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Transient Stability Analysis of a Multimachine Power System with TCSC Controller – A Zero Dynamic Design Approach

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ABSTRACT

In this paper a novel non-linear control scheme for Thyristor Controlled Series Capacitors (TCSCs) has been presented to analyze transient stability of a multimachine power system. The non-linear control strategy of the TCSC controller has been formulated by the Zero dynamic design approach. A WSCC type 3-machine 9-bus system has been considered for test system where two numbers of TCSC controllers are placed near the highest load bus in the network. The dynamic stability of the system has been achieved by investigating the stability of the internal states as well as the external states of the system. The stability of the internal states has been ensured by the Lyapunov stability theorem and the external states has been stabilized applying non-linear control law formulated by the zero dynamic design approach. The performance of the non-linear TCSC controller has been compared with its conventional design based on approximate linearization method. The effect of various operating points of non-linear TCSC controller has also been investigated for different loading conditions. The applicability of the above nonlinear control scheme is further demonstrated for a large power system comprising 14-areas, 24-machines and 203-buses. The simulation results for all the cases have been presented through time domain simulation of the proposed test systems with application of typical contingency and different loading conditions. It has been observed that the non-linear control scheme for the TCSC controller is more effective compared to its conventional design as well as its performance is quite satisfactory for different loading conditions in mitigating transient stability of a multimachine power system.

1. Introduction

The demand of electricity is increasing rapidly all over the world with urbanization of the society. To meet this enormous requirement of electricity, power systems are continuously upgrading as well as becoming more and more complex. In a complex system various types of problem may arise during its operation. Among them power system stability is one of the major concern. A power system may undergo transient instability when it is being subjected to a sudden and large contingency. Again low frequency oscillations (0.2–3.0 Hz) [1] in a power system may occur due to various disturbances such as variations in load, generation and faults in transmission lines. This problem has been addressed recently in [2]. Here small signal angular stability has been investigated for large scale wind firm power system. These oscillations not only deteriorate the stability of the power system but also may cause mechanical failure if not well damped or removed [3]. Therefore, the problem of power system stability has been a challenging issue for power system engineers and researcher since long. Power systems are highly enriched with complex and nonlinear dynamics. It can have multiple operation points. The nonlinearity becomes prominent at contingency. The conventional controllers are unsuitable in this situation. They are good in single operating point. In this paper authors attempt to design nonlinear controller to overcome the problem of conventional controllers.

Several research works have been carried out by the power system engineers since long. Flexible AC Transmission Systems (FACTS) are successfully employed nowadays to mitigate the power system stability problem. In [4,5] the design of Static Var Compensators (SVCs) using *differential geometric theory* and *direct feedback linearization theory* are presented respectively to improve transient stability of the power system. Static Synchronous Compensator (STATCOM) is also used in literatures to increase the stability of the power system [6,7]. A scheme of STATCOM controller with linearized Phillip-Heffron model is also reported in [8] to analyze and stabilize power system oscillation. Thyristor Controlled Series Capacitors (TCSCs), another important FACTS device, are found to be very effective and employed significantly nowadays by the power industry to improve transient stability and

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other power system problems [9]. In [10] the design of robust TCSC controller has been presented to mitigate transient stability of a multimachine power system. A heuristic optimization method based on Particle Swarm Optimization (PSO) has been applied here to optimize the parameters of the controller. This work has been modified in [11] by designing the coordinated Power System Stabilizer (PSS) and TCSC damping controller for the improvement of transient stability of multimachine power system where the PSO has also been utilized for parameter optimization of the controllers. Another heuristic algorithm, Chaotic Optimization Algorithm (COA) is employed in [12] to tune the parameters of a TCSC damping controller. In [13] the design of a robust nonlinear power system stabilizer has been shown to improve the transient stability of micro-grids (MGs) system. In this work the controller has been designed based on Parametric-Lyapunov Theorem. In [14] a method of design of nonlinear TCSC controller has been described and presented the effectiveness of that controller by comparing its performance with the performance of conventional TCSC controller. A design of optimal TCSC controller based on Linear Quadratic Regulator (LQR) and its stability analysis using Control Lyapunov Function (CLF) has been presented respectively in [15]. A design of nonlinear TCSC controller and its comparison with PSO based conventional controller has been presented in [16]. The design of an adaptive nonlinear TCSC controller has been reported in [17] for large disturbance attenuation where the parameter updating law for the controller has been formulated by using the back stepping method. A complete decentralized adaptive excitation control scheme has been presented in [18] to study the transient stability of large scale power systems. A Voltage Source Converter (VSC) excitation system based on PWM technique has been employed in [19]. Here, it has been shown that VSC based excitation system is an improved alternative method compared to the conventional thyristor based excitation system for enhancement of power system stability problem. The performance of General Unified Power Flow Controller (GUPFC) on small signal stability problem has been investigated in [20] where Power Sensitivity Model (PSM) has been used to represent the power system. A nonlinear control strategy based on Lyapunov direct method has been reported in [21] where static synchronous compensator (SSSC) is used to mitigate transient stability of a multimachine power system.

The coordinated design of power system stabilizer with FACTS controller has also been reported by several researchers. A coordinated design of STATCOM and excitation control based on zero dynamics design approach and pole assignment technique has been presented in [22]. In [23] the zero dynamic design approach has also been described for the design of STATCOM and excitation controllers coordinately to improve transient stability of the multimachine power system. In [24] a scheme of robust nonlinear control theory has been employed for coordinated controller design. Here two controllers *i.e.*, a generator excitation controller and an SVC controller are installed together to mitigate transient stability. A coordinated control comprising Unified Power Flow Controller (UPFC) and Power system Stabilizer (PSS) has been investigated further in [25] to damp down oscillations due to small signal disturbance. A method of nonlinear control scheme, the Bang-Bang Excitation Controller (BEC) has been presented in [26] to enhance the transient stability of multimachine power system where a coordinated control scheme is utilized between bang-bang excitation control and conventional control. A novel control strategy has been adopted in [27] where Teaching-Learning Algorithm (TLA) has been employed to solve the coordinated design problem of PSS and TCSC.

This paper presents a novel design method of non-linear TCSC controller. The method of zero dynamic design has been employed to execute the non-linear control law for the TCSC controller. The advantage of zero dynamic design approach is that the complexity in exact linearization of a non-linear system can be avoided. Two numbers of TCSC controllers are placed near the highest load bus in a multimachine network. The transient stability of the power system has been investigated with non-linear as well as conventional TCSC controllers. To the best of authors' knowledge the present work has not been explored details in existing literature. The whole work is organised as follows: Section 2 presents the affine non-linear model of the multimachine power system and also presented the theory of design of nonlinear control law for multimachine power system applying zero dynamic design principle. The design of nonlinear TCSC controller for 3-machine 9-bus system has been shown in Section 3. The stability of the internal states of this multimachine system has also been investigated in this section applying Lyapunov Stability Theorem. The control law for conventional controller is formulated by using LQR approach in Section 4. To design conventional controller approximate linearization of the system has been done adopting Jacobean linearization technique. Section 5 describes the simulation which comprises two sub sections; In Section 5.1 the performance of both the non-linear and conventional controllers is investigated and compared with application of typical fault and in Section 5.2 the performance of non-linear controller has been studied for different loading conditions. In Section 6 the applicability and performance of the nonlinear TCSC controller has been shown for a large 14 area power system (24-Machine 203 bus) for the same contingency and operating conditions.

2. Design of nonlinear controller for multimachine power system

2.1. Theory of design of nonlinear controller for multimachine power system via zero dynamic design principle

The theory of zero dynamics design method can be available in [28]. It is very useful method of feedback linearization technique. There is no need of exact linearization of all state equations in this design method. Here, a part of state equations i.e. external states are required to be linearized. In this method, dynamics of a system is classified as external dynamics and internal dynamics. The main concern in this method is that the external dynamics must be stable with good performance. In case of internal dynamics only the stability is the main concern, not the performance. The first step of this method is to find out the relative degree (r) of the system. If the relative degree of a system is less than its order (n), *i.e.* ($r < n$), the zero dynamic design approach can be implemented. If the relative degree is equal to the order of the system ($r = n$), the exact linearization technique is generally employed to execute nonlinear control law. The design procedure of control law is given as follows;

2.2. Affine model of multimachine power system

The affine nonlinear form of a MIMO system with 'm' input and 'm' output can be expressed [29] as

$$\dot{X} = f(X) + \sum_{i=1}^{m} g_i(X)u_i \tag{1}$$

and

$$y_i = h_i(X) \tag{2}$$

where $X \in R^n$; $f(X)$ and $g_i(X)$, $i = 1,2,\ldots,m$ are n-dimensional smooth vector fields; u_i is the ith input, $h_i(X)$ is a scalar function of 'X'.

2.3. Estimation of relative degree of multimachine system

According to this theory if the *Lie derivative* of a scalar function $h(X)$ along the vector field $g(X)$ is not equal to zero in the neighbourhood $\hat{R}$ i.e. $L_g L_f^{r-1} h(X) \neq 0$ then the relative degree of the system is said to be 'r' in the neighbourhood of $\hat{R}$ for SISO system. Similarly, for MIMO system given in (1) and (2) the relative degree set (r) can be estimated as $r = \{r_1 \;\; r_2 \ldots r_m\} = r_1 + r_2 + \cdots + r_m$ and each sub relative degree 'r_i' corresponds to output $y_i(t) = h_i(X)$, provided the following conditions hold in the neighbourhood of X^0,