A Survey of Differential Flatness-based Control Applied to Renewable Energy Sources

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***Abstract*- This paper presents an overview of various methods used to minimize the fluctuating impacts of power generated from renewable energy sources. Several sources are considered in the study (biomass, wind, solar, hydro and geothermal). Different control methods applied to their control are cited, alongside some previous applications. Hence, it further elaborates on the adoptive control principles, of which includes; Load ballast control, dummy load control, proportional integral and derivative (PID) control, proportional integral (PI) control, pulse-width modulation (PWM) control, buck converter control, boost converter control, pitch angle control, valve control, the rate of river flow at turbine, bidirectional diffuser-augmented control and differential flatness-based controller. These control operations in renewable energy power generation are mainly based on a steady-state linear control approach. However, the flatness based control principle has the ability to resolve the complex control problem of renewable energy systems while exploiting their linear properties. Using their flatness properties, feedback control is easily achieved which allows for optimal/steady output of the system components. This review paper highlights the benefits that range from better control techniques for renewable energy systems to established robust grid (or standalone generations) connections that can bring immense benefits to their operation and maintenance costs.**

Keywords: Renewable energy power generation, control/stabilization, Differential flatness, review analysis.

I. Introduction

The growing migration of population has led to a high need for electrical energy in far remote areas. This growing demand for power generated using renewable energy sources has taken over the global stage [1].

Renewable technologies (biomass, wind, solar, hydro and geothermal) offer clean sources of energy that can provide a cost-effective means of electricity to small rural standalone areas or injection into utility grid lines [2]. However, the main challenge of renewable power generation that their energy sources depend on climatic conditions (e.g. water flow rate, solar intensity and wind speed) which are highly non-linear and vary with the hours of the day and the seasons of the year. These variations of renewable energy sources, relate to variation of renewable power energy generated [3]. Hence, there is a need to provide electricity to consumers at a specific frequency and voltage level. It is in this view that the notion of stabilization (or control) becomes very important. The control of power generated using renewable energy sources is eliciting particular concern.

Different control techniques have been applied to enhance the stabilization of energy generated in renewable power systems, and primarily these can be separated into different categories such as:

- Mechanical control (at the input of prime mover (turbine) valves or mechanical breaks) [4, 5].
- Control using converters (PID control, PI control, PWM control) [6 - 9].
- Control at the load side (load ballast, dummy load, and electronic load controllers) [10 - 14].

The adoption of Differential Flatness based control to renewable energy sources for the stability and management of the output power is becoming an increasing reality. Differential flatness is a mathematical property of a system that is described by a set of differential equations [15]. The main advantage of this control method is the possibility to express the dynamic behavior of a system in terms of a fictitious output that defines the system's characteristics. This control approach has often been used in a variety of nonlinear systems across various engineering disciplines including robotics [16, 17], induction motors [18], vertical takeoff and landing (VTOL) aircraft, polymerization reactors [19], Van de Vusse reactor [20] and a continuous bioreactor [21]. The differential flatness property of a large class of chemical reactors has been shown by [22].

The term 'differential flatness' or 'flatness' does not describe a specific control algorithm, it is rather a general approach in the analysis and design of dynamical systems. Flatness can be viewed as a form of feedback linearization, its control technique combines the trajectory generation and trajectory tracking. The term 'flatness based control' can further be expatiated as: in at least one step in the design of a control algorithm, the explicit algebraic relation between full states (x) or inputs (u) and the flat outputs (y) and a number of its derivatives ($y,\dot{y},\ddot{y},..$) are been applied[23, 24]. This review paper presents an overview of various methods that can be used to minimize the fluctuating impacts of power generated from renewable sources with a view to outlining the benefits of differential flatness based control. This study aims to provide information on better control techniques towards establishing a reasonable grid (or standalone) power generation connection that can make an immense contribution to the operation and maintenance costs of renewable energy systems.

This paper is organized as follows: section 1 introduces the topic; section 2 gives a review of flatness based control technique applied to renewable energy; section 3 illustrates the basic flatness based control principle; section 4 gives a brief discussion of the reviewed literature, and section 5 deals with recommendations and conclusion of the study.

II. Review of Flatness based control technique applied to renewable energy.

A number of researchers have applied the flatness based theory in the field of renewable energy technology. This section is divided into different categories of renewable energy sources where the flatness based control has been applied, namely:

- Fuel cell (FC),
- Wind (W),
- Solar (PV),
- Hydro,
- Biomass,
- Tides,
- Oceans,
- Hydrogen,
- Geothermal energy.

Recent research studies are reviewed and summarized in Table 1, which provides the source authors, a summary of the research focus, renewable energy technology covered and comment on the key results of the work reviewed.

Table 1: REVIEW OF FLATNESS BASED CONTROL TECHNOLOGY APPLIED TO RENEWABLE ENERGY SOURCES.

Authors	Technology	Focus of the Review	Comments on key results
A. Gensior, T. P. Nguyen, J. Rudolph, H. Guldner, [25]	Wind (WT)	Research on loss optimization and control of a doubly fed induction generator and two power electronic converters is considered. A mathematical model is given and the flatness of the model is shown. The freedom in the choice of one component of the flat output chosen is used in other to reduce the power losses in the system.	Using the flatness principle, a trajectory tracking controller for the machine and the grid side converter are developed (Back-stepping approach).
A. Payman, S. Pierfederici, F. Meibody-Tabar, [26]	Fuel cell (FC) and Supercapacitor (SC)	Proposed to control a multi-source alongside multi-load electrical hybrid system (EHS). Supercapacitor-bank (SCB) and fuel cell are the main auxiliary sources. They supply two independent loads, connected to a direct current (DC) bus through unidirectional buck converters an observer is also proposed and designed to estimate either the fuel cell voltage against power (V-P) output characteristic or voltage against current (V-I) output.	The use of flatness based proposed observer allows the achievement of an efficient control of the system, hence; avoiding overcharging or discharging of an SCB.
A. Shahin, S. Eskander, H. Moussa, J. -P. Martin, B. Nahid-Mobarakeh, S. Pierfederici, [27]	Solar (PV)	Applied a new method based on flatness based control to advance reliability of parallel connected inverters. At one loop with high bandwidth and low voltage total harmonic distortion (THD) controller based on the flatness technique is proposed in a non-isolated power supply composed of N units.	Flatness based control by aligning in parallel quite a few units, the power supply system is able to meet high power requirements and the prospect of maintenance operation without interrupting the supply.
C. Join, G. Robert, M. Fliess, [28]	Hydro	Applied a concept known as Model-Free Control to hydroelectric run-of-the river power plants. In this; a level trajectory is planned for cascaded power plants, numerous dynamic simulations results confirm that with a modest and robust control algorithm. There are only three control parameters which are easy to tune and performances are robust for a large range of operating points.	The flatness based principle is used to control the set-point, even in severe operating conditions. With advantages as: Mathematical model of the process is no more necessary, consequently; complicated identification procedures are avoided.
D. He & X. Cai, [29]	Solar (PV)	Applies a novel feed-forward control based on flatness to a high voltage direct current (HVDC) source converter system. To track the reference trajectory such as active power, DC voltage, the transition limitation of current is being taken into account in the discrete time reference trajectory. The feed-forward part of input come from the function of input and flat output, and other feedback controller is used to eliminate errors.	Feed-forward makes flatness-based controller perform faster dynamic response as opposed to conventional dead-beat controls. Feed-forward is its main advantage for its enhancement of the dynamic performance.
D. Schlipf, D. Cheng, P. Wen, [30]	Wind (WT)	Evaluated a flatness-based feed forward control approach of wind turbines using Lidar. Its permit the calculation of the control action based on the trajectories of the rotor speed and tower motion using wind measurements, in this study, the planning of the trajectory is done online takes into consideration the contains due to the actuator regulating the rotor speed and minimize tower movements.	Using the technique of flatness, the feed forward signals of the collective pitch and generator torque update can be combined with conventional feed-back controllers to obtain a considerable reduction of the tower and shaft loads.
D. Wang, C. Liu and G. Li, [31]	Wind (WT)	Proposes an “optimal integrated control scheme” for the grid side voltage source converter (VSC). The control approach includes a main controller and an additional controller, in the main controller; a double loop controller based on differential flatness based theory is designed for grid side VSC and an auxiliary second harmonic compensation control loop based on an improved calculation method for grid side instantaneous transmission power is designed by the quasi proportional resonant (Quasi PR) control principle, which is able to simultaneously restrain the second harmonic components in active power and reactive power injected into the grid without considering the current control calculation for the respective references .	Flatness based enable a reduction of the direct current link overvoltage during grid faults, by adding a modified control factor to the traditional direct current voltage control loop in grid side VSC
F. Michaud and G. Robert, [32]	Hydro	Presented a robust control law based on the nonlinear differential flatness principle for the speed governor of hydraulic turbine control system participating to power frequency control.	The comparison of flatness base nonlinear structure with a linear proportional integral (PI) feed forward controller gives better

			results; less sensitive to process variations and lower overshoot.
G. Rigatos, P. Siano, P. Wira, V. L o i a, [33]	Fuel cell (FC)	Presents an approach to nonlinear control of fuel cells using differential flatness theory and Kalman filtering (KF). The design of a state-feedback controller is achieved and extended by considering an additional state variables the derivatives of the aggregate disturbance input. Subsequent, a Kalman filter based disturbance observer is applied to the linearized extended model of the fuel cells.	This flatness based control arrangement is robust to model uncertainties and external perturbations, and the Kalman filter based estimator enabled to identify the perturbation term and to compensate by including an additional element in the feedback control law.
H. C.Enriquez, J.C.Romero, and G.A. Ramos, [34]	Wind (WT)	Proposes an alternative robust observer based linear control technique to maximize energy capture in a 4.8MW horizontal axis variable speed wind turbine. The strategy is to use a generalized proportional integral (GPI) observer to reconstruct the aerodynamic torque in order to obtain a generator speed optimal trajectory. Then, a robust GPI observer based controller supported by an active disturbance rejection (ADR) approach allows asymptotic tracking of the generator speed optimal trajectory.	The proposed flatness based approach, controls the power coefficient through the generator angular speed and near to an optimum point at which power coefficient is maximized, the results show that the proposed control strategy is effective in terms of power capture and robustness.
H. Fürst, D. Schlipf1, M. I. Latour, and P. W. Cheng, [35]	Wind (WT)	The application of the promising methodology of feed forward control using nacelle-based lidar sensor measurements on a 10 MW wind turbine concept. The feed forward controller is designed such that disturbances from the changing wind speed to the generator speed are compensated by adding an update to the collective pitch rate signal of the normal feedback controller. The evaluation of the feed forward controller is done in two steps: Firstly; simulations using perfect lidar data measurements are applied to check the robustness of the controller against model uncertainties.	Flatness based principle leads to a conclusion that; the benefits of lidar assisted control might be even more attractive for 10 MW turbines, since the cost of lidar system will be the same while the load reduction might lead to larger cost reduction due the high overall cost compared to 5 MW wind turbines.
H. Xue, H. Li and Y. Wang, [36]	Solar (PV)	Work on a novel nonlinear differential flatness based control method for a distributed photovoltaic energy storage (PV-ES) direct current (DC) generation system. For high power applications, four phase parallel boost converters and four phase parallel bi-directional converters are implemented as a solar (PV) converter and a storage device, respectively.	Using flatness for the PV four phase parallel boost converters, an improved algorithm is designed to achieve maximum power point tracking (MPPT) control, to lessen current ripple and widen the range of PV module output voltage.
H.A. Aldwaihi and E. Delaleau [37]	Wind (WT)	Presented a novel control law for a permanent magnet synchronous generator (PMSG) driven by a wind turbine (WT) and connected to a battery bank via an AC/DC converter. The novel algorithm gives a simple method, based on trajectory planning, that reduces the copper losses in the PMSG stator, hence; achieves the maximum of power captured by the WT.	The key finding of the paper is to show that flatness based control (FBC) is compatible with any maximum power point tracking (MPPT) strategy.
I. Tegani, A. Aboubou, R. Saadi, M. Y. Ayad, M. Becherif, [38]	Solar (PV), Wind (WT) and Fuel cell (FC)	Presented a control design of a renewable energy hybrid power system, The energy generated is managed through a non-linear method based on the differential flatness property to improve on the control law, a predictive neural network (PNN) is used to ensure a better tracing for the reference trajectory signals.	The results show that the proposed flatness PNN is able to manage the power flow in a hybrid system with multi renewable sources, and providing more stability by decreasing the perturbation in the controlled DC bus voltage.
J.T. Agee and A. A. Jimoh, [39]	Solar (PV)	Demonstrates that the concept of differential flatness could be used to design controllers for a polar axis solar tracker that would enable a reduction in hardware costs. Three control objectives are realized using one controller structure, sensorless solar tracking is achieved using trajectories of motion.	It is deduced that the implementation of (or flatness based) trajectories of motion with the controller can reduce the drive power requirement and associated photovoltaic (PV) cost by about 31%, sensorless tracking offer the possibility of hardware cost reductions.
M. Aimene, A. Payman, B. Dakyo, [40]	Wind (WT)	A novel nonlinear control method based on differential flatness is applied to a high power wind energy conversion system connected to the grid. The control system is done by planning the appropriate trajectories on components of the output variable vector of the system, The studied system includes a three blade horizontal wind turbine and a permanent magnet synchronous generator (PMSG) which is connected to the grid through a back-back converter and a filter.	The advantage of the proposed flatness based method is the control of the system in its high performance level as well as during the transient state.
M. Benaouadj, M. Y. Ayad, M. Becherif, A. Aboubou, M. Bahri, O. Akhrif, [41]	Wind (WT)/ Solar (PV)/ Batteries and Supercapacitor (SC)	Look at the energy flow control of Wind/PV/Batteries/Super capacitors, the system is managed using a nonlinear control based on the flatness concept, the lead acid batteries are used to compensate the power demand which PV and wind generators cannot provide. Super capacitors are employed to relieve the batteries of repeated charging and discharging ensuring longer hybrid source lifetime.	The outcome in using the flatness based principle is to obtain an autonomous hybrid power sources to supply a residential load, coming from exchanging power among different components.
M. Benaouadj, A. Aboubou, M.Y. Ayad, M. Becherif, [42]	Solar (PV) and Batteries	Presented a work on stand-alone application, and to demonstrate role of supercapacitor as a transient power source, a non-linear control strategy based on the differential flatness approach is applied to manage energy flows in two systems, the first includes a photovoltaic (PV) source considered as a main source and lead acid	The simulation results have demonstrate that; with the principle of flatness based control, The direct current (DC) link voltage is controlled and regulated to its reference, the batteries and supercapacitors

		batteries used as a storage unit, the second is obtained with the hybridization of the PV source, lead acid batteries, and supercapacitors.	voltages and states of charge are maintained in their admissible intervals under conditions of high discharges, Thus, the storage unit and hybrid sources lifetimes increases.
M. Benaouadj, M. Y. Ayad, M. Becherif, A. Aboubou, [43]	Solar (PV)/ Wind (WT)/ Supercapacitor (SC)/ Batteries	Work on an autonomous Wind/Photovoltaic (PV) hybrid power sources using lead acid batteries and supercapacitors as storage elements. The lead acid batteries are used to compensate the power demand, which wind and PV generators cannot provide. Supercapacitors are employed to relieve the batteries of repeated charging and discharging ensuring longer hybrid source lifetime. The exchanged power among different components is managed using a non-linear control based on the flatness concept, to obtain an effective supply.	The possibility of power exchanged among different components is managed using a non-linear control based on the flatness concept to obtain an effective supply.
M. Josevski and D. Abel, [44]	Fuel cell (FC)	Proposed a flatness-base model predictive control (FMPC) to address an energy management problem of hybrid electric vehicles. A predictive controller for the optimization of the hybrid electric vehicle fuel efficiency is introduced, the idea is to use the concept of differential flatness to determine the evolution of a system's state across the prediction horizon without numerical integration. The entire nonlinear optimization problem is expressed as a function of a fictious output, called the flat output and its first derivative. The optimal distribution of the requested torque between propulsion devices is then determined by a static optimization.	Due to the adoption of flatness based control, FMPC resulted in improved fuel economy, as opposed to the LTV-MPC controller
M. Phattanasak, W. Kaewmanee, J. P. Martin, S. Pierfederici, B. Davat, [45]	Fuel cell (FC) and Solar (PV)	This paper presents an interleaved-double-dual-boost converter (IDDB) used in renewable energy application where high voltage gain is required, such as photovoltaic or fuel cell applications, The variation of the input voltage is compensated by trajectory planning process. Two kinds of controllers are applied to this converter, 1) a controller based on Flatness properties for regulating the output voltage (outer loop); 2) a sliding mode controller for inductor current (inner loop).	The principle of flatness based is used in converting the relatively low direct current (DC) voltage obtain from the renewable energy sources to a higher level for fulfilling the requirement of the inverter, limiting the converter losses and increasing the voltage gain.
M. Phattanasak, R. Gavagsaz-Ghoachani, J.P. Martin, S. Pierfederici, B. Davat, [46]	Fuel cell (FC) and Supercapacitor (SC)	Present a flatness based controller for a hybrid source system, An isolated three port bidirectional full bridge DC-DC converter is utilized to transfer energy dual direction between the load and the auxiliary source.	By using the principle of flatness based control, the fuel cell (FC) is used as a main power source, and the supercapacitor (SC) is employed as an auxiliary source to deal with the slow transient response of fuel cell (FC).
M. Phattanasak, W. Kaewmanee, P. Thounthong, P. Sethakul, M. Zandi, [47]	Wind (WT)	Work on a nonlinear control algorithm for a current fed DC-DC converter. Based on Flatness properties, a converter which can guarantee the responses during either start up or steady state is build, this converter consists of an inductor, a controllable full bridge converter, which is connected to a full bridge rectifier via a high frequency transformer.	The advantages of this flatness based converter include: galvanic isolation, low input current ripple and high voltage gain.
M. Treuer, T. Weissbach, M. Kurth, V. Hagenmeyer, [48]	Hydro	Presented a flatness based "two-degree-of-freedom control concept". In the principle, a smooth trajectory for set point changes of the generator output are provided, that takes into account the dynamics of the plant.	Applying the flatness base control technique, The trajectory planning for the plant is thereby addressed, therefore, result in limiting the gradients of set point changes of the power output.
M.H. Variani, K. Tomsovic, [49]	Wind (WT)	Investigate on the high penetration of distributed generation and alternative energy units in wind generation, the reference phase is tracks by the local control, which is obtained through economic dispatch at the global control level. As a result of applying the flatness based method, the "n" machine system is decoupled into "n" linear controllable systems in canonical form.	Flatness based control strategy result in a distributed automatic generation control (AGC) formulation which is absolutely easier to design, implement and demonstrates promising performance in mitigating frequency deviations as opposed to conventional AGC.
O. Kraa, R. Saadi, M. Becherif, M.Y. Ayad, [50]	Fuel cell (FC) and Supercapacitor (SC)	Uses the flatness and sliding mode control strategy of fuel cell and supercapacitors hybrid source, flatness is used to decouple the system into two sources so that each sub-system has a separate control target expressed in terms of a sliding surface. Secondly; The sliding mode controller is used to ensure instantaneously the power sharing between the direct current (DC) bus converters, it ensures that the SC and FC currents track well with their references that are calculated from the SC and FC powers.	The proposed flatness sliding control combination manage successfully the hybrid system energy with a stable and robust performance.
P. Song, Y. Li, L. Wang, C. Duan, [51]	Solar (PV)	Presented a controller for the modular multilevel converter. The generation of reference trajectories of state variables are planned in space according to the desired system output, and the implementation of the controller to generate the desired feed-forward input controller variable, according to system input equations.	The result point at eliminate the impacts of uncertainty of the converter model and factors as internal and external disturbances, the error feedback compensation is used to calibrate system flatness output and to track the reference trajectories rapidly.

P. Thounthong, [52]	Fuel cell (FC)	Presented a high gain boost converter (three level converter and transformer less converter) for fuel cell (FC) vehicle applications, a prototype FC power converter (1.2 kW three level boost converter) is developed in the laboratory.	With the use of flatness, the design controller parameters are straightforward and autonomous at the operating point.
P. Thounthong, A. Luksanasakul, P. Koseeyaporn, B. Davat, [53]	Fuel cell (FC) and Solar (PV)	Presented a control system of an energy hybrid power plant, fed by fuel cell (FC) and photovoltaic (PV) sources with a supercapacitor (SC) storage device and suitable for distributed generation applications, The PV is used as the primary source and the FC acts as a backup, feeding the deficient power (steady state) from the PV; and the SC functions as an auxiliary source and a short-term storage system for supplying the deficiency power (transient and steady state) from the PV and the FC, four phase parallel converters are implemented for the FC converter, PV converter, and SC converter, respectively.	By adopting the principle of flatness based, A simple solution is obtained for the fast response and stabilization problems in the power system, and validate excellent control algorithms during load cycles.
P. Thounthong, S. Pierfederici, B. Davat, [54]	Fuel cell (FC)	Adapted Flatness base technique to control a group of converter supplied by a fuel cell (FC) (main-source) and supercapacitor (auxiliary-source). The design controller parameters are independent of the operating point; moreover, communications between converters are taken into account by the controllers, and very high dynamics in disturbance rejection are achieved.	The flatness based method leads to the interactions among the controls of the converters in case they are designed separately.
R. Saadi, M. Benaouadj, O. Kraa, M. Becherif, M. Y. Ayad, A. Aboubou, M. Bahri, A. Haddi, [55]	Fuel cell (FC) and Supercapacitors (SC)	Presents a flatness based control algorithm for a direct current (DC) hybrid power sources used in electric vehicle (EV). The control procedure is based on the flatness properties of the system, fuel cell (FC) is considered as the main source, and supercapacitors (SC) pack considered as the auxiliary source. A correct planning of the trajectory of flat output, permit the control of the vehicle.	The benefit of this flatness based control procedure is that the state variable and control input are categorically estimated by the trajectories of the flat output derived from these outputs without the need to integrate any differential equation.
T. Rabbani, S. Munier, D. Dorchies, P.O. Malaterre, A. Bayen, X. Litrico. [56]	Hydro	Applied a flatness based controller to an open channel hydraulic canal. In this principle, an open loop controller is thus able to compute the upstream water discharge corresponding to a desired downstream water discharge.	Based on flatness principle, The result project that, the gravitational withdrawals along the canal reach, decreases the steady state error to 1% (gravitational lateral withdrawals assumption) as opposed to 6.2% (constant lateral withdrawals assumption).

Table 1 above has presented an overview of flatness based control that has been used to minimize the negative impacts experienced when applied to renewable energy sources, it further elaborates and comments on key results.

After analyzing this table, it can be concluded that any control system arrangement selected should be used to keep the generated energy output stable and steady with the aim of increasing the generating efficiency. The use of differential flatness is advantageous especially in nonlinear systems where the reduction of the number of variables to the outputs and the inherited reduction of parameters and equality constraints simplifies the calculations and establishes a robust control system. Because of this, they represent an interesting alternative to other control based methods, which involves the solution of complex differential equations.

III. Principle of Flatness Based Control.

The idea of differential flatness was first introduced in the early 90's [23]. This bring an alternate representation of the system where trajectory planning and nonlinear controller design is straightforward. This control theory is an interdisciplinary branch of engineering and mathematics that deals with the behaviour of dynamic system and how they can be modified by the use of a feedback signal. The usual objective of control theory is to control a system, often called the plant, so its output follows a desired control signal. Called the reference, which may be a fixed or changing value [15]. To achieve this, a controller is designed as in Figure 1 below.

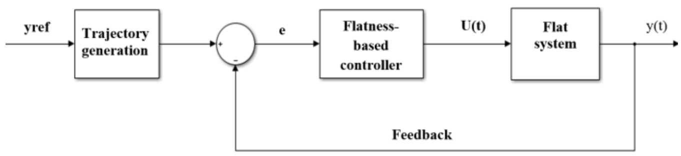

Figure 1: Flatness based control system.

Where:

- yref is the reference signal,
- e is the error signal,
- U(t) is the system input,
- y(t) is the system output.

To begin with, according to this principle, a system should initially be proved to be flat by selecting an appropriate flat output. Then, the reference trajectory should be planned on the chosen output so that the maximum power may be extracted from the source. The main advantage of this control method is the ability of solving a complex nonlinear system such as those of renewable energy in the transient state as well as the steady state which allows an optimal design of the system components [24, 54]. In addition, the proposed control strategy can improve performance of the system in the transient state as opposed to the traditional control approaches [57]. It should be noted that this control technique has been proposed to manage the energy in an electrical hybrid system [58], in systems of reactive energy compensation [59]. Also, it has been proposed to control a permanent magnet synchronous motor [37, 60] and to control induction motors [61].

Consider a general nonlinear system of the form:

$$x' = f(x) + g(x)u \quad (1)$$

$x = [x_1, x_2, \ldots x_n]T \;\; x \in \mathbb{R}^n$ (2)
$u = [u_1, u_2, \ldots u_m]T \;\; u \in \mathbb{R}^m$ (3)
If the state variable x can be parameterized by flat output y and its derivatives, the system is said to be differentially flat and admits the flat output $y = [y_1, y_2, \ldots, y_m]T$ [23, 24]. Then, the state variables and control variables can be written as follows:

$$x = \varphi_1\left(y,\; y',\ldots,\; y^{\beta}\right) \quad (4)$$

$$u = \varphi_2\left(y,\; y',\; \ldots, y^{(\beta+1)}\right) \quad (5)$$

With β being finite integer.
The set of equations (4) and (5) is denoted as differential parameterization of the system variables and is used in the controller design, by this process, a nonlinear flat system can be equivalent to a linear controllable system as described in reference [23, 24].

IV. Discussion of Publications

After investigating the various technologies, adopting the principle of flatness based control above, it is recorded that the control of power generation in renewable energy sources is focused on voltage / frequency regulation and stability improvement, and this can be further explained based on different technologies adopting the flatness based principle:

- The concept of adapting differential flatness based control in a fuel cell (FC) systems, is being applied more with significant advantages such as: flatness helps to improve the lifetime performance of fuel optimization, therefore; improving the fuel economy and good tracking performance of the clutch position as opposed to a linear time-varying MPC (LTV-MPC) [53]; flatness property has been used to decrease the steady-state error of a three level boost converter for vehicle application [52]; by adopting flatness based property better interactions are achieved between controls of the converters if they are designed separately, with a stable and robust performance, while limiting the converter losses [33, 54]; flatness has also been applied in a double dual boost converter to increase the voltage gain [45], and finally flatness property can be use to avoid overcharging or discharging of a supercapacitor-bank (SCB) applied to a multi-source / multi-load electrical hybrid system [26].
- The application of differential flatness principle in Solar (PV) power generating systems is prominent in renewable energy with credible advantages such as: A possibility of maintenance during operation is made possible without interrupting supply in a case in which flatness based control architecture is applied to parallel voltage source inverter topology [27]. Due to the flatness feed-forward enhancement performance, it is possible to achieve faster dynamic response, compared to conventional dead-beat control [29]. Flatness property can also be used to obtain maximum power point tracking (MPPT) control, when managing the power flow in a multi-renewable energy sources [36, 38]. In addition, there is an increase in lifetime performance when the flatness principle is applied to manage energy flows in two hybrid storage unit [49-50], and finally the application of the flatness property reduces the drive power requirement and associated PV cost.
- Flatness based control principle in a wind power generating system is also an area of interest with numerous advantages such as: when designing a flatness based converter, flatness reduces the number of sensors due to its property and has the possibility to control the system even during the transient state, like the conventional converter [40]. When applying flatness based control in megawatt wind turbines, with the aim of reducing fatigue and extreme loading, it improves the fault-tolerance and dynamic response capability, as well as its cost effectiveness [31, 35]. The flatness principle has provided robustness in changing operational conditions in a wind power generating system [34], and finally, applying flatness in wind (WT) systems can lead to better galvanic isolation, high voltage gain, low input current ripple and effective supply [47].
- The use of the flatness-based control system in a hydro power generating system is the least covered technology with definite advantages such as: flatness limits the mathematical model of the process; therefore, complex identification procedures are bypassed [28]. When comparing the flatness based control principle to the traditional Proportional integral (PI) control principle applied to hydro generating systems, the advantages of using flatness are as follows: lower overshoot, sensitive to process variations, limited gradients of set point changes and decreased steady-state error [32, 48].

V. Recommendation and Conclusions

This review paper has given an overview of different control methods applied in the field of renewable energy power generation. By using the differential flatness-based control method, the nonlinear dynamic system is made equivalent to a linear system, and the trajectories of all system variables can be directly and easily controlled be controlling the flat output and its derivatives, without solving differential equations.
The renewable energy power system considered in this study comprises of different power sources, including fuel cell (FC), solar (PV), wind (WT) generators and hydro power. Moreover, these resources have different characteristics in terms of tterms of their output power stabilization subject to the operational strategies. Flatness based design is adaptable to various control schemes and will not be affected by system operational conditions. Flatness is such a general property and the two fields that are in the centre of flatness based control are trajectory generation and trajectory tracking. The flatness based control techniques can consistently achieve a fast and dynamic performance. A review of work done regarding the differential flatness techniques for renewable energy systems in recent years, indicates a promising potential of such research characteristics in future.

VI. References.

[1] K. Kusakana, "Minimum cost solution of isolated battery-integrated diesel generator hybrid systems," *in SAUPEC*, Joohannesburg, 2015.

[2] K. Kusakana, "Optimisation of battery-integrated diesel generator hybrid systems using an ON/OFF operating strategy," *in Domestic Use of Energy (DUE)*, South Africa, 2015.

[3] K. Kusakana and H. Vermaak, "Cost and Performance Evaluation of Hydrokinetic-diesel Hybrid Systems", *Energy Procedia*, vol. 61, pp. 2439-2442, 2014.

[4] A. H. Glattfelder, L. Huser, P. Dörfler and J. Steinbach, Automatic Control for Hydroelectric Power, Switzerland: VA Tech Escher Wyss AG, 2003.

[5] B. Singh, S. Murthy and S. Gupta, "Analysis and implementation of an electronic load controller for a self-excited induction generator", *IEE Proceedings - Generation, Transmission and Distribution*, vol. 151, no. 1, p. 51, 2004.

[6] Z. Qi, Y. Liu, H. Liu and Z. Hao, "Power Control for Off-grid Wind Power System Based on Fuzzy PID Controller," in *Power and Energy Engineering Conference (APPEEC)*, Asia-Pacific, 2010.

[7] J. R. Massing, F. d. M. Carnielutti, V. F. Montagner, H. Pinheiro and L. A. Maccari, "A robust PI current controller for grid-connected renewable energy systems," in *Energy Conference (ENERGYCON)*, Belgium, 2016.

[8] F. Singh, S. Singh,"Stabilization of voltage in Wind Energy Conversion System using PWM Modulated Power Filter Compensator", Journal of renewable and sustainable energy research, Vol. 3, Issue 1, pp. 69-72, 2016.

[9] A. Merabet, M. Islam, R. Beguenane and A. Trzynadlowski, "Multivariable control algorithm for laboratory experiments in wind energy conversion", *Renewable Energy*, vol. 83, pp. 162-170, 2015.

[10] O. Yaakob, Y. M. Ahmed and M. A. Ismail, "Validation Study for Savonius Vertical Axis Marine Current Turbine Using CFD Simulation," in *Asia-Pacific Workshop on Marine Hydrodynamics (APHydro)*, Malaysia, 2012.

[11] A. Elbatran, O. Yaakob, Y. Ahmed and M. Jalal, "Novel approach of bidirectional diffuser-augmented channels system for enhancing hydrokinetic power generation in channels", *Renewable Energy*, vol. 83, pp. 809-819, 2015.

[12] H. Li, Z. Hu, K. Chandrashekhara, X. Du and R. Mishra, "Reliability-based fatigue life investigation for a medium-scale composite hydrokinetic turbine blade", *Ocean Engineering*, vol. 89, pp. 230-242, 2014.

[13] V. Nedelea, I. Dragomirescu, A. Ladislau and C. L. Ungureanu, "Ballast Load Control of Turbine-Generator Sets in the Micro-Hydro Range with a Turbine that has no Flow Regulating Value," *Analele Universităţii Eftimie Murgu Reşiţa. Fascicula de Inginerie,* vol. XVIII (2), pp. 201-208, 2011.

[14] M. Mohibullah, A. Radzi and M. Hakim, "Basic design aspects of micro hydro power plant and its potential development in Malaysia," in *Power and Energy Conference*, Malaysia, 2004.

[15] M. Fliess, J. Lévine, P. Martin and P. Rouchon, "Flatness and defect of non-linear systems: introductory theory and examples", *International Journal of Control*, vol. 61, no. 6, pp. 1327-1361, 1995.

[16] E. Markus, H. Yskander, J. Agee and A. Jimoh, "Coordination control of robot manipulators using flat outputs", *Robotics and Autonomous Systems*, vol. 83, pp. 169-176, 2016.

[17] E. Markus, J. Agee and A. Jimoh, "Flat control of industrial robotic manipulators", *Robotics and Autonomous Systems*, vol. 87, pp. 226-236, 2017.

[18] H. Thabet and M. Ayadi, "Flatness-based trajectory generation for induction machine control," in *Electrical Engineering and Software Applications (ICEESA)*, Tunisia, 2013.

[19] P. Rouchon," Necessary condition and genericity of dynamic feedback linearization", *Journal of Mathematical Systems Estimation and Control*, vol. 4, pp. 257–260, 1994.

[20] R. Rothfuss, J. Rudolph and M. Zeitz, "Flatness based control of a nonlinear chemical reactor model", *Automatica*, vol. 32, no. 10, pp. 1433-1439, 1996.

[21] R. Mahadevan and F. J. Doyle, "Nonlinear nonsquare control of a continuous bioreactor using flat outputs," in *Control Conference (ECC)*, European, 1999.

[22] M. Guay, "Linearizability of Chemical Reactors," in *Proceedings of the IFAC symposium on nonlinear control systems design*, Netherlands, 1998.

[23] M. Fliess, J. Lévine, P. Martin and F. Ollivier and. P. Rouchon, "Sur les systèmes non linéaires différentiellement plats," in *C.R. Acad. Sci.*, Paris, 1992.

[24] Y. Xu, F. Li, Z. Jin and C. Huang, "Flatness-based adaptive control (FBAC) for STATCOM," *Electric Power Systems Research,* p. 76–85, 2015.

[25] A. Gensior, T. Nguyen, J. Rudolph and H. Guldner, "Flatness-Based Loss Optimization and Control of a Doubly Fed Induction Generator System", *IEEE Transactions on Control Systems Technology*, vol. 19, no. 6, pp. 1457-1466, 2011.

[26] A. Payman, S. Pierfederici and F. Meibody-Tabar, "Energy Management in a Fuel Cell/Supercapacitor Multisource/Multiload Electrical Hybrid System", *IEEE*

Transactions on Power Electronics, vol. 24, no. 12, pp. 2681-2691, 2009.

[27] A. Shahin, S. Eskander, H. Moussa and S. Pierfederici, "A new approach based on flatness control to improve reliability of parallel connected inverters," in *IEEE Energy Conversion Congress and Exposition*, 2015.

[28] [7] C. Join, G. Robert and M. Fliess, "Model-Free Based Water Level Control for Hydroelectric Power Plants", *IFAC Proceedings Volumes*, vol. 43, no. 1, pp. 134-139, 2010.

[29] D. He and X. Cai, "A novel feed-forward control of voltage source converter high voltage DC", *Australian Journal of Electrical & Electronics Engineering*, vol. 9, no. 2, 2012.

[30] D. Schlipf and P. Cheng, "Flatness-based Feedforward Control of Wind Turbines Using Lidar", *IFAC Proceedings Volumes*, vol. 47, no. 3, pp. 5820-5825, 2014.

[31] D. Wang, C. Liu and G. Li, "An Optimal Integrated Control Scheme for Permanent Magnet Synchronous Generator-Based Wind Turbines under Asymmetrical Grid Fault Conditions", *Energies*, vol. 9, no. 4, p. 307, 2016.

[32] F. Michaud and G. Robert, "Flatness-based control of an hydro power plant," in *IEEE Mediterranean Electrotechnical Conference (MELECON)*, 2010.

[33] G. Rigatos, P. Siano, P. Wira and V. Loia, "A PEM Fuel Cells Control Approach Based on Differential Flatness Theory", *Intelligent Industrial Systems*, vol. 2, no. 2, pp. 107-117, 2016.

[34] H. Coral-Enriquez, J. Cortés-Romero and G. Ramos, "Robust Active Disturbance Rejection Control Approach to Maximize Energy Capture in Variable-Speed Wind Turbines", *Mathematical Problems in Engineering*, vol. 2013, pp. 1-12, 2013.

[35] H. Fürst1, D. Schlipf1, M. I. Latour and P. W. Cheng1, "Design and Evaluation of a Lidar-Based Feedforward Controller for the innwind.eu 10 MW Wind Turbine," in *EWEA Turbine Technology – Control and Loads*, France, 2015.

[36] H. Xue, H. Li and Y. Wang, "Nonlinear Differential Flatness Control of a Distributed," *WSEAS Transsatioms on Systems and Control,* vol. 11, no. E-ISSN: 2224-2856, pp. 53-61, 2016.

[37] H. A. Aldwaihi and E. Delaleau, "Maximum power point tracker of a wind generator based on the Flatness-based control," in *Energy Conversion Congress and Exposition (ECCE)*, 2011.

[38] I. Tegani, A. Aboubou, R. Saadi, M. Y. Ayad and M. Becherif, "Differential Flatness Using the Predictive Neural Network Control Law for Hybrid Power System," *International Journal of Renewable Energy Research-IJRER,* vol. 5, 2015.

[39] J. Agee and A. Jimoh, "Flat controller design for hardware-cost reduction in polar-axis photovoltaic systems", *Solar Energy*, vol. 86, no. 1, pp. 452-462, 2012.

[40] M. Aimene, A. Payman and B. Dakyo, "Flatness-based control of a variable-speed wind-energy system connected to the grid," in *Ecological Vehicles and Renewable Energies (EVER)*, 2014.

[41] M. Benaouadj, M. Y. Ayad, M. Becherif, A. Aboubou, M. Bahri and O. Akhrif, "Energy flow control of Wind/PV/Batteries/Supercapacitors autonomous hybrid power sources using the flatness concept," *in Systems and Control (ICSC)*, 2014.

[42] M. Benaouadj, A. Aboubou, M. Ayad and M. Becherif, "Nonlinear Flatness Control Applied to Supercapacitors Contribution in Hybrid Power Systems Using Photovoltaic Source and Batteries", *Energy Procedia*, vol. 50, pp. 333-341, 2014.

[43] P. Thounthong, S. Sikkabut, P. Mungporn, P. Sethakul, S. Pierfederici and B. Davat, "Differential flatness based-control of fuel cell/photovoltaic/wind turbine/supercapacitor hybrid power plant," *in Clean Electrical Power (ICCEP)*, 2013.

[44] M. Joševski and D. Abel, "Flatness-based Model Predictive Control for the Fuel Optimization of Hybrid Electric Vehicles", *IFAC-PapersOnLine*, vol. 48, no. 23, pp. 464-470, 2015.

[45] M. Phattanasak, W. Kaewmanee, J. Martin, S. Pierfederici and B. Davat, "Interleaved Double Dual Boost Converter for Renewable Energy System", *Advanced Materials Research*, vol. 931-932, pp. 904-909, 2014.

[46] M. Phattanasak, R. Gavagsaz-Ghoachani, J.-P. Martin, S. Pierfederici and B. Davat, "Flatness based control of an isolated three-port bidirectional DC-DC converter for a fuel cell hybrid source," in *Energy Conversion Congress and Exposition (ECCE)*, 2011.

[47] M. Phattanasak, W. Kaewmanee, P. Thounthong, P. Sethakul, M. Zandi, R. Gavagsaz-Ghoachani, J. P. Martin, S. Pierfederici and B. Davat, "Current-fed DC-DC converter with Flatness based control for renewable energy," in *Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, 2014.

[48] M. Treuer, T. Weissbach, M. Kurth and V. Hagenmeyer, "Flatness-based two-degree-of-freedom control of a pumped storage power station," in *Control Conference (ECC)*, European, 2007.

[49] M. Variani and K. Tomsovic, "Distributed Automatic Generation Control Using Flatness-Based Approach for High Penetration of Wind Generation", *IEEE Transactions on Power Systems*, vol. 28, no. 3, pp. 3002-3009, 2013.

[50] O. Kraa, R. Saadi, M. Becherif and M. Y. Ayad, “Flatness and sliding mode based controller of fuel cell and supercapacitors hybrid source,” in *Control, Engineering & Information Technology (CEIT)*, 2015.
[51] S. Pinggang, L. Yunfeng, W. Lina, J. Lang and D. Chengting, “Differential Flatness Based Design of Controller for Modular Multilevel Converter,” *Power System Technology,* vol. Vol. 37, no. 12, pp. 3475-3481 , 2013.
[52] P. Thounthong, "Control of a Three-Level Boost Converter Based on a Differential Flatness Approach for Fuel Cell Vehicle Applications", *IEEE Transactions on Vehicular Technology*, vol. 61, no. 3, pp. 1467-1472, 2012.
[53] P. Thounthong, A. Luksanasakul, P. Koseeyaporn and B. Davat, "Intelligent Model-Based Control of a Standalone Photovoltaic/Fuel Cell Power Plant With Supercapacitor Energy Storage", *IEEE Transactions on Sustainable Energy*, vol. 4, no. 1, pp. 240-249, 2013.
[54] P. Thounthong, S. Pierfederici and B. Davat, "Analysis of Differential Flatness-Based Control for a Fuel Cell Hybrid Power Source", *IEEE Transactions on Energy Conversion*, vol. 25, no. 3, pp. 909-920, 2010.
[55] R. Saadi, M. Benaouadj, O. Kraa, M. Becherif, M. Ayad, A. Aboubou, M. Bahri and A. Haddi, “Energy management of fuel cell/ supercapacitor hybrid power sources based on the flatness control,” in *Power Engineering, Energy and Electrical Drives (POWERENG)*, Istanbul, 2013.
[56] T. Rabbani, S. Munier, D. Dorchies, P. Malaterre, A. Bayen and X. Litrico, "Flatness-based control of open-channel flow in an irrigation canal using SCADA [Applications of Control]", *IEEE Control Systems Magazine*, vol. 29, no. 5, pp. 22-30, 2009.
[57] J. Dannehl and F. Fuchs, “Flatness-based voltage-oriented control of three-phase PWM rectifiers,” in *Power Electronics and Motion Control Conference*, Annu, 2008.
[58] A. Payman, S. Pierfederici, F. Meibody-Tabar and B. Davat, "An Adapted Control Strategy to Minimize DC-Bus Capacitors of a Parallel Fuel Cell/Ultracapacitor Hybrid System", *IEEE Transactions on Power Electronics*, vol. 26, no. 12, pp. 3843-3852, 2011.
[59] E. Song, A. Lynch and V. Dinavahi, "Experimental Validation of Nonlinear Control for a Voltage Source Converter", *IEEE Transactions on Control Systems Technology*, vol. 17, no. 5, pp. 1135-1144, 2009.
[60] E. Delaleau and A. Stankovic, “Flatness-based hierarchical control of the PM synchronous motor,” in *American Control Conference*, Boston, 2004.
[61] E Delaleau, J-P Louis, R Ortega, “Modeling and Control of Induction Motors,” *Int. J. Appl. Math. Comput.,* vol. 11, no. 1, pp. 105-129, 2001.