Applied Energy 224 (2018) 647–658

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Sensorless control strategy for light-duty EVs and efficiency loss evaluation of high frequency injection under standardized urban driving cycles

E. Trancho[a,*], E. Ibarra[b], A. Arias[c], I. Kortabarria[b], P. Prieto[a], I. Martínez de Alegría[b], J. Andreu[b], I. López[b]

[a] *Tecnalia Research and Innovation, Parque Científico y Tecnológico de Bizkaia, c/ Geldo, Edif. 700, 48160 Derio, Spain*
[b] *Department of Electronic Technology, UPV/EHU, C. Rafael Moreno Pitxitxi 3, 48013 Bilbao, Spain*
[c] *Institut d'Organització i Control, Universitat Politècnica de Catalunya, Diagonal, 647, 08028 Barcelona, Spain*

HIGHLIGHTS

- Full sensorless control proposed for electric vehicle drives.
- High frequency injection (HFI) successfully combined with Phase Locked Loop (PLL).
- Experimental results obtained from a real automotive 51 kW drive.
- An accurate simulation model proposed for system power loss estimation.
- Efficiency of EV sensorless operation tested for standard driving cycles.

ARTICLE INFO

Keywords:
Electric vehicle
PM-assisted SynRM
Efficiency
Sensorless
HFI
NEDC

ABSTRACT

Sensorless control of Electric Vehicle (EV) drives is considered to be an effective approach to improve system reliability and to reduce component costs. In this paper, relevant aspects relating to the sensorless operation of EVs are reported. As an initial contribution, a hybrid sensorless control algorithm is presented that is suitable for a variety of synchronous machines. The proposed method is simple to implement and its relatively low computational cost is a desirable feature for automotive microprocessors with limited computational capabilities. An experimental validation of the proposal is performed on a full-scale automotive grade platform housing a 51 kW Permanent Magnet assisted Synchronous Reluctance Machine (PM-assisted SynRM). Due to the operational requirements of EVs, both the strategy presented in this paper and other hybrid sensorless control strategies rely on High Frequency Injection (HFI) techniques, to determine the rotor position at standstill and at low speeds. The introduction of additional high frequency perturbations increases the power losses, thereby reducing the overall efficiency of the drive. Hence, a second contribution of this work is a simulation platform for the characterization of power losses in both synchronous machines and a Voltage Source Inverters (VSI). Finally, as a third contribution and considering the central concerns of efficiency and autonomy in EV applications, the impact of power losses are analyzed. The operational requirements of High Frequency Injection (HFI) are experimentally obtained and, using state-of-the-art digital simulation, a detailed loss analysis is performed during real automotive driving cycles. Based on the results, practical considerations are presented in the conclusions relating to EV sensorless control.

1. Introduction

Electric Vehicles (EV) represent an attractive technology in response to such serious environmental and societal issues as fossil fuel dependency, urban pollution and climate change [1–4]. Besides, EVs provide other benefits, as they can be used as additional energy storage systems for future smart grids [5]. According to a number of analysts, the EV market will have a promising future. Some forecasts expect a global stock of 200 million EV units by 2030 [6]. However, these technologies have higher manufacturing costs than conventional vehicles [7]. As vehicle costs [3], driving ranges [1,8,9], reliability [11,10], and safety [11] are prioritized by consumers, significant

---

* Corresponding author.
E-mail addresses: elena.trancho@tecnalia.com (E. Trancho), edorta.ibarra@ehu.eus (E. Ibarra), antoni.arias@upc.edu (A. Arias), inigo.kortabarria@ehu.eus (I. Kortabarria), pablo.prieto@tecnalia.com (P. Prieto), inigo.martinezdealegria@ehu.eus (I. Martínez de Alegría), jon.andreu@ehu.eus (J. Andreu), iraide.lopez@ehu.eus (I. López).

https://doi.org/10.1016/j.apenergy.2018.05.019
Received 24 October 2017; Received in revised form 3 May 2018; Accepted 4 May 2018
0306-2619/

Nomenclature

V_i	voltage amplitude produced by the HFI (V)
w_i	HF perturbation rotation speed (rad/s)
f_i	HF perturbation rotation frequency (Hz)
ω_{th}	transition point between HFI and observer (rad/s)
$\hat{\mathbf{e}}_{\alpha\beta}$	estimated back-EMF in the $\alpha\beta$ reference frame (V)
$\mathbf{i}_{\alpha\beta}$	machine voltages in the $\alpha\beta$ reference frame (V)
$\mathbf{v}_{\alpha\beta}$	machine currents in the $\alpha\beta$ reference frame (V)
R_s	stator resistance (Ω)
L_s	stator inductance (H)
L_d	stator inductance in the d-axis (H)
L_q	stator inductance in the q-axis (H)
Ψ_{PM}	permanent magnet flux linkage (Wb)
ω_e	electrical speed (rad/s)
$\widehat{\omega}_e$	estimated electrical speed (rad/s)
θ_e	rotor electrical position (rad)
$\widehat{\theta}_{e,PLL}$	PLL estimated rotor electrical position (rad)
$\widehat{\theta}_{e,HFI}$	HFI estimated rotor electrical position (rad)
$\widehat{\theta}'_{e,HFI}$	HFI estimated rotor electrical position (rad) without considering polarity
Δ_e	angle deviation (rad)
P	rotor pole-pair
P_N	maximum power (W)
ω_{max}	maximum speed (rad/s)
R_{Fe}	magnetic resistance (Ω)
v_d	d-axis voltage (V)
v_q	q-axis voltage (V)
v_d^*	d-axis reference voltage (V)
v_q^*	q-axis reference voltage (V)
i_d	d-axis current (A)
i_q	q-axis current (A)
i_d^*	d-axis reference current (A)
i_q^*	q-axis reference current (A)
Ψ_d	d-axis flux (Wb)
Ψ_q	q-axis flux (Wb)
$v_{d,ST}$	d-axis Super-twisting voltage (V)
$v_{q,ST}$	q-axis Super-twisting voltage (V)
$v_{d,eq}$	d-axis equivalent voltage (V)
$v_{q,eq}$	q-axis equivalent voltage (V)
c_d	d-axis equivalent voltage regulation parameter
c_q	q-axis equivalent voltage regulation parameter
λ_d	d-axis STA regulation parameter
λ_q	q-axis STA regulation parameter
Ω_d	d-axis STA regulation parameter
Ω_q	q-axis STA regulation parameter
T_{em}	electromagnetic torque (N m)
$i_{Fe,d}$	d-axis iron loss current (A)
$i_{Fe,q}$	q-axis iron loss current (A)
$i_{mag,d}$	d-axis magnetizing current (A)
$i_{mag,q}$	q-axis magnetizing current (A)
P_L	machine power losses (W)
$P_{L,Cu}$	machine copper losses (W)
$P_{L,Fe}$	motor magnetic losses (W)
$P_{cond,IGBT}$	IGBT conduction losses (W)
T_{sw}	switching period (s)
f_{sw}	switching frequency (Hz)
V_{ce}	collector-emitter voltage (V)
$V_{ces,max}$	maximum blocking voltage (V)
V_{ces}	typical collector-emitter voltage (V)
i_c	instantaneous collector current (A)
I_{max}	maximum collector current (A)
I_{nom}	nominal collector current (A)
$T_{vj,IGBT}$	IGBT junction temperature (°C)
$P_{sw,IGBT}$	IGBT switching losses (W)
E_{ON}	IGBT turn-on energy losses (J)
E_{OFF}	IGBT turn-off energy losses (J)
R_G	gate resistance (Ω)
C_{DC}	DC-link capacitance (F)
$P_{cond,D}$	diode conduction losses (W)
V_F	diode forward voltage (V)
i_F	diode forward current (A)
$P_{sw,D}$	diode switching losses (W)
E_{RR}	diode recovery energy losses (J)
$P_{loss,inv}$	inverter power losses (W)
ω_{wheel}	vehicle wheel speed (rad/s)
ω_{dc}	driving cycle speed (m/s)
T_{wheel}	vehicle wheel torque (N m)
r_{wheel}	vehicle wheel radius (m)
F_{roll}	rolling resistance (N)
F_{Aero}	aerodynamic resistance (N)
$F_{Inertia}$	inertia force (N)
M_{car}	total vehicle mass (g)
a_g	gravity acceleration (m/s)
μ	rolling friction coefficient
ρ	air density (kg/m^3)
C_d	drag coefficient
A_f	vehicle cross section (m^2)
M_{rot}	equivalent mass of rotating parts (%)
a_{car}	car acceleration (m/s^2)
GR	gear ratio
η_{GR}	gear ratio efficiency (%)
T_{trans}	transmission torque (N m)
T_{Idling}	idling torque (N m)
P_{GT}	idling losses (W)
E_{batt}	battery energy (J)
Γ_{sim}	simulation factor
t_{sim}	simulation completion time (s)
$t_{behaviour}$	simulation time (s)
$E_{loss,mot}$	motor total energy losses (J)
$E_{loss,Cu}$	motor copper energy losses (J)
$E_{loss,Fe}$	motor magnetic energy losses (J)
$E_{loss,inv}$	inverter total energy losses (J)
$E_{loss,condQ}$	IGBT conduction losses (J)
$E_{loss,swQ}$	IGBT switching losses (J)
$E_{loss,condD}$	diode conduction losses (J)
$E_{loss,swD}$	diode switching losses (J)
η_{mot}	motor efficiency (%)
η_{inv}	inverter efficiency (%)
η_{driv}	drive efficiency (%)

Acronyms

EKF	Extended Kalman Filter
ELO	Extended Luemberger Observer
EMF	Electro-Motive Force
EUDC	Extra Urban Driving Cycle
EV	Electric Vehicle
FFT	Fast Fourier Transform
FPGA	Field Programmable Gate Array
FW	Field Weakening
HF	High Frequency
HFI	High Frequency Injection
IGBT	Insulated Gate Bipolar Transistor
IPMSM	Interior Permanent Magnet Synchronous Machine
LUT	Look-Up Table
MRAS	Model Reference Adaptive System
MTPA	Maximum Torque per Ampere
MTPV	Maximum Torque per Volt
NEDC	New European Driving Cycle