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Identification and modelling of Air Separation Unit for extraction of Oxygen using SystemIdentification Techniques

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Abstract: Visakhapatnam steel plant (VSP) is one of the most modernized steel plants in the world. The plant is equipped with number of new technologies like large-scale industrial computerization and automation, latest instrumentation etc. It produces better profits, only if the plant is operated at international levels of efficiency and productivity. Earlier, the Air Separation Plant (ASP) at VSP is automated using relay logic system.Subsequently they are replaced with Programmable Relay Logic Controllers (PLC's). In industries where large machinery is used, engineers have found it very difficult to analyse the problems associated with the working of a nonlinear time invariant system which have huge time lags in the process and nonlinearity makes it difficult to analyse the system's controllability and stability. Hence, many of the new projects are carried out on the latest instrumentation technology to employ Distributed Control System (DCS). Advancements in the field of digital signal processing opens many other features for optimized process control. These digital systems are highly reliable and it takes low down time for maintenance or trouble shooting. So in today's environment there is a strong need to go to the DCS for all the industries to get the reliable information, effective control for the long un-interruptible, efficient operation of the equipment.Therefore to build a DCS, the system is to be Identified and modelled first. Hence the main objective of the work is to identify and model the distillation column of Air Separation Unit (ASU) in ASP. In this work an attempt is made to identify and model the ASU system using Box – Jenkins, ARMAX and Subspace Identification methods.

Key Words - System Identification, Modelling, Box-Jenkins (BJ) model, ARMAX model, Subspace / State-Space (SS) Model, fit for Purity of Oxygen and fit for Flow of Oxygen

I. Introduction

The ASP at VSP is designed to meet the maximum daily demand of gaseous Oxygen and gaseous Nitrogen. Steel is manufactured or obtained upon blowing pure form of Oxygen gas at a pressure of 9-11 kg / cm^2 on to hot air metal (liquid iron) being heated at 1400^{o}c. Therefore, for the preparation of quality steel pure form of Oxygen is required. Though there are several methods of extraction of Oxygen the only general procedure widely used on an industrial scale consists of extracting Oxygen and other components of air from air by liquefaction and distillation at cryogenic temperatures. Oxygen is extracted from air because it is abundantly available in nature.

II. Problem Identification

The ASU do not have any blue prints of the circuits or models of the equipment. But only the technical information for operation and maintenance is shared. The technical persons at VSP working in the ASU are operating and functioning the unit as per the operation and maintenance manual supplied to them.Though the system is being controlled through some Pneumatic valves partially, ASU is not fully automated at present. Off late, many of the recent industries are going for the latest instrumentation technology employing Distributed Control System (DCS). The DCS provides the complete plant control.So in today's environment there is a strong need to go for the DCS for all the industries to get the reliable information of the measuring parameters for effective control of the long un-interruptible, efficient operation of the equipment.The work in this paper attempts to identify and model the distillation column of ASU in ASP.

From the literature survey [1-5], it is clear that the methods of Autoregressive (AR), Autoregressive with Exogenous Inputs (ARX), Autoregressive Moving Averages (ARMA), Box Jenkins (BJ) and Autoregressive Moving Averages with Exogenous Inputs (ARMAX) are all derived from the general parametric model structure used in the System Identification referred in equation 3.1. The work is also presented with Subspace Identification method and all the three mentioned methods are implemented using matlab and the results are compared.

Though the ASU system is a multi-input and multi-output (MIMO) system, it is considered as multi-input and single-output (MISO) system for identification and modelling, as the main important output product of the system is Oxygen in ASP for steel making.

III. METHODOLOGY

The main objective of the work is system identification and modelling of distillation column of ASU to extract Oxygen. System identification is the process of developing or improving the mathematical representation of a physical system using experimental data.Both parametric and nonparametric models are considered. The most general parametric model structure used in the System Identification [1, 2] is given by

$$A(q)y(t) = \frac{B(q)}{F(q)}u(t-n_k) + \frac{C(q)}{D(q)}e(t) \qquad (3.1)$$

where $y(t)$ and $u(t)$ is the output and input sequences, respectively and $e(t)$ is a white noise sequence with zero mean value.
The polynomials $A(q)$, $B(q)$, $C(q)$, $D(q)$, and $F(q)$ [1-4] are defined in terms of the backward shift operator.

$A(q) = 1 + a_1q^{-1} + \cdots + a_{na}q^{-na}$
$B(q) = b_1 + b_2q^{-1} + \cdots + b_{nb}q^{-nb+1}$
$C(q) = 1 + c_1q^{-1} + \cdots + a_{nc}q^{-nc}$
$D(q) = 1 + d_1q^{-1} + \cdots + d_{nd}q^{-nd}$
$F(q) = 1 + f_1q^{-1} + \cdots + f_{nf}q^{-nf}$, and
q^{-1} is the backward shift operator, defined by $q^{-1}u(t) = u(t-1)$.

Generally, the general structure represented by 3.1 is not used for modelling but the different forms of polynomial are set to identify different models. Here the models considered are Box-Jenkins (BJ) and ARMAX.

3.1 Box-Jenkins (BJ) model

The general ARMAX model structure [6-7] is given by

$$y(t) = \frac{B(q)}{F(q)}u(t-n_k) + \frac{C(q))}{D(q)}e(t) \qquad (3.2)$$

The Box-Jenkins (BJ) structure [8-10] provides a complete model with disturbance properties modelled individually from system dynamics. The Box-Jenkins model is useful for disturbances that enter late in the process. For example, measurement of noise on the output is a disturbance late in the process.

3.2 ARMAX model

The general ARMAX model structure [11-19, 31, 33] is given by

$$A(q)y(t) = B(q)u(t - n_k) + C(q)e(t) \tag{3.3}$$

The ARMAX model structure includes disturbance dynamics [18, 19]. ARMAX models are useful for dominating disturbances that arrive early in the process, such as at the input. The ARMAX model has more flexibility in handling the disturbance of modelling than the ARX model.

3.3 Subspace / State-Space (SS) Model

The above classical parametric system identification methods reduce a performance function which depends on the sum of squared errors. These methods work fine in many cases. But, for complex systems characterized by being of high order i.e. having many parameters, with several inputs and outputs, and having a large number of measurements, the classical methods get effected from numerous problems. These experience many local minima in the performance function and thus a lack of convergence to global minima. It is necessary to specify complicated parameterization of system orders and delays. They also suffer potential problems with numerical instability and extreme computation time to perform the iterative numerical minimization methods desired [20-30]. In addition, modern control methods require a state-space model of the system. For such of these similar cases of ASU, the State-Space (SS) identification method [31, 32] is also one of the appropriate model structures.

The following equations [20-30] describe a state-space model.

$$x(n+1) = Ax(n) + Bu(n) + Ke(n) \tag{3.4}$$
$$y(n) = Cx(n) + Du(n) + e(n) \tag{3.5}$$

where
$x(n)$ is the state vector,
$y(n)$is the system output,
$u(n)$the system input and
$e(n)$is the stochastic error.
A, B, C, D, and K are the system matrices.
The dimension of the state vector $x(n)$ is the only setting required for providing the state-space model.

In general, the state-space model provides a more complete representation of the system, especially for MIMO systems, than polynomial models because the state-space model is similar to a first principle model. The identification procedure does not contain nonlinear optimization. So the estimation arrives at a solution irrespective of the initial conditions. Further, the parameter settings for the state-space model are simpler than polynomial models. The order or the number of states is required to be selected for the model. The order comes from previous knowledge of the system. The order is also to be determined by analysing the singular values of the information matrix.

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The other polynomial models, including the ARMAX, output-error, Box-Jenkins, and general-linear models, involve iterative, nonlinear optimization in the identification procedure. They require excessive computation time, and the minimization gets stuck at a false local minimum, especially when the order is high and the signal-to-noise ratio is low. However, these models are useful when the stochastic dynamics are important because they provide more flexibility for the stochastic dynamics.

IV. Validation of Work

The results obtained for the above referred methods are discussed in this section. Validation is performed on the basis of fit measure and Pole-zero plots are considered for assessing the stability.

fitMeasure [30] is defined as $fit = \left(1 - \frac{|\hat{y}(t) - y(t)|^2}{|y(t) - \bar{y}(t)|^2}\right) \times 100\ \%$ (4.1)

where $\hat{y}(t)$ is the simulated output, $y(t)$ is the measured output and $\bar{y}(t)$ is the mean of the measured output. A fit value of 100% means that the simulation output is same as the measured output. If the simulation output is equal to the mean of the measured output, the fit measure referred in equation 4.1 would become zero. Hundred samples of each input data (air input, air inlet to turbine input, reflux input) and hundred samples of corresponding output data (purity of Oxygen) are utilized for identifying the model for various orders (n = 1 to 5 or 6). The respective results for each method are presented in the following section. Utilizing system identification tool box of MATLAB and input data (air input, air inlet to turbine input, reflux input) and output data of Oxygen purity, the transfer functions for various orders are obtained for different inputs. The transfer functions are denoted as $T_{nu_1}(z)$, $T_{nu_2}(z)$ and $T_{nu_3}(z)$.

Where n is the order of the system, u_1 is the air input, u_2 is the air inlet to turbine flow and u_3 is the reflux input.The stability of the simulated model for different orders is inferred from the pole zero plots obtained from the transfer function $T_{nu_3}(z)$.

V. Results and Discussions:

5.1 BJ method: This section presents the results for different model orders described by Box – Jenkinsmodel.Box-Jenkins method was implemented in identifying the distillation column for air separation in ASP at VSP.

Sample results for BJ method for order n=1 are presented infigure 5.1 (a) and (b).

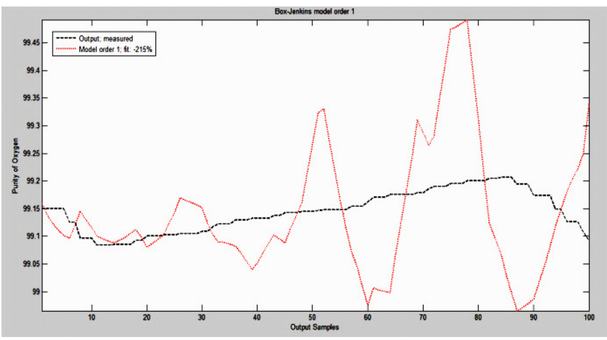

Figure 5.1(a): fit for purity of Oxygen for n=1

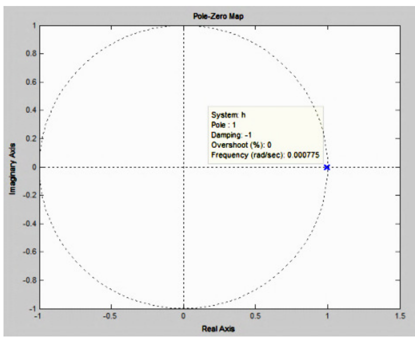

Figure 5.1 (b): Pole zero plots for n=1

Transfer function $T_{1u_1}(z)$for purity of Oxygen output $y_1$and air input u_1 is given by

$$T_{1u_1}(z) = \frac{-4.342 \times 10^{-5}}{z - 0.9982}$$

Transfer function $T_{1u_2}(z)$for purity of Oxygen output $y_1$and air-inlet to turbine input u_2 is given by

$$T_{1u_2}(z) = \frac{2.557 \times 10^{-5}}{z - 0.9894}$$

Transfer function $T_{1u_3}(z)$for purity of Oxygen output y_1 and reflux input u_3 is given by

$$T_{1u_3}(z) = \frac{0.002157}{z-0.9972}$$

The simulated results for orders 1, 2, 3, 4 and 5 are tabulated in the table 5.1. The fit for purity of Oxygen is recorded as -215 %, -64.01 %, -13.68 %, 72.63 % and 58.46 % respectively for model order 1, 2, 3, 4 and 5. Though the tabulated results show the modeled system is stable for the orders 1, 2 and 3 from pole-zero plots, but the fit for purity of Oxygen is very poor for these cases. However the fit for purity of Oxygen for orders 4 and 5 is 72.63 % and 58.46 %, but the system is unstable for these model orders since all the poles does not lie within the unit circle of the transfer functions $T_{4u_1}(z)$ $andT_{5u_1}(z)$respectively.

Table 5.1 Trends of Oxygen purity for BJ method for n= 1 to 5

Order of the System	$fit$for Purity of Oxygen (%)	Poles	Stability
1	-215	All Poles are within the unit circle	Stable
2	-64.01	All Poles are within the unit circle	Stable
3	-13.28	All Poles are within the unit circle	Stable
4	72.63	One Pole is outside the unit circle	Unstable
5	58.46	One Pole is outside the unit circle	Unstable

From the simulation results it's clear that the distillation column as such is not suitable to model mathematically using this Box-Jenkins method.

5.2 ARMAX method: Similarly the simulated results i.e., fit for purity of Oxygen and fit for flow of Oxygen are shown in figures 5.2 (a) and 5.2 (b) respectively for n=1 to 5 orders.

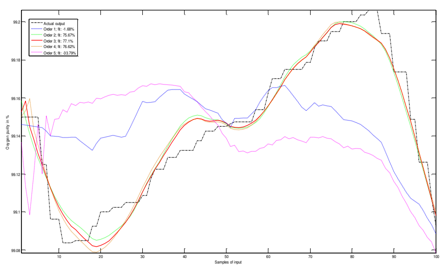

Figure 5.2 (a): fit for purity of Oxygen for n= 1 to 5

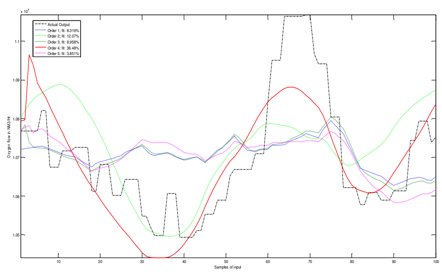

Figure 5.2 (b): fit for flow of Oxygen for n= 1 to 5

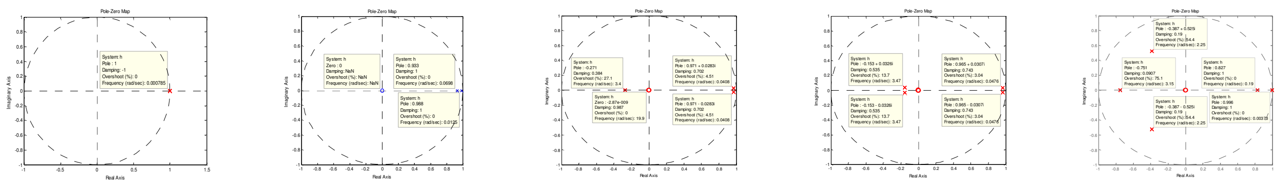

Figure 5.2 (c): Pole-Zero plots for n= 1 to 5

The consolidated results of fit for purity of Oxygen for n = 1 to 5 and fit for flow of Oxygen for n = 1 to 5 are also shown in figures 5.2 (a) and 5.2 (b) respectively. The simulated results for ARMAX model for different order are tabulated as shown in table 5.2. The fit for purity of Oxygen is -1.68 %, 75.61 %, 77.1 %, 76.62 % and -33.79 % for model order 1, 2, 3, 4 and 5 are shown in figure 5.2 (a). The fit for flow of Oxygen is recorded as 8.32 %, 12.07 %, 8.96 %, 36.48 % and 3.85 % for model order 1, 2, 3, 4 and 5 are shown in figure 5.2 (b). Though the tabulated results show the modeled system is stable for all the orders but the complexity of the system increases with increase in order. The stability of the system is justified from the pole-zero plots shown in figure 5.2 (c)of the transfer functions $T_{1u_1}(z)$, $T_{2u_1}(z)$, $T_{3u_1}(z)$, $T_{4u_1}(z)$ and $T_{5u_1}(z)$respectively for the orders n = 1 to 5.

Table 5.2 Comparison of Oxygen purity and flow for ARMAX method for n = 1 to 5

Order of the System	fitforPurity of Oxygen	fit for Flow of Oxygen	Poles	Stability
1	-1.68	8.32	All poles are within the unit circle	Stable
2	75.61	12.07	All poles are within the unit circle	Stable
3	77.1	8.96	All poles are within the unit circle	Stable
4	76.62	36.48	All poles are within the unit circle	Stable
5	-33.79	3.85	All poles are within the unit circle	Stable

In this section the principles of ARMAX modelling were implemented along with an important technique to identify the parameters of the ARMAX model. From the simulation results it is clear that the distillation column could be modelled mathematically and is approximated nearly equal to the actual system for 4thorder which produces satisfactory results and is also stable as inferred from the pole-zero plots as seen from figure 5.2 (c). Further the results obtained for higher order are not producing satisfactory results either for flow or for purity. Also the system complexity would increase with increase in order and becomes equally difficult and complex to realize and identify the system.

However the maximum fit of the flow of Oxygen is only 36.48 % for 4th order as seen in table 5.2, which is quite low. But the system has to be modelled for both Oxygen flow and Oxygen purity approximately resembling that of the actual distillation column. The necessary model is a compromise between the fit for purity of Oxygen and fit for flow for Oxygen for the respective order of the system to be chosen as per the requirements of the plant.To achieve this, a stochastic approach is adopted in next section by way of implementing state space models for advanced and modern system identification.

5.3. Subspace Identification method: Similarly the simulated results i.e., fit for purity of Oxygen and fit for flow of Oxygen are shown in figures 5.3 (a) and 5.3 (b) respectively for n=1 to 6 orders.

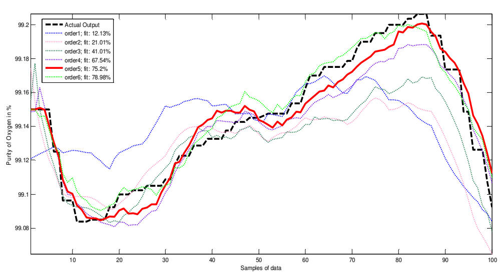

Figure 5.3 (a): fit for purity of Oxygen for n= 1 to 6

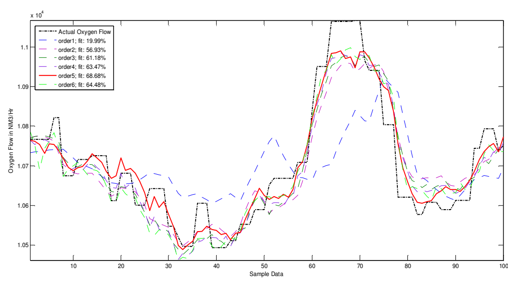

Figure 5.3 (b): $fit$for flow of Oxygen for n= 1 to 6

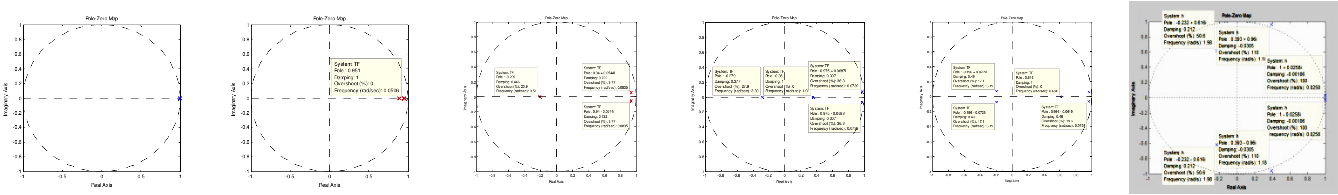

Figure 5.3(c): Pole-Zero plots for n= 1 to 6

The consolidated results of fit for purity of Oxygen for n = 1 to 6 and fit for flow of Oxygen for n = 1 to 6 are also shown in figures 5.3 (a) and 5.3 (b) respectively. The simulated results for Subspace Identification model for different order are tabulated as shown in table 5.3. The fit for purity of Oxygen is 12.13 %, 21.01 %, 41.01 %, 67.54 %, 75.2 % and 78.98 % for model order 1, 2, 3, 4, 5 and 6 respectively are shown in figure 5.3 (a). The fit for flow of Oxygen is recorded as 19.99 %, 56.93 %, 61.18 %, 63.47 %, 68.68 % and 64.48 % for model order 1, 2, 3, 4, 5 and 6 respectively are shown in figure 5.3 (b). Though the tabulated results show the modeled system is stable for all the orders but the complexity of the system increases with increase in order. The stability of the system is justified from the pole-zero plots shown in figure5.3 (c) for the transfer functions $T_{1u_1}(z)$, $T_{2u_1}(z)$, $T_{3u_1}(z)$, $T_{4u_1}(z)$,$T_{5u_1}(z)$and $T_{6u_1}(z)$respectively for the orders n = 1 to 6.

Table 5.3: Comparisons of Oxygen purity and flow for Subspace Identification (n = 1 to 6)

Order of the System	fit for Purity of Oxygen	fit for Flow of Oxygen	Poles	Stability
1	12.13	19.99	All poles are within the unit circle	Stable
2	21.01	56.93	All poles are within the unit circle	Stable
3	41.01	61.18	All poles are within the unit circle	Stable
4	67.54	63.47	All poles are within the unit circle	Stable
5	75.2	68.68	All poles are within the unit circle	Stable
6	78.98	64.48	Two poles are outside the unit circle	unstable

From the tabulated results shown above, the system is modelled nearly equal to the actual system for the case of Oxygen purity for 4^{th} and 5^{th} order and also it is stable. Further the system becomes unstable for 6^{th} order as is evident from figure 5.3 (a). The system complexity would increase with increase in order and becomes equally difficult and complex to realize and identify the system.

VI Conclusions:

Box-Jenkins method is not suitable for Identification and Modelling of ASU. ARMAX method for 4^{th} order is suitable for Identification and Modelling ASU. Subspace Identification method for 4^{th} and 5^{th} order are suitable for Identification and Modelling ASU. Further it is suggested that Subspace Identification for 4^{th} order is opted compared to 5^{th} order, this is only from the point of view of reducing the complexity of the system. Further among ARMAX and Subspace Identification methods, Subspace method is better suitable to identify and model ASU.

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