CHAPTER 7: CONTROL OBJECTIVES AND SPECIFICATIONS

7.1 INTRODUCTION

The non-linear model was verified as sufficiently accurate to represent the actual process, and the linear model has been accepted as an approximation for control purposes. Now it is necessary to look at the control objectives and specifications. The control objectives stem from the problems that are experienced on the plant. To transform them to a meaningful set of quantitative control specifications, however, it is necessary to analyse the linear system and determine what control configuration would be the best. The specifications are then made for the specific configuration.

In Section 7.2 the control objectives are given in a qualitative discussion. In Section 7.3 an algebraic analysis of the linear system investigates the stability, observability and output-controllability of the linear system. In Section 7.4 the quantitative control specifications are given.

7.2 CONTROL OBJECTIVES

The control objectives for this system are based on two equally important but conflicting agendas. They are process efficiency improvement and environmental protection.

Since the EAF cannot be entirely sealed off, there is always a hazard of pollution in the workshop. Gas, loaded with dust, can exit the EAF through any unsealed openings if the negative relative pressure of the EAF is not large enough. The gas contains high levels of CO at a high temperature, and can thus cause a severe safety hazard in the workshop. As a result the EAF is required to operate at a negative relative pressure.

The negative relative pressure causes a loss of energy, as a large amount of heat is extracted with the off-gas, since a powerful forced draught has to be applied to maintain the negative relative pressure. The agenda of process efficiency improvement calls for lower energy waste, which would lead to shorter tap-to-tap times, since the steel would reach the required tap temperature quicker. One benefit of improved control would be that the negative relative pressure would be kept consistently smaller, resulting in less energy being wasted.

Besides the negative relative pressure, the agenda of environmental protection also requires that the off-gas must be cleaned by an appropriate filter system. The carbon monoxide content in the gas that is emitted in the atmosphere must be sufficiently low, and all dust must be removed from the gas before it is emitted into the atmosphere. The system under study makes use of post-combustion in the water-cooled duct to reduce the carbon monoxide level. It then uses a baghouse filter system to filter out the dust.

The baghouse can ignite and explode if the carbon monoxide content of the off-gas entering it is too high, or if the off-gas temperature is too high. Should this happen, the regulatory authorities can require the entire EAF operation to cease until the baghouse filter system is repaired. To avoid this the carbon monoxide level in the off-gas and the off-gas temperature must be limited to safe levels.

7.3 LINEAR SYSTEM ANALYSIS

There are three objectives for this analysis. Firstly to take a look at stability of the linear model. Secondly to look into observability of the model, and thirdly to analyse output-controllability.

7.3.1 Stability

The simplest stability analysis is a look at the eigenvalues of the A-matrix, see Table 7.1:

Table 7.1 Eigenvalues of A-matrix

Real Part	Imaginary Part
-8.5991	
-1.1111	
-1	
-0.083333	
-0.0027321	
-0.0026838	
-0.0026838	
-0.002153	
-0.00096723	
-0.00087352	+3.8408e-005
-0.00087352	-3.8408e-005
-0.00054087	
-2.1531e-005	
-1.8119e-017	+4.0619e-014
-1.8119e-017	-4.0619e-014
-1.278e-019	
-4.5671e-020	

Since $\mathrm{Re}[\lambda_j(A)]<0$ for all j, the linear system is stable for finite inputs [42]. The simulations support this indication, since no sign of instability was found in any of the simulations.

7.3.2 Observability

For the internal states of the system to be completely observable from the output-measurements, the observability matrix have to be of maximum rank [42,43]. The observability matrix (Ob) is given by equation (7-1) (where $\mathbf{Ob} \in \Re^{102\mathrm{x}17}$):

$$\mathrm{Ob} = [C; CA; CA^2; CA^3; \ldots; CA^{16}; CA^{17}] \tag{7-1}$$

For a tolerance of 1 the rank of the observability matrix was 5, and for a tolerance of 10^{-7} the rank was 12. This indicates that the internal states of the system are not completely observable from the outputs. This is expected, since the C-matrix contain only seven columns with nonzero elements. The states corresponding to zero-columns in the C-matrix are not observable. This is also confirmed by an eigenvector analysis, as described by [44].

7.3.3 Output-Controllability

In this dissertation, the aim is to control outputs rather than internal states. It therefore makes more sense to also look at output-controllability [37]. Output-controllability for a system such as equation (6-1) is guaranteed if the output-controllability matrix has full rank.

In the system under study there are only two manipulated variables, but there are four outputs. One task of the control-designer is to determine which outputs should be controlled, and which should be left alone. Since the output-controllability analysis is based on conventional methods, it would yield meaningful results only if the analysis is done on at most two outputs at a time. In contrast, the control law that will be given in the next chapter is capable of using two manipulated variables (MVs) to control three or four controlled variables (CVs). However, if the CVs are more than the MVs, their control is interdependent. For the present analysis, however, it is necessary to consider only two outputs at a time, so that they can be controlled independently. Four combinations will be investigated:

- Relative pressure (y_1) and liquid metal temperature (y_2) – C1;
- Relative pressure (y_1) and off-gas composition (y_3) – C2;
- Relative pressure (y_1) and off-gas temperature (y_4) – C3;
- Off-gas composition (y_3) and off-gas temperature (y_4) – C4.

Each time the respective rows were extracted from the C-matrix, and placed in a reduced substitute, C1 to C4. Then the output-controllability matrices Q_1 to Q_4 were computed, according to equation (7-2) (where $Q_x \in \Re^{2x34}$):

$$Q_x = [C_xB, C_xAB, C_xA^2B, C_xA^3B, \ldots, C_xA^{16}B, C_xA^{17}B] \tag{7-2}$$

To determine the rank of each output-controllability matrix, the Matlab® function "rank" was used. "Rank" determines the number of singular values of the argument matrix "Q_x" that are larger than the tolerance "tol". This is equivalent to estimating the number of rows that are linearly independent. If Q_x has a rank of two, it is of full rank, and output-controllability for that specific configuration is guaranteed. Six different tolerances were used to determine the rank of each of the matrices. Table 7.2 shows the tolerances and the rank of each matrix at each tolerance:

Table 7.2 Output-controllability matrices: tolerances and ranks

Tolerance	Rank(Q1)	Rank(Q2)	Rank(Q3)	Rank(Q4)
50.0	1 – deficient	1 – deficient	2 – full	1 – deficient
10.0	1 – deficient	1 – deficient	2 – full	2 – full
3.5	1 – deficient	1 – deficient	2 – full	2 – full
1.5	1 – deficient	2 – full	2 – full	2 – full
1.0	1 – deficient	2 – full	2 – full	2 – full
0.7	2 – full	2 – full	2 – full	2 – full

From Table 7.2 the following deductions can be made:

- The common factor between C1, C2 and C3 is the relative pressure, and as it is always controllable in C3, it is assumed that it is also always controllable in C1and C2.
- The common factor between C3 and C4 is the off-gas temperature, and as it is always controllable in C3, it is assumed that it is also always controllable in C4.
- A further analysis on each output alone is done to extract additional knowledge about the linear system. The same output-controllability matrix is calculated as in equation (7-2). The difference is now that the C matrix used consists of only one row. The tolerance at which the rank of each output-controllability matrix becomes deficient was determined and normalised. The tolerance of the relative pressure is three orders of magnitude larger than any of the other tolerances, indicating that it is much more controllable.
- The order of controllability is C3, C4, C2, and C1. It may therefore be assumed that the order of output-controllability is y_1, y_4, y_3 and y_2.
- The least controllable output is the liquid metal temperature, which makes sense, since no controller can be expected to have much effect on the temperature of a 160-ton liquid metal pool, by manipulating an off-gas stream in the order of 10 kg/s.
- The off-gas CO mass-fraction is a controllable output, but from the analysis it is clear that it is less controllable than the relative pressure or the off-gas temperature. It would probably require much stronger control actions to regulate or limit.

7.4 CONTROL SPECIFICATIONS

The control specification stems from the control objectives given in Section 7.2, as well as from the linear system analysis given in Section 7.3.

The control objectives require that the relative pressure should be regulated at a negative pressure, yet close to atmospheric pressure. The control objectives also require that the controller strive for higher energy efficiency as embodied in the liquid metal temperature (integration of energy). It is also required that the off-gas CO content and off-gas temperature must both be limited to protect the baghouse filter system.

The output-controllability analysis shows that the relative pressure and the off-gas temperature are both controllable. It also shows that the off-gas CO content is controllable, although it will probably require much stronger control actions to effect a meaningful response.

The analysis also shows that it will probably be futile to attempt to control the liquid metal temperature. Preliminary experiments confirmed this deduction [11]. In industry the DRI feed rate is used to control the liquid metal temperature, with the electric arc providing the main energy input. The oxygen injection also strongly influences the liquid metal temperature.

Based on these findings a set of meaningful controlled variables for the off-gas system are then the relative pressure, and the off-gas composition and temperature. The relative pressure is first priority, unless the other variables exceed acceptable limits.

A number of excursions were made to steel manufacturers, to gain insight into the problem. In conversations with process experts a few guidelines were obtained, and the specifications given here are influenced by those guidelines. The worst case scenario given in the design drawings also influences the specifications. In order to accommodate the conflicting control objectives within the specifications a compromise is necessary.

- Regulate the relative pressure at –5 Pa;
- Limit the CO mass fraction in the off-gas to 0.01 kg/kg = 1%;
- Limit the off-gas temperature to 500°C = 773 K;
- Do not attempt to regulate or control the liquid metal temperature, but take it into account as a measure of the energy-efficiency.

Fig.7.1 gives a more exact description of the process input-output relationships.

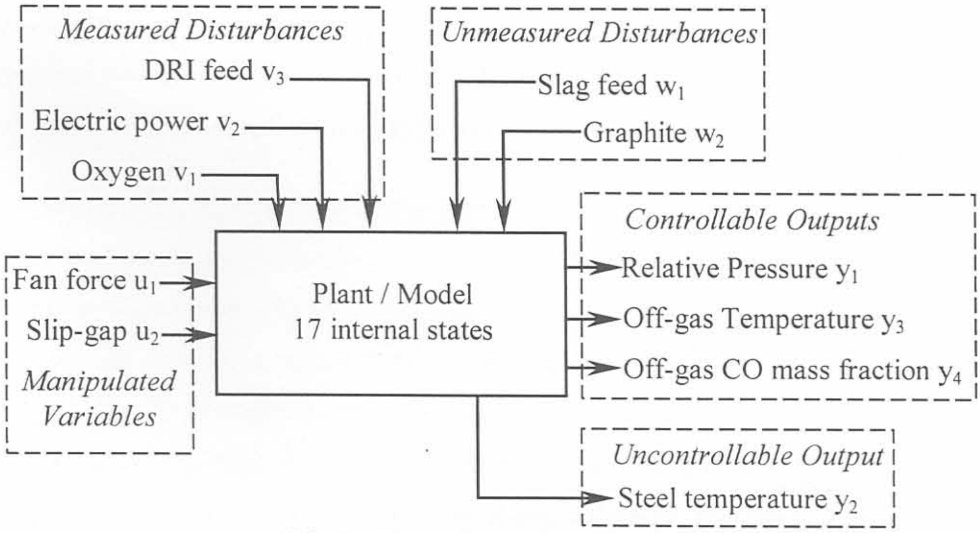

Figure 7.1 Input – Output diagram

7.5 CONCLUSION

The control objectives were given in a qualitative discussion. A linear system analysis showed that the linear system is stable. It was also determined that the relative pressure and the off-gas composition and temperature are all controllable outputs, but that the liquid metal temperature is not, since it is controlled by variables that are regarded as measurable disturbances for this dissertation. Based on the qualitative control objectives and the linear system analysis, and also based on guidelines from the industry, the necessary quantitative control specifications were given.