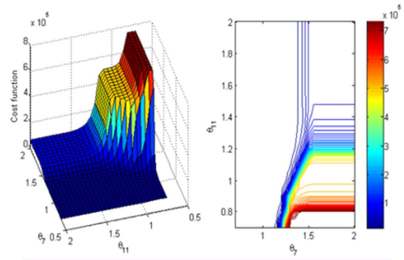
- modelling and simulation
- control design
- system troubleshooting
- technology transfer and training
- energy efficiency investigation
- software tools

industrial systems and control

Advanced Control of Permanent Magnet Synchronous Motors

This document briefly reviews the problem and control methods representing the state of the art for developing algorithms for controlling permanent magnet synchronous motors (PMSM). Initially, this type of electric motor is described, and classical control methods are reviewed. In the second part, modern advanced control solutions are presented. Industrial Systems and Control (ISC) Ltd is expert in advanced control systems development, developing sophisticated algorithms to optimize the performance of a system, including modern hybrid/electric vehicles and related subsystems, e.g. electric motors.



Permanent Magnet Synchronous Motor in e-Mobility

PMSM has been considered as a potential candidate for EV applications due to their compact structure with small size and weight, high torque to inertia ratio, high efficiency, wide speed range, low noise, and robustness in operation. Focusing on the EV application, a fast torque response of the electrical drive is required to meet the instantaneous torque demand commanded by the driver through the pedal action. Moreover, the PMSM-drive should have a quick torque/speed recovery capability after being subject to sudden system disturbances.

Field Oriented Control of PMSM

The standard control method for both PMSMs and induction machines is Field Oriented Control (FOC) with a cascade structure, where three linear controllers (usually PI) are employed, one for tracking the reference position/speed and two for the regulation of currents in the direct-quadrature (d, q) reference frame. When Pulse Width Modulation (PWM) is used, this control architecture is often referred to as PI-PWM.

This strategy is based on the control principle of a separate excited DC motor; in that case, the armature current directly controls the torque, while the excitation current is responsible for the magnetizing flux generation. For that kind of DC motor, the two currents are independently accessible and the armature magnetomotive force is orthogonal with respect to rotor flux, through mechanical commutation system such as brushes and commutators. In the case of AC motors (synchronous or induction), the spatial angle between rotating stator field and rotor flux changes depending on the load characteristics. Field oriented control emulates the DC conditions in a AC motor structure, by monitoring the rotor field position and orienting the stator field so that the angle between both fields is maintained at 90 degrees. Consequently, the maximum torque condition can be achieved, and the rotor speed can be controlled independently.

Using the PI based regulators, a certain amount of overshoot is associated to reference input variation; by modifying the parameters of the controllers, the output result can be improved. Nowadays, in induction and synchronous AC machines drive this method has displaced the scalar volts-per-Hertz control, because of its accuracy and reliability. For the same reasons, in industrial applications FOC offers safer real-time performance. The continuous and fast evolution of microcontrollers – in terms of computational capability and reduction of power consumption – is boosting the adoption of vector control technique even for lower level motor drives.

Industrial Systems and Control Ltd.

ISC Ltd. works across industrial sectors and has gained wide experience in a range of applications. It is this peripheral vision which is valuable for automotive companies, which have a complete understanding of current advances in the automotive industry. ISC Ltd. has particular expertise and experience on the following areas and methodologies:

- Physical system modelling and simulation, including training simulators.
- Developing tailored optimal or predictive control solutions for real-world applications.
- Production of bespoke estimation and filtering algorithms for nonlinear control.
- Use of stochastic or robust controls for different industries like wind energy and marine.
- Design of Machine Learning algorithms for industrial and embedded domains.
- Training courses mostly for the automotive industry based in the US.

Our Expertise

- **In-depth understanding of control technologies**
- **Extensive experience in diverse industrial applications**
- **High-fidelity modelling of system behaviour**
- **Expert analysis of complex problems**
- **Proven project management and research skills**

Our Core Competencies

- **Dynamic modelling & simulation**
- **Control strategy design and implementation**
- **Optimization**
- **Algorithm development**
- **Benefits analysis and technology review**
- **Research & Development**
- **Troubleshooting**
- **Training**

Our Philosophy

- **Approaching problems with an open mind**
- **Dedicated to identifying practical and innovative solutions without compromising performance.**
- **Imparting understanding and empowering clients to drive improvements themselves.**

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Predictive Control of PSMS

In recent years Model Predictive Control (MPC) has attracted considerable attention in power converters and electrical drives. The main idea of MPC is to obtain the control actions by solving at each sampling time a finite horizon optimal control problem based on a given prediction model of the controlled process and an estimation of its current state.

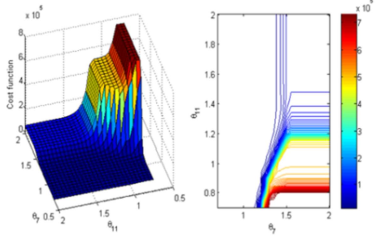
At the cost of a relatively high on-line computational burden, it provides a coordinated operation of the available actuators to track multiple references and satisfy bounds on inputs, outputs, and states of the process. It is well suited to handle multivariable and constrained control problems. The application of MPC in the power electronics and electrical drives field is mainly motivated by two facts: the mathematical models of these systems, needed by MPC, are well known, and several constraints have to be considered in the design of the controller.

The use of MPC for PSMS torque control is based on Linear Parameter-Varying (LPV) models. The use of Linear Parameter Varying (LPV) prediction models has provided an effective solution to develop MPC algorithms for linear and nonlinear systems. However, the computational effort is a crucial issue for LPV-MPC, which has severely limited its application, especially in embedded control. Indeed, for dynamical systems of high dimension commonly found in embedded applications, the time needed to form the Quadratic Programming (QP) problem at each time step, can be substantially higher than the average time to solve it, making the approach infeasible in many micro controller boards.

ISC has expertise in optimal constrained control and in related methods for computationally efficient implementation of such controllers. As an example, one of our recent projects considered the development of an algorithm that drastically reduces this computational complexity for a particular class of LPV systems. The rebuilding phase of the QP problem has been accelerated at the cost of a slightly increased sub-optimality by an innovative method. The solution, developed in two different forms indicated as Rebuild-Free (RF_1 and RF_2)-MPC, achieved impressive results in PMSM Torque Control as shown in the following table.

Performance comparison of standard LPV-MPC vs efficient ISC solutions for PMSM Torque Control

	$LPV - MPC$	$RF_1 - MPC$	$RF_2 - MPC$
Average Execution Time [s]	0.00083	0.00033	0.00031
Max Execution Time [s]	0.00112	0.00057	0.00055
Execution time improvement [%]	--	32.33	33.74
Sub-optimality [%]	--	3.4649	3.5129



Clients Include

- Torotrak: variable transmission system.
- Visteon: applying LabVIEW to automotive power control.
- General Motors: SI engine control.
- General Motors: SCR system identification.
- General Motors: Control model calibration.
- Toyota: Diesel engine control.
- Cummins: Diesel engine design methods assessment.
- Ford: Autonomous vehicle control.
- FCA: Training Activity via Electronic throttle design study.
- NXP: Hybrid Electric powertrain control.

Recent Automotive Training Courses

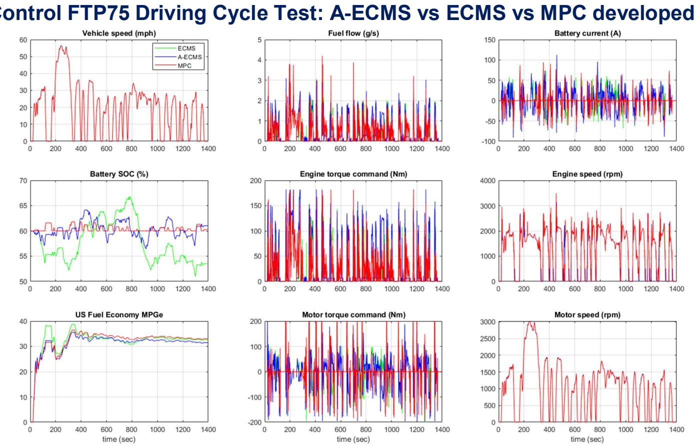
- Ford at Dearborn annual courses between 2004-2019
- Cummins at Columbus, 2018
- Toyota at Ann Arbor 2014 & 2018
- Chrysler at Auburn Hills 2011-2016
- Freescale in Glasgow and Detroit 2008
- NXP in Glasgow 2018
- GM Detroit 2015
- Jaguar in Coventry and Gaydon 2006 & 2009
- Riccardo in Leamington and Shoreham 2006 & 2009
- Visteon in Detroit 2004

"Approaching a problem with an open mind is an important aspect of the ISC philosophy, as is using the simplest, most cost-effective solution."

ISC Expertise in Automotive Control and Optimization

Over the last 2 decades ISC Ltd has been involved in a number of research and development projects with both universities and companies. The development of advanced control systems represents the main services provided by ISC to study and design ad-hoc solutions for optimizing the behavior of a system to be controlled.

HEV Control FTP75 Driving Cycle Test: A-ECMS vs ECMS vs MPC developed by ISC



The collaboration between ISC and automotive companies has been consolidated by a multitude of projects, activities and training courses, to establish partnerships during the last 20 years. ISC expertise covers advanced techniques for modelling and controlling automotive systems and sub-systems, including vehicle dynamics control and the development of models/controllers for engines, autonomous and HEV/EVs.