Flatness based TCSC Controller for Transient Stability Enhancement of Power System

Ch.Venkatesh T.Deepak K.Rajesh K.Krishna A.K Kamath
Electrical Engineering Department
Veermata Jijabai Technological Institute (V.J.T.I)
Matunga Mumbai-400019
Email: chanti.venky47@gmail.com

***Abstract*—This paper gives a different viewpoint of flatness which uses a coordinate change based on a Lie-Backlund approach to equivalence in developing flatness-based feedback linearization and its application to the design of model predictive control (MPC) based flexible-AC transmission systems (FACTS) controller for power system transient stability improvement. The flat output provides the framework to derive the endogenous feedback compensator, which can result in a constant linear controllable system, for a given nonlinear system. The MPC has been applied on the linear system, which is in terms of flat outputs by which it is easy to compute the control efforts required to stabilize the system in post-fault region. The proposed flatness-based TCSC controller using MPC strategy is validated using MATLAB simulation results for single-machine-infinite-bus (SMIB). The simulation results have proved the effectiveness of the proposed control strategy, even when the fault is cleared after critical clearing time.**

***Keywords*: Endogenous Feedback, FACTS, Flatness, Model Predictive Control (MPC), Transient stability.**

I. Introduction

In the competitive market environment with increasing demand and limited transmission network, the existing power transmission network is pushed to operate at its maximum permissible limit. This has led major concern to the transient stability related problems, in order to maintain system continuity and reliability. To enhance the transient stability of power system, along with fast fault clearance, proper compensation is also required in post-fault region. The inaccurate compensation may lead to adverse effect rather than improving stability, so it is necessary to find out the optimal value of compensation required, considering the system operating restrictions.

With reference to above problems, flexible AC transmission systems (FACTS) devices are playing important role in power system performance improvement.

The thyrisor controlled series compensation (TCSC) is the most preferred device over other FACTS family members for its simplicity and easy operation for improving system performance, under normal as well as abnormal conditions, such as fault. In its simplest form, during post-fault, inserting proper series capacitive reactance can help in increasing system recovery. The TCSC was used mainly for power system oscillation damping and a brief overview of different control schemes for power system enhancement using TCSC are discussed in [1]. In [2], the transient stability was improved by using fixed series capacitors, in which maximum compensation was introduced in the faulty line. However, it was unable to provide the flexible adjustment of series capacitance as per requirement and sometimes may lead to overcompensation. Jiang and Lei, used the feedback linearization technique in [3] treating the power system as affine nonlinear system and developed a nonlinear controller using globally linearized model of power system.

With reference to above background, the flatness-based feedback linearization has also received a lot of attention resulting in the earlier work reported by many researchers [4-7]. Although this technique has been applied to several nonlinear and linear mechanical systems [4-7] its application to power system related issues is not well developed .The flatness based approach uses the characterization of system dynamics to generate a suitable output. In a situation where the output does not have a physical meaning or interpretation, the linearization could be done through a measurable system component that has a relationship to it.

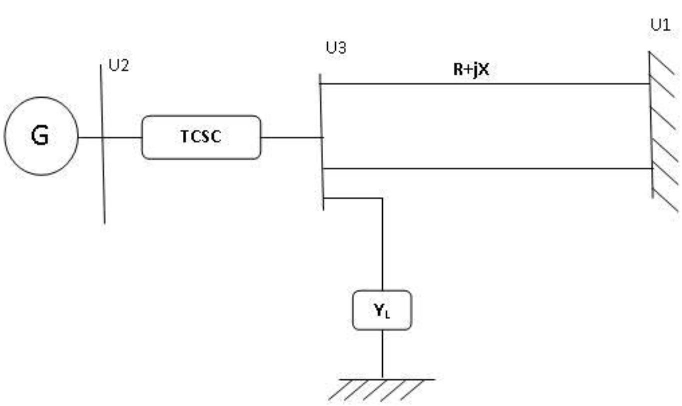
Though flatness is intimately related to feedback linearization, in this paper a different viewpoint of flatness is followed, which uses a coordinate change based on a Lie-Backlund approach to equivalence, and flatness proposed by M. Fliess. A SMIB system is considered whose rotor angle, delta, is taken as the flat output, and the states and control are represented in terms of this flat output. The flat output provides the framework to derive the endogenous feedback compensator, which can result in a constant linear controllable system, for a given nonlinear system. The endogenous feedback linearization means existence of a compensator and a diffeomorphism, which preserves dimensions even after transformation. The MPC has been applied on the linear system, which is in terms of flat outputs by which it is easy to compute the control efforts required to stabilize the system in post-fault region. This control scheme retains the global stability due to a significance of flat output and the improvement of the performance due to MPC which uses receding horizon control principle (RHC). In this paper an attempt has been made to highlight the stability issues of a nonlinear system and usefulness of MPC applications to power system related problems. The more advanced control schemes of MPC can better track changes on the set point because it has knowledge on how the set point is going to change and how the system reacts to a given change in the control variable. When working with nonlinearities and multiple inputs and outputs this offers a set of smaller, easier-to-handle control problems that PID algorithms cannot address.

A method using flatness-based feedback linearization combined with MPC based TCSC, controller has been proposed in this paper. The feedback linearization scheme requires the generation of a flat output from which the control law can be easily designed. The key contribution of paper is to propose and develop a novel strategy of flatness-based feedback linearization combined with MPC to enhance the transient stability of SMIB system using TCSC.

The proposed flatness-based TCSC controller using MPC strategy is validated using MATLAB simulation results for SMIB. The simulation results have proved the effectiveness of the proposed control strategy, even when the fault is cleared after critical clearing time. The total paper is divided into seven major sections starting from first introduction. The second section discusses about the nonlinear model of SMIB, while section III emphasize on flatness-based control strategy. Section IV gives brief overview of RHC scheme while section V develops a flatness-based RHC scheme for application to power system. Section VI gives MATLAB simulation results and some observations and section VII concludes the paper with future scope of work.

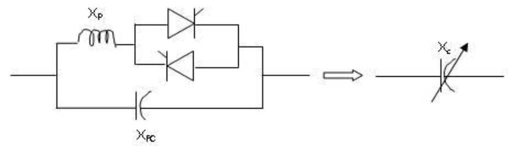
II. NONLINEAR MODEL OF SMIB

This section presents a nonlinear model of SMIB system affine in control where the control input used is the firing angle of TCSC controller. As shown in figure 1, a SMIB system is considered where TCSC is inserted in series with the transmission line to control the line flows.



Fig(1): SMIB with TCSC.

Insertion of series reactance in line as figure 1 above will give flexibility to control transmission line reactance, to improve stability. The configuration of TCSC is as shown in figure 2, consists of a fixed capacitor in parallel with a thyristor controlled reactor. Controlling the firing angle of thyristor can regulate the TCSC reactance and its degree of compensation.



Fig(2): Simplified TCSC model as variable reactance.

TCSC can be operated in inductive as well as capacitive mode as per the system requirements. However as the major concerned of present study is improving transient stability, it is considered to operate only in capacitive mode. The overall reactance X_c of the TCSC is given in terms of the firing angle as

$$X_{tcsc}(\alpha) = X_c - \frac{{X_c}^2\left(\alpha + \sin(\alpha)\right)}{(X_c - X_l)\,\pi} + 4\,\frac{{X_c}^2\left(\cos(1/2\,\alpha)\right)^2\left(k\tan(1/2\,\alpha) - \tan(1/2\,\alpha)\right)}{\left(X_c k^2 - X_c - Xlk^2 + X_l\right)\pi} \quad (1)$$

Consider the second order model of SMIB system as given in [8]

$$\begin{aligned} \dot{x_1} &= x_2 \\ \dot{x_2} &= \frac{P_m}{M} - \frac{|E||V|sin(x_1)}{M(X + X_{tcsc}(\alpha))} \end{aligned} \quad (2)$$

Where $x_1 = \delta, x_2 = \triangle\omega$, E is generator terminal voltage, V is infinite bus voltage, P_m is the mechanical input power, M is the inertia constant of the machine, X is the transmission line reactance, X_{tcsc} is the reactance of TCSC and α is the firing angle of the TCSC controller. System (2) is of the form

$$\dot{x} = f(x, \lambda) \quad (3)$$

where $\lambda = 1/(X + X_{tcsc}(\alpha))$ is the parameter which varies when a fault occurs which results in change in transmission line reactance. Due to change in transmission line reactance, transients are introduced in the system which die down either by using damping control or by FACTS controllers or both. Notice that (2) does not consider a damping control. Here, TCSC reactance is used to stabilise the system which is affine in control of the form can be obtained as.

From (2) and (3),

$$\dot{x} = \tilde{f}(x) + \tilde{g}(x)\omega(\alpha) \quad (4)$$

where $\omega(\alpha)$ is λ

$\tilde{f}(x) = \begin{bmatrix} x_2 \\ \frac{P_m}{M} \end{bmatrix}$ and $\tilde{g}(x) = \begin{bmatrix} 0 \\ -\frac{|E||V|sin(x_1)}{M} \end{bmatrix}$

Taylor series expansion of $\omega(\alpha)$ w.r.t α is expressed as follows

$$\omega(\alpha) = \omega(\alpha_0) + \frac{\partial\omega(\alpha)}{\partial\alpha}|_{\alpha=\alpha_0}\triangle\alpha \quad (5)$$

Notice here that the higher order terms have been neglected. This leads to an affine in the control form representation of the system. Truncating the series after the first order term may not be permissible in case of feedback control when the variations in the firing angle are large around the nominal value. But for an open loop scheme,which is considered here, neglecting the higher order terms may be viewed as a sort of penalty on the control function and hence does not interfere with the structure of the control problem.

Using (4) and (5) we get

$$\dot{x} = F(x) + G(x)u \tag{6}$$

where $u = \triangle\alpha$,

$$F(x) = \tilde{f}(x) + \tilde{g}(x)\omega(\alpha_0) \tag{7}$$

$$G(x) = \tilde{g}(x)\frac{\partial\omega(\alpha)}{\partial\alpha}|_{\alpha=\alpha_0} \tag{8}$$

Thus, a nonlinear model of SMIB which is affine in control is achieved. The control input is the change in firing angle which is expressed as $\triangle\alpha = \alpha - \alpha_0$. Using RHC control strategy we design a control 'u' such that the system (6) is stabilised at the set point.

III. FLATNESS-BASED CONTROL STRATEGY

A. Flatness basics

Flatness was first defined by Fliess et al. [4, 9] using the formalism of differential algebra. In differential algebra, a system is viewed as a differential field generated by a set of variables (states and inputs). A model is described by a differential system. $\dot{x} = f_i(x,u)$ i=1,2,3.....n

x_i denote the state variables and $u = (u_1,\ldots,u_m)$ the control vector. The system is said to be flat if one can find a set of variables, called the flat outputs, such that the system is (non-differentially) algebraic over the differential field generated by the set of flat outputs. Roughly speaking, a system is flat if we can find a set of outputs (equal in number to the number of inputs) such that all states and inputs can be determined from these outputs without integration.

The unique feature of allowing a parameterization of all system variables makes of flatness a tool for analysis revealing the nature of each system variable in its isolated relation with a centrally important set of variables from viewpoint of controllability and observability. The invertible parameterization, involved in the flat outputs definition, thus creates a local bijection between system state solutions and arbitrary trajectories in the flat output space. There is no uniqueness of the flat output even if there is usually a favorite flat output expressing physical properties. The concept of flatness can be seen as a nonlinear generalization of the Kalman's controllability and of the Brunovsky decomposition. Hence, every linear controllable system is flat.

More recently, flatness has been defined in a more geometric context, where tools for nonlinear control are more commonly available. There are two different geometric frameworks for studying flatness and provide constructive methods for deciding the flatness of certain classes of nonlinear systems and for finding these flat outputs if they exist. One approach is to use exterior differential systems and regard a nonlinear control system as an affine system on an appropriate space [10]. In this context, flatness can be described in terms of the notion of absolute equivalence defined by E. Cartan [11]. Another geometric approach to study flatness is by using "Jet Bundles". In this paper a somewhat different geometric point of view is adopted, relying on a Lie-Backlund framework as the underlying mathematical structure. It offers a compact framework in which to describe basic results and is also closely related to the basic techniques that are used to compute the functions that are required to characterize the solutions of flat systems (the so-called flat outputs). In jet bundle approach a mapping from an infinite dimensional manifold whose coordinates are not only made up of original variables but also of jets of infinite order is dealt.

Fliess and coworkers have introduced the notion of an endogenous feedback which is essentially a dynamic feedback and they have shown that feedback linearisability via endogenous feedback is equivalent to differential flatness.

B. Endogenous Dynamic Feedback

Let us consider the system(X,f)whose representation in finite dimension is $\dot{x} = f_i(x,u)$. A dynamic feedback is the data of a differential equation $\dot{z} = \beta(x,z,v)$ and a feedback $u = \alpha(x,z,v)$. The closed loop system is thus

$$\dot{x} = f(x,\alpha(x,z,v)) \tag{9}$$

$$\dot{z} = \beta(x,z,v) \tag{10}$$

Such a dynamic feedback may have unexpected properties such as the uncontrollability of the closed-loop system or its non invertibility, i.e it is not possible to recover the original system by applying another dynamic feedback.

IV. BRIEF REVIEW OF RECEDING HORIZON SCHEME

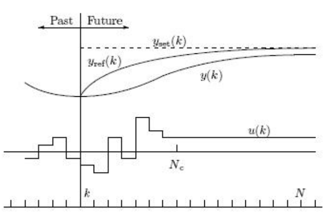
A. Introduction

Model predictive control is a control strategy developed around certain common key principles. First is explicit on-line use of a system model to predict the system output at future time instants. Secondly calculation of an optimal control action based on the minimization of one or more cost functions with or without constraints. The various MPC algorithms differ mainly in the type of model used to represent the system and its disturbances, as well as the cost functions to be minimized, with or without constraints.

An important difference between MPC and PID kind design method is the explicit use of a model. MPC can provide high performance when models are accurate. Moreover, MPC is one of the very few strategies, which guarantee the accomplishment of constraint specifications

B. Basic operation

In general, the MPC problem is formulated as solving on-line a finite horizon open-loop optimal control problem subject to system dynamics and constraints involving states and controls. Figure 3 shows the basic principle of MPC. Based on measurements obtained at time t, the controller predicts the future dynamic behavior of the system over a prediction horizon N and determines (over a control horizon $Nc \leq N$) the input such that a predetermined open-loop performance objective function is optimized. If there were no disturbances and no model-plant mismatch, and if the optimization problem could be solved for infinite horizons, then one could apply the input function found at time $t = 0$ to the system for all times $t > 0$. However, this is not possible in general. Due to disturbances and model-plant mismatch, the true system behavior is different from the predicted behavior. In order to incorporate some feedback mechanism, the open-loop manipulated input function obtained will be implemented only until the next measurement becomes available. The time difference between the recalculation/measurements can vary, however often it is assumed to be fixed, i.e the measurement will take place every δ sampling time-units. Using the new measurement at time Δt, the whole procedure prediction and optimization is repeated to find a new input function with the control and prediction horizons moving forward.



Fig(3):Principle of model predictive control

The finite horizon open-loop optimal control problem described above is mathematically formulated as follows:

$$min \sum_{j=0}^{N-1} [x_{k+j}^T Q x_{k+j} + u_{k+j}^T R u_{k+j}] \quad (11)$$

where x_{k+j}= predicted state Q,R=weighting matrices, u=control vector. The above optimization problem is solved to obtain a set of control laws, out of which only the current best control action is implemented as per RHC principle.

V. FLATNESS BASED RECEDING HORIZON SCHEME

Flatness is undoubtedly related to the general problem of system equivalence. As a consequence, flatness is intimately related to feedback linearization. In this paper we propose a methodology based on Lie-Backlund approach to equivalence of systems.In this setting, two systems are said to be equivalent if any variable of one system may be expressed as a function of the variables of the other system and their finite number of time derivatives. Two such systems are then said to be isomorphic in the Lie-Backlund sense. Using this notion of Lie-Backlund isomorphism we show that the SMIB dynamics correspond to a trivial system by Endogenous feedback. Here in the above system (2) $x_1 = \delta$ is taken as the flat output and the states and control are represented in terms of flat outputs

$$\dot{\delta}_1 = \delta_2 \quad (12)$$

$$\dot{\delta}_2 = \frac{P_m}{M} - \frac{|E||V|sin(x_1)}{M(X + X_{tcsc}(\alpha))} = V \quad (13)$$

Given system has been linearized using endogenous Feedback which means the existence of compensator of the form $\dot{z} = \beta(x,z,v)$ $u = \alpha(x,z,v)$ a diffeomorphism that yields a dynamics given by

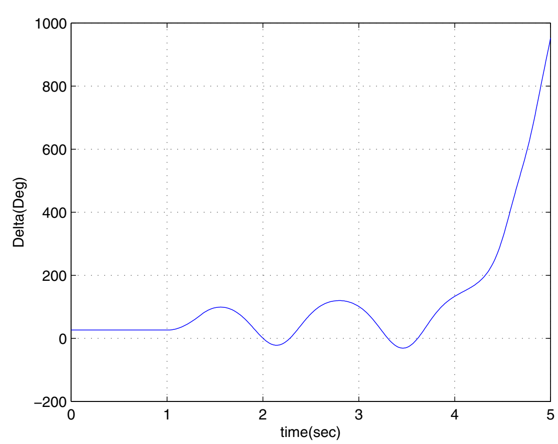
$$\dot{x} = f(x, \alpha(x,z,v)) \quad (14)$$

$$\dot{z} = \beta(x,z,v) \quad (15)$$

This results in a constant linear controllable system and the MPC has been applied on the linear system which is in terms of flat outputs by which it is easy to compute the control effort required to stabilize the system after fault has occurred. These control schemes retain the global stability due to a significance of flat output and the improvement of the performance due to a receding horizon scheme. Thanks to the flatness property of the system that this is just an output tracker for the flat output $y = \delta$, since the state and input can be expressed in the coordinates $(\delta, \dot{\delta}, \ddot{\delta})$. This Control scheme is faster as it uses unconstrained optimization for driving optimal reactance for stabilizing the system. For system represented in (6), MATLAB simulation has been carried out and the results have been represented here.

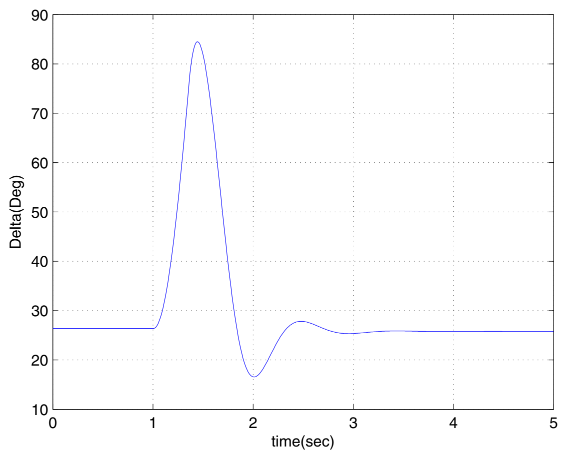
VI. SIMULATION RESULTS

The given SMIB is first simulated for fault clearing time greater than critical clearing time. The fault was cleared at 350ms, and it is observed in rotor angle variation with time, that system is unstable for this fault clearing time as shown in Fig. 4.



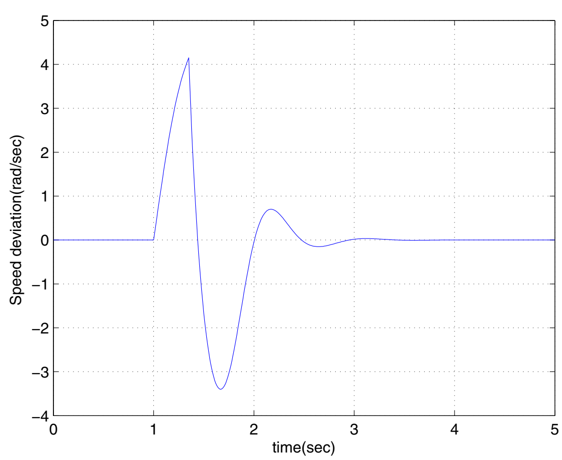
Fig(4):Variation of rotor angle with time without controller

Keeping the fault clearing time same, when the flatness-based controller was applied with RHC strategy, it can be seen from fig 5, that system recovers its stability. The performance of controller as seen in the plot figure can be further improved or modified as per requirements with the help of MPC tuning parameters i.e. Q and R in (9). The weight matrix Q expresses the importance of the close tracking of the reference for various states, while the weight matrix R can be used to define the preferred control. In short, the overall controller performance such as aggressiveness, accuracy etc is tuned by the weighting coefficients Q and R.



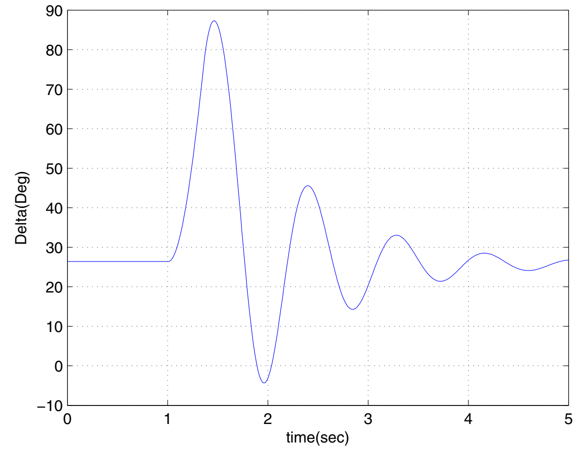
Fig(5):Variation of rotor angle with flatness+RHC based TCSC controller for Q=0.1 and R=1

Fig. 6 shows the speed deviation of SMIB with time, confirming that the system will remain in synchronism by introducing proper compensation derived by flatness+RHC-based controller, even if the fault is cleared after critical clearing time.

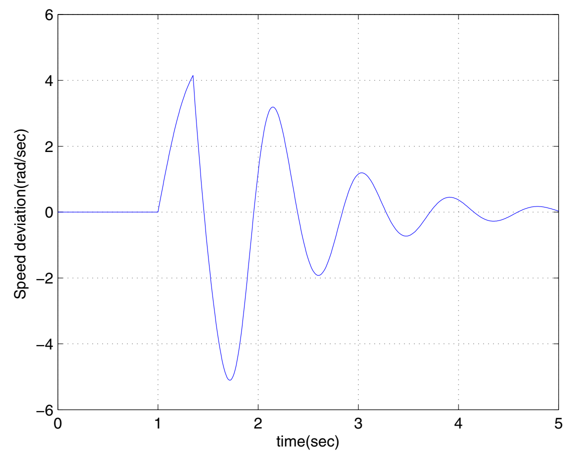


Fig(6): Plot of speed deviation with time using flatness+RHC based TCSC controller for Q=0.1 and R=1

The magnitude of elements value of Q and R does not matter as discussed in [14], but their mutual ratios/ relations does matter in deciding controller performance.



Fig(7): Variation of rotor angle with flatness+RHC based



Fig(8): Plot of speed deviation with time using flatness+RHC based TCSC controller for Q=1 and R=1

VII. Conclusion

The paper has developed a novel scheme of TCSC controller using the flatness+RHC scheme. It is observed that the controller is very effective and ensures guaranteed stability. The paper has given a different view point of flatness and have developed a flatness-based feedback linearization and shown its application in designing of TCSC controller using RHC principle. The major contribution of paper is in terms of application of flatness concept and RHC principle for power system transient stability problem. The future work is proposed to extend this idea of flatness+RHC scheme for multi-machine transient stability problem considering its detail dynamic model of the system. It is also planned to coordinate various FACTS devices for multi-machine system and develop effective controller based on scheme developed in this paper.

VIII. Acknowledgements

The authors would like to acknowledge N.M Singh and Sushama Wagh for their discussion and constructive suggestions in improving quality of paper.

IX. APPENDIX

A. Single-machine-infinite-bus system data Based on [13], the generator and network data for single-machine-infinite-bus system shown in Fig.1 is as given below.

$H = 5.0MJ/MVA$

$X'_d = 0.3pu$

$f = 60Hz$

$P_e = 0.8pu$

$Q = 0.074pu$

$V = 1.0pu$

$X_t = 0.2pu$

$X_{L1} = X_{L2} = 0.3pu$

REFERENCES

[1] X. Zhou and J. Liang,"Overview of control schemes for TCSC to enhance the stability of power systems," Generation, Transmission and Distribution, IEE Proceedings-, vol. 146, pp. 125-130, 1999.

[2] E. W. Kimbark, "Improvement of System Stability by Switched Series Capacitors," Power Apparatus and Systems, IEEE Transactions on, vol. PAS-85, pp. 180-188, 1966.

[3] D. Jiang and X. Lei, "A nonlinear TCSC control strategy for power system stability enhancement," in Advances in Power System Control, Operation and Management, 2000. APSCOM-00. 2000 International Conference on, 2000, pp. 576-581 vol.2.

[4] M. Fliess, J. Levine, 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. [Online]

[5] Levine, J. and Nguyen, D. V., " Flat output characterization for linear systems using polynomial matrices," Systems Control Letters 48 , (2003) pp. 69-75.

[6] M. Fliess,J. Levine,P. Martin,P. Rouchon,"A Lie-Backlund approach to equivalent and flatness of nonlinear systems". *IEEE Transactions on Automatic control*, 38:700-716,1999.

[7] L. Kirschner, D. Retzmann, and G. Thumm, "Benefits of FACTS for power system enhancement", 2005 IEEE/PES Transmission and Distribution conference and exhibition: Asia and Pasific Dalian, China.

[8] S. R. Wagh, et al., "A nonlinear TCSC controller based on control Lyapunov function and receding horizon strategy for power system transient stability improvement," in Control and Automation, 2009. ICCA 2009. IEEE International Conference on, 2009, pp. 813-818.

[9] Ph. Martin,R.M. Murray, P. Rouchon "Flat Systems" Mini-Course ECC'97.

[10] M. van Nieuwstadt, M. Rathinam, and R.M. Murray. "Differential flatness and absolute equivalence". In Proc. of the 33rd *IEEE Conference on Decision and Control*, pages 326-332, Lake Buena Vista, 1994.

[11] W.M. Sluis. *Absolute Equivalence and its Application to Control Theory*. Ph.D.thesis, University of Waterloo, Ontario, 1992.

[12] J.Levine, "Analysis and control of non linear systems"-A Flatness based approach springer 2009.

[13] S.Hadi, "Power System Analysis", Tata McGraw-Hill Publishing Company Limited 2002.

[14] S. K. Bhil, et al., "Transient stability enhancement of power system using MPC based TCSC controller," in Power and Energy Society General Meeting, 2009. PES '09. IEEE, 2009, pp. 1-7.