CONTINUOUS GENERALIZED PREDICTIVE CONTROL OF AN EXPERIMENTAL FOUR-TANK LEVEL PROCESS

BY

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DEDICATION

This work is dedicated to Almighty God.

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LIST OF ABBREVIATIONS

ADC	Analogue Digital Converter
ASC	Application Specific Controller
BC	Building Controller
CAC	Custom Application Controller
CAGPC	Continuous-time Anti-windup Generalized Predictive Control
CGPC	Continuous Generalized Predictive Control
DAC	Digital Analog Converter
DC	Direct Current
DDC	Direct Digital Control
dSPACE	Digital Signal Processing and Control Engineering
EBC	Emulated Based Control
GMV	Generalized Minimum Variance
GPC	Generalized Predictive Control
GPH	Gallon Per Hour
GUI	Graphic User Interface
HVAC	Heating, Ventilating, and Air Conditioning
IAE	Integral Absolute Error
IBWM	International Bureau of Weight and Measures
ISE	Integral Square Error
LHP	Left Half Plane
LMPC	Linear Model Predictive Control

LQ	Linear Quadratic
LRPC	Long Range Predictive Control
MAP	Mean Arterial Pressure
MIMO	Multi Input Multi Output
MP	Minimum Phase
MPC	Model Predictive Control
MRAC	Model Reference Adaptive Control
MV	Minimum Variance
NMP	Non Minimum Phase
PC	Personal Computer
PI	Proportional Integral
PID	Proportional Integral Derivative
PLC	Programmable Logic Controller
PMMA	Poly-Methyl Methacrylate
PWM	Pulse Width Modulation
QFT	Quantitative Feedback Theory
QTS	Quadruple Tank System
RAGPC	Robust Anti-Windup Generalized Predictive Control
RGA	Relative Gain Array
RHP	Right Half Plane
RLS	Recursive Least Square
SCADA	Supervisory Control and Data Acquisition
SISO	Single Input Single Output

SMC	Sliding Mode Controller
USB	Universal Serial Bus

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ABSTRACT

The four-tank level process, a typical multi input multi output (MIMO) system exhibit complex dynamics, nonlinearities and strong interaction as seen in most industrial process plants. The complex and dynamic nature of MIMO systems, necessitate the quest for an advanced control technique that could handle strong interactions. In this study, an experimental four-tank system was designed and interface for the implementation of continuous generalized predictive control (CGPC) and other classical controllers for both minimum phase (MP) and non-minimum phase (NMP).

The designed and constructed four-tank system was modeled using mass balance and Bernoulli's law. All components that require high precision were calibrated. The non-linear model of the system was linearized to determine the operating points. State space as well as the transfer function for the two operating phases were obtained. The Relative gain array (RGA) was used to determine a suitable decentralized input-output pairing control structure. Using input-output pairing suggested by RGA, an adopted CGPC algorithm written in MATLAB was employed to design appropriate CGPC loop controllers. Classical PID controllers based on internal model control (IMC) and auto tuning PID were parameterized and implemented on the system. These controllers were used for both the simulation and the real time experiments using MATLAB/Simulink. The controllers' performance evaluation of the system for both MP and NMP was based on integral absolute error (IAE) and integral square error (ISE) performance indexes and other time-domain performance metrics.

The results of the experiments showed that the physical system was adequately matched with the obtained transfer functions. The steps responses obtained for both simulations and experimentations portrait that of an interacting multivariable system. Furthermore, satisfactory performances was achieved for simulation and the real time experiments with comparative lower values of IAE and ISE particularly for the MP. A gross value of ISE 13.63, 9.81 and 54.14 and IAE values of 18.61, 18.52 and 78.14 were for estimated for auto tuned PID, CGPC and IMC respectively. Also, an overall percentage overshoot of 4.91, 3.01 and 5.25% were recorded respectively for MP. On the other hand, larger value of ISE 49.48, 6267.2, 2701, and IAE values of 79.24, 4136 and 1016.4 and percentage over shoot of 0.56, 15.50 and 1.61% were obtained respectively for auto tuned PID, CGPC and IMC respectively for NMP.

The newly designed and interface four-tank experimental system will provide a platform to demonstrate and illustrate several control concepts due to its nonlinearity and complex dynamics. The system will help students to connect between control theory and the real-world thereby adding realism to control education. This study established that a satisfactory control response of the four-tank level process can be achieved with CGPC especially when operating at the MP.

CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

A typical chemical plant is tightly integrated processes which exhibit nonlinear behaviour and complex dynamic properties (Gatzke *et al*., 1999). For decades, chemical process industries had relied on single loop linear controllers to regulate plants. The control of process variables such as fluid level, temperature, pressure, and pH are important tasks in process industries; a small fluctuation in any of these can put the system in an unstable state. These variables must be monitored throughout the life span of the process; otherwise, the plant might be operating in an uncontrolled or unpredicted manner. This behaviour may also result from the influence of surrounding plants or environmental factors.

It is a common practice in process industries to pump fluid from one tank to the other, the fluids are pumped either for further processing or store as a final product (Jayaprakash *et al.*, 2013). Thus, the liquid level must be regulated at all times to avoid spillage, pressure build-up or implosion. Moreover, a series of tanks might be needed in a single process, as a result, tanks are coupled together. Coupled tanks most times interact with each other thereby resulting in a serious control problem.

In process industries, (such as oil and gas, wastewater treatment, power plant, pharmaceutical and food industries) level problems are frequently encountered. Level control in tanks and other process equipment is very important and is of great interest to system engineers (David and Lei, 2005; Ashish, 2014) because an improper level control can results in system shutdown, waste of energy, overflow or emptiness of process vessels, unsafe working conditions, shorter equipment life span and so on. Processes with only one output being controlled by a single manipulated variable are classified as single input single output (SISO) systems. However, many processes do not conform to this control configuration. In practice, many industrial processes usually involve control of at least two variables (decision) through manipulation of other two variables (manipulated) and such systems are termed multi-input multi-output (MIMO) or multivariable systems (Seborg *et al.,* 2004). MIMO systems are in great demand and need much attention in process industries; of course, it is more complicated to control than SISO systems due to interactions, inherent nonlinearity, and dynamic complexity. Thus, the control strategies employed in MIMO processes are quite different as a result of strong coupling between the controlled and manipulated variables compared to the latter (Angeline and Jayashree, 2014). In addition, control of nonlinear MIMO systems is cumbersome because nonlinear processes do not obey superposition and homogeneity laws (Nagammai *et al.,* 2015). Therefore, an advanced control technique must be employed to control MIMO systems.

In control community, it is a usual practice to extend an established technique for scalar systems to multivariable cases. Nearly every control techniques – Proportional integral and derivative (PID), pole-placement, model reference, linear quadratic (LQ) have both the discrete-time and continuous-time version, predictive control is not an exception (Demircioglu and Ercan, 2000). In recent times, long range predictive control (LRPC) design techniques have attracted much attention as fundamental design methods for self-tuning controllers (Clarke and Mohtadi, 1989). These methods seem to be superior in terms of robustness, optimal control performance compares to other self-tuning control methods (Demircioglu and Gawthrop, 1991; Osunleke, 2010).

Generalized predictive control (GPC) proposed by Clarke *et al*. (1987) is a good alternative to previously used self-tuning controllers, despite in discrete-time version, it provides considerable improvement over generalized minimum variance (GMV) and other strategies. It tends to overcome the problem of previously used algorithms. Continuous generalised predictive control (CGPC), a continuous-time version of GPC, was developed by Demircioglu and Gawthrop (1991) to combat other pitfalls of previous algorithms and had proved beyond doubt to have better control performance than the discrete-time GPC. CGPC had proven to be a proficient control technique that is capable of handling both simple and complex processes (Clarke *et al.*, 1987) ranging from open-loop stable and unstable processes, processes with dead time, as well as non-minimum phase (NMP) processes.

This research work focuses on practical application of CGPC to a real-time experimental four-tank control rig. The Four-tank process was designed in Lund University to illustrate performance limitations for multivariable systems posed by ill-conditioning, right half plane (RHP) zeros and model uncertainties (Johansson and Nunes, 1998). The four-tank system often time called quadruple tank process (QTS) exhibit transmission zero as it transits from minimum phase (MP) to non-minimum phase (NMP) by simple valve adjustment. NMP systems are characterized with RHP zeros. Systems with RHP zeros present difficulty when applying control strategies. Both NMP and unstable systems occur mostly in real industrial processes. Systems engineers must, therefore, be aware of this kind of processes, because they are an important source of control problem in real multivariable systems. Nevertheless, systems in the MP tends to be more stable and easy to control compare to NMP because the latter's behaviour cannot be predicted accurately (Johansson and Nunes, 1998; Yousof and Mojtaba, 2015).

1.1 Aim and Objectives

The aim of this research is to design an experimental four-tank system and implement continuous generalized predictive control and other classical controllers.