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Feedback Fuzzy State Space Modeling and Optimal Production Planning for Steam Turbine of a Combined Cycle Power Generation Plant

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Abstract: The main purpose of a Combined Cycle (CC) power generation plant is to minimize the energy/heat losses. In this research an inverse Feedback Fuzzy State Space Model (FFSSM) for the steam turbine of the CC is modeled. The algorithm maximizes the power production with optimal input parameters. The overall turbine section consists of the high pressure intermediate pressure and the low pressure subsections. The model suggests the optimal inputs/outputs for each subsection of the steam turbine in the allowable desired ranges. The inverse modeling approach determines the optimal operating conditions keeping in view the total available throughput against the desired operating conditions. The algorithm proposes more flexible operating conditions for the three stages of the steam turbine. The primary superiority of the proposed algorithm over the more direct ones is the ability to operate on more flexible operating conditions.

Key words: Feedback Fuzzy State Space Modeling (FFSSM), combined cycle power plant, steam turbine, Fuzzy sets, pressure, algorithm

INTRODUCTION

A combined cycle power plant is a large scale electric power generation plant whereby electricity is produced with the help of both gas turbine and steam turbine. In such plants the highly heated exhaust outputs of the gas turbine are utilized by a boiler and then by a steam turbine to generate more electricity (Ordys, 1994). Energy is transferred from one type of turbine to another in the form of heat/gas flow. In most of the cases, the exhaust gases of the gas turbine are utilized to generate heat and steam which is then inputted to the steam turbine. Some examples of CC are presented by Ahluvalia and Domenichini (1990), Jericha and Hoeller (1991) and Yacobucci (1991). The largest CC plant with 14 gas turbines and 14 steam turbines having a capacity of 2000 MW is in Japan.

A typical power generation plant with steam turbine consists of a combination of boiler, steam turbine, generator, condenser and feed water system. Many types of steam turbines are reported in literature (Bolland, 1991). The important input/output variables are concerned with the steam parameters at inlets/outlets, parameters of generators and safety and control measures. For the purpose of safety and control high pressure steam values and various steam flowing valves adjust and maintain the speed, power and pressure in the steam turbine (Ahluvalia and Domenichini, 1990; Kure-Jensen and Hanisch, 1991). The steam turbine of the power plant is connected to the boiler. The interconnection of the steam turbine with the boiler is shown in Fig. 1. The blocked diagram shows that the output of boiler part is the input of the steam turbine. On the other hand, outputs from the steam turbine are the input to boiler thus making a feedback loop. The overall stream turbine system of the

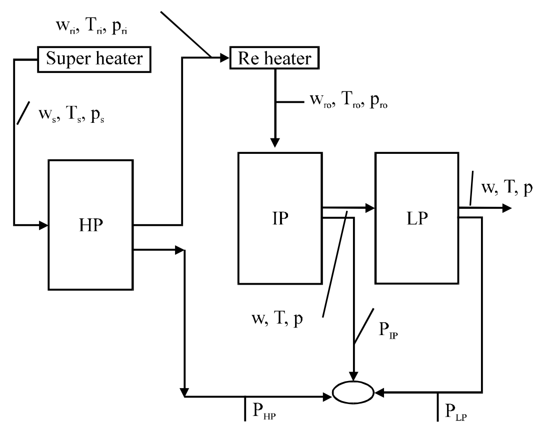

Fig. 1: Interconnections between a steam turbine and a boiler

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power plant is composed of three subsections categorized as High Pressure (HP) Intermediate Pressure (IP) and Low Pressure (LP) on the basis of the respective pressure nozzles.

The inputs w_s, T_s, p_s are supplied to the HP section of steam turbine from the super heater component of the boiler. The outputs of the HP w_{ri}, T_{ri}, p_{ri} are inputted to the reheater section of the boiler thus making a feedback cyclic loop. After activation these variables are again inputted to the IP section of the steam turbine as w_{ro}, T_{ro}, p_{ro}. The outputs of the IP section w, T, p are inputted to LP section. At each section of the steam turbine the output consist of one feed forward response in the form of power generated and three feedback responses as mass flowing between the sections, pressures at nozzles and temperature of the steam.

In this study, a Fuzzy State Space Model of the steam turbine section of CC power plant is presented. The research is based on the FSSM modeled by Razidah *et al*. (2009) and Razidah (2005). In the research, Razidah employed the idea proposed by Ahmad *et al*. (1997), Ahamd *et al*. (2004) and Ahmad (1998). The algorithm suggests the optimal operating conditions for the steam turbine section of the CC power plant in a Fuzzy environment. The best input (output) parameters between the desired and the induced are determined. The steady state operating data has been obtained from the Ordys (1994).

MATERIALS AND METHODS

State space modeling of the steam turbine: A detailed treatise on the modeling of the steam turbine is available by Ray (1980). The mathematical equations developed by Ray (1980) take into consideration the impulses and reaction stages of the steam turbine. Some studies like IEEE Committee (1991) and Anonymous (1973) present simpler linear models of the steam turbine considering the stability of the electrical networks. For a high supervisory control and reduced complexity, a simple model is constructed based on the IEEE Model keeping in view the important associated non linearity. The model assume that:

- Superheated steam is assumed an ideal gas
- The turbine is divided into the HP, IP and LP stages based on the high, medium and low pressure nozzles
- Kinetic energy at inlets of each stage is negligible
- The mass flowing between inputs and outputs is assumed to be first order lag
- The energy stored at each stage are lumped

The three sections, the storage steam and the energy dynamics follow a complete turbine stage consisting of a series of impulse and or reactions at each stage. In this connection, the impulse/reaction at each stage are equation as:

$$\frac{d}{dt}\left(\rho_0 h_o\right) = \frac{1}{V}\left(w_{in}h_{in} - w_{ou}h_o\right) \quad (1)$$

$$\frac{d}{dt}\left(w_{ou}\right) = \frac{1}{\tau_s}\left(w_{in} - w_{ou}\right) \quad (2)$$

$$\frac{d}{dt}\left(\rho_{ou}\right) = \frac{1}{V}\left(w_{in} - w_{ou}\right) \quad (3)$$

The ideal gas equations, nozzle equation, uniform polytropic expansion-temperature ratio, enthalpy change of isentropic expansion for perfect gas are shown in Eq. 4-7:

$$T_o = \frac{h_o - h_{in}}{c_p} + T_{in} \text{ and } p_o = R\rho_o T_o \quad (4)$$

$$r^{\left(\frac{2}{m}\right)} - r^{\left(\frac{m+1}{m}\right)} = \frac{w_{ou}^2}{A^2\rho_o p_o}\left(\frac{m-1}{2\eta_\infty m}\right) \quad \text{where } m = \frac{\gamma}{\gamma - \eta_\infty(1-\gamma)} \quad (5)$$

$$\frac{T_{ou}}{T_o} = \left(\frac{p_{ou}}{p_o}\right)^{\eta_\infty\left(\frac{\gamma-1}{\gamma}\right)} \quad \text{where } \gamma = \frac{c_p}{c_p - R} = \frac{c_p}{c_v} \quad (6)$$

$$\Delta h_I = c_p T_o (r^{R/c_p} - 1) \quad (7)$$

The section efficiency, the output pressure of each section, the output temperature at each section, outlet enthalpy, the output power generated by each section and the total power induced by all sections of the steam turbine are presented:

$$\eta = \frac{1 - r^{\eta_\infty\left(\frac{\gamma-1}{\gamma}\right)}}{1 - r^{\left(\frac{\gamma-1}{\gamma}\right)}} \quad (8)$$

$$p_{ou} = rp_o \quad (9)$$

$$T_{ou} = T_o r^{\eta_\infty\left(\frac{\gamma-1}{\gamma}\right)} \quad (10)$$

$$h_{ou} = h_o + c_p(T_{ou} - T_o) \quad (11)$$

$$P_{ou} = \eta \Delta h_I w_{ou} \quad (12)$$

$$P_{st} = P_{HP} + P_{IP} + P_{LP} \quad (13)$$

From Eq. 4 we have:

$$T_o = \frac{h_o - h_{in}}{c_p} + T_{in}$$

And:

$$T_o = \frac{p_o}{R\rho_o}$$

and solving for h_{in} we get:

$$\frac{p_o}{R\rho_o} = \frac{h_o - h_{in}}{c_p} + T_{in} \Rightarrow h_{in} = \frac{c_p}{R\rho_o}\left[T_{in} + \frac{R\rho_o h_o}{c_p} - p_o\right]$$

and use it in Eq. 1.

$$\frac{d}{dt}(\rho_0 h_o) = \frac{w_{in}}{V}.\frac{c_p}{R\rho_o}T_{in} + \frac{w_{in}}{V}.\frac{c_p}{R\rho_o}.\frac{R\rho_o h_o}{c_p} - \frac{w_{in}}{V}.\frac{c_p p_o}{R\rho_o} - \frac{w_{ou}h_o}{V} \quad (14)$$

Now using:

$$p_{ou} = rp_o \Rightarrow p_o = \frac{p_{ou}}{r}$$

and the ideal gas:

$$p_{ou}T_{ou} = rp_{in}T_{in} \Rightarrow p_{ou} = \frac{rp_{in}T_{in}}{T_{ou}}$$

substitute in Eq. 14:

$$\frac{d}{dt}(\rho_0 h_o) = \frac{w_{in}}{V}.\frac{c_p}{R\rho_o}T_{in} + \frac{w_{in}h_o}{V} - \frac{w_{in}}{V}.\frac{c_p}{R\rho_o}.\frac{p_{in}T_{in}}{T_{ou}} - \frac{w_{ou}h_o}{V} \quad (15)$$

Now Eq. 5:

$$w_{ou} = A\rho_o\sqrt{\frac{2\eta_\infty m\rho_o\left(r^{\left(\frac{2}{m}\right)} - r^{\left(\frac{m+1}{m}\right)}\right)}{(m-1)p_o}}$$

And using it in Eq. 2:

$$\frac{d}{dt}(w_{ou}) = \frac{1}{\tau_s}\left(w_{in} - A\rho_o\sqrt{\frac{2\eta_\infty m\rho_o\left(r^{\left(\frac{2}{m}\right)} - r^{\left(\frac{m+1}{m}\right)}\right)}{(m-1)p_o}}\right) \quad (16)$$

Also from Eq. 5:

$$w_{ou} = A\rho_o\sqrt{\frac{2\eta_\infty m\rho_o\left(r^{\left(\frac{2}{m}\right)} - r^{\left(\frac{m+1}{m}\right)}\right)}{(m-1)p_o}}$$

and using it in Eq. 3:

$$\frac{d}{dt}(\rho_{ou}) = \frac{1}{V}\left(w_{in} - A\rho_o\sqrt{\frac{2\eta_\infty m p_o(r^{\left(\frac{2}{m}\right)} - r^{\left(\frac{m+1}{m}\right)})}{(m-1)\rho_o}}\right) \quad (17)$$

From Eq. 15-17 we have:

$$\begin{bmatrix}(\rho_0 h_o)' \\ w'_{ou} \\ \rho'_{ou}\end{bmatrix} = \begin{bmatrix} \frac{-w_{ou}}{V} & 0 & 0 \\ 0 & -\left(\frac{A\sqrt{\frac{2\eta_\infty m\rho_o(r^{\left(\frac{2}{m}\right)} - r^{\left(\frac{m+1}{m}\right)})}{(m-1)p_o}}}{\tau_s}\right) & 0 \\ 0 & 0 & -\left(\frac{A\sqrt{\frac{2\eta_\infty m p_o(r^{\left(\frac{2}{m}\right)} - r^{\left(\frac{m+1}{m}\right)})}{(m-1)\rho_o}}}{V}\right)\end{bmatrix}\begin{bmatrix}h_o \\ p_o \\ \rho_o\end{bmatrix} + \begin{bmatrix}\frac{h_o}{V} & -\frac{w_{in}}{V}.\frac{c_p}{R\rho_o}.\frac{T_{in}}{T_{ou}} & \frac{w_{in}}{V}.\frac{c_p}{R\rho_o} \\ \frac{1}{\tau_s} & 0 & 0 \\ \frac{1}{V} & 0 & 0\end{bmatrix}\begin{bmatrix}w_{in} \\ p_{in} \\ T_{in}\end{bmatrix} \quad (18)$$

For the development of the output we take into consideration:

$$w_{ou} = \frac{P_{ou}}{\eta\Delta h_I} \quad (19)$$

$$p_{ou} = rp_o \quad (20)$$

$$T_{ou} = T_o r^{\eta_\infty\left(\frac{\gamma-1}{\gamma}\right)} = \left(\frac{c_p T_{ou} + h_o - h_{ou}}{c_p}\right) r^{\eta_\infty\left(\frac{\gamma-1}{\gamma}\right)}$$

By using Eq. 11:

$$T_o = \frac{c_p T_{ou} + h_o - h_{ou}}{c_p} \text{ and } \rho_o h_o = x_o$$

$$T_{ou} = \left(\frac{c_p T_{ou} - h_{ou}}{c_p}\right)\frac{\rho_o h_o}{x_o} r^{\eta_\infty\left(\frac{\gamma-1}{\gamma}\right)} + \frac{h_o r^{\eta_\infty\left(\frac{\gamma-1}{\gamma}\right)}}{c_p} \quad (21)$$

By using Eq. 5 in Eq. 12:

$$P_{ou} = \eta\Delta h_I w_{ou} = \eta A\Delta h_I \rho_o \sqrt{\frac{2\eta_\infty m p_o (r^{\left(\frac{2}{m}\right)} - r^{\left(\frac{m+1}{m}\right)})}{(m-1)\rho_o}} \quad (22)$$

The output equation is as below:

$$y = \begin{bmatrix} 0 & r & 0 \\ \frac{r^{\eta_\infty\left(\frac{\gamma-1}{\gamma}\right)}}{c_p} & 0 & \left(\frac{c_p T_{ou} - h_{ou}}{c_p}\right)\frac{h_o}{x_o} r^{\eta_\infty\left(\frac{\gamma-1}{\gamma}\right)} \\ 0 & 0 & \eta A\Delta h_I \sqrt{\frac{2\eta_\infty m p_o (r^{\left(\frac{2}{m}\right)} - r^{\left(\frac{m+1}{m}\right)})}{(m-1)\rho_o}} \end{bmatrix} \begin{bmatrix} h_o \\ p_o \\ \rho_o \end{bmatrix} + \left[\frac{1}{\eta\Delta h_I}\right]\left[P_{ou}\right] \quad (23)$$

Equation 18 along with Eq. 23 forms the state space model of a particular section of a steam turbine. The same model is applicable to all the sections of steam turbine except the IP where the steam storage takes place in the reheater section of the boiler.

Feedback Fuzzy State Space Model (FFSSM) for the steam turbine: Based on the FSSM Model proposed in Razidah *et al*. (2009), we develop a Feedback Fuzzy State Space Model for the various sections of the steam turbine.

Let the input u_{i1} and u_{i2} in the intervals I_{i1} and I_{i2}, take Fuzzy sets $F_{I_{i1}}$ and $F_{I_{i2}}$ such that $F_{I_{i1}} \in I_{i1}$ and $F_{I_{i2}} \in I_{i2}$ to be the preferred values for the input u_{i1} and u_{i2} Here for $x_1 \in F_{I_{i1}}$ and $x_2 \in F_{I_{i2}}$ the values $F_{I_{i1}}(x_1)$ and $F_{I_{i2}}(x_2)$ represents the degree of occurrence of x_1 and x_2 in the intervals I_{i1} and I_{i2}. It is proved that the Fuzzy parameters $F_{I_{i1}}$ and $F_{I_{i2}}$ on u_{i1}, $u_{i2} \in I_{i1}$, $I_{i2}, \subset \Re$ (i_1, $i_2 \in \aleph$) are normal and convex (Razidah, 2005). The functions SgF_1 and SgF_2 are the induced performance parameters for the feed forward and the feed back responses whereas F_{SgF_1} and F_{SgF_2} are the Fuzzy induced parameters for these responses, respectively. The proposed algorithm determines the Fuzzy optimal values between the induced Fuzzy sets and the preferred Fuzzy parameters ($F_{I_{i1}}$ and F_{SgF_1}) and ($F_{I_{i2}}$ and F_{SgF_2}) for feed forward and feedback outputs, respectively.

- Let the preferred parameter $SgF: \Re^n \to \Re$ consists of the feed forward performance parameter $SgF_1: \Re^n \to \Re$ and feedback performance parameter $SgF_2: \Re^n \to \Re$ where $SgF = SgF_1 + SgF_2$ so that:

$$SgF_1(u_{11}, u_{21}, \ldots, u_{n1}) = r$$

$$SgF_2(u_{12}, u_{22}, \ldots, u_{n2}) = d$$

- For each input find the a_k cuts $F_{I_{i1}}$ of and $F_{I_{i2}}$ (i_1, $i_2 \in \aleph$)
- Form 2^n combinations of the end points of intervals representing a_k cuts for the fuzzified inputs $F_{I_{i1}}$ and $F_{I_{i2}}$
- Find:

$$(r_j)_{\alpha_i} = SgF_1(u_{11}, u_{21}, \ldots, u_{n1})_{\alpha_i}$$

$$(d_j)_{\alpha_i} = SgF_2(u_{12}, u_{22}, \ldots, u_{n2})_{\alpha_i}$$

- In this step, researchers find the Fuzzy induced values for feed forward and feedback outputs given as under:

$$\left(F_{Ind_1}\right)_j = \left[\min(r_j), \max(r_j)\right]$$

And:

$$\left(F_{Ind_2}\right)_j = \left[\min(d_j), \max(d_j)\right], j = 1, 2, 3, \ldots, 2^n$$

- For the feed forward and feedback output F_{SgF_1} and F_{SgF_2} we find the alpha cuts
- Intersecting the Fuzzy induced with the Fuzzy preferred parameters:

$$\left[F_{Ind_1} \Lambda F_{SgF_1}\right]$$

$$\left[F_{Ind_2} \Lambda F_{SgF_2}\right]$$

- Calculate the Fuzzy optimal values:

$$f_1^* = \text{Sup}\left[F_{Ind_1} \Lambda F_{SgF_1}\right]$$

And:

$$f_2^* = \text{Sup}\left[F_{Ind_2} \Lambda F_{SgF_2}\right]$$

- Calculate the end points for $F_{I_{i1}}$ and i = 1, 2, 3,..., n
- For the Fuzzy optimal values f_1^* cuts and f_2^* of $F_{I_{i1}}$ $F_{I_{i2}}$ and find the end points of intervals for the feed forward and feedback outputs
- Use the extension of Optimized Deffuzified Value Theorem for SgF_1^* and SgF_2^*:

$$r^* = SgF_1^* (u_{11}, u_{21},..., u_{n1})$$

And:

$$d^* = SgF_2^* (u_{12}, u_{22},... u_{n2})$$

RESULTS AND DISCUSSION

The Fuzzy state space algorithm for the steam turbine of the combined cycle power generation plant is programmed on Matlab® Computational Software. The steady state operating data is obtained from Ordys (1994). As previously shown in Fig. 1, the steam turbine consists of three sections with three inputs and four outputs at each section. The inputs w_s, T_s, p_s to the HP section of steam turbine are from the super heater component of the boiler. The outputs of the HP $w_{ouhp} = w_{ri}$, $T_{ouhp} = T_{ri}$, $p_{ouhp} = p_{ri}$ are supplied to the re-heater section of the boiler. After the necessary treatment they are again inputted to the IP section as $w_{inIP} = w_{ro}$, $T_{inIP} = T_{ro}$, $p_{inIP} = p_{ro}$. The outputs of the IP section $w_{ouLP} = w$, $T_{ouLP} = T$, $p_{ouLP} = p$ are supplied to LP section. The LP section finally gives $w_{ouLP} = w$, $T_{ouLP} = T$, $p_{ouLP} = p$ as outputs. The power generated at HP, IP and LP sections are denoted as P_{HP}, P_{IP} and P_{LP}, respectively and is lumped as $P_{st} = P_{HP}+P_{IP}+P_{LP}$. The Table 1 and appendix show the preferred values of the input parameters at each of the sections of the steam turbine. The fuzzified input parameters with a step size of 0.2 for α-cuts are shown in the Table 2. The Fuzzy induced values F_{Ind_i} of the preferred values S_{gF_i} for the feed forward and the feedback responses are found with the help of α-cuts. The feed forward and feedback responses for high pressure section of the steam turbine can be formulated as a linear combination of the input variables as given:

$$w_{ri} = 0.0000026 (w_s+p_s+T_s) \quad (24)$$

$$T_{ri} = 0.00013 (w_s+p_s+T_s) \quad (25)$$

$$p_{ri} = 0.30 (w_s+p_s+T_s) \quad (26)$$

$$P_{ouHP} = 0.70 (w_s+p_s+T_s) \quad (27)$$

For the Intermediate Pressure (IP) the feed forward and feedback responses are formulated as below:

$$w = 0.0000076 (w_{ro}+p_{ro}+T_{ro}) \quad (28)$$

$$T = 0.00046 (w_{ro}+p_{ro}+T_{ro}) \quad (29)$$

$$p = 0.360 (w_{ro}+p_{ro}+T_{ro}) \quad (30)$$

Table 1: Input parameters at each section of the steam turbine

Section	Inputs	0	1	0
High Pressure (HP)	w_s (kg sec^{-1})	10	12	14
	p_s (Pa)	3525100	4525100	5525100
	T_s (K)	714	717	720
Intermediate Pressure (IP)	w_{ro} (kg sec^{-1})	9	10.459	12
	p_{ro} (Pa)	1200000	1303400	1400000
	T_{ro} (K)	720	727.25	730
Low Pressure (LP)	w (kg sec^{-1})	9	10.459	12
	p (Pa)	400000	477700	550000
	T (K)	590	609.54	620

Table 2: Fuzzified input parameters for each section of the steam turbine

		α-cuts					
Section	Inputs	0	0.2	0.4	0.6	0.8	1.0
High Pressure (HP)	w_s (kg sec^{-1})	10-14	10.4-13.8	10.8-13.6	11.2-13.4	11.6-13.2	12-12
	p_s (Pa)	3525100-5525100	3725100-5325100	3925100-5125100	4125100-4925100	4325100-4725100	4525100-4525100
	T_s (K)	714-717 -	714.6-714.4	715.2-715.8	715.8-715.2	716.4-714.6	717-717 -
Intermediate Pressure (IP)	w_{ro} (kg sec^{-1})	9-12 -	9.2918-11.8	9.5836-11.6	9.8754-11.4	10.1672-11.2	10.459-10.459
	p_{ro} (Pa)	1200000-1400000	1220700-1361400	1241400-1342000	1262000-1322700	1282700-1303400	1380700-1303400
	T_{ro} (K)	720-730 -	721.45-729.8	722.9-729.6	724.35-729.4	725.8-729.2	727.25-727.25
Low Pressure (LP)	w (kg sec^{-1})	9-12 -	9.2918-11.8	9.5836-11.6	9.8754-11.4	10.1672-11.2	10.459-10.459
	p (Pa)	400000-550000	415540-535540	431080-521080	446620-506620	462160-492160	477700-477700
	T (K)	590-620 -	593.908-619.8	597.816-619.6	601.724-619.4	605.632-619.2	609.54-609.54

Table 3: Fuzzified output parameters for each section of the steam turbine

		α-cuts					
Section	Outputs	0	0.2	0.4	0.6	0.8	1.0
High Pressure (HP)	P_{ouHP} (W)	2468100-3868100	2608100-3728100	2748100-3588100	2888100-3448100	3028100-3308100	3168100-3168100
	w_{ri} (kg sec^{-1})	9.1671-14.3672	9.6871-13.8472	10.2071-13.3272	10.7272-12.8072	11.2472-12.2872	11.7672-11.7672
	p_{ri} (Pa)	1057700-1657800	1117700-1597700	1177700-1537700	1237700-1477700	1297700-1417700	1357700-1357700
	T_{ri} (K)	458.3571-718.3584	484.3572-692.3583	510.3574-666.3582	536.3575-640.3580	562.3576-614.3579	588.3578-588.3578
Intermediate Pressure (IP)	P_{ouIP} (W)	2401500-2801500	2442800-2762800	2484200-2724200	2525500-2685600	2566900-2646900	2608300-2608300
	w_{ouIP} (kg sec^{-1})	9.1255-10.6456	9.2827-10.4988	9.4399-10.3520	9.5971-10.2051	9.7543-10.0583	9.9114-9.9114
	p_{ouIP} (Pa)	432260-504270	439710-497310	447150-490360	454600-483400	462040-476450	469490-469490
	T_{ouIP} (K)	552.3353-644.3413	561.8489-635.4537	571.3625-626.5661	580.8761-617.6785	590.3897-608.7909	599.9033-599.9033
Low Pressure (LP)	P_{ouLP} (W)	4006000-5506300	4161400-5361700	4316900-5217100	4472300-5072400	4627800-4927800	4783200-4783200
	w_{ouLP} (kg sec^{-1})	8.2523-11.3430	8.5725-11.0451	8.8928-10.7472	9.2130-10.4492	9.5332-10.1513	9.8534-9.8534
	p_{ouLP} (Pa)	28042-38544	29130-37532	30218-36520	31306-35507	32394-34495	33482-33482
	T_{ouLP} (K)	304.4552-418.4803	316.2688-407.4889	328.0824-396.4975	339.8960-385.5060	351.7096-374.5146	363.5232-363.5232

Table 4: Proposed output responses for each section of the steam turbine

Sections	Outputs	Range	Suggested	Calculated	Percent errors
High Pressure (HP)	P_{ouHP} (W)	[2468100-3868100]	3374600	3868100	14.6234
	w_{ri} (kg sec^{-1})	[9.1671-14.3672]	12	14.3672	19.7263
	p_{ri} (Pa)	[1057700-1657800]	1389000	1657700	19.3484
	T_{ri} (K)	[458.3571-718.3584]	601.6900	718.3578	19.3900
Intermediate Pressure (IP)	P_{ouIP} (W)	[2401500-2801500]	2745300	2801500	2.0462
	w_{ouIP} (kg sec^{-1})	[9.1255-10.6456]	10.4590	10.6456	1.7838
	p_{ouIP} (Pa)	[432260-504270]	477700	504270	5.5611
	T_{ouIP} (K)	[552.3353-644.3413]	609.5400	644.3394	5.7091
Low Pressure (LP)	P_{ouLP} (W)	[4006000-5506300]	5007600	5506300	9.9586
	w_{ouLP} (kg sec^{-1})	[8.2523-11.3430]	10.4590	11.3424	8.4463
	p_{ouLP} (Pa)	[28042-38544]	37089	38544	3.9230
	T_{ouLP} (K)	[304.4552-418.4803]	375.9800	418.4769	11.3030

$$P_{ouIP} = 2.0\,(w_{ro}+p_{ro}+T_{ro}) \quad (31)$$

For low pressure section, the output responses are as follows:

$$w_{ouLP} = 0.0000206\,(w+p+T) \quad (32)$$

$$T_{ouLP} = 0.00076\,(w+p+T) \quad (33)$$

$$p_{ouLP} = 0.070\,(w+p+T) \quad (34)$$

$$P_{ouLP} = 10.0\,(w+p+T) \quad (35)$$

The alpha cuts of the fuzzified outputs are shown in Table 3. The proposed values of the outputs are shown in the Table 4. The Fuzzy optimal values denoted by f_i^* for the preferred and induced values of the outputs responses are visualized (Fig. 2a-d and 3a-d) for each section of the steam turbine. Table 4 and 5 show the optimal values of the outputs and inputs for each section of the steam turbine. In this connections, the inputs of the HP section assumes the values 13.0647 kg sec^{-1}, 5525100 Pa, 718.1292 K with

Table 5: Optimal values for inputs and percentage errors in calculated and preferred inputs for each section of the steam turbine

Sections	Inputs	Suggested	Calculated	Percent error
High Pressure (HP)	w_s (kg sec^{-1})	12	13.0647	8.8723
	p_s (Pa)	4525100	5525100	22.0989
	T_s (K)	717	718.1292	0.1575
Intermediate Pressure (IP)	w_{r*} (kg sec^{-1})	10.459	11.2033	7.1165
	p_{ro} (Pa)	1303400	1399998.8842	7.4113
	T_{ro} (K)	727.25	728.4063	0.1590
Low Pressure (LP)	w (kg sec^{-1})	10.459	11.1756	6.8516
	p (Pa)	477700	549998.4619	15.1347
	T (K)	609.54	618.3515	1.4456

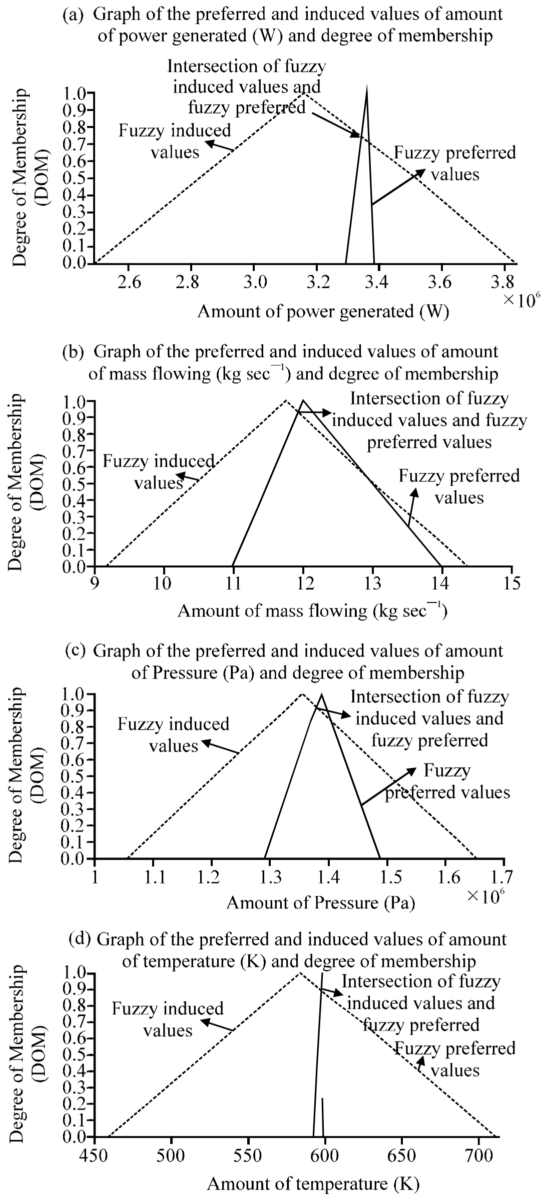

Fig. 2: Graph of the preferred and induced values of; a) power generated and degree of membership for HP section; b) Mass flowing and degree of membership for HP section; c) Pressure and degree of membership for HP section and d) Temperature and degree of membership for HP section

percentage errors of 8.8723, 22.0989 and 0.1525, respectively giving the outputs as 3868100 W power generated, 14.3272 kg sec^{-1} as mass flowing, 1657700 Pa as pressure, 718.3578 K as output temperature with percentage errors of 14.6234, 19.7236, 19.3484 and 19.3900, respectively between the desired and the

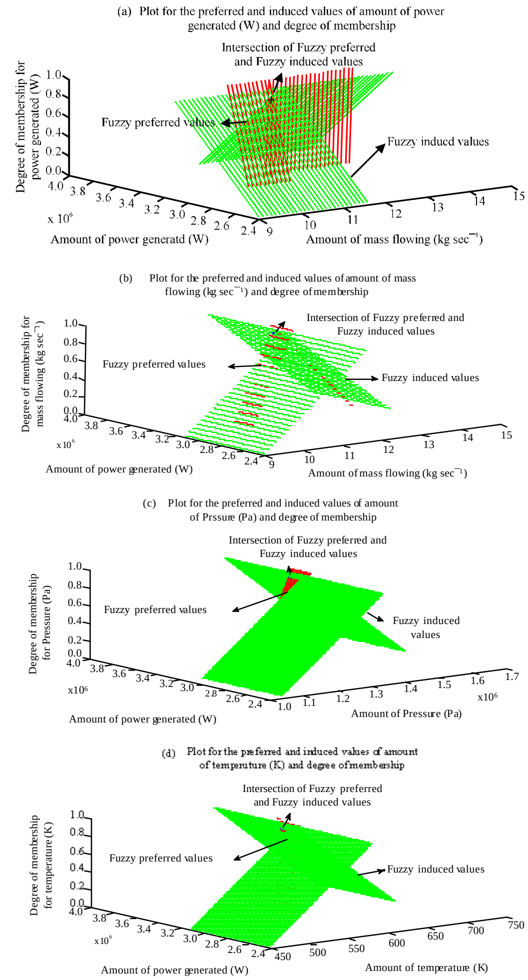

Fig. 3: Three dimensional graph of the preferred and induced values of; a) Power generated and degree of membership for HP section; b) Mass flowing and degree of membership for HP section; c) Pressure and degree of membership for HP section and d) Temperature and degree of membership for HP section

Fuzzy induced values. For the inputs of the IP section the algorithm proposes the values 11.2033 kg sec^{-1}, 1399998.8842 Pa, 728.4063 K with percentage errors of 7.1165, 7.4113, 0.1590, respectively giving the outputs 2801500 W power generated, 10.6456 kg sec^{-1} as mass flowing, 504270 Pa as pressure, 644.3394 K as output temperature having percentage errors of 2.0462, 1.7838, 5.5611 and 5.7091, respectively between the desired and the Fuzzy induced values. Finally, the values of the inputs for the LP section of the steam turbine are proposed to be 11.1756 kg sec^{-1}, 549998.4619 Pa and 618.3515 K having percentage errors of 6.8516, 15.1347 and 1.4456, respectively with the outputs 5506300 W as power generated, 11.3424 kg sec^{-1} as mass flowing, 38544 Pa as pressure, 418.4769 K as output temperature having percentage errors of 9.9586, 8.4463, 3.9230 and 11.3030, respectively between the desired and the induced values.

The computing time of the algorithm programmed on Matlab® Software is 0.5156, 0.6094 and 0.6563 sec for the HP, IP and LP sections, respectively of the steam turbine.

CONCLUSION

The study is devoted to the inverse Fuzzy state space modeling of the steam turbine, an integral part of the Combined Cycle (CC) power generation plant. The model consists of the processes of fuzzification, Fuzzy process and defuzzificaiton. The state space model of the steam turbine is modeled. Since all sections (HP, IP and LP) of the steam turbine have same input/output parameters, the same model is applied to all sections of the steam turbine. The input/output parameters of each section of the steam turbine are optimized on different alpha cuts and the best solution is identified. The percentage errors between the desired and the induced solutions show the credibility of the algorithm. The errors can be further refined by changing the α-cuts to smaller partitions. The superior abilities of the algorithm can be counted as its flexibility to operate on various operating conditions, fastness, reasonability and robustness of the algorithm.

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APPENDIX

Variables	Values	Description
h_{in}	3.3117×10^6 (J kg^{-1})	Enthalpy of inlet steam
ρ_{in}	13.662 (kg m^{-3})	Density of inlet steam
h_{ouhp}	3.0298×10^6 (J kg^{-1})	Enthalpy of outlet steam
$\eta_{\infty h}$	0.8	Polytrophic efficiency of HP section
A_{hp}	0.003 (m^2)	Exit flow area of HP section
C_{php}	2430 (J kg^{-1} K)	Specific heat for high pressure steam at constant pressure
V_{hp}	5.66 (m^3)	Steam storage volume for HP sections
τ_{hp}	1 (sec)	Mass flow time constant of HP section
r_{told}	0.333	Inlet/outlet pressure ratio for HP section
ρ_0	13.5353 (kg m^{-3})	Density of steam in HP section storage
x_0	4.421×10^7 (J m^{-3})	Energy of steam per unit volume for HP section storage

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