

Economic evaluation and design of an electric arc furnace controller  
based on economic objectives

Daniël Jacobus Oosthuizen

Professor L.K. Chau

Professor G.J. van der Watt

## **ECONOMIC EVALUATION AND DESIGN**

Department of Electrical, Electronic and Computer Engineering

Master of Engineering (Electronic Engineering)

# **CONTROLLER BASED ON ECONOMIC OBJECTIVES**

## **ABSTRACT**

The increasing demand in metal production has led to more research interest in the control of an Electric Arc Furnace (EAF) and its associated power system. The cost of the electricity used by the EAF is usually the largest item of operating costs.

The work presented in this thesis deals with the economic evaluation and design of an EAF controller based on economic objectives. The main objective is to minimize the cost of the electricity used by the EAF.

**Daniël Jacobus Oosthuizen**

Submitted in partial fulfillment of the requirements for the degree

Master of Engineering (Electronic Engineering)

in the

Faculty of Engineering, the Built Environment and

Information Technology

UNIVERSITY OF PRETORIA

Electric arc furnaces are highly nonlinear systems. They have a large number of feedback, and most of them are discrete. The load may change at any time, even though a uncircised motor is connected to the furnace. The furnace is controlled. Disturbances are caused by the load changes and the voltage fluctuations.

November 2001



Economic evaluation and design of an electric arc furnace controller discussed in detail. The based on economic objectives operational techniques, possible threats to data integrity, costs Daniël Jacobus Oosthuizen of budgeting tools form part of the complete experimental Professor I.K. Craig one is presented to ensure that useful data is generated and the valid Professor P.C. Pistorius measuring the value of the evaluation framework forms the basis of Department of Electrical, Electronic and Computer Engineering (EECE) (manual and MPC) Master of Engineering (Electronic Engineering) and the originality of the article, and

information is used to ensure that the test data is not corrupted by the disturbances statistical testing is performed to ensure that the result is statistically significant.

## ABSTRACT

Simulation results indicate large potential benefits available to MPC control. In particular, the economic benefits of Model Predictive Control (MPC) over conventional manual control on an Electric Arc Furnace (EAF) are determined by means of a simulation study. The structure used for the MPC controller is chosen such that the objective function, which is minimised by the controller, corresponds to the cost of a tap. Minimisation of the objective function thus constitutes minimising EAF operational cost. The major factors contributing to the cost of the tap are thus determined and their contributions relative to each other quantified. The procedure of translating functional control objectives into economic objectives is discussed, as is the relative cost contribution of the feed additions to the EAF.

An existing EAF model is expanded by modelling the slag foam depth. The foam depth is useful in ensuring efficient energy transfer to the melt. Great emphasis is placed on ensuring that the simulation study is representative of operational conditions typically experienced in industry. Only continuous measurements are therefore used for continuous feedback, and measurements taken at discrete time intervals are only fed back at the time intervals indicated by plant data. The full non-linear model is used to simulate the plant, even though a linearised model is implemented as the internal plant model for the MPC controller. Disturbances are chosen based on plant data and suggestions from industry.

The process of an experimental design for controller evaluation is discussed in detail. The selection of an appropriate experimental technique, possible threats to data integrity, tools for data analysis and capital budgeting tools form part of the complete experimental procedure. A framework is presented to ensure that useful data is generated and that valid conclusions are made concerning the data. This evaluation framework forms the basis of the experimental procedure used to compare the two control strategies (manual and MPC). The simulation study represents a test conducted over a period of one month, and randomisation is used to ensure that the test data is not correlated to the disturbances. Hypothesis testing is performed to ensure that the result is statistically significant.

## CONCLUSION

Simulation results indicate large potential benefits attributable to MPC control. Improved utilisation of feed materials can potentially reduce the cost per ton of steel by 0.8 %. The major portion of the potential benefits is however due to the elimination of unscheduled delays, by ensuring that steel specifications are met at tapping, and that off-gas limits are not exceeded at any stage during the tap. These factors account for potential savings in excess of 7 % due to increased throughput.

Keywords: Electric Arc Furnace, Model Predictive Control, Economic evaluation, Experimental design, Hypothesis testing, Dynamic models.

In bestaande begroend model is uitgebrei daar die vervaardiging van staal volgens 'n nie-lineêre kontrollering op 'n elektriese oefenoven effektiwiteit en ekonomiese voordele van 'n nie-lineêre kontrollering word. Kort gesê word gele deur 'n standaardstelsel vanaf hand tot hand om wees van omstandighede wat tydens 'n oefentap belangrik is. Die kontrole van die oefentap moet kontinue beschikbaar en vand daarom 'n tussenvergadering. Afsonderlike kontrole van die oefentap bystappe beskikbaar is wou sien verliggaar op die toestande van die oefenoven. Die volledige nie-lineêre model is gevind om die vervaardiging van staal te optimaliseer. Die model is gebaseer op die interne aansigte stelsel vir die Model-Voer, die Model-Reactie, die Model-Sens en gebaseer op aanlegdata en voorstellende deur aanslag gevonden.

Experimentele ontwerp met die enige ma beheerders wat aangesluit moet word in die konsante van 'n geplante eksperimentale kontrol, posisie en bedryf moet in die eksperimentele procedures vir die manlike en projek evaluering. Teoretiese werk moet daarnaas in die eksperimentele procedure.

Economic evaluation and design of an electric arc furnace controller based on economic objectives

Die eksploreerde data word gebruik om die basis van die eksperimentele procedure wat gebruik is om Daniël Jacobus Oosthuizen te vergelyk (Model Voorspellende Beheer en hand-beheer). 'n Professor I.K. Craig beskryf van een manier word deur die simulasiestudie voorgestel Departement Elektriese, Elektroniese en Rekenaar Ingenieurswese tussen die drie en die Magister in Ingenieurswese (Elektroniese Ingenieurswese) bepaal of die resultante statisties behoudend is.

## OPSOMMING

Die finansiële voordele van 'n Model Voorspellende Beheerder is bepaal deur dit te vergelyk met konvensionele hand-beheer op 'n elektriese boogoond. Die struktuur van die beheerder is sodanig gekies, dat die doelwit-funksie wat deur die beheerder gemonimeer word ooreenkom met die koste van 'n tap. Minimering van die doelwit-funksie is dus ekwivalent daaraan om die bedryfskoste van die boogoond te minimeer. Die belangrikste faktore wat bydra tot die koste van 'n tap is daarom geïdentifiseer en die relatiewe bydraes tot die totale koste gekwantifiseer. Die omskrywing van funksionele doelwitte in terme van finansiële doelwitte is bespreek en die relatiewe kostes van die toevoer-materiale bepaal.

'n Bestaande boogoond model is uitgebrei deur die skuimslakdiepte te modelleer. Die skuimslakdiepte is van belang, aangesien effektiewe energie-oordrag na die bad hierdeur beïnvloed word. Klem is daarop gelê dat die simulasiestudie verteenwoordigend moet wees van omstandighede wat tipies in die industrie aangetref word. Slegs metings wat kontinu beskikbaar is word daarom kontinu teruggevoer. Metings wat slegs op diskrete tydstippe beskikbaar is word slegs teruggevoer op dié tydstippe aangedui in aanlegdata. Die volledige nie-lineêre model is gebruik om die aanleg te simuleer, al is 'n lineêre model gebruik as die interne aanleg-model vir die Model Voorspellende Beheerder. Steurings is gebaseer op aanlegdata en voorstelle deur aanleg personeel.

Eksperimentele ontwerp met die doel om beheerders te evalueer is in detail bespreek. Die keuse van 'n gesikte eksperimentele tegniek, potensiële bedreigings vir data integriteit, procedures vir data analise en projek-evaluering tegnieke maak deel uit van die eksperimentele prosedure.

'n Raamwerk is voorgestel waarbinne verseker kan word dat bruikbare data gegenereer sal word en dat geldige gevolgtrekkings gemaak kan word oor die data. Hierdie evaluieringsraamwerk vorm die basis van die eksperimentele prosedure wat gebruik is om die twee beheerstrategieë te vergelyk (Model Voorspellende Beheer en hand-beheer). 'n Toets uitgevoer oor die bestek van een maand word deur die simulasiestudie voorgestel. Ewekansige tegnieke is gebruik om te verseker dat geen korrelasie tussen die data en die steurings bestaan nie. Hipotese toetsing is gebruik om te bepaal of die resultate statisties beduidend is.

Die simulasiestudie duï op groot potensiële finansiële voordele weens Model Voorspellende Beheer. Beter benutting van toevoer-materiale kan die koste per ton staal potensieel verminder met 0.8 %. Die grootste deel van die potensiële besparing is egter vanweë die eliminasie van ongeskeduleerde onderbrekings. Dit word bewerkstellig deur te verseker dat aan staal temperatuur en -samestelling spesifikasies voldoen word wanneer getap word en dat die afgas temperatuur nie gespesifieerde limiete oorskry nie. Hierdie faktore kan potensieel lei tot addisionele besparings van groter as 7 % danksy verhoogte deurset.

Sleutelterme: Elektriese boogoond, Model Voorspellende Beheer, Ekonomiese evaluering, Eksperimentele ontwerp, Hipotese toetsing, Dinamiese modelle.

## ACKNOWLEDGEMENTS

I would like to thank Prof. I.K. Craig and Prof. P.C. Pistorius for their meaningful guidance in the course of this dissertation. I would also like to thank Mintek for their financial support.

### 3.2 Background

Information regarding typical operational practices on Electric Arc Furnaces (EAFs) was obtained from Iscor and Corus steel, U.K. I would like to thank Mr. Philip Schutte and his colleagues at Iscor in particular, for their willingness to discuss sensitive information and to answer endless questionnaires within a limited time span. I also would like to thank Mr. Andrew Chown and his colleagues at Corus steel for their willingness to discuss their furnace practices at short notice. The information obtained during these two interviews provided useful insight into aspects typically not considered during purely theoretical analyses.

### 3.3 Proof reading

I would like to thank everyone involved in proof reading and formatting this dissertation. Your contribution is appreciated.

### 3.4 Acknowledgements

I would like to thank my wife, Tina, for her motivation and support during the dissertation. Finally, I would like to thank the Lord for giving me the determination and the ability to complete this dissertation.

### 3.1 Introduction

#### 3.2 Background

#### 3.3 Components of EAF operation

##### 3.3.1 Oxygen lance and electrodes

##### 3.3.2 Electrical circuitry and control systems

##### 3.3.3 Furnace operation in the steel plant

##### 3.3.4 Slag removal

##### 3.3.5 Steel making

##### 3.3.6 CO emission

##### 3.3.7 Relative furnace power

##### 3.3.8 Off-gas temperature

##### 3.3.9 Slag foam depth

### 3.4 Conclusion

## Chapter 4: Model Predictive Control

# TABLE OF CONTENTS.

4.1. Introduction	37
Chapter 1: Introduction.	1
1.1. Motivation.	1
1.2. Background.	2
1.3. Problem statement.	3
1.4. Contribution.	3
1.5. Dissertation approach.	4
1.6. Organisation.	5
3.2.1. Model transformation	6
Chapter 2: Process Overview.	7
2.1. Introduction.	7
2.2. Process Description.	7
2.3. Simulation model.	11
2.4. Control objectives.	13
2.5. Modelling of slag foaming.	19
2.6. Conclusion.	21
3.3.1. Cost implications	22
Chapter 3: The cost of EAF operation.	22
3.1. Introduction.	22
3.2. Background.	22
3.3. Cost components of EAF operation.	23
3.3.1. Operational cost considerations.	23
3.3.2. Cost implication of controlled variables.	26
3.3.2.1. Percentage carbon in the steel melt.	27
3.3.2.2. Steel temperature.	28
3.3.2.3. Steel mass.	30
3.3.2.4. CO emission.	31
3.3.2.5. Relative furnace pressure.	31
3.3.2.6. Off-gas temperature.	33
3.3.2.7. Slag foam depth.	34
3.4. Conclusion.	36

Chapter 4: Model Predictive Control.	37
4.1. Introduction.	37
4.2. Background.	38
4.3. Design strategy.	41
4.4. Conclusion.	44
4.5. Thesis validity.	51
Chapter 5: Controller design.	45
5.1. Introduction.	45
5.2. Plant linearisation.	45
5.2.1. Model transformation.	45
5.2.2. Linear model derivation.	47
5.2.3. Comparison of linear and non-linear plant models.	50
5.3. Open loop system analysis.	55
5.4. Design procedure.	56
5.4.2. Control and prediction horizons.	56
5.4.3. Constraints on manipulated variables.	57
5.4.4. Constraints on controlled variables.	57
5.4.5. Weights.	59
5.4.5. Setpoints.	63
5.4.6. Additional tuning.	65
5.5. Closed loop system analysis.	66
5.5.1. Stability.	67
5.5.2. Frequency domain analysis.	67
5.5.3. Sampling interval verification.	72
5.6. Controller implementation.	73
5.7. Conclusion.	79
7.3.7.3. Statistical conclusion validity.	80
7.3.7.4. Conduct conclusion validity.	80
7.3.8. State the hypothesis that needs to be tested.	80
7.3.9. Design an experiment to generate unbiased product data.	80
7.3.10. Monitor the experiment and make sure it is carried out properly.	80
7.3.11. Analyse the generated data and determine sample statistics for each.	80
7.3.12. Test and accept or reject the hypothesis.	80
7.3.13. Estimate the monetary benefits.	80
7.3.14. Do an economic project evaluation.	80

Chapter 6: The evaluation of control systems.	80
6.1. Introduction.	80
6.2. Experimental techniques for comparative experiments.	80
6.3. Statistical tools. <i>and Recommendations</i>	84
6.4. The duration of an experiment.	87
6.5. Threats to validity.	88
6.6. An evaluation framework.	89
6.7. The economic evaluation of controllers.	92
6.8. Conclusion.	97
Chapter 7. Simulation Study.	98
7.1. Introduction.	98
7.2. Modelling of feed variations.	99
7.3. Evaluation strategy.	100
7.3.1. Process understanding.	100
7.3.2. Define the problem to be solved.	101
7.3.3. Determine the variables to be measured.	101
7.3.4. Determine the accuracy of the measurements and calibrate instrumentation.	102
7.3.5. Determine the distribution of a derived variable by examining the propagation of error through the system.	102
7.3.6. Make a list of factors influencing the value of the response variable, which could invalidate the result.	103
7.3.7. Threats to validity.	104
7.3.7.1. Internal validity.	104
7.3.7.2. External validity.	105
7.3.7.3. Statistical conclusion validity.	105
7.3.7.4. Conduct conclusion validity.	106
7.3.8. State the hypothesis that needs to be tested.	106
7.3.9. Design an experiment to generate unbiased production data.	107
7.3.10. Monitor the experiment and make sure it is carried out as planned.	108
7.3.11. Analyse the generated data and determine sample statistics for each.	108
7.3.12. Test and accept or reject the hypothesis.	110
7.3.13. Estimate the monetary benefits.	113
7.3.14. Do an economic project evaluation.	114

7.4. Discussion.	115
7.5. Conclusion.	116
Chapter 8: Conclusions and Recommendations.	117
8.1. Summary of dissertation contents.	117
8.2. Conclusions.	118
8.3. Recommendations.	120
References	121
Attachment A	125
Implementation of EAF control systems.	

The potential economic benefits of EAFs are well known and have been extensively studied [1]. The potential reduction in energy costs can result in a significant reduction in the cost of steel production [2], which is particularly beneficial for smaller, optimised units. In addition, the lack of need for measurement and control feedback makes the design of EAFs relatively simple [3]. The implementation of EAF control systems is often limited by the availability of sensors and the advantage that unmeasured variables can be estimated [4]. In general, there are many sub-systems of EAFs for which measurements are relatively easily obtained or easily controlled, e.g. the positioning of electrodes [5] by linear position sensors, the use of sensors to calculate optimal feed addition to the melt [6] and the use of sensors to measure the temperature of the slag [7]. However, because of the high temperatures, the difficulty of access to the slag and the complexity of optimisation of the EAF system, EAF control systems are often considered to be among the most difficult to control [8].

Steel producers are often required to meet strict quality requirements, which are usually specified, in order to ensure that all specifications are met in the steel produced [9]. A controller capable of reducing production costs is vital to allow manufacturers to increase profit as expenses in improving steel quality often increase significantly. It has been reduced considerably. A simulation study concerning iron smelting in EAFs under different EAF operating conditions would provide a useful guide to estimating the cost of implementing advanced control schemes on the increasing number of EAFs worldwide.