Chapter 6

Control Problem Formulation

6.1 Introduction

In this section an initial control problem is formulated for the Steckel hot rolling mill. The suggested control scheme for the ongoing study is concisely discussed. Limitations on the control inputs are identified taking into account that the proposed control scheme is a supervisory MPC[1] controller. Predictive control methods [86] were investigated and the interested reader is referred to authoritative literature [15, 20, 85, 22, 87, 18, 80, 1] dealing with the theory and application of predictive controllers to industrial processes. In [18] the application of a supervisory GPC[2] controller to a hot rolling mill process is shown, justifying the choice of MPC in this study.

6.2 The Control Problem

6.2.1 Background

It was stated in section 1.1 that current automation projects focuses on the Automatic Gauge Control (AGC) systems, profile and shape control systems, and the control of temperature and the mechanical properties of the strip. Other control systems that are investigated concentrate on the minimizing of head- and tail end strip losses [19].

The profitability of a rolling mill is a function of the mill throughput and the quality of the strip produced [3]. This statement is motivated by the following:

- Throughput improvements: The conventional hot rolling operation has developed significantly during the last thirty years. The main driving force behind this development was to increase the

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[1] Model Predictive Control.

[2] Generalized Predictive Control.

output [3]. As an example typical mill output has increased from 2MT per year (before 1960) to 6MT per year (1970-1980) [3].

- Quality improvements: Since 1980 extra emphasis for rolling mill operation has been added. Over capacity of steel production has introduced much more competition and the quality of the produced strip, i.e. dimensional accuracy, surface finish, flatness, and physical properties [4, 5, 3], is used to distinguish strip manufacturers from each other. In more recent years only a few new hot mills have been built, with the emphasis being on revamping existing mills. Current designs therefore concentrate on improving quality and reducing the operation costs.

In order to improve the product quality and the throughput the control engineer has about four dynamic manipulated variables to control: the exit thickness; the tension in the strip whilst rolling; the mechanical properties of the strip; and the shape and profile of the strip.

The mechanical properties of the strip are controlled indirectly by controlling the temperature of the strip to follow a specified temperature versus time profile derived from considering the metallurgy of the strip [5]. The temperature of the strip in the finishing mill is controlled by controlling the rolling speed of the mill and the descaling sprays on either side outside the roll gap. In order to control the final coiling temperature of the strip, the temperature of the strip is controlled to follow a cool down temperature profile. The strip's final pass exit speed from the roll gap and the speed of the strip on the run out table as well as top and bottom water curtain sprays are used as actuators to control the final coiling temperature and the mechanical properties of the strip [25].

The aim of thickness control is to regulate the exit thickness from the roll gap to within the customer specified quality tolerances e.g. strip thickness mean and thickness standard deviation. Modern and advanced control methods can be employed to decrease the thickness standard deviation and decrease the thickness mean closer to the customer's lower thickness bound, resulting in material savings [19]. The thickness controller must be able to reject disturbances such as non-uniform input thickness, hardness variations, input tension variations, output tension variations and friction variations [3] whilst maintaining an uniform output gauge. Normal AGC (Automatic Gauge Controller) systems consist of a BISRA-Davy gaugemeter compensator [27, 1, 21] and a closed loop thickness controller using a delayed[3] X-ray measurement of the output gauge. The measurement transport delay in the feedback loop can make the feedback control system unstable. A Smith Predictor is normally used to compensate for this transport delay.

Potential benefits from the fast actuators on new upgraded mills can be limited if good tension control is not performed. Fast roll gap movements introduced to correct thickness disturbances generate transient tension changes. This results in uncontrolled thickness variations after the roll gap if no tension control is done [3]. Thickness variations not only have an adverse effect on quality and profit

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[3] This delay is attributed to the distance that the strip has to travel from the exit of the roll gap to the X-ray device position

but may also lead to mill instability during the rolling of later passes and subsequent cold rolling.

The control of the tensions in the strip whilst rolling are regulator problems [55]. Both tensions are controlled around their associated steady state values that is applied to the strip in order to decrease the rolling load, and effectively increasing the mill's capability to make larger thickness reductions. This increase in reduction capability can ultimately lead to an increase of the throughput of the mill by reducing the number of passes necessary to reach the required exit thickness.

As stated earlier, tension deviations are disturbances for the thickness control loop and therefore these deviations has to be minimized. If these deviations go uncontrolled and the tension in the strip is higher than the yield stress of the material, the strip can deform plastically outside the roll gap and can ultimately tear. The tension deviations can be controlled by controlling the speed of the coiler motors and the rolling mill speed. The large inertias of the motors and their mechanical loads (coiler drums with or without strip wound on it) in conjunction with the limited electric torque of the motors bound the angular acceleration or deceleration of the motors.

It is further assumed that tension is established in the mill before the mill drive is accelerated towards the mill threading speed. Camisani-Calzolari et al. [19] identified a potential economic benefit from speeding up and decelerating the mill optimally. In this investigation the linearized plant was identified on the acceleration ramp of the main mill motor. This is to asses if a modern control method such as MPC can be utilized to decrease losses associated with off-specification head ends. Following the same reasoning, a similar investigation can be conducted on the deceleration ramp of the main mill motor.

The control of shape/flatness and crown/profile fall outside the scope of this dissertation, but the capability exists in the mill simulator to investigate the crown/profile behaviour of the rolling process.

6.2.2 Initial control problem formulation

The simulator was developed in order to reflect the thickness crown evolution of the strip (this includes the centerline gauge) and the tension in the strip whilst rolling. Thus the initial control problem focuses on the control of the centerline exit thickness and tension regulation.

The initial control problem can be stated as follows:

- Thickness control: The exit thickness of the strip has to be regulated within a certain specified thickness range, in the presence of disturbances as was described in section 6.2.1.
- Tension control: The tensions in the strip have to be regulated around their steady state values. The tension deviations have to be negated to limit their influence on the exit thickness.

In section 6.4 specifications for the manipulated variables and the output variables are discussed. In the following section the proposed control method is concisely discussed.

6.3 Model predictive control (MPC)

6.3.1 Background

The most common Model Based Predictive Control (MBPC) methods are MPC (model predictive control) and GPC (generalized predictive control) and some of the lesser known methods are UPC (unified predictive control) [20]. These methods are all related and in this section the background on the development of MPC and GPC are given. The similarities for these two methods are also highlighted.

MPC as it is known today were rediscovered in the late 1970's when the two most influential papers on MBPC, namely "Model Predictive Heuristical Control" (IDCOM - IDentification/COMmand) by Richalet et al. (1978, France) and Dynamic Matrix Control (DMC) by Cutler and Ramarker (1979, USA), were published [15, 87]. The publication of these two papers generated a lot of interest in the field of predictive control at the start of the 1980's [15].

Clarke et al. (1987) published the first comprehensive exposition of Generalized Predictive Control (GPC) [87, 88, 89]. Morari [15] states that although the ideas underlying DMC and GPC are similar the two methods were developed with different objectives in mind. Clarke states in [88] that GPC is an adaptive method that borrows an idea from the Dynamic Matrix Control method of Cutler and Ramarker. Fischer [90] gives a good personal perspective and summary of the different process control methods documented in the literature. He distinguishes between the two methods and their different objectives as is reported in [86]. Although there is not clarity on the definition the similarities are compelling.

Predictive control methods uses an internal model of the process to predict how the plant will react to a certain input vector sequence. The optimization of the control input vector sequence is done in a receding horizon time principle. The internal model and the receding horizon principle will briefly be discussed.

Internal model

The IMC (Internal Model Control) structure was first defined by Garcia and Morari (1982) and referenced in [87]. In figure 6.1 the IMC structure is showed. In this figure HG is the pant, $H\widetilde{G}$ is the internal process model, A^* is the disturbance predictor/filter and G_c^* is the controller. The measured output is given as c and the reference signal is given as R. For a comprehensive exposition of IMC the interested reader is referred to Morari's Robust Process Control book [91].

Receding horizon control

Predictive controllers use a receding horizon principle. At each time step the optimal (or sub-optimal) control sequence is computed in order to minimize a certain performance index subject to constraints on the manipulated and controlled variables. The optimized control law is obtained by procedures followed in the solving of classical optimal control problems [93] and feasible control problems [94]. What sets the receding horizon approach apart from optimal control is that after the computation of the optimal control sequence only the first control sample of the control law sequence is applied to the plant. The horizon is then shifted onwards with one time sample and the whole optimization is repeated incorporating the new information of plant measurements.

An open-loop optimal strategy [93] would simply assert the optimal set of future controls $\{u\{k+j), j=0...\}$ while the receding horizon approach makes the MBPC method into a closed-loop feedback control law. Feedback of the current plant output measurement $y(k)$ is via the prediction equations. This feedback is often referred to as the realignment of the process [95].

In figure 6.2 the idea of the receding horizon is displayed graphically. At time k the future control sequence $\{u(k), ..., u(k+N-1)\}$ is optimized in order to minimize a performance index, $J(u,k)$, subjected to input and output constraints. The result of this optimization may differ depending on the structure of the performance index [20]. The different predictive controllers are unified in the aim to compute the optimal control sequence that will force the future control output signal $y(k+j)$ as close to the reference signal $r(k+j)$ [4] without violating any input/output constraints. At time k the first element of the optimized control sequence are applied to the plant and the optimization is restarted with the shifted horizon at time $k+1$ [98].

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[4] The reference trajectory is denoted by $w(t)$ in numerous GPC articles [96, 88, 89, 97] and in Soeterboek's book [20]. It was decided to denote the reference trajectory as $r(t)$, which corresponds with classical control notation.

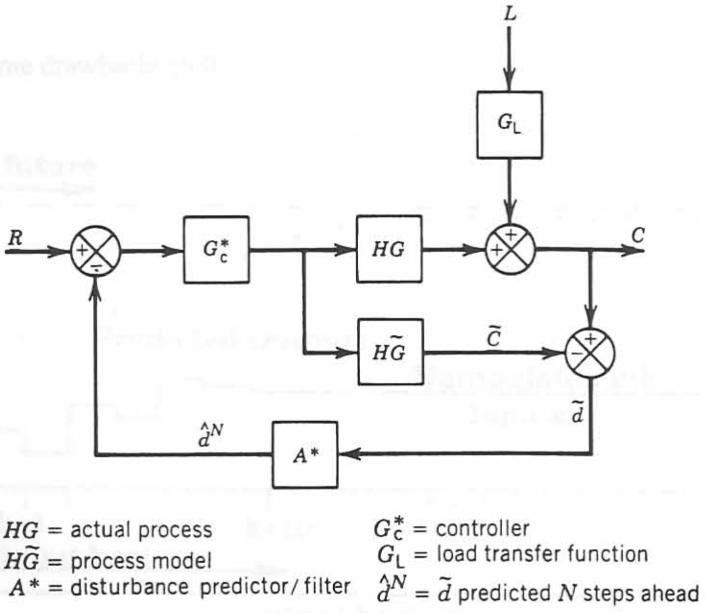

Figure 6.1: IMC Structure (This figure was adopted from [92])

6.3.2 Why MBPC?

MBPC is widely accepted in the process industry and posses many attributes which make MBPC a successful approach to industrial controller design [98, 95]:

- Simplicity: The basic ideas of MBPC do not require complex mathematics and are intuitive.
- Richness: The basic MBPC components e.g. the internal model, the horizons, the objective function etc. can be tailored to the details of the investigated problem.
- Practicality: The practical way in which input and output constraints can be handled in a natural way distinguishes MBPC from other control algorithms. Industrial processes have their limitations in rated capacities, technological requirements and are supposed to deliver outputs within the quality specifications bounds. MBPC can handle these limitations in a systematic way.
- Demonstrabilty: The MPC control concept has worked profitably in many industrial applications even before the theory for MBPC matured to its current state.
- Adaptability: Although not all of the MBPC methods have the ability to adapt the plant model the extension to an adaptive scheme does not seem that difficult. The adaptation of the plant model is a self tuning feature of some MBPC in order to handle structural changes such as actuator failures, changes in system parameters and system structure of the plant.

MBPC does have some drawbacks [98]:

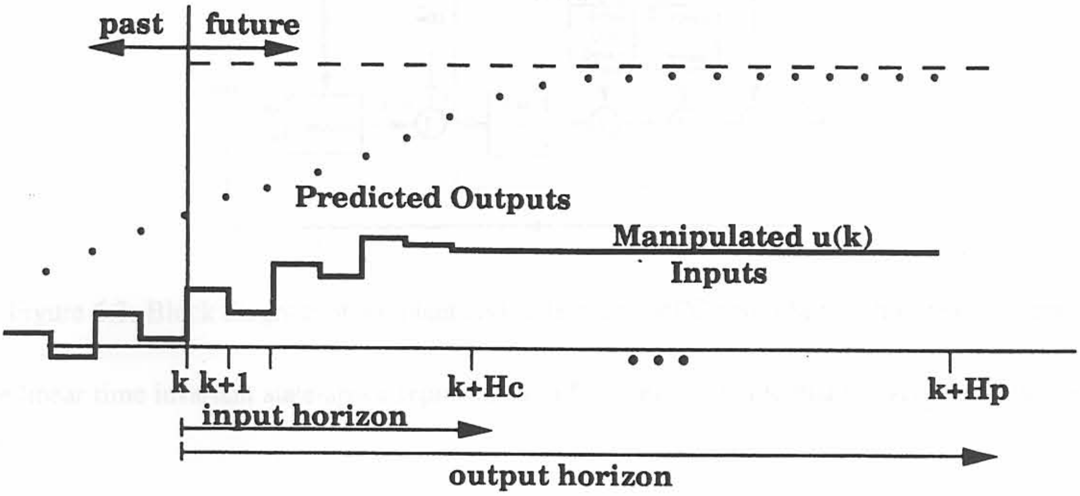

Figure 6.2: The Moving Horizon Approach (This figure is taken from an article by M. Morari in[95] page 24).

- A detailed process model has to be available. Sometimes this model derivation can take up to 80% of the project time[5] .
- The methodology is open and many variations have led to a large number of MBPC methods as will be shown later.
- Theoretical proof of the closed loop plant's stability and robustness are difficult to derive although in practice stability and robustness are easy to obtain.

6.3.3 MPC theory

In this section MPC will be described using the linear time invariant state-space representation of the plant. The equations will be concisely listed according to the notation used in the Matlab MPC toolbox [85]. The interested reader can find the derivations of DMC and MPC in [87, 85, 95].

Although the GPC method is also mentioned the emphasis for this dissertation is on MPC. This is attributed to the following:

- The availability of the Matlab MPC toolbox [85] as a design tool.
- Previous research work conducted by J.G. Bekker[6] [22] on the application of MPC to control the off-gas process of an Electric Arc Furnace.

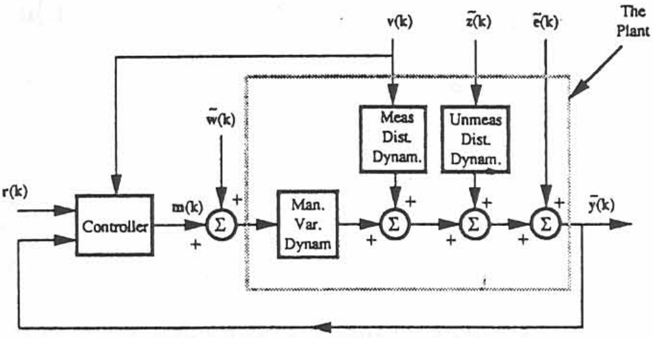

Figure 6.3: Block diagram of the plant and state-space MPC controller with state estimation.

The linear time invariant state-space representation for a multivariable plant is given as (also see fig. 6.3):

$$\mathbf{x}(k+1) = \Phi\mathbf{x}(k) + \Gamma\mathbf{u}(k) + \Gamma_d\mathbf{d}(k) + \Gamma_w\mathbf{w}(k) \tag{6.1}$$

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[5] This statement give justification for the development of a nonlinear plant model in this dissertation, and using it to identify a detailed process model.

[6] Previously at the Measurement and Control Group at the University of Pretoria.

$$\begin{aligned}\mathbf{y}(k) &= \bar{\mathbf{y}}(k) + \mathbf{z}(k)\\ &= \mathbf{C}\mathbf{x}(k) + \mathbf{D}_u\mathbf{u}(k) + \mathbf{D}_w\mathbf{w}(k) + \mathbf{z}(k)\end{aligned} \tag{6.2}$$

with,

$\Phi, \Gamma, \Gamma_d, \Gamma_w, \mathbf{C}, \mathbf{D}_u, \mathbf{D}_w$: Discrete state-space coefficient matrices

$\mathbf{x}(k)$: State vector

$\mathbf{u}(k)$: Input vector

$\mathbf{d}(k)$: Measured disturbance vector

$\mathbf{w}(k)$: Unmeasured disturbance vector

$\mathbf{z}(k)$: Measurement noise vector

The unmeasured disturbance and the noise can be deterministic or stochastic of nature. The state estimation for the state can be derived in an analogous way to the LQG procedure [85]. It is assumed that the future disturbances will be zero and the internal model is to estimate the future state of the plant[7]:

$$\mathbf{x}(k+1|k) = \Phi\mathbf{x}(k|k-1) + \Gamma\mathbf{u}(k) + \Gamma_d\widehat{\mathbf{d}}(k) + \Gamma_w\mathbf{w}(k) \tag{6.3}$$

The cost function that needs to be minimized is,

$$J(m, p, \mathbf{Q}, \mathbf{R}) = \underset{u(.)}{min}\left[\sum_{i=1}^{p}\mathbf{x}^T(k+i|k)\mathbf{Q}\mathbf{x}(k+i|k) + \sum_{i=1}^{p}\mathbf{u}^T(k+i-1)\mathbf{R}\mathbf{u}(k+i-1)\right] \tag{6.4}$$

with,

m: the control horizon

p: the prediction horizon

$\mathbf{Q}, \mathbf{R}$: Weighting matrices on the states and the inputs respectively.

From Eq. 6.4 it is seen that the states are weighted with a variable gain matrix as opposed to DMC where the tracking error is weighted [87].

6.3.4 Control law computation: On-line optimization

The MPC control method constitute a quadratic optimization problem. A fast convergent optimization algorithm is needed to solve the optimization problem on line. Many of optimization routines can be found in the literature. The routines can be divided into a search based or gradient based method.

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[7] Corrections based on measurements are $\mathbf{x}(k|k) = \mathbf{x}(k|k-1) + \mathbf{K}(\mathbf{y}_m(k) - \mathbf{y}(k|k-1))$ [95].

The optimization routine used for the on-line solving of the MPC control law depends on the chosen norm used in the objective function [87]. If the objective function was expressed using a linear norm then Linear Programming will suffice.

In most of the cases the objective function uses the quadratic norm to express the performance index, thus quadratic programming is utilised to solve the quadratic problem. Dantzig's algorithm discussed in [22, 99] is a popular quadratic algorithm used in the Matlab MPC toolbox [85] to simulate the constrained close loop MPC controlled plant. This algorithm was also used by J.G. Bekker [22] in his investigation into the control of the off gas process of an Electric Arc Furnace.

6.3.5 Stability and constraint handling

After the last decade a lot has been done to develop the predictive controller theory [15]. Morari gives a good summary of the current state of the research in [15]. Researchers [100, 101, 102, 103, 104, 105] have showed that by choosing the prediction horizon infinite the stability of the constrained predictive control method can be proven. Other researchers did not make this infinite horizon assumption as documented in [106, 107]. In [86] these key issues are discussed in more detail.

6.3.6 Tuning of Predictive Control algorithms

One of the features that make MBPC methods so attractive is the ease of tuning. Important performance criteria that need to be satisfied with the chosen tuning parameters are good setpoint tracking, sufficient disturbance rejection (regulation behaviour) and robustness against model mismatch. The tuning parameters that can be used to tune a MBPC controller depends on what performance index was implemented [20, 98]. For MPC the following parameters are used to tune the controller:

- m: The control horizon;
- p: The prediction horizon;
- $\mathbf{Q}$: Positive semidefinite output weighting matrix;
- $\mathbf{R}$: Positive definite input weighting matrix

Tuning rules are discussed in [20, 98] and are not repeated here.

Remarks

When $\mathbf{R}$ is the zero matrix the control input vector is not penalized and the resulting control law might tend to bang bang control (heavy control action). The choice of $\mathbf{R}$ and $\mathbf{Q}$ should be such that the terms in the objective function contribute equally to the value of the performance index.

6.4 Controller specifications

The main control objective is to maintain uniform output gauge with a reduced thickness standard deviation as was discussed in section 6.2. The tension control has to be regulated in order to decrease the adverse effect tension deviations has on the thickness control loop.

From measured plant data of the Steckel Mill under investigation, the AGC system used on this mill is capable of regulating the centerline gauge with a standard deviation of $\sigma_{y_1} = 0.02mm$ ($3\sigma_{y_1} = 60\mu m$)[8] for the chosen operating point . From the logged data nothing can be concluded regarding constraints on the tension outputs of the process. The solution of the constrained optimization of a performance index yields an optimal solution satisfying the constraints [94] on the manipulated and controlled variables. The on-line optimization time is dictated by the speed of the process.

The output constraint imposed on the output gauge is[9],

$$9.7184mm - 60\mu m \leq y_1 \leq 9.7184mm + 60\mu m. \tag{6.5}$$

The output limit on the tensions is specified as,

$$0 \leq y_2 \leq 131kN + 3.5MN < k(\epsilon, \dot{\epsilon}, \theta)A_{cross_1}, \tag{6.6}$$

$$0 \leq y_3 \leq 119kN + 2.4MN < k(\epsilon, \dot{\epsilon}, \theta)A_{cross_2}. \tag{6.7}$$

From the limits imposed on the tension outputs it is evident that the tension setpoints ($T_{1_{sp}} = 131kN$ and $T_{2_{sp}} = 119kN$) can be increased. The following constraints are applicable on the dynamic hydraulic stroke,

$$|u_1| \leq 1mm. \tag{6.8}$$

This limitation is taken as the stroke domain for which the linear model was identified. The choice for the range of linearization is and defined in section 5.4.1.1. In [18] it is suggested that a dynamic hydraulic stroke of 5mm is excessive when a regulatory GPC controller tries to negate the effects of a 1mm hydraulic stroke disturbance.

A rate constraint can be imposed on the hydraulic stroke and it is suggested by T.S. Bilkhu [1] that the rate constraint of a 15Hz hydraulic system is,

$$|\dot{u}_1| \leq 4m.s^{-1}, \tag{6.9}$$

and a maximum acceleration of the hydraulic system is,

$$|\ddot{u}_1| \leq 500m.s^{-2}. \tag{6.10}$$

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[8] The controlled variables y_i and the manipulated variables u_i (for $i \in [1, 2, 3]$) are defined in section 5.4.

[9] The average exit gauge value was obtained from the logged data for two similar strips rolled by the Steckel Mill under investigation.

As was reported in section 5.4.1.1 the hydraulic systems modelled on either side of the mill closely resemble a 15Hz hydraulic system and the constraints specified in equations 6.9 and 6.10 can be used.

The limits on the coiler speed inputs are imposed to reflect the valid linear range obtained from the step tests (see section 5.4.1.2) are defined as follows:

$$-0.2m.s^{-1} \leq u_2 \leq +0.2m.s^{-1}, \tag{6.11}$$

$$-0.2m.s^{-1} \leq u_3 \leq +0.2m.s^{-1}. \tag{6.12}$$

These 3 phase cyclodrive synchronous motors, for the Steckel Mill under consideration, are rated at 5MW. The rated torque of each motor is 60 $MN.m^{-1}$, with a startup torque capability of 250% for a maximum of 60 seconds. In [1, 108] similar magnitudes are specified for coiler motors. The speed control of synchronous AC motors is discussed in [109]. In this dissertation the emphasis falls on process modelling and it is thus assumed that cascaded speed controllers are in place.

The most important limit on the speed control inputs are the rates at which the motor speeds should change. Each motor has a limited amount of torque available to accelerate the mechanical load. The load can not be accelerated immediately ($\dot{u}_i(t) \neq \infty, \forall i \in [2, 3]$) due to the large inertia associated with the strip on the coiler bobbin, the bobbin itself, and the rotor of the motor [109]. The strip on the bobbin and the coiler drum itself form the load of the motor, and an investigation into the changing inertia of this strip-bobbin combination needs to be done. Values of the dimension and mass of the bobbin ($R_{coil\&drum}$) are unknown and the radius of the strip on the bobbin combination increase according to the relationship $R_{coil\&drum} = \frac{\vartheta_{coiler\ tangential}}{\omega_{coiler\ drive}}$.

In this work it is suggested that the rate constraints on the acceleration of the coiler motors are more important than the actual speed limits of these two control inputs. The equation of dynamic stability for a synchronous machine is calculated [109] by equating the torques of the motor and load system, and is given as,

$$T_{max} sin\delta = K_j\ddot{\delta} + K_d\dot{\delta} + T_L, \tag{6.13}$$

where,

T_{max}: The maximum rated torque of the synchronous motor;

δ : The power angle[10];

$K_j\ddot{\delta}$: The acceleration torque of the motor;

$K_d\dot{\delta}$: The damping torque of the system;

T_L : The load torque.

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[10] At steady state the load and motor torques are equal at the power angle.

The load torque incorporates the varying mass and radius of the coiled strip and bobbin combination. The limit on the angular acceleration of the coiler motor can be calculated using Eq. 6.13 and the fact that $\ddot{\delta}$ and the motor angular acceleration ($\ddot{\theta}_m$) are the same.

The tangential acceleration of the strip at the coiler motors, $\dot{u}_1, \forall i \in [2,3]$ are related to the angular acceleration of the coiler motor according to the relationship, $u_i = \ddot{\theta}_{coiler_{front/back}} R_{coil\&drum_{front/back}}, \forall i \in [2,3]$. The unavailability of some of the parameters in Eq. 6.13 make it difficult to fix the rate limits on u_2 and u_3, and it is proposed that this problem should be addressed before a MPC controller is designed for the process.

6.5 Conclusions

In this chapter an introduction of control problems associated with rolling mills is given. An initial control problem is formulated and the proposed control method is discussed. Limitations on the manipulated variables are given, taking into account that the proposed control method is MPC. These limitations are important in determining whether the constrained optimization problem is feasible or not.