERGY CONVERSION IN NON-LINEAR SWITCHED RELUCTANCE MACHINES

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Keywords: switched reluctance machine, zero-volt loop.

Abstract

The non-linear switched reluctance (SR) machine energy conversion optimization is a challenging computational task due to the non-linearly varying current and torque and numerous design and operating parameters. Zero-volt loop (ZVL) control method of the SR machine is an effective method of operation that optimizes torque production and minimizes the magnetic and the switching losses. This paper presents simple and rapid energy optimization computation method that enables accurate search of ZVL of a given SR machine design.

1 Introduction

The electromagnetic energy conversion of a saturable (SR) machine is achieved by the increase of the phase winding flux-linkage as a function of the phase current and rotor angular motion of the machine as shown schematically in Fig. 1. This increase in flux-linkage, as the current is traversed along the path 0ABC0, represents the energy stored in the established magnetic field, W_f, and the co-energy, W', that is converted into torque.

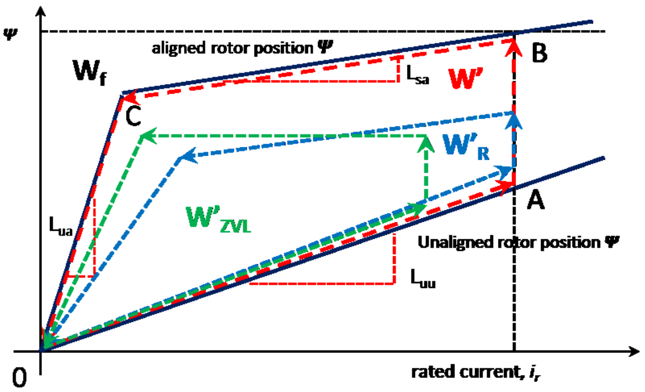

Figure 1 Flux-linkage diagram for the saturable SR machine

The electromagnetic energy conversion of a saturable SR machine is expressed as a partial derivative of the co-energy with respect to the rotor angle, with a condition of constant current value in the instant the rotor angle is traversed [1], thus

$$T = \left[\frac{\partial W'}{\partial \theta}\right]_{i=constant} \tag{1}$$

Therefore, with the help of Equation (1) and the knowledge of the precomputed flux-linkage values as functions of current and parametrised with respect to the angle increment it is possible to compute the total torque a given SR machine is capable of generating [2].

Various computational schemes have been proposed to compute the co-energy and non-linear torque from the flux-linkage maps [2], [3], however all these methods are either too simplistic and inaccurate or too complex. A simple closed-form scheme for the non-linear co-energy computation has been proposed in [4] and [5] that demonstrated relatively close agreement with the fully non-linear numeric calculations [2], as in the following equation:

$$W' = \frac{1}{2}\left[\begin{matrix}(L_{sa} - L_{uu})i_r{}^2 + (L_{ua} - L_{sa})i_s i_r + \\ +\Psi_s i_r - \Psi_s i_s\end{matrix}\right] \tag{2}$$

Here the respective inductances, L, the flux linkages, Ψ, and the phase current values, i, are all available from the pre-computed flux-linkage map of the SR machine design that is being analysed. Due to the direct relationship between the phase current, the co-energy and the electromagnetic torque in equation (1) there is the need to minimize the current and maximize the torque in order to operate the machine at its highest efficiency point. However, since this optimization involves non-linearly varying quantities this necessitates some sophisticated optimization effort, as presented in [6] and [7] for example. The torque-current optimization task becomes even more challenging once the entire torque-speed envelope of the SR machine operation is considered, as in the variable speed SR machine drives [1]. The operating torque values between the peak and the no-load of the machine are always required in such important applications as automotive traction motors [6]. To overcome these optimization challenges a simple, yet accurate, computational scheme is required that can enable rapid computations of the non-linear torque production using as few of the machine design and operating parameters as possible. This paper presents such method for the energy conversion optimization of non-linear SR machines.

2 Optimization of Zero-volt loop energy conversion

References [6] and [7] have recognized the importance of the SR machine phase current trajectory within the flux-linkage map, as in Figure 1, for the optimization of the electromagnetic torque production in the less-than-rated torque levels of the machine operation. From these prior investigations it is evident that the electromagnetic losses in the machine as well as the switching losses in the transistor switches of the converter can be all effectively reduced if the zero-volt loop control of the phase current is realized within the flux-linkage map. Figure 2 compares the zero-volt loop current locus with a non-zero-volt loop current locus as would be needed for the less-than-rated torque load of the machine.

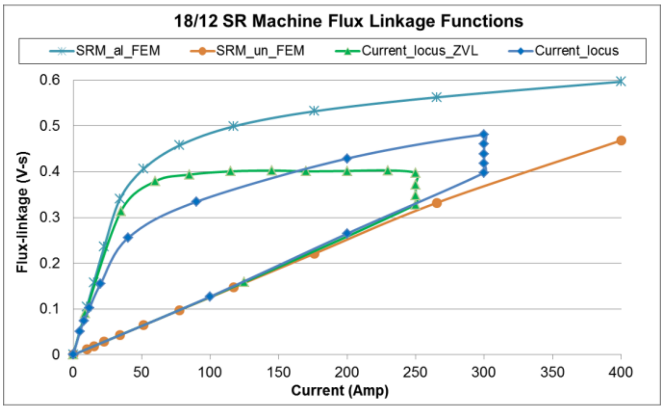

Figure 2 The precomputed non-linear flux-linkage map of an SR machine, showing fully aligned and unaligned curves and ZVL versus non-ZVL current profiles

The characteristic flat shape of the phase current in the portion of the loop along the current axis in Figure 2 is due to the zero-volt operation of the transistor switches of the machine converter [6], [7]. Results of these investigations showed, that the zero-volt loop operation is highly desirable from the energy minimization point of view at partial torque loads of SR machines. Therefore, computational schemes presented in [4] and [5] were utilized in this investigation to optimize the ZVL current profile with respect to the non-ZVL current profile, and thus to obtain exactly the same quantity of energy converted. Figure 3 shows the results of the cumulative co-energy conversions obtained from the computations utilising Equation (2) for the ZVL and the conventional (non-ZVL) current control schemes. As can be seen, the current peak values are different, however as the torque continues towards the fully aligned position (i.e. zero degrees angle) the cumulative energy converted is practically equal.

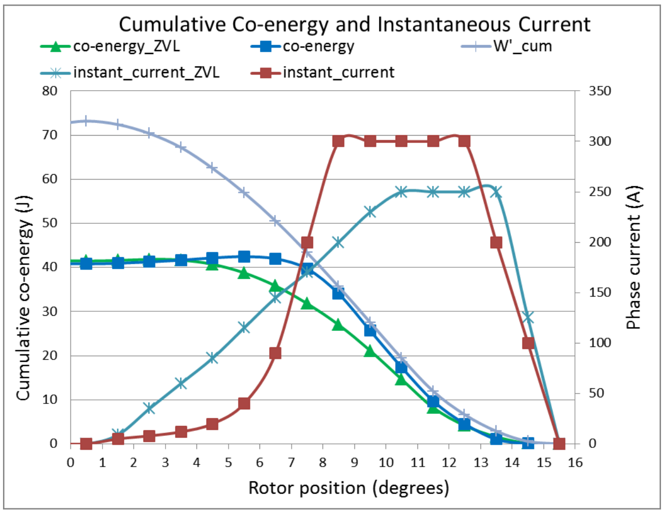

Figure 3 Phase current and their respective cumulative energies, ZVL and non-ZVL

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