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Influence of machine control strategy on electric vehicle range

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Abstract—An optimized control strategy for induction machines is presented and compared to classic strategies. The described method allows to optimize voltage and frequency for a steady state equivalent circuit model of three-phase induction machine. This method is applied to an electric vehicle by simulating driving cycles and calculating energy consumption. The potential gain for the optimized control strategy is discussed.

Keywords—induction machine, control strategy, driving cycle, energy efficiency, optimization

I. INTRODUCTION

Electric vehicles (EV) are one of the solutions to solve local pollution issues. With the current technologies, their main limitation is a limited range compared to internal combustion engines. This range can be increased due to improved design of the electric powertrain, by relying on modeling and simulation tools in order to optimize the system [1]. Usually, the electric powertrain design starts with geometry sizing of each component [2]. The electric machine design can be defined with a direct sizing formulation [3], or with an optimization procedure to explore different possibilities [4]. To simplify this optimization, control strategy is usually not a priority and a basic control is set up; this strategy is studied in a latter design step [5][6]. This paper deals with the benefits of control strategy optimization on a model that will be adapted for optimal design process. The objective is to investigate the effect of the control strategy on the energy consumption of an electric vehicle during driving cycles. The proposed optimization strategy maximizes efficiency for each operating point in order to minimize overall energy consumption. The studied machine type is a three-phase induction machine modeled with an analytical steady state equivalent circuit taking into account iron losses and saturation [7]. The paper is organized as follows. Section II describes the machine model. The optimized control strategy is presented in section III. Finally a comparison between this strategy and a classic constant flux control strategy is discussed.

II. INDUCTION MACHINE MODEL

The studied machine is a 4 poles squirrel cage induction machine dedicated to an electric vehicle. The machine is modeled with a per phase equivalent circuit. This steady state analytical model has low computational time and enough accuracy for energy estimation on driving cycle [6][8].

A. Equivalent circuit

Notations:

\( V_I \): per-phase voltage (V)  
\( V_{Imax} \): machine max available voltage (V)  
\( E \): electromotive force (V)  
\( r_I \): stator resistance (Ω)  
\( x_I \): stator leakage reactance (Ω)  
\( r_2' \): rotor resistance (Ω)  
\( x_2' \): rotor leakage reactance (Ω)  
\( r_m \): iron loss resistance (Ω)  
\( x_m \): magnetizing reactance (Ω)  
\( l_i \): inductance of part \( i, i \epsilon \{1,2',m\} \) (H)  
\( l_{mad} \): magnetizing inductance part depending only on the geometry (H)  
\( l_{1S} \): stator slot leakage inductance (H)  
\( l_{12} \): head of winding inductance (H)  
\( l_{1S} \): stator zig-zag inductance part depending only on the geometry (H)  
\( s \): slip  
\( \omega_s \): stator pulse (rad/s)  
\( \Omega_s \): rotor mechanical speed (rad/s)  
\( f \): stator frequency (Hz)  
\( p \): poles pair number  
\( K_s \): saturation coefficient  
\( T \): torque (Nm)

For a squirrel cage rotor, the equivalent circuit is the following [9]:

![Fig. 1. Induction machine equivalent circuit](image)

The reactance values \( x_i (x_I, x_{2'}, x_m) \) depend on the stator frequency \( f \) through the relation:
\[ x_t = l_1 \omega_s = l_1 2 \pi f \] (1)

The slip \( s \) is calculated as:
\[ s = \frac{\omega_s - p \omega_r}{\omega_r} \] (2)

The focus of this paper is the impact of the control strategy optimization, that’s why the geometry will be fixed. If \( V_i \) (respectively \( E \), \( f \), and \( \Omega_c \) are known, the circuit can be solved (see [9]); the outputs are \( E \) (respectively \( V_i \)), torque, currents, losses, efficiency, power factor, and temperatures if a thermal model is added. Flux and currents are supposed to be ideal sin waves (1st harmonic model). For a machine dedicated to electric vehicle with variable speed and torque, saturation and iron losses can’t be neglected, and the voltages \( V_i \) and \( E \) need to be calculated by solving the equivalent circuit.

**B. Saturation**

Saturation is taken into account in \( l_m \) and \( l_1 \) inductances, with a saturation coefficient \( K_s \) [10][11]:
\[ l_m = \frac{l_{m0}}{K_s} \] (3)
\[ l_1 = l_{11} + l_{12} + \frac{l_{13}}{K_s} \] (4)

The \( K_s \) coefficient is calculated as described in Fig. 2. Inductions are computed in different parts of the machine: air gap, stator tooth, stator yoke, rotor tooth, and rotor yoke. Fig. 2 is a flow chart summing up the calculations. A control strategy is needed to get the output torque equal to torque setpoint by finding the adequate \( E \) and \( f \).

**C. Iron losses**

Iron losses \( P_{iron} \) are computed analytically, and depend on frequency and inductions in the different parts of the machine. They are divided into eddy current and hysteresis losses [12]. Then the iron loss resistance \( r_m \) is calculated by:
\[ r_m = \frac{3 \times 6^2}{P_{iron}} \] (5)

**D. Validation**

The model has been validated on a study case machine with experimental results. The following table gives the model error compared to the experiments:

<table>
<thead>
<tr>
<th>Output</th>
<th>Model error Operation point 1</th>
<th>Model error Operation point 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque</td>
<td>6%</td>
<td>7%</td>
</tr>
<tr>
<td>Total losses</td>
<td>7%</td>
<td>5%</td>
</tr>
<tr>
<td>Current</td>
<td>3%</td>
<td>4%</td>
</tr>
</tbody>
</table>

Operating point 1 is at low speed, middle torque, while point 2 is at high speed, low torque. Other operating points have been validated with an error always under 10%.

**III. CONTROL STRATEGY OPTIMIZATION ALGORITHM**

Several pairs \( (E,f) \) can lead to the same operating point (rotor speed,torque) [8]. Choosing the best \( (E,f) \) in terms of efficiency or current represents the control strategy optimization in this work. A usual method to get these values is to keep the flux constant, which means keep the \( E/f \) ratio constant. But \( E \) can’t be directly controlled, so a simplification is often made: \( V_i \) is kept constant [6]. This hypothesis is true if the voltage difference between \( V_i \) and \( E \) is low. For better performances, these values can be optimized with different objectives such as minimizing current or maximizing efficiency in an optimization loop. These strategies also have to limit the machine voltage to a maximum threshold called \( V_{max} \).

In this paper, three strategies will be compared: A) “\( V_i/f=k_1 \)” / B) “\( E/f=k_2 \)” / C). Optimization. \( k_1 \) and \( k_2 \) are two constants for operating points without field weakening.

A. “\( V_i/f=k_1 \)” strategy

With the “\( V_i/f=k_1 \)” strategy, the \( k_2=V_i/f \) ratio is kept constant until \( V_i \) reaches the maximum then \( k_2 \) has to decrease for field weakening. This \( k_2 \) is usually calculated at the nominal operating point [13]. Keeping this ratio constant generally goes with the hypothesis that resistance \( r_1 \) is low so \( E \) can be approximated with \( V_i \) [10]. With this method, the required torque is not respected, especially for low speeds where \( r_1 \) can’t be ignored. The following plot represents the torque error in % when considering \( E=V_i \). Speed and torque are displayed per unit (p.u.).
For maximizing range on a driving
objective \( E/f = k \)

\[
E = f k_2
\]
In this paper, only operating points with positive torque are considered. Minimum frequency $f_{\text{min}}$ corresponds to the rotor mechanical speed:

$$f_{\text{min}} = \frac{p \cdot \omega_r}{2 \pi}$$  \hfill (9)

Since slip frequency is always low, $f$ is only a few Hertz more than $f_{\text{min}}$. The selected algorithm is sequential quadratic programming (SQP) with the fmincon MATLAB® function. This method is strongly recommended to handle constraints [14]. This method computational time is higher: ~40s for 500 operating points.

IV. APPLICATION ON A DRIVING CYCLE

Before calculating the energy consumption on driving cycles with a study case on a small vehicle, efficiency and power maps have been plotted to compare the 3 strategies.

A. Speed/Torque maps

The following figures represent the efficiency map for all speed and torque operating points. The maximum torque is limited by the maximum current available and the maximum power by the maximum voltage $V_{\text{max}}$.

Fig. 6. Optimization strategy flow chart

Fig. 7. Efficiency map with “$V_1/f=k_1$” strategy

Fig. 8. Efficiency map with “$E/f=k_2$” strategy and focus at speed=0.325p.u.

Fig. 9. Efficiency map with Optimization strategy

The behavior at approximately speed=0.325p.u. on Fig. 7 and 8. comes from the maximum voltage $V_{\text{max}}$ that have been reached. This can be observed by looking at the “$E/f$” ratio for a constant torque, e.g Torque=0.25 p.u.

Fig. 10. “$E/f$” coefficient curves for the 3 strategies and a constant torque

Then the efficiency maps have been subtracted:
In term of efficiency, differences are mainly located at the small torque/speed operating points, where power is low and doesn’t have a strong impact on energy consumption. To assess this influence, the following plots show an electrical power comparison:

Fig. 11. Efficiency map comparison: [“$E/f=k_2$” map – “$V_1/f=k_1$” map]

Fig. 12. Efficiency map comparison: [Optimization map – “$V_1/f=k_1$” map]

Fig. 13. Efficiency map comparison: [Optimization map – “$E/f=k_2$” map]

Fig. 14. Power map comparison: [“$E/f=k_2$” map – “$V_1/f=k_1$” map]

Fig. 15. Power map comparison: [Optimization map – “$V_1/f=k_1$” map]

Differences in term of energy consumption will only be observed if the driving cycle has operating points in the low speed/torque area. The high torque/low speed area is only for specific situations such as starting the vehicle in a slope. The differences may not have influence for driving cycle without slope.

B. Driving cycle

In order to evaluate energy consumption, the WLTC (Worldwide harmonized Light vehicles Test Procedures) driving cycle has been chosen. This cycle has been created to define a global standard for energy consumption estimation from light duty vehicles. It is divided in three class depending on power-weight ratio. Passenger cars are generally in class 3: power (W)/weight (kg) > 34. The WLTC class 3 driving cycle is itself divided in 4 parts: low, mid, high, very high. For our study, WLTC low and mid will be tested.

Fig. 16. WLTC driving cycle for class 3 vehicles
WLTC operating points for positive torque request have been plotted on top of the previous power comparison for our study case to evaluate their influence on the consumed energy.

Fig. 17. Power comparison + WLTC low operating points

Fig. 18. Power comparison + WLTC mid operating points

WLTC low operating points are concentrated in the area with the more differences. Then the energy consumption is compared in the following table. WLTC Low with “\(V/f = k_1\)” method is taken as the reference for the comparison.

<table>
<thead>
<tr>
<th>Method</th>
<th>WLTC Low</th>
<th>WLTC mid</th>
</tr>
</thead>
<tbody>
<tr>
<td>“(V/f = k_1)”</td>
<td>100%</td>
<td>120.8%</td>
</tr>
<tr>
<td>“(E/f = k_1)”</td>
<td>99.1%</td>
<td>120.5%</td>
</tr>
<tr>
<td>Optimization</td>
<td>88.1%</td>
<td>118.3%</td>
</tr>
</tbody>
</table>

The gain with optimization procedure is ~12% for WLTC low driving cycle which is not negligible and may influence the geometry sizing if included in a design optimization loop.

V. CONCLUSION

Optimizing induction machine control strategy allows to obtain significant improvements on efficiency and energy consumption of EV powertrains. The paper shows the influence of an optimized control strategy compared to a classic “\(V/f\)” method. The next step is to introduce the optimized control in a larger design optimization loop, integrating motor geometry and other powertrain elements.

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