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A short overview of the electrical machines control based on Flatness-technique

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Optimal linear controllers and high computational non-linear controllers are normally applied to control the nonlinear systems. Flatness control method is a control technique for linear systems as well as nonlinear systems by static and dynamic feedback namely as endogenous dynamic feedback. This method takes into account the non-linear behavior of the process while preventing complicated computations. An important feature of flat systems is that their states and inputs can be expressed in terms of flat output variables and a finite number of its derivatives. Systems with flat properties have several advantages in different categories such as power electronics, electrical hybrid systems, electrical machines, etc. The objective of this paper is to provide an overview of this control method in electrical machines. In this application, using this control technique prepares the power and frequency regulation, prevents the system from the uncontrollable behavior, etc. Since the outputs of flat systems are not unique and no systematic method exists to figure out these outputs, in this paper the flat variables are introduced to help researchers to comprehend flat systems components.

Keywords:Flatness, Control, Doubly Fed Induction Motor, Permanent Magnet Synchronous Machine, Synchronous Machine.

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I INTRODUCTION

Differentially flat or flat systems is first introduced in 1992 by [1–6]. For systems which are differentially flat, it implies that all state and input variables can be expressed in terms of flat output (possibly fictitious) variables and a finite number of its derivatives without integrating any differential equation [7–12]. If the system has the properties of flat system, it can be linearized with respect to the flat outputs. The outputs of flat systems are not unique and no systematic method exists to figure out these outputs. More precisely, the concept of flatness can be explained as a change of coordinates that transforms the system into the forms, where calculations become elementary since the coordinates and the vector field describing the system are cleared out [6].

A necessary and adequate condition to describe the differential flatness property is suggested by [1–5] based on Lie-B̈acklund (L-B) isomorphisms [6, 13, 14], which can reduce the system complexity by decreasing both the number of variables and the equations [4]. Consider

$$\dot{x} = f(x,\ u) \tag{1}$$

where $x = [x_1, x_2,\ \ldots, x_n]^T$ and $u = [u_1, u_2,\ \ldots, u_m]^T$ denote the state and input vectors, respectively.

This system is differentially flat, if, there exists a vector $y \in R^m$ called flat output, in the form of $y = [y_1,\ y_2,\ \ldots,\ y_m]^T$ convincing the following three properties: first, the elements of y are differentially independent; second, there exists an L-B isomorphic map , such that:

$$y = (x, \dot{u},\ \ldots,\ u^{(\beta)}) \tag{2}$$

and at last there exists an L-B isomorphic map $\phi = [\phi_1\ \phi_2]^T$, such that:

$$x = \phi_1 \left(y, \dot{y}, \ldots, y^{(\alpha)}\right) \tag{3}$$

$$u = \phi_2 \left(y, \dot{y}, \ldots, y^{(\alpha+1)}\right) \tag{4}$$

and are finite numbers of derivatives.

For a flat system, if the inputs and outputs of the flat components are chosen as the inputs and outputs of the control system, the system can be linearized using endogenous feedbacks (i.e. either static or dynamic state feedback) with respect to the flat outputs [4, 6]. Consequently, if y is a flat output of the system whose state is x and input u, assumed to be measured, and if y_{REF} is the reference trajectory of the output, denote by $e_i^{(j)} = y_{REF,\ i}^{(j)} - y_i^{(j)}$, $i = 1,\ \ldots,\ m$, the components of the error, an endogenous dynamic feedback can be computed such that the system reads $y_i^{(\alpha+1)} = \theta_i$. The tracking control problem can be written as:

$$\theta_i = y_{REF,i}^{(\alpha+1)} + \sum_{j=0}^{\alpha} K_{ij} e_i^{(j)} \quad i = 1,\ 2,\ \ldots,\ m \tag{5}$$

where parameters K_{ij} are chosen such that the m polynomials $s^{(\alpha+1)} + \sum_{j=0}^{\alpha} K_{ij} s^j$ have their roots with negative real part, $i = 1,\ \ldots,\ m$ [6,12,14].

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Fig. 1 shows the general diagram of the flatness control method. It consists trajectory generation, control law, inverse model and system blocks. Trajectory generation consists in the off–line generation of a path, and the associated control actions that generate the path. The desired trajectory of the output process will be expressed by the flat output reference trajectory [15]. In the control level, we are particularly involved in the design of a control law able to track the reference trajectory called trajectory tracking even if some unknown disturbances force the system to deviate from it. For flat systems, this control law can be executed from (5). Substituting the expression for θ_i gives the equation for the closed–loop static state feedback, in which one obtains the inverse dynamic [6].

The theory of flatness is well developed and has been made available by many books, in parallel, a high number of applications have been studied, mostly in power electronics including DC–DC converters [16–18], inverters [19] and AC–DC converters (rectifiers) [20, 21], hybrid systems [15, 22–32, 34] and electrical machines [35–48]. Other application fields are chemical reactors [49,50], flight control systems [51], robot [52], and many more [53]. In this section, an overview of using flatness–based nonlinear control method is proposed for various configurations of electrical machines [35–48].

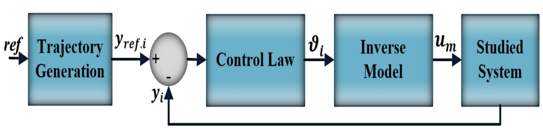

Figure 1: General diagram of flatness based control method.

The research works published between 2009 and 2016 in IEEE Xplore are analyzed by performing a search using the keywords "flatness control technique." This search generated more than 150 papers on differential flatness–based method to different applications published in conferences and journals. For electrical machines this statistics are shown in Fig. 2.

This paper is organized as follows: In Section II, an overview of electrical machines are presented. The flatness based control technique in electronic machines is introduced in Section III. Finally, the conclusions of the study are given in Section IV.

II ELECTRICAL MACHINES OVERVIEW

Nowadays, the development of the electric vehicles is widely attracted in electrical engineering. These drive systems may include the Permanent Magnet Synchronous Machines (PMSM), DC machines [54], induction machines (IM), synchronize machines and doubly–fed induction machines (DFIG). Permanent Magnet Synchronous Machines (PMSM) have been extensively used as both motors for industrial machines and generators for renewable energy power plants due to its advantages of high torque density and power density, high efficiency and the ease of the control.

However, the PMSM model is nonlinear coupled and is subjected to parameter variations with temperature and saturation. Some nonlinear control methods are implemented to control PMSM considering the nonlinear PMSM dynamics [35,55–58].

Other machines, which are widely used in industrial applications, are the induction machines (IMs) due to their robustness, reliability, low price and free maintenance. IMs are particularly operated as motors. The dynamical system of induction motors is nonlinear due to sudden changes in mechanical load and speed variations in most of the applications. Thus, the variable voltage and frequency of induction motors are mostly employed to control speed and torque of these machines [59, 60]. Moreover, Doubly fed induction machine (DFIM) is a kind of induction machine with both stator and rotor windings which is extensively used as generators (DFIGs), particularly in variable–speed wind energy applications with a static converter connected between the stator and the rotor [61, 62]. In the last decade, an increasing interest in using this topology for hydro–power generation systems, wind–power generation systems, and turbine engine power generation systems has taken place. Because of the popularity of DFIGs for the wind energy generation, the suitable control for this application including Control methods for grid–connected wind energy conversion systems, stand–alone systems, frequency support using DFIGs, low–voltage ride–through (LVRT) control, etc., have been widely investigated [63, 64].

III FLATNESS BASED CONTROL TECHNIQUE IN ELECTRONIC MACHINES

The flatness property of AC and DC machines is introduced in [35–48] to guarantee the power and frequency regulation. It can also prevent the system from the uncontrollable behavior and prepare system robustness during disturbances, etc. Some papers using this control technique are presented in Table II. It introduces all the state, input and output flat components in the literature. Depends on what is supposed to be controlled, the flat outputs are different. Furthermore, the flat outputs are not unique and no systematic method exists to find out these outputs. Fig. 3 and Fig. 4 show the general control block diagram for [38] and [48] which are described in details in the following.

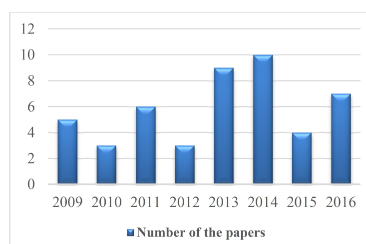

Figure 2: Number of publications between 2009 to 2016.

In [36], the flatness control technique is applied in permanent magnet synchronous motor (PMSM) to investigate the robustness and the stability. The flat output components of this synchronous motor are the load torque T_e, rotor position θ and the current in d–axis i_d whereas the state variables are the mechanical speed Ω, current in d–axis (i_d), voltage in dq–axis $(v_d$ and $v_q)$.

A cascaded flatness control is performed for a PMSM in [37] to abolish the system state static errors. Two–loop feedback control structure was used with a current control loop and speed control loop. The dq axis stator current and the angle of flux orientated coordinate system are considered the flat output components as depicted in Table II.

In [35], a speed sensorless control of PMSM is implemented. In the first part, the flatness control is associated with PI controller, this solution shows good robustness with respect to parameter variations and guarantees torque and speed tracking. In the second part, the high order sliding mode speed observer is used to overcome the occurring chattering phenomena. In this setting, the major drawback of the flatness control is that it requires exact knowledge of the motor parameters and any variation in the parameters or the load torque will reduce the controller performance. In order to overcome this problem a feedback stabilization control is proposed. As illustrated in Table II, the rotor speed and stator direct current are candidates as flat output variables.

A PMSM fed by bidirectional Quasi Z–source inverter (Q–ZSI) is controlled in [38] using a one–loop flatness–based control technique. The properties of using this control technique are to saturate the state and control variables to avoid the system from the uncontrollable behavior and prepare robustness during perturbations. This technique has revealed the high mastering of the transient states and the high bandwidth of a one–loop control. As it can be seen in Table 2, the flat components are:

$$x = (i_L,\ v_C,\ i_d, i_q)^T \in R^5 \tag{6}$$

$$u = (v_d,\ v_q,\ d)^T \in R^3 \tag{7}$$

$$y = \begin{cases} y_e = \left((L+M)\, i_L^2 + C v_c^2\right)/2 \\ y_\Omega = \Omega \\ y_d = L_d i_d + \Psi_f = \Psi_d \end{cases} \tag{8}$$

Table 1: Definition of the variables of the PMSM fed by Q–ZSI [38].

Item	Description
$i_L = i_{in} + i_2$	Inductive current
$v_C = v_{C1} + v_{C2}$	Capacitive voltage
d	Duty cycle of Q–ZSI command
$L_d = L_q$	Stator inductance
Ψ_f	Magnet flux linkage
Ω	Rotor angular speed
L	Quasi Z–source inductors
M	Quasi Z–source mutual inductor
C	Quasi Z–source capacitors

The variables of the above equations are illustrated in Table 1. To prove that the system is flat and each state or input variables can be written in function of the flat output components and their successive derivatives, it is derivated two times the flat output. All the state components (6) are expressed in terms of flat outputs and its first derivatives as shown in (9) to (12).

$$i_d = h_{i_d}(y_d) \tag{9}$$

$$i_q = h_{i_q}(y_\Omega,\ \dot{y_\Omega}) \tag{10}$$

$$i_L = h_{i_L}(\dot{y_e}, y_\Omega,\ \dot{y_\Omega}) \tag{11}$$

$$v_c = h_{v_c}(y_e,\ \dot{y_e}, y_\Omega,\ \dot{y_\Omega}) \tag{12}$$

The expression of the input variable d, v_d and v_q are obtained by derivating a second times the flat component.

$$d = h_d(y_e,\ \dot{y_e}, \ddot{y_e}, y_\Omega,\ \dot{y_\Omega},\ \ddot{y_\Omega}) \tag{13}$$

$$v_d = h_{v_d}(y_d,\ \dot{y_d}, y_\Omega,\ \dot{y_\Omega}) \tag{14}$$

$$v_q = h_{v_q}(y_d, \ddot{y_\Omega}\ , y_\Omega,\ \dot{y_\Omega}) \tag{15}$$

Finally, all the control variables (7) are expressed in terms of flat output variables and a finite number of its derivatives. This proves the flatness property of the considered system [38]. Fig. 3 shows the general block diagram of a flatness control for a PMSM [38]. As it is depicted, the inputs for the trajectory generation are the desired reference values of the state variables. Then, given these state variables and solving (3) for y_Ω^{ref}, y_e^{ref} and y_d^{ref}, the desired output references are found. The expressions for $\ddot{y_\Omega}$, $\ddot{y_e}$and $\dot{y_d}$ are calculated using the control equations for the closed–loop static state feedback. Eventually, the inverse dynamic is applied for the appropriate inputs for the system.

In [39,40], this control technique is applied for a PMSM used in a variable speed wind–energy system connected to a grid via a back–to–back converter. As depicted in Table II, the d–axis flux and mechanical speed are chosen as flat output variables which are well tracked their references. The major properties of this control technique are the high dynamic performance and good robustness against variations of the parameters.

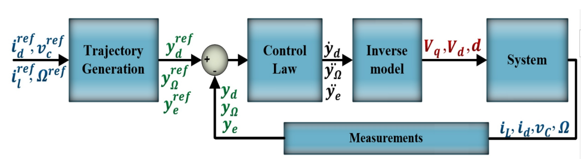

Figure 3: Flatness–based Permanent Magnet Synchronous Machines control block diagram.

The flatness–based control technique is also applied in [41] to control DC/DC Buck–Power–Converter and DC–motor system. Two controllers are first operated separately, however both of them are followed a common objective which allows the angular speed to track the desired trajectory. Thus, the angular speed was a candidate as flat output according to Table II. Using flatness properties, a robust control under uncertainties associated with different system parameters was achieved. Moreover, the concept of flatness–based control technique is utilized in [42] to control a synchronous machine. To simplify the calculation, it was assumed that the generator terminals are connected to the infinite bus and the dynamics of the static excitation system is neglected. The load angle δ and the mechanical power p_m as the flat output components are considered. The system was subjected to the three–phase short circuit fault for a period of three cycles. The benefits of the flatness performance are the stabilization of the sample power system under different fault conditions and parameter variations are achieved.

In [43], the flatness–based adaptive fuzzy control is applied to design the excitation control signal of a single machine infinite bus power system. The paper has modeled the generator using one–axis model. The loss of transmission lines is negligible. As indicated in Table II, the load angle F is considered as a flat output variable in order to track the reference trajectory for the generator angle. The control strategy can elevate the transient stability of the power system under a three–phase to ground faults. This technique is extended in [44] to control frequency and power flow for an automatic generation control (AGC) of a multi–machine system. Flatness–based control technique is implemented on a 3–area, 10–machine and the 39–bus system. All the state, control and output components of flatness can be seen in Table II. It was assumed that the active output power at the generator internal nodes was stated as a function of terminal voltage and the terminal voltage angle and magnitude that depend on the network equations. Moreover, the flux decay dynamics are neglected. The advantage of this control technique is that the set of nnlinear equations corresponding to an n–machine system is split into n–linear controllable sub–systems [65].

In [45], a nonlinear differential flatness–based control is proposed for an induction machine fed by a voltage source converter to control the inner current, outer flux and speed loops. This control technique is extended with fuzzy logic in [46, 47] to improve the control performance of an induction motor. The model of motor is considered as a three–phase voltage source inverter–fed squirrel cage induction motor in d–q reference frame. The flatness control is utilized to generate a suitable output, whereas the fuzzy logic is used to eliminate the effects of the time–varying nonlinear system.

In [48], a two–level structure based on flat systems properties is utilized for Doubly Fed Induction Generators (DFIG). The main components of the system are turbine, DFIG, converters, and the DC–link. To simplify the system, it was assumed that the converters and DC–link are free of losses. The electrical torque T_e and rotor flux argument θ are considered as the flat output components. By employing the flatness property, active power control and frequency regulation have been achieved. Fig. 4 shows the general block diagram of a flatness control for a doubly–fed induction machine [48]. As it can be seen, in the trajectory generation level, the desired active and reactive power of a doubly fed induction generator denoted by P_g^{ref} and Q_g^{ref} are used to develop the set points for trajectory generation. Then, given P_g^{ref} and Q_g^{ref} and solving (3) forθ^{ref}andT_e^{ref}, the desired output references are found. The reference values for flat outputs, θ^{ref} and T_e^{ref} are received from trajectory generations. The flat outputs are compared with the reference values and the error times a proportional gain results in the first derivative of the outputs as described in (16).

$$\begin{aligned} \dot{\theta} &= K_{\theta}(\theta^{ref} - \theta) \\ \dot{T}_e &= K_{T_e}({T_e}^{ref} - T_e) \end{aligned} \quad (16)$$

The advantages of the flatness–technique for the proposed nonlinear systems are also brought up in Table III. The choice of using the flatness technique in the aforementioned papers is justified by the numerous benefits the strategy offers. For instance, the complete 6th order model of the induction motor satisfies differential flatness properties since all its state variables and control inputs can be expressed as functions of the flat outputs [11]. The flat outputs are chosen to be the rotor's turn angle and orientation angle of the magnetic flux. Moreover, in the control design for PMSM, the problem of the system state static errors is minimized using flatness technique by considering the nonlinear characteristics of PMSM. This problem is still the remain interesting questions in PMSM. Unlike other optimal linear controllers such as adaptive fuzzy control schemes which are based on several assumptions about the structure of the nonlinear system as well as about the uncertainty characterizing the system's model, the proposed adaptive fuzzy control scheme based on differential flatness theory offers an exact solution to the design of adaptive controllers for unknown dynamical systems [9]. This technique has also a great power in automatic generation control of a multi–machine system. All the classical control methods such as secondary frequency control, the integral of square error, proportional–integral, integral–derivative, proportional–integral–derivative and integral–double derivative controllers are adequate for the traditional centralized system controls. Moreover, they suffer from the need for careful coordination of local controllers with overall system objectives [19].

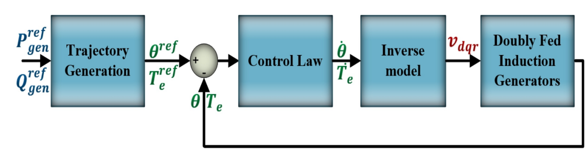

Figure 4: Flatness–based doubly–fed induction machine control block diagram.

IV CONCLUSION

In this paper, an overview of differential flatness–based techniques of control of the electrical machines have been surveyed and categorized. It provides researchers a global perspective of flat systems components proposed in the literature. These flat components are including state, input and flat outputs. More precisely, the main challenge of this control technique is the construction of the flat outputs. This paper has attempted to introduce the flatness variables of different configurations of electrical machines. For each system depending on what is supposed to be controlled, the flat variables differ from each other. In a DC–motor system to allow the angular speed to track the desired trajectory, it is chosen as a flat output whereas in the power system generator, the load angle is considered as a flat output to track the reference trajectory for the generator angle. In general, the main objectives of this control technique in electrical machines are as follows: the use of reference trajectories of the flat outputs allows ensuring a safe operation during the start–up and steady–state. Furthermore, in order to reduce the disorder impact, flat controllers use the reference reactions instead of pertubation reactions. Therefore, the transient states can be analytically foreseen by producing feasible trajectories, which cannot be gained through classical approaches. Consequently, it has been perceived and proven that the outputs of flat systems with a clear engineering and physical meaning are not unique and no systematic method exists to figure them out these outputs.

Table 2: Studied electrical machines based on flatness control.

Ref	Studied system	State Variables		Input Variables		Output Variables	
[37]	Permanent magnet–excited synchronous motor	i_{sd} i_{sq} v_s	$-d$–axis stator current $-q$–axis stator current - Angle of flux orientated coordinate system	u_{sd} u_{sq} Ω_s	-d–axis stator voltage $-q$–axis stator voltage - Stator circuit velocity	i_{sd} i_{sq} v_s	$-d$–axis stator current $-q$–axis stator current - Angle of flux orientated coordinate system
[35]	Permanent magnet synchronous motor	$i_d i_q$ Ω	- Stator direct current - Stator *quadrature* current - Rotor Speed	V_{dn} V_{qn}	- Stator direct voltage ref - Stator quadrature voltage reference	y_1 y_2	- Stator direct current - Rotor Speed
[38]	Permanent magnet synchronous machine	$i_d i_q$ Ω v_C i_L	- d–axis current machine - q–axis current machine – Mechanical Speed - Capacitive voltage v_{C_1}+v_{C_2} - Inductive current i_{in}+i_2	V_d V_q d	- d–axis voltages machine - q–axis voltages machine - Duty cycle of Q–ZSI command	y_Ω $y_d y_e$	- Mechanical speed - d–axis flux - Energy stored in the Q–ZSI
[39, 40]	Permanent Magnet Synchronous Generator	$I_d I_q$ Ω	$-d$–axis current machine $-q$–axis current machine - Mechanical Speed	V_d V_q	- d–axis voltages machine - q–axis voltages machine	y_Ω y_d	- Mechanical speed - d–axis flux
[41]	DC–motor system	$i_a \Omega$	- Armature current - Angular speed	v	-Voltage in the motor armature terminal	Ω	- Rotor angular speed
[43]	Power System Generator	x_1 x_2 x_3	- Load angle - Generator speed deviation - Stator voltage	E_{fd}	- Excitation control input	F	- Load angle
[44]	Multi-machine system	δ_i Ω_i P_{gvi} P_{mi}	- Rotor electrical angle - Rotational speed of rotor - Governor power - Mechanical power	P_i^{ref}	- Speed changer position	δ_i	– Rotor electrical angle, i denotes the i^{th} generator

Table 3: Studied electrical machines Performances based on flatness control.References

Reference	**Performance**
[38]	- Revealing of both the high mastering of the transient states and the high bandwidth of a one–loop control. - Preventing the system from having an uncontrollable behavior during disturbances.
[44]	- Controlling the frequency and tie-line power flow considering the overall system reliability, speed, and robustness. - Interpretation of promising performance in mitigating frequency and tie–line flow deviation. - Providing a platform for non–conventional units to contribute to load following and frequency control.
[48]	- Opportunity for wind plants to contribute in frequency regulation. - Explanation of promising results in tracking the desired reactive power and the active power. - No need of the field orientation since the stator current and the voltage and rotor current are directly used in control design.
[39, 40]	- Ability of predicting behavior of the system in the transient state and the steady state. - Improving the performance of the system in transient state in comparison with the traditional vector control techniques. - Well tracking of the output system variables (y_d and y_Ω) reference trajectories. - No effect of the DC–bus by the variations of the generator's speed. - A high dynamic performance and robustness against variations of the parameters. - An optimal design of the system components.
[43]	- Designing the excitation control signal of a single machine power system for tracking a reference trajectory for the generator angle. - Providing the transient stability of the power system under a three–phase to ground fault occurring near the generator terminal
[41]	- Well tracking of the angular speed for the DC motor even at abrupt changes in J (inertia value) and b (viscous friction constant value). - Well tracking of the angular speed for the DC motor even at uncertainties in the system parameters R (output load) and E (external voltage source). - Providing the voltage profiles that must be tracked by the Buck converter.
[35]	- Good robustness with respect to parameter variations and torque and speed tracking guarante

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