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Sandip K. Lahiri

Multivariable Predictive Control

Applications in Industry



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To my parents, wife Jinia and two lovely children Suchetona and Srijon

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Preface

In chemical process industries, there is an ongoing need to reduce cost of production and increase profit margin. Due to cut-throat competition on a global level, the major chemical industries are now competing to optimize raw material and utility consumption, to reduce waste, to reduce emission, and to minimize pollution. Multivariable model predictive control (MPC) is considered as an excellent tool to achieve those goals. The benefit of implementing MPC are many. MPC optimizes the plant operation on a continuous basis, reduces waste and utility consumption, minimizes raw material consumption, and maximizes production. Due to these benefits, all major chemical industries, petrochemical industries, and oil refineries throughout the globe are implementing MPC in their plants.

However, there are no dedicated books available to discuss the basic concepts of MPC, provide practical guidelines, and explain industrial application procedures.

The main idea of writing this book is to fill this gap with the following people in mind: managers, process engineers, control engineers, operators working in the process industries, and chemical engineering students who want to pursue process control career.

MPC is normally implemented by an external MPC consultant company or experts such as AspenTech, Honeywell, and Shell. The practicing process engineers or process control engineers working in the plant normally have much less exposure or knowledge to implement MPC. The available books in market on MPC don't cover the practical aspects to implement commercial MPC software.

The available books on MPC emphasize unnecessary theoretical details, which are normally not required by the practicing engineers, and those theories have very little relevance for commercial implementation of MPC software. This book discusses the practical aspects of MPC implementation and maintenance. The consultants or experts coming from MPC vendor companies normally implement MPC, hand over the technology to client plant, and then leave. After they leave, the responsibility goes to plant process engineers and control engineers to keep the MPC software running, derive maximum benefit from it, and sustain those benefits by proactive maintenance. So plant engineers need to have a thorough understanding about the different features of MPC software and key implementation steps. Often, due to unavailability of literature on this subject, plant engineers lack the knowledge and understanding of MPC.

The book is intended to build an overall understanding of MPC implementation and how to derive maximum benefit from MPC. It covers everything that a practicing process engineer or process control engineer needs to know to build an effective MPC application. Practical considerations of MPC implementation are emphasized over

unnecessary theoretical details. The book covers a wide range of subjects of MPC applications, starting from an initial functional design stage to final implementation stage. Readers will also get enlightened as to why many MPC applications fail in industries across the globe. The root causes of this failure are discussed in detail so that readers of the book can safeguard and take preventive and corrective action beforehand to avoid MPC failure.

As this book covers a wide range of topics, the materials are organized in such a way that helps the reader to locate the relevant chapters quickly, to be able to understand them readily, and to apply them in the right context. The book is organized in the following way.

Overview of Contents

Chapter 1 gives an overview of the importance of multivariable predictive control (MPC) in chemical process industries in the context of today's competitive business environment. The benefits of implementing MPC over normal Proportional-Integral-Derivative (PID)-type regulatory control and how MPC brings this benefit in real commercial chemical plant are explained in detail here. A brief description of MPC working principle is also discussed. The purpose of process control in chemical process industries (CPIs) is to ensure safety, maintain product quality and operational constraints while trying to maximize economic benefit. Traditionally, PID controllers are used in CPIs. However, PID controllers are not efficient to handle multivariable processes with significant interactions. Multivariable model predictive optimizing controller understands these process interactions and makes multiple small moves with the help of its model predictive capability. By doing this, it slowly brings the process to the most economic operating zone while maintaining all the process parameters within their limits. MPC acts as a supervisory controller above base-level PID control and is situated at the middle of a multilevel control hierarchy. The relevance of multivariable predictive control (MPC) in chemical process industry in today's business environment is very high while industries are struggling to reduce operating cost, maximize profit margin, and reduce waste. MPC stabilizes the process by utilizing its model predictive capability and thus allows the operation near to constraints. MPC is applied in oil refinery, petrochemical, fertilizer, and chemical plants across the globe and they bring huge amount of profit. The chapter ends with practical examples of MPC implementations in various process industries starting from petrochemicals, petroleum refinery to fertilizer and many other chemical plants.

Chapter 2 deals with theoretical foundation of MPC. Different variables and commonly used terms in MPC are introduced in the chapter. Different features of MPC controller are explained in detail. A simple algorithm explains the reader the underlying calculation steps of MPC technology. Simplified dynamic control strategy of MPC controllers are discussed in detail to develop an understanding of how it works. One of the major features of MPC is its future prediction and constraint handling capability. The theoretical background of these two main features is explained in detail with examples.

Model predictive controllers (MPCs) have many features. They are multivariable controllers with model-based predictive capability. They continuously optimize the process

by rigorously planning and executing small movement in manipulated variables (MVs). As simple architecture, they have data collection module, control variable (CV) prediction module, steady-state optimization module, and dynamic optimization module. The process starts with reading current value of controlled variable and MV, and using its internal process model it predicts the future value of controlled variable. In every execution, it reconciles this prediction value with actual process measurements to compensate for model inaccuracies. Also, it calculates the size of the control process (i.e., number of MV and CV available for control purpose) in every execution and sees whether any change in size is made by panel operator. Its steady-state optimization module then calculates the optimum targets for CV and MV and feeds this information to dynamic module to plan detail MV movement to achieve those targets. Depending on various tuning parameters and MV–CV limits, dynamic module initially plans for a series of MV movements so that those targets can be achieved and process can be brought to the most economic optimum zone. The first step of MV movement is actually implemented through PID controllers and all other moves are discarded. In next execution, again all the calculations are repeated.

The chapter explains all of the aforementioned features in a simple way.

Historical developments of different MPC technology are described in detail in Chapter 3. First-generation MPC was developed in 1970s. Over the years, MPC technology went through various modifications and additions of different features and reached currently as fifth generations MPC technology. The genesis of these developments over the years, the need, and innovations at different generations are discussed in this chapter. MPC control algorithm is developed over the years starting from 1970s. The initial IDCOM, an acronym for Identification and Command and Dynamic matrix control (DMC) algorithms represent the first generation of MPC technology (1970–1980); they had an enormous impact on industrial process control and served to define the industrial MPC paradigm. Engineers at Shell Oil continued to develop the MPC algorithm and addressed the weakness of first-generation algorithm by injecting quadratic program (QP) in DMC algorithm. The QDMC algorithm can be regarded as representing a second generation (1980–1985) of MPC technology, comprising algorithms that provide a systematic way of implementing input and output constraints. However, after initial phase, MPC technology slowly started to get huge profit and gain wider acceptance during the 1990s. The Identification and Command, modified version (IDCOM-M), Hierarchical constraint control (HIECON), Single Multivariable Control Architecture (SMCA), and Shell Multivariable Optimizing Controller (SMOC) algorithms represent a third generation of MPC technology (1985–1990); others include the predictive control technology (PCT) algorithm sold by Profimatics, and the RMPC algorithm sold by Honeywell. In the era of 1990–2000, increased competition and the mergers of several MPC vendors have led to significant changes in the industrial MPC landscape. Major MPC companies started acquisition and wanted to dominate the market. AspenTech and Honeywell got out as the winners of this phase and represent fourth-generation MPC (1990–2000). Today, we are witnessing a further technology development that is not so much focused on improving the algorithms, but to improve the development steps. This represents fifth-generation algorithm (2000–2015). The focus is put to make those steps smoother, faster, and easier, for both the developer and the client, and to do as much as possible remotely. The chapter enlightens readers on all of the aforementioned areas.

Implementing MPC in chemical plants is itself a project and involves lot of steps. Chapter 4 gives an overview about the various stages of MPC implementation starting from an assessment of existing regulatory control, functional design of MPC, model building and final MPC implementation stages. It starts with preliminary cost–benefit analysis to evaluate approximate payback period. Assessment of base control loop and strengthening it is a basic requirement to build a solid foundation upon which MPC works. In functional design step, a list of controlled and MVs are identified. Plant step test is carried out to collect dynamic data of CV for a step change in MV. These step test data are utilized to build models in model building stage. Potential soft sensors are made where online analyzers are either not available or very costly. The suitability of developed model for control purpose is checked in off-line simulation mode. After that, controller is commissioned in actual plant and online tuning is done to achieve the desired controller action. As a last step, performance monitoring and benefit assessment of installed MPC controller is done. An essential part of each step is to train the plant operators and engineer regarding different features of MPC and how to operate the installed MPC application. The chapter also explains the steps involved in MPC projects with vendor.

Normally, the implementation of MPC involves cost that includes MPC software, hardware cost, and MPC vendor cost. Client plants who want to implement MPC always want to know about the benefit or payback period of MPC implementations before they decide to go for MPC implementation. Chapter 5 describes cost–benefit analysis procedures before MPC implementation.

Preliminary cost–benefit analysis is usually carried out before starting MPC project. The purpose is to estimate the actual benefit after MPC implementation. A scouting study of process analysis and economic opportunity analysis is done to know the potential areas where MPC can bring profit. By its model-based predictive capability MPC stabilizes the process and reduces variability of key process parameters. This reduction of variability enables operators to shift the set point closer to the constraints. Operation closer to constraints translated into more profit. By statistical analysis, this increase of profit due to MPC implementation is calculated. Finally, a scientific cost–benefit analysis is done to evaluate the payback period. The results of the cost–benefit analysis help the plant management to take economic decision to implement MPC in plant. An example with practical case study is also given to explain the cost–benefit analysis procedure.

Chapter 6 explains the procedure to assess the health of regulatory base control layer of plant. MPC cannot work efficiently if base control layer or regulatory control layer is weak. Hence, strengthening base control layer is an important prerequisite to build the good foundations of MPC. Over the years, process industries technical community realizes the importance of monitoring the base control loop performance. The benefits gained from detecting the weakly performed control loop and subsequently improving their performance are huge. Assessment of regulatory base control layer in plant starts with understanding different common failure mode of valves, sensor, controller, and so on. Control valves may malfunction due to hysteresis, stickiness, and improper valve sizing. Sensors exhibit different problems such as noisy indication, improper calibration, and overfiltration, to name a few. Controllers commonly have tuning problems. Sometimes, process also has problems such as variable gains and too much interaction. Due to a large number of control loops present in any moderate-sized process

industries, manual evaluation of each control loop performance is not feasible. Online systematic performance monitoring of control loops through various key performance indices (KPIs) and matrices is the need of the hour. This gives rise to a new technology/software called control performance monitoring/assessment (CPM/CPA). Performance KPIs are generated and monitored online, and they are grouped as follows: traditional KPIs, statistical-based metrics, business/operational metrics, and advanced indices. The chapter ends with giving a short exposure of controller tuning for PID controllers.

Functional design is the most important step in MPC project. Functional design is the proper planning and design of MPC controller to achieve operational and economic objective of the plant. There is no standard procedure to be followed to do a functional design. It depends on expertise and experience of MPC vendor or control engineer, plant operating people, and plant process engineering people.

Chapter 7 explains in detail about various aspects and practical considerations of functional designs of MPC controller in actual commercial plants. This step starts with understanding of process opportunity and process constraints. Process controls objective, controller scope, and identification of CV–MV–DV list is done in this step. Exploring the potential optimization opportunity is a key job in functional design stage. Identification of any scope to implement the inferential calculations or soft quality estimators is also done in this stage. Conceptualization of economic objective of controller and form of linear program (LP) and quadratic program (QP) objective function is finalized in this step.

Functional design of MPC controller started with the identification of controlled and MV and subsequent planning for MPC model structures. Practical considerations to identify process and equipment constraints are also discussed to help the reader formulate a robust, safe, and reliable MPC model. Good step test data is of paramount importance in MPC model building and its overall functioning. How to ideally perform step test in actual shop floor of the plant and do's and don'ts of step test are discussed in detail. The chapter also briefly explains the requirement of soft sensor building.

Chapter 8 deals with preliminary process step and step test. Step test is considered as one of the major steps in MPC project. In step testing, step change in MVs is given and the impact of it on CVs with time is collected through step test data. These data are used to build process model. Both open-loop and closed-loop test are practiced in industry, and both methods have their own advantages and limitations. As the MPC models are data-driven empirical models and those data are generated in step test, it is very important to carry out this test with all precautions. The quality of developed model will be as good or as bad as step test data. Hence, it is important to know all do's and don'ts of step testing method. To reduce the unnecessary problems in step test, a preliminary process test or pre-stepping is done before step test. The purpose is to identify all the possible bad actors of step test and rectify them beforehand. The chapter explains various do's and don'ts in step test.

Chapter 9 describes in detail about the various model building procedures available in commercial software. Process models are dynamic MV–CV relationship generated from step test data. In model building step, a suitable model structure with proper order is first identified. Later on, model coefficients are evaluated from step test data by statistical fitting operation. Various data cleaning methods and outliers detection are discussed. Basic steps of process identifications start with execution of step test and collection of data, pre-processing and cleaning of data, selection of model structure and

order, and determination of model parameters. There are a lot of predefined dynamic model structures available in the library of commercial identification software. Knowing those structures and their key strength and weakness and finally identifying a suitable structure to accurately model the step data is the key of system identification step.

Theoretical background of various available models and their implication in MPC is explained in detail in the chapter. One of the major requirements for robustness of MPC model is to validate the developed data-driven MPC model from practical process knowledge so that the model captures the underlying physics of the process. This important aspect is discussed in detail to give the reader a flavor regarding efficient and robust model building. Practical considerations to prioritize MVs to control particular CV in multivariable environment are discussed in detail so that user can maximize the economic benefit after MPC implementation.

An inferential or soft sensor is a mathematical relation that calculates or predicts a controlled property using other available process data. When it is very difficult or costly to measure an important parameter online, such as distillation tower top product impurity, soft sensors are used to predict that inferential property from other easy measurable parameters such as top temperature and pressure. Sometimes, soft sensors are used as backup of an existing analyzer to reduce or eliminate dead time, both from the process and the analyzer cycle.

Chapter 10 is dedicated for soft sensors available in various process industries. What are soft sensors and how to make them is the main idea of the chapter. Various commonly used algorithms to build fast principle-based and black-box-based soft sensors models are discussed in detail. Why some soft sensors fail in industry and precautions needed to make successful robust soft sensors are described in the chapter.

Usually, four types of soft sensors are used in industry, namely, first principle-based soft sensor, data-driven soft sensors, gray model-based soft sensors, and hybrid model-based soft sensors. There are many methods to develop industrial soft sensors and usually they include the following steps: data collection and data inspection, data preprocessing and data conditioning, selection of relevant input-output variables, aligning data, model selection, training and validation, analyzing dynamics, and finally deployment and maintenance.

Due to the difficulties in developing first principle-based soft sensors, data-driven soft sensors are very popular in industry. Major data-driven methods for soft sensing which dominates the industry and discussed in this chapter are principle component analysis, partial least squares, artificial neural networks, neuro-fuzzy systems, and support vector machines.

After development of process model, it is important to know how the developed controller will perform in online mode before its actual deployment in real plant. Off-line simulation refers to running the controller in a separate off-line PC to see the MV-CV dynamic responses of the process. One major task of off-line simulation is to set the different tuning parameters of the controller. The purpose is to perform off-line tuning and other corrections as much as possible so that the application runs effortlessly in actual plant at real time.

Chapter 11 is dedicated to off-line simulation of MPC model—an important prerequisite step for the MPC online implementation. How to set up off-line simulation in MPC software and how to derive maximum benefit from them is the main focus of the chapter. Constraint handling capability of developed MPC model can be assessed in