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Multiple model and observer design for a water-based PV/T collector

Ahmed Rachid and Zain Ul Abdin

Abstract—In this paper, a multiple thermal model for a water-based photovoltaic-thermal (PV/T) collector is constructed by mathematical transformation, using the boundedness of non-linear terms. Simulations have been performed and the results indicate that the convex polytopic transformation can accurately represent the non-linear model. Further, a Linear Matrix Inequality (LMI) approach is used to design an observer for estimating the states of the system. The efficiency and performance of the proposed observer in estimating the states of the system are shown through simulation.

Index Terms—photovoltaic-thermal systems, convex polytopic model, observer design, LMI, simulations.

I. INTRODUCTION

Solar energy harvesting is becoming more popular and widely adopted. This is due to many factors: the rise in fuel prices, drop-in prices of solar photovoltaic, climate change, potential applications [1] and raise awareness about the advantages and availability of solar energy. Common components to capture and convert solar energy, on one hand, is photovoltaic (PV) module and on the other hand solar thermal (ST). Photovoltaic-thermal (PV/T) system provides heat and electricity by combining the two modules into one integrated unit. The cold fluid is injected from one end and warm-fluid is collected from the other side of the collector. This circulation of the fluid plays an essential role in removing excess heat from the panel which enhances PV module efficiency [2]. The fluid can be water, air, nanofluid, or phase change material (PCM). Numerous theoretical, numerical, and experimental studies have been made worldwide in the past few decades with the aim of maximizing the PV/T panel's technical and economical performances in terms of electrical as well as thermal outputs.

Several approaches for obtaining multiple models have been provided by Chadli and Borne [3] that include multiple model representation using a neural approach, mathematical transformation, linearization, and construction by identification. A mathematical thermal model of an air-based PV/T system has been developed by Ul Abdin and Rachid [4], using a bond graph approach. Based on the obtained model, six different transfer functions were identified connecting the air output temperature to the air input flow for different operating points. The corresponding model can fairly relate to the real non-linear system. However, the model is just valid on a few operating points. A multiple model description for the Pantograph-catenary (PAC) is presented by Rachid [5] and Linear matrix inequalities (LMI's) are

used to control the PAC multiple model. In the context of observer's design, several works have been proposed for state estimation [6], [7]. A general observer theory is developed with an emphasis on a single output system and a new procedure, based on a special canonical form for multiple-output systems has been developed by Luenberger [8]. It is presented that an observer's estimate of the system state vector may be utilized in place of the actual state vector in linear or non-linear feedback designs without loss of stability. A new air-based mathematical model and its fractional-order observer in the time domain was established by Ouhsaine et al. [9]. The temperatures of all nodes are estimated and the asymptotic stability of the estimation error is analyzed. Further, linear matrix inequality (LMI) is used to compute the observer gains. A comparative study has been performed both numerically and experimentally by Wang and Gao [10] to analyze the performances and characteristics of three advanced state observers, including the high-gain observers, the sliding-mode observers, and the extended state observers. The results showed that the extended state observer has better performance in dealing with dynamic uncertainties, disturbances, and sensor noise than the high-gain observer and sliding-mode observer.

In this paper, a non-linear model of a water-based PV/T system is converted into multiple models using the boundedness of non-linear terms, based on a convex polytopic transformation of non-linear scalar functions. The major objective of this study is to design an observer that provides an estimate of a given real system. The observer gain is computed using linear matrix inequality (LMI). Simulations are performed and the results illustrate the efficiency of the proposed observer in estimating the states of the system.

The remainder of this paper is organized as follows: a thermal mathematical model of a hybrid water-based system is presented in section II(A). In section II(B), a multiple model is developed by mathematical transformation, using the boundedness of the non-linear terms. Section III provides a design of the observer whereas section IV contains the simulation results of this study. Finally, the paper ends with conclusions in section V.

II. MODELLING

A. Thermal model of a water-based PV/T collector

The thermal model of a water-based PV/T collector comprises multiple layers in a specific order as presented in Figure 1. The cross-sectional view shows that the collector consists of; a glass that is open to the surrounding environment, a PV cell layer which is followed by a tedlar film, an absorber layer, a metallic tube pressed between

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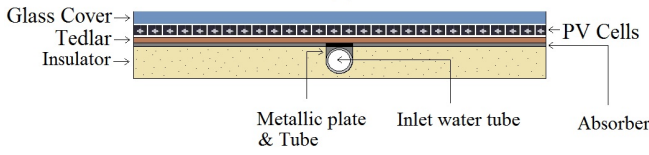


Fig. 1: Sectional view of water-based photovoltaic-thermal (PV/T) collector [11].

multiple layers through which fluid (water) flows and an insulated frame to avoid thermal losses. T_g , T_c , T_t , T_r , T_m , T_w and T_i are the temperatures of various components of the collector. The governing equations of the thermal model were determined using a bond graph approach which is a graphical approach [11].

The equations are respectively given by:

Glass:

$$M_g C_g \frac{dT_g}{dt} = A_{mod} [\alpha_g I_{sun} - h_{r,gs}(T_g - T_s) - h_{v,am}(T_g - T_{am}) - h_{c,gc}(T_g - T_c)] \quad (1)$$

PV cell:

$$M_c C_c \frac{dT_c}{dt} = A_{mod} [\tau_g \alpha_c I_{sun} \beta + h_{c,gc}(T_g - T_c) - h_{c,ct}(T_c - T_t)] - I_{sun} A_{mod} \eta_{ref} [1 - \beta_p(T_c - T_{c,ref})] \quad (2)$$

Tedlar:

$$M_t C_t \frac{dT_t}{dt} = A_{mod} h_{c,ct}(T_c - T_t) - A_{tm} h_{c,tm}(T_t - T_m) - A_{tr} h_{c,tr}(T_t - T_r) \quad (3)$$

Absorber:

$$M_r C_r \frac{dT_r}{dt} = A_{tr} h_{c,tr}(T_t - T_r) - A_{rm} h_{c,rm}(T_r - T_m) - A_{ri} h_{c,ri}(T_r - T_i) \quad (4)$$

Metallic tube:

$$M_m C_m \frac{dT_m}{dt} = A_{tm} h_{c,tm}(T_t - T_m) + A_{rm} h_{c,rm}(T_r - T_m) - A_{mi} h_{c,mi}(T_m - T_i) - A_{mw} h_{v,mw}(T_m - T_w) \quad (5)$$

Fluid (water):

$$M_w C_w \frac{dT_w}{dt} = A_{mw} h_{v,mw}(T_m - T_w) + \dot{m}_w C_w (T_{wi} - T_{wo}), \quad (6)$$

where T_{wi} is the inlet water temperature and T_{wo} is the outlet water temperature with T_w , the mean of two temperatures.

$$T_w = \frac{(T_{wi} + T_{wo})}{2}$$

Insulator:

$$M_i C_i \frac{dT_i}{dt} = A_{mi} h_{c,mi}(T_m - T_i) + A_{ri} h_{c,ri}(T_r - T_i) - A_{mod} h_{v,iam}(T_i - T_{am}) \quad (7)$$

The radiation heat transfer coefficient between glass layer and sky ($h_{r,gs}$) [11] contains the states and since the term is

not varying much so we consider it as a constant by taking the mean of all the values. The thermal model then can be expressed in the state-space form:

$$\begin{cases} \dot{x}(t) = Ax(t) + B(x(t))u(t) + Gv(t) \\ y(t) = Cx(t) + Dv(t) \end{cases}, \quad (8)$$

where the state x contains state variables and are defined as;

$$x = [T_g \ T_c \ T_t \ T_r \ T_m \ T_w \ T_i]^T$$

The output y is the outlet water temperature T_{wo} , mass-flow rate $\dot{m}_w$ is defined as controlled input u , v contains disturbances and can be written as:

$$v = [T_{am} \ I_{sun} \ T_{wi}]^T$$

We assume that the components of v are known.

The state matrix A is defined as follows:

$$A(t) = \begin{bmatrix} a_{11} & a_3 & 0 & 0 & 0 & 0 & 0 \\ b_1 & a_{22}(t) & b_4 & 0 & 0 & 0 & 0 \\ 0 & c_1 & a_{33} & c_2 & c_3 & 0 & 0 \\ 0 & 0 & d_1 & a_{44} & d_2 & 0 & d_3 \\ 0 & 0 & e_1 & e_2 & a_{55} & e_3 & e_4 \\ 0 & 0 & 0 & 0 & f_1 & -f_1 & 0 \\ 0 & 0 & 0 & g_1 & g_2 & 0 & a_{77} \end{bmatrix},$$

where

$$a_{11} = -(a_1 h_{r,gs} + a_2 + a_3)$$

$$a_{22}(t) = b_2 + b_3 I_{sun}(t)$$

$$a_{33} = -(c_1 + c_2 + c_3)$$

$$a_{44} = -(d_1 + d_2 + d_3)$$

$$a_{55} = -(e_1 + e_2 + e_3 + e_4)$$

$$a_{77} = -(g_1 + g_2 + g_3)$$

$$B(x(t)) = [0 \ 0 \ 0 \ 0 \ 0 \ -f_2(T_w(t) - T_{wi}) \ 0]^T$$

$$G = \begin{bmatrix} k_{11} & a_5 & 0 \\ 0 & b_5 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ g_3 & 0 & 0 \end{bmatrix}$$

$$C = [0 \ 0 \ 0 \ 0 \ 0 \ 2 \ 0]$$

$$D = [0 \ 0 \ -1]$$

The parameters are defined in the appendix section.

B. Multiple model construction

In order to simplify $B(x(t))$ for the thermal model (8), we make a change of variable which will allow us later to design the observer. A new sixth state $\theta_w(t)$ is introduced as:

$$\theta_w(t) = T_w(t) - T_{wi} \quad (9)$$

The thermal model with this change of variables becomes:

$$\begin{cases} \dot{\bar{x}}(t) = A(t)\bar{x}(t) + \bar{B}(\bar{x}(t))u(t) + \bar{G}v(t) - P\dot{T}_{wi} \\ y(t) = C\bar{x}(t) + \bar{D}v(t) \end{cases}, \quad (10)$$

where the state $\bar{x}$ contains state variables and is defined as;

$$\bar{x} = [T_g \ T_c \ T_t \ T_r \ T_m \ \theta_w \ T_i]^T$$

The new matrices $\bar{B}(\bar{x}(t))$, $\bar{G}$, and $\bar{D}$ can be written as:

$$\bar{B}(\bar{x}(t)) = [0 \ 0 \ 0 \ 0 \ 0 \ -f_2\theta_w(t) \ 0]^T$$

$$\bar{G} = \begin{bmatrix} k_{11} & a_5 & 0 \\ 0 & b_5 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & e_3 \\ 0 & 0 & -f_1 \\ g_3 & 0 & 0 \end{bmatrix}$$

$$P = [0 \ 0 \ 0 \ 0 \ 0 \ 1 \ 0]^T$$

$$\bar{D} = -D = [0 \ 0 \ 1].$$

There are several methods that can be used to procure multiple model which includes identification, linearization, and mathematical transformation [3]. The proposed multiple model method is based on a convex polytopic transformation of non-linear functions that uses boundedness of non-linear terms. In the model (10), a_{22} is the varying term and is given by:

$$a_{22} = h(I_{sun}) = b_2 + b_3 I_{sun}, \quad (11)$$

where $h(I_{sun})$ is bounded: $b_2 + \underline{I_{sun}}b_3 \leq h(I_{sun}) \leq b_2 + \overline{I_{sun}}b_3$.

Thus, the nonlinear term can be transformed such that:

$$h(I_{sun}) = \mu_1 \cdot [b_2 + \underline{I_{sun}}b_3] + \mu_2 \cdot [b_2 + \overline{I_{sun}}b_3],$$

where $\underline{I_{sun}} = \min\{I_{sun}\}$, $\overline{I_{sun}} = \max\{I_{sun}\}$ and

$$\mu_1 + \mu_2 = 1 \quad (12)$$

which enables us to obtain:

$$\mu_1 = \frac{I_{sun} - \underline{I_{sun}}}{\overline{I_{sun}} - \underline{I_{sun}}} \quad (13)$$

$$\mu_2 = \frac{\overline{I_{sun}} - I_{sun}}{\overline{I_{sun}} - \underline{I_{sun}}} \quad (14)$$

The corresponding multiple model is given by:

$$\begin{cases} \dot{\hat{x}} = \sum_{i=1}^2 \mu_i A_i \hat{x} + \bar{B}(\hat{x})u + \bar{G}v - P\dot{T}_{wi} \\ y = C\hat{x} + \bar{D}v \end{cases} \quad (15)$$

The number of models depend on the number of non-linear terms. If there exist j non-linear terms, then the multiple model constitutes no more than 2^j local models. Thus, there are 2 possible local models available described by A_1 and A_2 as follows

$$A_1 = \begin{bmatrix} a_{11} & a_3 & 0 & 0 & 0 & 0 & 0 \\ b_1 & b_2 + \underline{I_{sun}}b_3 & b_4 & 0 & 0 & 0 & 0 \\ 0 & c_1 & a_{33} & c_2 & c_3 & 0 & 0 \\ 0 & 0 & d_1 & a_{44} & d_2 & 0 & d_3 \\ 0 & 0 & e_1 & e_2 & a_{55} & e_3 & e_4 \\ 0 & 0 & 0 & 0 & f_1 & -f_1 & 0 \\ 0 & 0 & 0 & g_1 & g_2 & 0 & a_{77} \end{bmatrix}$$

$$A_2 = \begin{bmatrix} a_{11} & a_3 & 0 & 0 & 0 & 0 & 0 \\ b_1 & b_2 + \overline{I_{sun}}b_3 & b_4 & 0 & 0 & 0 & 0 \\ 0 & c_1 & a_{33} & c_2 & c_3 & 0 & 0 \\ 0 & 0 & d_1 & a_{44} & d_2 & 0 & d_3 \\ 0 & 0 & e_1 & e_2 & a_{55} & e_3 & e_4 \\ 0 & 0 & 0 & 0 & f_1 & -f_1 & 0 \\ 0 & 0 & 0 & g_1 & g_2 & 0 & a_{77} \end{bmatrix}$$

III. OBSERVER DESIGN

Designing observers for non-linear systems is a challenging problem due to its importance in automatic control design such as control, monitoring and fault diagnosis. In this section, an observer is designed for estimating the states of the multiple model (15). This is somehow like the Takagi-Segeno approach. Linear matrix inequality (LMI) is used to compute the observer gain. First, let us notice $\bar{B}(\bar{x})$ can be written as:

$$\bar{B}(\bar{x}) = \frac{-f_2 C^T C}{4} \bar{x} \quad (16)$$

Then (15) becomes

$$\dot{\hat{x}} = \sum_{i=1}^2 \mu_i A_i \hat{x} - \frac{f_2 C^T C}{4} \hat{x} u + \bar{G}v - P\dot{T}_{wi} \quad (17)$$

By adding and subtracting $\frac{f_2 C^T \bar{D}}{4} v u$ in (17), we get:

$$\dot{\hat{x}} = \sum_{i=1}^2 \mu_i A_i \hat{x} - \frac{f_2 C^T C}{4} \hat{x} u - \frac{f_2 C^T \bar{D}}{4} v u + \frac{f_2 C^T \bar{D}}{4} v u + \delta,$$

where $\delta = \bar{G}v - P\dot{T}_{wi}$ and since, $y = C\hat{x} + \bar{D}v$, the above equation becomes:

$$\dot{\hat{x}} = \sum_{i=1}^2 \mu_i A_i \hat{x} - \frac{f_2 C^T y}{4} u + \frac{f_2 C^T \bar{D}}{4} v u + \delta \quad (18)$$

Proposition:

An observer of system (15) is given by

$$\begin{cases} \dot{\hat{x}} = \sum_{i=1}^2 \mu_i A_i \hat{x} - \frac{f_2 C^T}{4} \hat{y} u + \frac{f_2 C^T \bar{D}}{4} v u + g(\hat{y}) + \delta \\ \hat{y} = C\hat{x} + \bar{D}v \end{cases} \quad (19)$$

where $g(\tilde{y})$ is chosen as:

$$g(\tilde{y}) = \frac{f_2 C^T}{4} \tilde{y} + L_i C \tilde{x} \quad (20)$$

which can also be written as:

$$g(\tilde{y}) = (L_i + \frac{f_2 C^T}{4}) \tilde{y} \quad (21)$$

and $L_i = L = (1/2)X^{-1}C^T$, $i = 1, 2$; X is the positive definite symmetric matrix satisfying the LMI's.

$$\begin{cases} A_i^T X + X A_i - C^T C < -2\gamma X, & i = 1, 2 \\ X > 0 \end{cases}, \quad (22)$$

where $\gamma > |f| > 0$, $(-f)$ being the lowest the fastest pole of (15).

Proof:

The observer error $\tilde{\bar{x}} = \bar{x} - \hat{\bar{x}}$ satisfies the equation

$$\dot{\tilde{\bar{x}}} = \sum_{i=1}^2 \mu_i (F_i) \tilde{\bar{x}}, \quad (23)$$

where $F_i = A_i - LC$

$$\dot{\tilde{\bar{x}}} = \sum_{i=1}^2 \mu_i (A_i - LC) \tilde{\bar{x}} \quad (24)$$

with $L = (1/2)X^{-1}C^T$

$$\sum_{i=1}^2 \mu_i A_i - LC = \sum_{i=1}^2 \mu_i A_i - \frac{1}{2} X^{-1} C^T C \quad (25)$$

premultiplying (25) by X , we get:

$$X \left(\sum_{i=1}^2 \mu_i A_i - LC \right) = X \sum_{i=1}^2 \mu_i A_i - \frac{1}{2} C^T C \quad (26)$$

by transposing (26):

$$\left(\sum_{i=1}^2 \mu_i A_i - LC \right)^T X = \sum_{i=1}^2 \mu_i A_i^T X - \frac{1}{2} C^T C \quad (27)$$

by adding (26) and (27):

$$\begin{aligned} X \left(\sum_{i=1}^2 \mu_i A_i - LC \right) + \left(\sum_{i=1}^2 \mu_i A_i - LC \right)^T X \\ = \sum_{i=1}^2 \mu_i A_i^T X + \sum_{i=1}^2 \mu_i X A_i - C^T C \end{aligned} \quad (28)$$

$$= \sum_{i=1}^2 \mu_i (A_i^T X + X A_i - C^T C) < -2 \sum_{i=1}^2 \mu_i \gamma X \quad (29)$$

Since, $\sum_{i=1}^2 \mu_i = 1$, (29) can be written as:

$$= \sum_{i=1}^2 \mu_i (A_i^T X + X A_i) - C^T C < -2\gamma X \quad (30)$$

Next, let σ be an eigen value of X and z an associated eigen vector that is $Fz = \sigma z$. The last inequality yields:

$$F^T X + X F < -2\gamma X \quad (31)$$

Premultiplying by z^* and postmultiplying by z , (31) gives:

$$z^* F^T X z + z^* X F z < -2\gamma z^* X z \quad (32)$$

with $z^* F^T = \bar{\sigma} z^*$, (32) becomes:

$$\bar{\sigma} z^* X z + z^* X \sigma z < -2\gamma z^* X z \quad (33)$$

since, $X > 0$, $\rightarrow \Re(\sigma) < -\gamma$.

IV. SIMULATION RESULTS

Initially, the simulations are performed to see the response of the non-linear model (10) and its corresponding multiple model (15) using MATLAB. The obtained results indicate a good representation of the non-linear system. In addition, simulations have been run for the proposed observer scheme. Using LMI toolbox *feasp* and by choosing $\gamma = 1$, (22) is solved for X . It should be noted that inlet water temperature is assumed as a constant. The multiple thermal model is simulated by randomly choosing systems initial condition $\bar{x}_0 = [23 \ 25 \ 23 \ 23 \ 23 \ 3 \ 20]^T$ and observers initial condition $\hat{\bar{x}}_0 = [23 \ 25 \ 23 \ 23 \ 23 \ 5 \ 20]^T$.

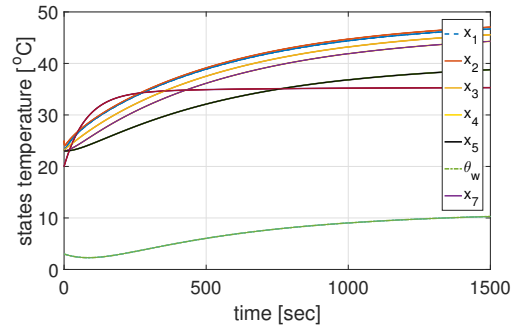


Fig. 2: Real states of the system.

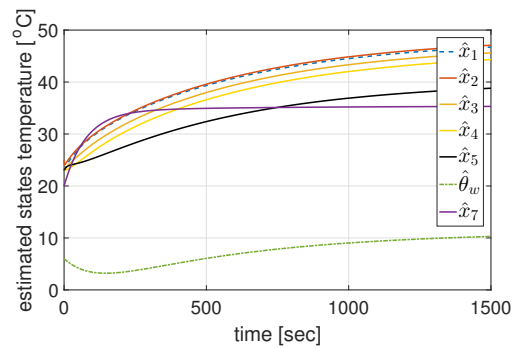


Fig. 3: Estimation of states.

The system real states $\bar{x}$ presented in Figure 2 are tracked by the observer states $\hat{\bar{x}}$ as illustrated in Figure 3. It can be observed that there is a reasonable agreement between the real and the estimated states of the system. The estimation error $\tilde{\bar{x}}$ is plotted in Figure 4, respectively. The estimation error converges to zero for all of the states, thus displaying the effectiveness of the proposed observer.

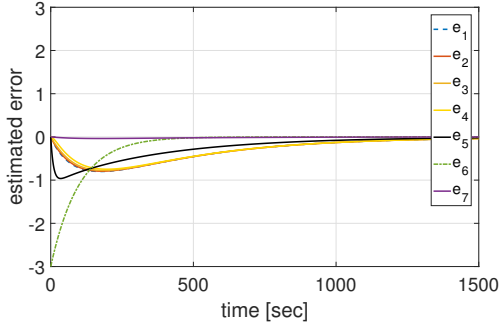


Fig. 4: Estimation error.

V. CONCLUSIONS

A multiple model for a water-based PV/T collector is constructed in this study. Additionally, an observer is proposed that is efficient in estimating system states as shown by simulation results. Realistic disturbances can be included to examine the stability and accuracy of the observer. Further, there is a need for physical experimentation of the observer to get a better knowledge of its feasibility and efficiency in real conditions. The practical experimentation will be done around equilibrium points and these points will be changed for validation.

NOMENCLATURE

Symbols

A	area
C	specific heat capacity
$d_{i/o}$	inner/outer diameter of the tube
I_{sun}	solar radiation
M	mass
T	temperature
h_c	conduction heat transfer coefficient between two components
h_r	radiation heat transfer coefficient between two components
h_v	convective heat transfer coefficient between two components

Greek letters

α	absorptivity
β	packing factor
β_p	temperature coefficient
η_{ref}	reference efficiency
τ	transmissivity

Subscripts

am	ambient
c	PV cell
g	glass cover
i	thermal insulator
m	tube
r	absorber
s	sky
t	tedlar
w	fluid (water)

APPENDIX

$$\begin{aligned}
 a_1 &= \frac{A_{mod}}{M_g C_g}, a_2 = \frac{A_{mod} h_{v,am}}{M_g C_g}, a_3 = \frac{A_{mod} h_{c,gc}}{M_g C_g}, \\
 a_4 &= \frac{0.0552 A_{mod}}{M_g C_g}, a_5 = \frac{A_{mod} \alpha_g}{M_g C_g} \\
 b_1 &= \frac{A_{mod} h_{c,gc}}{M_c C_c}, b_2 = \frac{A_{mod} (-h_{c,gc} - h_{c,ct})}{M_c C_c}, \\
 b_3 &= \frac{A_{mod} \eta_{ref} \beta_p}{M_c C_c}, b_4 = \frac{A_{mod} h_{c,ct}}{M_c C_c}, \\
 b_5 &= \frac{A_{mod} \tau_g \alpha_c \beta - \eta_{ref} - \eta_{ref} \beta_p T_{c,ref}}{M_c C_c}, \\
 c_1 &= \frac{A_{mod} h_{c,ct}}{M_t C_t}, c_2 = \frac{A_{tr} h_{c,tr}}{M_t C_t}, c_3 = \frac{A_{tm} h_{c,tm}}{M_t C_t}, \\
 d_1 &= \frac{A_{tr} h_{c,tr}}{M_r C_r}, d_2 = \frac{A_{rm} h_{c,rm}}{M_r C_r}, d_3 = \frac{A_{ri} h_{c,ri}}{M_r C_r}, \\
 e_1 &= \frac{A_{tm} h_{c,tm}}{M_m C_m}, e_2 = \frac{A_{rm} h_{c,rm}}{M_m C_m}, e_3 = \frac{A_{mw} h_{v,mw}}{M_m C_m}, \\
 e_4 &= \frac{A_{mi} h_{c,mi}}{M_m C_m}, f_1 = \frac{A_{mw} h_{v,mw}}{M_w C_w}, f_2 = \frac{2C_w}{M_w C_w}, \\
 g_1 &= \frac{A_{ri} h_{c,ri}}{M_i C_i}, g_2 = \frac{A_{mi} h_{c,mi}}{M_i C_i}, g_3 = \frac{A_{mod} h_{v,iam}}{M_i C_i},
 \end{aligned}$$

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