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Practice article

Distributed control architecture for real-time model predictive control for system-level harmonic mitigation in power systems

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HIGHLIGHTS

- System architecture for Model Predictive Control utilizing repetitive and distributed control.
- Utilizing MPC for system-wide harmonic mitigations in power systems.
- The results shows that the application holds the necessary real-time requirements.
- The main contribution lays in the cross-section between method and application.

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ABSTRACT

It can be challenging to design and implement Model Predictive Control (MPC) schemes in systems with fast dynamics. As MPCs often introduce high computational loads, it can be hard to assure real-time properties required by the dynamic system. An understanding of the system's behavior, to exploit system properties that can benefit real-time implementation is imperative. Moreover, MPC implementations on embedded local devices rarely allows flexibility to changes in model and control philosophy, due to increased complexity and computational loads. A change in control philosophy (run-time) can be quite relevant in power systems that can change from an integrated to a segregated state. This paper proposes a distributed control hierarchy with a real-time MPC implementation, designed as a higher-level control unit, to feed a lower-level control device with references. The higher-level control unit's objective in this paper is to generate the control reference of an Active Power Filter for system-level harmonic mitigation. In particular, a novel system architecture, which incorporates the higher-level MPC control and handles distribution of control action to low-level controllers, as well as receiving measurements used by the MPC, is proposed to obtain the application's real-time properties and control flexibility. The higher-level MPC control, which is designed as a distributed control node, can be swapped with another controller (or control philosophy) if the control objective or the dynamic system changes. A standard optimization framework and standard software and hardware technology is used, and the MPC is designed on the basis of repetitive and distributed control, which allows the use of relatively low control update rate. A simulator architecture is implemented with the aim of mimicking a Hardware-In-Loop (HIL) simulator test to evaluate the application's real-time properties, as well as the application's resource usage. The results demonstrates that the implementation of the harmonic mitigation application exhibits the real-time requirements of the application with acceptable resource usage.

1. Introduction

Model predictive control (MPC), which is founded on optimization, utilizes a model of the system to online forecast system behavior and optimize the forecast to produce the best control decision at the current time instance [1,2]. The model, which is an approximation of the physical system that represent the dynamics under investigation, is initialized by measurements, or estimates, of the system's current state. A cost function, defining the objective of the control and constraints, may be applied to

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Nomenclature

$\mathbf{i}_j$	Current in *abc* frame, electrical segment j (A)
$\mathbf{v}_j$	Voltage in *abc* frame, electrical segment j (V)
L_j	Impedance, electrical segment j (H)
C_j	Capacitance, electrical segment j (F)
R_j	Resistance, electrical segment j (Ω)
$\mathbf{x}$	Dynamic states vector (–)
$\mathbf{z}$	Algebraic states vector (–)
$\mathbf{u}$	Control vector (–)
$\mathbf{g}(\cdot)$	Equality constraints function (–)
$\mathbf{h}(\cdot)$	Inequality constraints function (–)
$\mathbf{l}(\cdot)$	Stage cost function (–)
$\mathbf{V}(\cdot)$	Objective function (–)

reflect the system's physical and operational limitations. At each sampling interval the future control action is obtained by solving online a finite horizon optimal control problem. A range of different MPC schemes have been developed for systems with different properties and requirements, including deterministic as well as stochastic, linear and nonlinear systems. Hence, MPC is not one single method but rather a set of methods and algorithms that forms a control philosophy [3]. A general, but simplified, illustration of MPC is portrayed in Fig. 1.

Since the early advents of MPC in the process industries, thousands of successful MPC applications have been implemented in the same industries [1,4,5]. A lot of research has been directed to the MPC's area of application, and MPC has been investigated within several industries and fields of research in the pursuit of smart control schemes. The desired outcome of this research has been to improve existing non-optimal control strategies, or to solve challenging control problems where conventional control theory alone does not provide a sufficient solution. In this regard, MPC is often used as a higher-level controller feeding one or multiple lower-level controllers with references, or set-points, to be tracked.

In the field of electrical power engineering, MPC has been frequently investigated as a vital option for optimal control of power converters [6–14], where the switching of the Power Electronics (PE) devices has been the main focus of control. As examples, in [9] an indirect Finite Control Set (FCS) MPC is investigated for the optimal control of the Modular Multilevel Converter's (MMC) switching. In [15] MPC is applied to power system protection schemes, ship energy management [16], control of batteries in a peak-shaving application is discussed in [17], frequency control in [18], control of distributed energy resources in [19,20], and mitigation of harmonic distortions in [21–26]. MPCs do often introduce high computational loads that might require the computational loads to be shared among multiple distributed controller units. [27,28] do not utilize MPCs, however, present interesting applications using multi-layered and distributed optimization-based control strategies for optimal power flow in transmission and distribution systems. Even though simultaneous real-time optimization and control is one of the most desirable properties of MPC, there is still a vast area of applications in electrical power engineering where multi-layered control is common practice, utilizing ad-hoc offline optimization strategies [29,30]. An example of such an application is mitigation of harmonic distortions.

Harmonic distortions, which are any deviation from the pure sinusoidal voltage or current waveform, introduce active power losses and contributes to reactive power in the system [31]. Methods for mitigating harmonic distortion include the use of passive and active filters. Unlike passive filters, the active filters can be controlled, and, depending on the control philosophy, be able to adapt to changes in the harmonic distortion spectra. This is a desirable functionality, especially in power systems with dynamic load profiles. The most applied control philosophy for active filters involves the mitigation of harmonic distortion at a specific location in the power system (e.g. [31,32]). However, as active filters can be controlled to dynamically track a current reference, a single active filter can be designed to track a current reference that can optimize the harmonic profile of the entire system. This task can be performed in real-time by a tailor-designed MPC.

This paper proposes a scheme for real-time MPC implementation in a case-study of system-level harmonic profile optimization, where the common practice has been the use of offline optimization for the choice of set-points for the converter controllers. The main contribution and novelty in this paper lies in the real-time system framework and implementation of an MPC designed for such a task, in contrast with the state of the art solution based on offline optimization for set-point definition. In specific, the novelty lies on the use of a standard hardware and software platform for the real-time implementation of a Continuous Control Set (CCS) MPC application for optimal mitigation of harmonic distortions, as discussed in [21–25]. By exploiting the periodic nature of the voltage and current waveforms to use relatively low control update rate, a repetitive MPC control philosophy is selected and a dedicated real-time framework is proposed. The MPC implementation is split in two levels, by exploiting the architecture of this dedicated hardware–software platform. In the higher level, the MPC is designed as a higher-level distributed control node that feeds a lower-level (local) controller with references, or control set-points. The MPC, or the higher-level distributed control node, can be swapped with another controller on-the-fly if the control philosophy or the dynamical system changes. Hardware-in-Loop (HIL) simulation experiments are conducted to verify the system architecture with regards to the MPC's execution cost and the time delay introduced by the framework and the communication link. The novel framework enables a reliable and fast nonlinear MPC to be implemented in this challenging application by using standard optimization frameworks and standard software and hardware technology without resorting to hard real-time systems implemented on embedded devices, such as FPGAs and PLCs, and formal verification.

The paper is organized as follows: The problem formulation and adopted control philosophies are addressed in Section 2, Section 3 presents the system architecture and the implementation of the MPC and its framework and middleware. Furthermore, Section 4 presents a HIL test of the system architecture. Finally, Section 5 concludes the work.

2. Problem formulation

The MPC uses a model, or a state estimator, of the system to predict future behavior and be able to calculate the best possible control action to control the system to meet a desired objective. At the same time, the MPC has to comply with the system's physical and operational constraints. In the following, the derivation of the MPC and its model on standard form for the optimal harmonic mitigation application, as introduced in [24,25] for a two-bus shipboard power system, will be discussed. The different hardware layers and adopted control philosophy will be introduced.