Flatness-based control for steam-turbine power generation units using a disturbance observer

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Abstract
Steam-turbine power plants still supply a significant part of the electric power consumed worldwide. The viability of steam turbine power units depends on their efficiency to a great extent and the control method applied to the them is of major importance for achieving their improved functioning. The authors propose flatness-based control and non-linear Kalman Filtering for power generation units comprising synchronous generators connected to steam turbines. It is shown that the dynamic model of this power system is a differentially flat one. This property signifies that all its state variables and its control inputs can be expressed as its differential functions of selected state variables, the latter standing for the flat outputs of the system. This allows for its transformation into a linear canonical form in which the design of a feedback controller and the solution of the state estimation problem becomes possible. Moreover, by introducing a Kalman Filter-based disturbance observer it becomes possible to identify in real time the perturbation terms that affect the power system's model. Through the proposed flatness-based controller, fast and accurate tracking of all reference setpoints is achieved by the state vector elements of the power unit. Moreover, through the proposed Kalman Filter-based disturbances estimator, the control loop is given additional robustness against modelling errors and external perturbations.

1 | INTRODUCTION

In parallel to renewable energy systems deployment during the last years, a large part of the produced electric power still comes from conventional thermal power stations, and particularly from steam-turbine power plants or from power stations of combined cycle [1–7]. For this reason steam turbines (and also gas turbines) are widely used for providing the mechanical power and torque that causes the rotational motion of power generators [8–12]. Aiming at providing a solution to the joint control problem of power generators receiving power from steam or gas turbines, several non-linear control methods have been developed [13–17]. This control problem is a nontrivial one, due to the complex nonlinear dynamics of the system that comprises jointly the power generator and the steam turbine, due to model inaccuracies as well due to the difficulty in measuring specific state vector elements (e.g. magnetic flux at the power generator or internal pressure variables at the turbine) [18–22]. Other approaches to the problem of modelling and non-linear control of steam-turbine power generation units can be found in [23–27].

In this article a new solution, based on differential flatness theory, is proposed for the non-linear control system that comprises a steam turbine and a synchronous generator. First, it is proven that the dynamic model of the power system is a differentially flat one [28–33]. This means that all its state variables and its control inputs can be expressed as differential functions of selected state vector elements, the latter known as flat outputs of the system. Through state-variables transformations (diffeomorphisms) one can finally express all state variables of the system as functions of the flat outputs and their derivatives. By proving that the system is differentially flat, one
can assure that input-output linearisation of the system is possible and that it can be transformed into an equivalent linear canonical form. Through its linearised description one can solve both the control and the state estimation problem.

To compensate for the disturbances that may affect the power system, as well as for model uncertainty and parametric variations, it has been proposed to use the Kalman filter-based disturbance observer. Actually, the derivative-free non-linear Kalman filter is employed, comprising the Kalman filter’s recursion on the linearised equivalent model of the system, plus inverse state variables transformations which allow for obtaining estimates for the state variables of the initial non-linear model [34–36]. The proposed disturbance observer identifies in real-time both the nonlinear state vector elements of the systems, as well additive input disturbance terms affecting it. After the perturbation inputs have been identified their compensation becomes possible with the inclusion of suitable elements in the functions of the feedback control inputs.

Steam-turbine power plants are estimated to supply nearly half of the electric power consumed worldwide. The low cost of coal and of other fossil fuels, as well as the immense capabilities for nuclear power generation stand for a major reason for continuing investments in steam turbine power units. However, the viability of the steam turbine power plants depends to a great extent on the improvement of their efficiency: (i) for achieving cleaner energy production and for adhering to the strict environmental regulations which have been set in action during the recent years and (ii) for over-taking the advantages that gas-turbine power units have (for instance higher conversion rates, lower development and installation costs, shorter start-up and shut-down times) [37–40]. Obviously the control methods which are applied to steam-turbine power generation units are of major importance for achieving their improved functioning. Fast and accurate tracking of reference setpoints by the state variables of steam turbine power plants signifies the capability to reach the designated power production rates, to achieve uninterrupted power generation and synchronisation with the power grid and finally to stay resilient against external perturbations or endogenous parametric changes. The differential flatness theory-based control and state estimation methods which are developed in this article contribute towards achieving these objectives.

The present article has a meaningful contribution because it shows the use of differential flatness theory towards solving the control and state estimation problems of steam-turbine power plants comprising a steam turbine serially connected to a synchronous generator [41–43]. It is shown that such an electric power system consisting of individual components which satisfy the differential flatness property is also differentially flat. Then for such a power system one can solve both the related control and state-estimation problem by applying a differential flatness theory-based change of state variables which brings the system into an input-output linearised form. For the latter state-space description one can design a stabilising feedback controller as well as a Kalman filter which estimates both the non-measurable state variables of the steam turbine power generation system and the perturbation terms that affect it. The article’s findings are genuine and the performance of the proposed differential flatness theory-based control and estimation method is tested and confirmed.

The structure of the article is as follows: in Section 2 the dynamic model of the power system is given consisting of a steam turbine and a synchronous power generator. In Section 3 the differential flatness properties of the model of the considered power system are proven. In Section 4 a flatness-based controller is designed for stabilising the dynamics of the power system. In Section 5 a Kalman filter-based disturbance observer is developed aiming at estimating in real-time and compensating for additive disturbance terms that affect the power system’s model. In Section 6 the performance of the flatness-based control scheme is tested through simulation experiments. Finally, in Section 7 concluding remarks are stated.

2 | DYNAMIC MODEL OF THE STEAM-TURBINE AND SYNCHRONOUS GENERATOR POWER UNIT

The power generation unit comprises: (i) the electrical part which is the synchronous power generator and (ii) the thermal power part which is the boiler supplying steam to the turbine [1, 43].

2.1 | Dynamics of the synchronous generator

\[
\dot{\delta} = \omega \\
\dot{\omega} = -\frac{D}{2J}(\omega - \omega_0) + \frac{\omega_0}{2J}(P_m - P_e)
\]

(1)

where \(\delta\) is the turn angle of the generator’s rotor, \(\omega\) is the rotation speed of the rotor with respect to synchronous reference, \(\omega_0\) is the synchronous speed of the generator, \(J\) is the moment of inertia of the rotor, \(P_e\) is the active power of the generator, \(P_m\) is the mechanical input torque to the generator which is associated with the mechanical input power, \(D\) is the damping constant of the generator and \(T_e\) is the electrical torque which is associated with the generated active power. Moreover, the following variables are defined: \(\Delta \delta = \delta - \delta_0\) and \(\Delta \omega = \omega - \omega_0\) with \(\omega_0\) to denote the synchronous speed. The generator’s electrical dynamics is described as follows [43]:

\[
\dot{E}_q' = \frac{1}{T_{d_q}}(E_f - E_q)
\]

(2)

where \(E_q'\) is the quadrature-axis transient voltage of the generator, \(E_q\) is the quadrature axis voltage of the generator, \(T_{d_q}\) is the direct axis open-circuit transient time constant of the generator and \(E_f\) is the equivalent voltage in the excitation
The algebraic equations of the synchronous generator are given by

\[
E_q = \frac{x_{ds}}{x'_{ds}} E'_q - (x_d - x'_d) \frac{V_i}{x_{ds}} \cos(\Delta \delta)
\]

\[
I_q = \frac{V_i}{x'_{ds}} \sin(\Delta \delta)
\]

\[
I_d = \frac{E'_q}{x'_{ds}} - \frac{V_i}{x_{ds}} \cos(\Delta \delta)
\]

\[
P_e = \frac{V_i E'_q}{x'_{ds}} \sin(\Delta \delta)
\]

\[
Q_e = \frac{V_i E'_q}{x'_{ds}} \cos(\Delta \delta) - \frac{V^2_i}{x_{ds}}
\]

\[
V_i = \sqrt{(E'_q - X'_{dI_d})^2 + (X'_d I_q)^2}
\]

where \(x_{ds} = x_d + x_T + x_L\), \(x'_{ds} = x'_d + x_T + x_L\), \(x_d\) is the direct-axis synchronous reactance, \(x'_d\) is the reactance of the transformer, \(x_T\) is the direct-axis transient reactance, \(x_L\) is the reactance of the transmission line, \(I_d\) and \(I_q\) are direct and quadrature axis currents of the generator, \(V_i\) is the infinite bus voltage, \(Q_e\) is the generator reactive power delivered to the infinite bus and \(V_i\) is the terminal voltage of the generator. Substituting the electrical equations of the synchronous generator given in Equation (3) into the equations of the electrical and mechanical dynamics of the rotor given in Equations (1) and (2), respectively, the complete model of the single machine infinite bus model is obtained:

\[
\dot{\delta} = \omega - \omega_0
\]

\[
\dot{\omega} = -\frac{D}{2J} (\omega - \omega_0) + \omega_0 \frac{P_m}{2J} - \omega_0 \frac{1}{2J} \frac{V_i E'_q}{x'_{ds}} \sin(\Delta \delta)
\]

\[
\dot{E'_q} = -\frac{1}{T'_d} E'_q + \frac{1}{T'_d} \frac{V_i}{x'_{ds}} x_d - \frac{x'_d}{x'_{ds}} V_i \cos(\Delta \delta) + \frac{1}{T'_d} E_f
\]

where \(T'_d = \frac{x'_{ds}}{x_{ds}} T_d\) is the time constant of the field winding, and \(E_f\) is the excitation voltage.

## 2.2 Dynamics of the steam turbine

The dynamics of the steam turbine is described by the following equations:

\[
\dot{P}_m = \frac{1}{T_b} [-P_m + P_T \mu]
\]

\[
\dot{P}_T = \frac{1}{C_{SH}} [k \sqrt{P_D} - P_T - P_m \mu]
\]

\[
\dot{P}_D = \frac{1}{C_D} [D_Q - k \sqrt{P_D} - P_T]
\]

\[
\dot{D}_Q = \frac{1}{T_B} [-D_Q + B]
\]

where \(P_m\) is the mechanical power provided to the generator by the steam turbine, \(P_T\) is the pressure before the turbine, \(P_D\) is the pressure in the drum and \(D_Q\) is the mass flow of steam in the boiler (steam efficiency). Other parameters of this model are defined as follows: \(B\) is the flow of the fuel to boiler, \(C_D\) is the time constant due to drum capacity, \(C_{SH}\) is the time constant due to volume in superheater, \(k\) is the coefficient related to the flow of steam, \(T_B\) is the boiler’s time constant and \(T_b\) is the time constant due to volume in turbine and reheater.

The steam-turbine and synchronous-generator power unit is shown in Figure 1:

Next, we define:

\[
X = [x_1, x_2, x_3, x_4, x_5, x_6, x_7]^T
\]

\[
=[\Delta \delta, \Delta \omega, E'_q, P_m, P_T, P_D, D_Q]^T
\]

as the state vector of the system, while the control inputs vector of the system is set to be \(U = [u_1, u_2]^T = [E_f, B]^T\). This results into the following state-space description of the system:

\[
\dot{x}_1 = x_2
\]

\[
\dot{x}_2 = \frac{D}{2J} (x_2 - \omega_0) + \omega_0 \frac{x_4}{2J} - \omega_0 \frac{1}{2J} \frac{V_i x_3}{x'_{ds}} \sin(x_1)
\]

\[
\dot{x}_3 = \frac{1}{T_d} x_3 + \frac{1}{T_d} \frac{x_4 - x'_d}{x'_{ds}} V_i \cos(x_1) + \frac{1}{T_d} u_1
\]

\[
\dot{x}_4 = \frac{1}{T_b} [-x_4 + x_5 \mu]
\]

\[
\dot{x}_5 = \frac{1}{C_{SH}} [k \sqrt{x_6 - x_5} - x_5 \mu]
\]

\[
\dot{x}_6 = \frac{1}{C_D} [x_7 - k \sqrt{x_6 - x_5}]
\]

\[
\dot{x}_7 = \frac{1}{T_B} [-x_7 + u_2]
\]

As a result of the above, the state-space model of the system is written in the following matrix form:
\[
\begin{align*}
\begin{pmatrix}
\dot{x}_1 \\
\dot{x}_2 \\
\dot{x}_3 \\
\dot{x}_4 \\
\dot{x}_5 \\
\dot{x}_6 \\
\dot{x}_7
\end{pmatrix} &=
\begin{pmatrix}
x_2 \\
-D \frac{2f}{T_s} (x_2 - \omega_0) + \omega_0 \frac{x_4}{2f} - \omega_0 \frac{1}{2f} \frac{V_s x_3}{x_{ds}^2} \sin(x_1) \\
\frac{1}{T_d} x_3 + \frac{1}{T_d} \frac{x_d - x_d'}{x_{ds}^2} V_s \cos(x_1) \\
\frac{1}{T_b} (-x_4) + \frac{x_5}{T_b} \\
\frac{1}{C_{SH}} [k \sqrt{x_6 - x_5} - \frac{x_5}{C_{SH}}] \\
\frac{1}{C_D} [x_7 - k \sqrt{x_6 - x_5}] \\
\frac{1}{T_s} \dot{x}_7
\end{pmatrix}
\end{align*}
\]

\[
\mathbf{f}(x) = \begin{pmatrix}
x_2 \\
-D \frac{2f}{T_s} (x_2 - \omega_0) + \omega_0 \frac{x_4}{2f} - \omega_0 \frac{1}{2f} \frac{V_s x_3}{x_{ds}^2} \sin(x_1) \\
\frac{1}{T_d} x_3 + \frac{1}{T_d} \frac{x_d - x_d'}{x_{ds}^2} V_s \cos(x_1) \\
\frac{1}{T_b} (-x_4) + \frac{x_5}{T_b} \\
\frac{1}{C_{SH}} [k \sqrt{x_6 - x_5} - \frac{x_5}{C_{SH}}] \\
\frac{1}{C_D} [x_7 - k \sqrt{x_6 - x_5}] \\
\frac{1}{T_s} \dot{x}_7
\end{pmatrix}
\]

\[
\mathbf{G}(x) = \begin{pmatrix}
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0
\end{pmatrix}
\]

\[
\mathbf{u} = \frac{1}{T_{do}} \begin{pmatrix}
u_1 \\
u_2
\end{pmatrix}
\]

where \( x \in \mathbb{R}^{7 \times 1}, f(x) \in \mathbb{R}^{7 \times 1}, G(x) \in \mathbb{R}^{7 \times 2} \) and \( u \in \mathbb{R}^{2 \times 1} \), with

\[
\dot{x} = f(x) + G(x)u
\]

The state-space description of the power system can be also written in the concise matrix form:

\[\text{FIGURE 1} \quad \text{Steam-turbine and synchronous-generator power unit}\]
Differential flatness is an endogenous property for several dynamical systems and is related to the following two features: (i) all state variables of the system and its control inputs can be expressed as differential functions of a subset of its state variables, where the latter stand for the system’s flat outputs, and (ii) the flat outputs of the system are differentially independent, which means that they are not connected through a relation of the type of a linear differential equation. The property of differential flatness signifies also that the system can be transformed into an input-output linearised form and this is the Lie-Backlund equivalence. Besides, differentially flat systems can be also written in the linear canonical Brunovsky form, for which Equation (15) and by solving with respect to state variable \( x_\gamma \), one has

\[
x_\gamma = C \dot{x}_0 + k \sqrt{x_5 - x_5} \tag{25}
\]

Therefore, state variable \( x_\gamma \) is also a differential function of the system's flat output. Finally, by solving Equation (16) with respect to the control input \( u_2 \), one gets

\[
u_2 = T g \gamma + x_\gamma \tag{26}
\]

which means that control input \( u_2 \) can be expressed as a function of the flat output and its derivatives. In conclusion all state variables and the control inputs of the model of the steam-turbine and synchronous generator are differential functions of the flat output vector and as a result of this the considered power system is a differentially flat one.

After defining reference setpoints for the elements of the flat outputs vector \( x_1^d \) and \( x_2^d \) and using Equations (20–26), one can compute the reference setpoints for the rest state variables of the power system, that is \( x_0, x_1, x_2, x_3, x_4, x_5 \) as differential functions of \( x_1^d \) and \( x_2^d \). This provides a systematic method for selecting the setpoints for the non-linear optimal control problem of the steam-turbine and of the synchronous-generator system.

### 4 | DESIGN OF A STABILISING FLATNESS-BASED CONTROLLER

The above relation signifies that state variable \( x_5 \) is also a differential function of the flat output of the system. From Equation (14) and after solving with respect to \( x_5 \), one obtains

\[
x_5 = x_5 + \left( C_{g5} \dot{x}_5 + x_5 \mu \right)^2 \tag{24}
\]

From Equation (24) it can be concluded that state variable \( x_5 \) is a differential function of the flat output. Moreover, from Equation (15) and by solving with respect to state variable \( x_\gamma \), one has

\[
x_\gamma = C_\delta \dot{x}_0 + k \sqrt{x_5 - x_5} \tag{25}
\]

The flat output of the power generation system has been defined as \( Y = [x_1, x_4] \). By differentiating the first state-space equation given in Equation (10) one obtains

\[
\dot{x}_1 = x_2 \Rightarrow 
\]

\[
\dot{x}_1 = -\frac{D}{2j} (x_2 - \omega_0) + \omega_0 \frac{x_4}{2j} - \omega_0 \frac{1}{2j} \frac{V_x x_3}{x_3} \sin(x_1) \tag{27}
\]

By differentiating \( x_1 \) once again in time, one gets

\[
x_1^{(3)} = -\frac{D}{2j} (\dot{x}_2 - \omega_0) + \frac{\dot{x}_4}{2j} \frac{V_x x_3}{x_3} \sin(x_1) + x_3 \cos(x_1) \tag{28}
\]
By substituting the time-derivatives of the state variables in the aforementioned relations, we get:

\[ x_1^{(3)} = -\frac{D}{\tau^2} x_1 + a_0 x_4 \]

\[ -a_0 \frac{1}{\tau} V_s x_3 \sin(x_1) + a_0 \frac{1}{\tau^2} [-x_4 + x_5 \mu] \]

\[ + a_0 \frac{1}{\tau^2} V_s x_3 \cos(x_1) - a_0 \frac{1}{\tau^2} \sin(x_1) \left[-\frac{1}{\tau} x_3 \right] \]

\[ + \frac{1}{\tau} x_d - \frac{1}{\tau} V_s \cos(x_1) \]

\[ - a_0 \frac{1}{\tau^2} \sin(x_1) \frac{1}{\tau} u_1 \]

This is a relation in the form:

\[ x_1^{(3)} = f_1(x) + g_1(x)u_1 \]  

(30)

Next, by differentiating Equation (13) in time, we obtain:

\[ \dot{x}_4 = -\frac{1}{\tau^2} (x_4 + x_5 \mu) \Rightarrow \]

\[ x_4 = \frac{1}{\tau^2} \left\{ \frac{1}{T_b} \left[-x_4 + x_5 \mu \right] + \frac{1}{C_{SH}} [k\sqrt{x_6 - x_5} - \mu x_5] \right\} \]

\[ x_4 = \frac{1}{\tau^2} \left(-x_4 + x_5 \mu + \frac{1}{T_b} \frac{k}{C_{SH}} (x_6 - x_5)^{1/2} (x_6 - x_5) \right) \]

\[ + \frac{1}{T_b} \frac{1}{C_{SH}} k (x_6 - x_5)^{1/2} \left[ k\sqrt{x_6 - x_5} - \frac{1}{T_b} \left[-x_4 + x_5 \mu \right] \right] \]

\[ + \frac{1}{C_{SH}} [k\sqrt{x_6 - x_5} - \frac{1}{C_{SH}} k (x_6 - x_5)^{1/2}] \]

\[ + \frac{1}{C_{SH}} \left[ k\sqrt{x_6 - x_5} \right] \]

\[ - \frac{1}{T_b} \frac{1}{C_{SH}} k \frac{1}{C_{SH}} \left[ k\sqrt{x_6 - x_5} - \mu x_5 \right] \]

\[ \Rightarrow x_4^{(3)} = \left\{ -\frac{1}{T_b} - \frac{1}{T_b} [-x_4 + x_5 \mu] \right\} \]

By continuing the differentiations of \( x_4 \), one obtains:

\[ x_4^{(4)} = -\frac{1}{T_b^2} \left\{ -\frac{1}{T_b} [x_4 + x_5 \mu] \right\} \]

\[ + \frac{1}{C_{SH}} \left[ k\sqrt{x_6 - x_5} - \mu x_5 \right] \mu + \]

\[ + \frac{1}{T_b} \frac{1}{C_{SH}} k \frac{1}{C_{SH}} \left[ k\sqrt{x_6 - x_5} - (x_6 - x_5) \right] \]

\[ + \frac{1}{C_{SH}} \left[ k\sqrt{x_6 - x_5} \right] \]

\[ - \frac{1}{T_b} \frac{1}{C_{SH}} k \frac{1}{C_{SH}} \left[ k\sqrt{x_6 - x_5} - \mu x_5 \right] \]

\[ \Rightarrow x_4^{(4)} = f_2(x) + g_2(x)u_2 \]  

(35)
In aggregate one arrives at an input-output linearised form for the power generation unit that comprises the steam-turbine and the synchronous generator:

\[
\begin{pmatrix}
  x_1^{(3)} \\ x_4^{(4)}
\end{pmatrix} = \begin{pmatrix}
  f_1(x) \\ f_2(x)
\end{pmatrix} + \begin{pmatrix}
  g_1(x) & 0 \\ 0 & g_2(x)
\end{pmatrix} \begin{pmatrix}
  u_1 \\ u_2
\end{pmatrix}
\]  

(36)

In this manner, a complete input-output decoupling of the power system is achieved. Moreover, by defining the new control inputs \( v_1 = f_1(x) + g_1(x)u_1 \) and \( v_2 = f_2(x) + g_2(x)u_2 \), one obtains:

\[
x_1^{(3)} = v_1, \quad x_4^{(4)} = v_2 \tag{37}
\]

Next, the following feedback control law is considered:

\[
u_1 = \frac{1}{g_1(x)} \left[ x_1^{(3)} - f_1(x) - k_1^1 (\tilde{x}_1 - \tilde{x}_1) \right] - k_1^d (\tilde{x}_1 - \tilde{x}_1)
\]

\[
u_2 = \frac{1}{g_2(x)} \left[ x_4^{(4)} - f_2(x) - k_4^1 (\tilde{x}_4 - \tilde{x}_4) \right] - k_4^d (\tilde{x}_4 - \tilde{x}_4) \tag{38}
\]

By applying the previous control law and by defining the tracking error variables as \( e_1 = x_1 - x_{1,d} \) and \( e_4 = x_4 - x_{4,d} \), one has:

\[
\begin{align*}
  e_1^{(3)} + k_1^1 \tilde{e}_1 + k_1^1 \tilde{e}_1 + k_1^d e_1 = 0 \\
  e_4^{(4)} + k_4^1 \tilde{e}_4 + k_4^1 \tilde{e}_4 + k_4^d e_4 = 0 \tag{39}
\end{align*}
\]

Thus, by suitably selecting the feedback control gains \([k_1^1, k_2^1, k_3^1]\) and \([k_4^1, k_2^2, k_3^2, k_4^2]\) so that the characteristic polynomials associated with the previous tracking error differential equations to be Hurwitz stable, one assures that:

\[
\begin{align*}
  \lim_{t \to \infty} e_1 &= 0 \Rightarrow \lim_{t \to \infty} x_1 = x_{1,d} \\
  \lim_{t \to \infty} e_4 &= 0 \Rightarrow \lim_{t \to \infty} x_4 = x_{4,d} \tag{40}
\end{align*}
\]

The elimination of the tracking error for the flat outputs of the power system assures also the elimination of the tracking error for all state variables of the model.

\[ y_1^{(3)} = v_1 + \tilde{d}_1, \quad y_1^{(4)} = v_2 + \tilde{d}_2 \tag{41} \]

It is considered that the disturbances \( \tilde{d}_1 \) and \( \tilde{d}_2 \) are described by their time derivatives up to order 2, that is:

\[ \tilde{d}_1 = f_{d1}, \quad \tilde{d}_2 = f_{d2} \tag{42} \]

Actually, every signal can be described by its derivatives up to order \( n \) and the associated initial conditions. However, since estimation of the signals \( d_1 \) and \( d_2 \) and of their derivatives will be performed using Kalman filtering, there is no prior constraint about knowing these initial conditions.

The state vector of the system is extended by considering as additional state variables the disturbance inputs and their derivatives. Thus, the new state variables are \( z_1 = y_1, \ z_2 = \tilde{y}_1, \ z_3 = \tilde{\tilde{y}}_1, \ z_4 = y_2, \ z_5 = \tilde{y}_2, \ z_6 = \tilde{\tilde{y}}_2, \ z_7 = y_3, \ z_8 = \tilde{y}_3, \ z_9 = \tilde{\tilde{y}}_3, \ z_{10} = \tilde{d}_1, \ z_{11} = \tilde{d}_2 \). In this manner, and by defining the extended state vector \( Z = [z_1, z_2, \ldots, z_{11}]^T \) one arrives at a state-space representation for the system which is in the linear canonical (Bleovsky) form:

\[
\begin{pmatrix}
  \dot{z}_1 \\
  \dot{z}_2 \\
  \dot{z}_3 \\
  \dot{z}_4 \\
  \dot{z}_5 \\
  \dot{z}_6 \\
  \dot{z}_7 \\
  \dot{z}_8 \\
  \dot{z}_9 \\
  \dot{z}_{10} \\
  \dot{z}_{11}
\end{pmatrix} =
\begin{pmatrix}
  0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}
\begin{pmatrix}
  z_1 \\
  z_2 \\
  z_3 \\
  z_4 \\
  z_5 \\
  z_6 \\
  z_7 \\
  z_8 \\
  z_9 \\
  z_{10} \\
  z_{11}
\end{pmatrix}
\]

(43)

\[
Z = \begin{pmatrix}
  1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}
\]

(44)

The previous description of the system is written in the linear state-space form:

\[ y_1^{(3)} = v_1 + \tilde{d}_1, \quad y_1^{(4)} = v_2 + \tilde{d}_2 \]
\[ \dot{z} = A \hat{z} + B \hat{u} \]
\[ z^\prime = Cz \]  

(45)

To perform simultaneous estimation of the non-measurable state-vector elements and of the disturbance inputs, the following disturbance observer is defined:

\[ \dot{\hat{z}} = A \hat{z} + B_o \hat{v} + K_f (z_m - \hat{z}_m) \]
\[ z^\prime = C_o \hat{z} \]  

(46)

\[ \hat{v} = [v_1, v_2]^T, A_o = A, C_o = C \text{ and} \]
\[ B_o = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}^T \]  

(47)

The gain of the disturbance observer is computed through the Kalman filter recursion. The application of Kalman filtering on the linearised equivalent description of the power system is the so-called Derivative-free nonlinear Kalman filter. Matrices, \( A_o, B_o \) and \( C_o \) are discretised using common discretisation methods. This provides matrices \( A_d, B_d \) and \( C_d \). Matrices \( Q \) and \( R \) denote the process and measurement noise covariance matrices. Matrix \( P \) is the state-vector error covariance matrix. The Kalman filter comprises a measurement update and a time update stage.

**Measurement update:**

\[ K_f (k) = P^\prime (k) C_d^T (C_d P^\prime (k) C_d^T + R)^{-1} \]
\[ \hat{x}(k) = \hat{x}^\prime (k) + K_f (k) [z_m - \hat{z}_m] \]
\[ P(k) = P^\prime (k) - K_f (k) C_d P^\prime (k) \]  

(48)

**Time update:**

\[ P^\prime (k + 1) = A_d P(k) A_d^T + Q \]
\[ \hat{x}^\prime (k + 1) = A_d \hat{x}(k) + B_d \hat{v}(k) \]  

(49)

By obtaining \( \hat{z}_8 = \hat{d}_1 \) and \( \hat{z}_{10} = \hat{d}_3 \) the stabilising feedback control of the power system is modified as follows:

\[ u_1 = \frac{1}{g_1(x)} \begin{pmatrix} x_1^{(3)} - f_1(x) - k_1^1 (\hat{x}_1 - \hat{x}_{1,d}) \\ -k_2^2 (\hat{x}_1 - \hat{x}_1^d) - k_3^2 (x_1 - x_{1,d}) \end{pmatrix} - \hat{z}_8 \]
\[ u_2 = \frac{1}{g_2(x)} \begin{pmatrix} x_4^{(4)} - f_2(x) - k_1^2 (x_4^{(3)} - x_{4,d}) - k_2^2 (\hat{x}_4 - \hat{x}_{4,d}) \\ -k_3^2 (\hat{x}_4 - \hat{x}_4^d) - k_3^2 (x_4 - x_{4,d}) \end{pmatrix} - \hat{z}_{10} \]  

(50)

**Remark 1** It is possible to measure those state variables of the system which stand also for its flat outputs: (i) \( x_1 \)

is the deviation of the turn angle of the synchronous generator from the turn angle that is obtained for synchronous rotation speed (ii) \( x_4 \) \( t \) is the mechanical power that is provided by the turbine to the rotor of the generator. The first-order derivatives of the aforementioned state variables are estimated with the use of the Kalman filter-based disturbance observer, which is also known as the derivative-free non-linear Kalman filter. Consequently, all state variables used for the implementation of feedback control can either be measured or they can be estimated with the use of Kalman filter.

**Remark 2** The Kalman filter-based disturbance estimator is of dimension 11. The state-space model of the monitored steam turbine and synchronous generator power unit is of dimension 7. Next, the state vector of the system is extended by including as additional state variables (i) the disturbance terms that affect the control inputs of the system, (ii) the first order derivatives of the aforementioned perturbation terms. Thus one has four more state variables and arrives at an extended state vector of the system with dimension equal to 11. The implementation of the disturbance observer requires moderate computational effort and actually estimates of the state variables and of the disturbance inputs of power unit can be obtained at each sampling period.

**Remark 3** By estimating in real-time the non-measurable state variables one can implement state estimation-based control. This is important because acquiring sensor measurements for all state variables of the system can be in certain cases technically difficult (for instance measurements about the magnetic flux and the quadrature axis voltage of the generator, or pressure measurements in the various compartments of the turbine). Besides by estimating in real-time the additive disturbance inputs that affect the power generation system, one can also compensate for them, after introducing additional terms to the control inputs. The additive disturbance inputs terms comprise both the effects of exogenous perturbations which are superimposed to the control inputs of te system, and the effects of model uncertainty terms. The estimation and compensation of such disturbance inputs with the use of the considered disturbance observer improves the robustness of the control loop. The robustness properties of the control scheme are those of linear quadratic Gaussian (LQG) control.

**Remark 4** The dynamics of the electric power generation unit which comprises both the steam turbine and the synchronous generator is in continous time; so is the flatness-based controller which is designed for the system. For the computer-based implementation of the control scheme, the state-space model of the power
unit is discretised and next this discrete-time equivalent of the system receives as input the consecutive samples of the flatness-based control algorithm. Therefore, the computer-based implementation of the control method considers finally a discrete-time model for the power system and a discrete-time representation of the control signal. In this context, the use of the discrete-time recursion of the Kalman filter is precise and correct. The disturbance observer that is used for estimating the state variables and the disturbance inputs of the system is initially formulated in continuous time, while its computer-based implementation through the Kalman filtering stages, is carried out in discrete-time. As a result of the above, the proposed control and estimation method is well grounded and rigorous and assures the stability of the control loop.

**Remark 5** Differential flatness theory-based control follows the concept of transformation of the system into an input-output linearised form and to the related Brunovsky canonical form. In that sense, the flatness-based control method is related to global linearisation methods. However, the method is applied to a wider class on nonlinear dynamics. This is because, unlike Lie algebra-based control, flatness-based control can be applied to an extended class of non-linear systems, given by the set of all systems which are differentially flat or equivalently the systems which admit input-output linearisation. On the other-side, the application of Lie algebra-based control is constrained to the systems that admit input-to-state linearisation. The robustness of the control method to model mismatch and to exogenous disturbances is assured by including in the control loop a Kalman filter-based disturbance observer. This allows for estimating in real-time the terms that perturb the system's functioning. By identifying disturbances, their compensation also becomes possible, after including an additional term in the system's control inputs.

**6 | SIMULATION TESTS**

The efficiency of the proposed control scheme was tested through simulation experiments. Flatness-based control was applied to the previously analysed model of the power system that comprises the steam-turbine and the synchronous generator. Indicative values about the parameters of the model are given in [1], however, the control scheme can tolerate model inaccuracy and parametric variations. The measurable state variables of the power unit were taken to be its flat outputs that the rotor's turn angle $x_1 = \theta$ and the mechanical power $x_4 = P_m$ provided to the synchronous generator by the steam turbine. The derivative-free non-linear Kalman filter was used as a disturbance observer, for estimating simultaneously the non-measurable state variables of the model and the additive disturbance inputs that were affecting it.

The obtained results are depicted in Figures 2–13. The real value of the state variable is depicted with a blue line, the estimated value of it is depicted as the green line while the reference setpoint is depicted as the red line. The depicted variables have been expressed in the per unit system. It can be noticed that, despite implementation of a state estimation-based control scheme and despite the presence of external disturbances, flatness-based control achieved fast and accurate tracking to the reference setpoints for all state variables of the system. It can be clearly noticed that the derivative-free non-linear Kalman filter, designed as a disturbance estimator, can identify in real-time the additive input disturbances that affect...
the power unit’s model, and this also allows for their compensation with the use of the updated feedback control of Equation (50).

The advantages of using a global linearisation-based control method for the dynamic model of the thermal power stations comprising steam or gas turbines and synchronous generators are outlined as follows: (i) the transformation that is performed on the power unit’s states-space model is an exact one and does not introduce any modelling errors, (ii) by expressing the dynamic model of the power unit into the linear canonical form it is assured that the separation principle holds and that the design of the control problem can be solved independently from the design of the state-observer, (iii) by using the Kalman filter as a disturbance observer the estimation and compensation of perturbation terms that affect the power unit’s model is achieved and thus the robustness of the control scheme is improved, (iv) the robustness properties of the control method are equivalent to those of LQG control and (v) by using the Kalman filter as a disturbance observer it is assured that the optimality of the estimation performed by the Kalman filter is retained.

To analyse further the stability and robustness properties of the control method, two new tables are given next: (i) in Table 1 results are provided about the Root Mean Square Error (RMSE) of the tracking error of the individual state variables of the steam turbine power generation unit, (ii) in Table 2 results are provided about the robustness of the control method against parametric variations. It can be noticed that the deviation of the turn speed of the generator form the synchronous speed is negligible.

**FIGURE 3** Test case 1: (a) control inputs $u_1$ and $u_2$ applied on the power system (blue lines) and (b) disturbance inputs $d_1$ and $d_2$ affecting the power system (red lines) and their estimates provided by the Kalman filter disturbance observer (blue lines).

**FIGURE 4** Test case 2: (a) tracking of reference setpoints (red lines) by the flat outputs $x_2 = \omega$ and $x_4 = P_m$ of the steam-turbine and synchronous generator system (blue lines), and estimated value (green line) and (b) control inputs $v_1$ and $v_2$ of the power system computed on the linearised equivalent model.
Besides, it can be seen that the control loop is insensitive to parametric changes in the model of the power unit.

In an overview of the article’s theoretical developments and experimental results the following can be noted:

(i) The design of a stabilising feedback controller for the steam-turbine power generation unit, based on differential flatness theory, follows a procedure with clear implementation stages. The first stage is to apply state variables transformations (diffeomorphisms) so as to write the state-space model of the system into an equivalent linearised form. The second stage is to solve both the control and state estimation problem for the power unit using its equivalent linearised description and methods which have been well confirmed in the case of linear dynamical systems. The third stage is to apply inverse transformations so as to compute the control inputs and the state variables estimates of the initial non-linear state-space description. Elaborating on the second stage, it has been already explained in the manuscript that the feedback gains selection has been carried out using the pole-placement technique (eigenvalues assignment method) on the linearised equivalent model of the system and this certainly assures global stability. Since there is a joint control and state estimation scheme, the stability and robustness properties of the resulting control loop are similar to those of LQG control. Finally, it is noted that the redesign of the article’s Kalman filter as a disturbance observer allows to compensate for disturbances that affect the steam-turbine power unit, thus improving the stability and
robustness properties of the proposed flatness-based control scheme further.

(ii) Differential flatness theory allows primarily for transforming a non-linear dynamical system into an equivalent linearised state-space description where the solution of both the control and state estimation problem is enabled. It does not designate the exact feedback control method that will be applied on the linearised equivalent state-space description of the system. Once the system has been linearised, the standard procedure for implementing flatness-based control is to apply the pole-placement technique (eigenvalues assignment) to the linearised equivalent model. Apart from that, there has been design of ‘flatness-based controllers’ implemented in ‘successive loops’ and indicative results about this approach can be found in [42].

(iii) The problem of non-linear control and stabilisation for the power generation unit that comprises a steam turbine and a synchronous generator can be also treated with the use of a novel non-linear optimal control method [44]. The flatness-based control approach which is proposed in the present article is based on the global linearisation of the dynamics of the steam-turbine and synchronous generator power unit, whereas in the non-linear optimal control approach an approximate linearisation concept has been followed. Thus instead of using state variables’ transformations which rely on differential flatness theory so as to bring the power system's dynamics into an equivalent linear state-space description, in the non-linear optimal control method the state-space model of the power unit undergoes linearisation with the use of first-order Taylor series expansion and

\[ \text{FIGURE 7} \quad \text{Test case 3: (a) control inputs } u_1 \text{ and } u_2 \text{ applied on the power system (blue lines) and (b) disturbance inputs } d_1 \text{ and } d_2 \text{ affecting the power system (red lines) and their estimates provided by the Kalman filter disturbance observer (blue lines)} \]

\[ \text{FIGURE 8} \quad \text{Test case 4: (a) tracking of reference setpoints (red lines) by the flat outputs } x_2 = \omega \text{ and } x_4 = P_m \text{ of the steam-turbine and synchronous generator system (blue lines), and estimated value (green line) and (b) control inputs } v_1 \text{ and } v_2 \text{ of the power system computed on the linearised equivalent model} \]
through the computation of the associated Jacobian matrices. Although in the differential flatness theory-based approach the linearisation process affects the entire state-space of the power unit, in the non-linear optimal control approach linearisation is performed around a temporary operating point which is updated at each time-step of the control algorithm. Furthermore, in the differential flatness theory-based control method the selection of the gains of the stabilising feedback controller is an offline procedure which relies on the pole-placement (eigenvector assignment) method, while in the non-linear optimal control method the gains of the stabilising feedback controller are updated at each sampling period through the solution of an algebraic Riccati equation. Besides, in the differential flatness theory-based control method state estimation is performed with the use of a flatness-based variant of Kalman filtering, whereas in the case of the non-linear optimal control method state estimation for the steam-turbine and synchronous generator power unit is performed with the use of the H-infinity Kalman Filter.

(iv) For common functioning conditions of the synchronous generator which is connected to the steam-turbine (i.e. synchronisation to the reference frequency of the power grid) no excessive values of the control inputs of the steam-turbine power unit may appear. Besides, what should be noted about the proposed power generation scheme is that the synchronous generators can be directly controlled by the power of the steam-turbine, without the need for intervention of voltage source converters. This simplifies the functioning of the integrated power unit and

### Figures

#### Figure 9
Test case 4: (a) control inputs $u_1$ and $u_2$ applied on the power system (blue lines) (b) disturbance inputs $d_1$ and $d_2$ affecting the power system (red lines) and their estimates provided by the Kalman filter disturbance observer (blue lines)

#### Figure 10
Test case 5: (a) tracking of reference setpoints (red lines) by the flat outputs $x_2 = \omega$ and $x_4 = P_m$ of the steam-turbine and synchronous generator system (blue lines), and estimated value (green line) and (b) control inputs $v_1$ and $v_2$ of the power system computed on the linearised equivalent model
makes this power system be more reliable and less prone to failures. This is among the reasons for which steam-turbine power units can contribute significantly, even nowadays, to the stabilisation of the electric power grid.

(v) The simulation tests which have been presented in the article rely on the definition of setpoints for the state variables of the steam-turbine and synchronous generator power unit. These setpoints have been defined after using the differential flatness properties of this power system. As noted before, the flat outputs of the power system are the turn angle of the synchronous generator and the mechanical power of the turbine which provides rotational motion to the generator. Knowing that the generator is a synchronous one, it is straightforward to define the associated turn angle and angular speed setpoints. Besides, the setpoint for the mechanical power of the turbine can be chosen by knowing the power ratings of the turbine, that is the feasible variation ranges for the turbine's power. Once, setpoints have been defined for the flat outputs of the power system, one can select setpoints for all state variables of the power unit by understanding that these state variables can be written as differential functions of the flat outputs. The article's simulation experiments have confirmed that the flat outputs of the steam-turbine and synchronous generator power unit converge to the related setpoints and thus all state variables of this system converge also to the setpoints associated with them.

7 | CONCLUSIONS

A new non-linear control method based on differential flatness theory has been proposed for the model of a power generation unit that comprises a steam turbine connected
with synchronous generators. The contribution of this research work has been in two directions: (i) it has proven the differential flatness properties of the dynamical system that comprises a steam turbine serially connected to a synchronous generator and (ii) it has introduced a differential flatness theory-based disturbance observer that is capable of estimating simultaneously the non-measurable state variables of the system and the additive disturbance inputs that affect it. The observer relies on the use of the Kalman filter recursion on the input-output linearised model of the power unit's dynamics which is obtained after successive differentiations of the flat outputs.

First, the differential flatness properties of the power unit have been proven. Actually, it has been shown that all state variables and the control inputs of the power system can be written as differential functions of specific state variables, the latter standing for the flat outputs of the system. By proving the differential flatness properties for the power system it also became clear that the system could be transformed into an equivalent linear canonical form. For the state-space description that was obtained out of this global linearisation procedure, it became possible to solve both the control and the state estimation problem of the system.

Next, the use of a Kalman Filter-based disturbance estimator has been proposed with the aim to provide the control loop with robustness against model uncertainty and external perturbations. The estimator, also known as the derivative-free non-linear Kalman filter, consisted of (i) the application of the Kalman filter’s recursion on the equivalent linearised model of the power system, as well as (ii) the use of inverse transformations which allowed for obtaining the estimates of the state variables of the initial non-linear model. The proposed filtering method achieved identification of perturbation inputs affecting the power system in real-time. By obtaining this information, the disturbances’ compensation also turned possible through the inclusion of additional terms in the feedback control inputs.

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