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Control and modelling of multi-machine power system stabilizer with FACTS

Abstract*. The Multi-machine system controlled and modelling using the FACTS-PSS controller is one of the most recently application to control the active or reactive power flow transmission line, also to incorporate them with power system stabilizer (FACTS-PSS). The flexible alternating current transmission system (FACTS) as new technology based on high-advances in power electronics in high switching frequency semi-conductor, Control theory and microprocessors technology, as Thyristor Controlled Series Compensator (TCSC), Static Var Compensator (SVC), those static devices controller designed for consolidating network efficiency, reliability, controllability, high quality demand, and power transfer capability of AC transmission systems.*

Streszczenie. *System wielomaszynowy sterowany i modelowany za pomocą sterownika FACTS-PSS jest jedną z najnowszych aplikacji do sterowania linią przesyłową przepływu mocy czynnej lub biernej, również w celu połączenia ich ze stabilizatorem systemu elektroenergetycznego (FACTS-PSS). Elastyczny system przesyłu prądu przemiennego (FACTS) jako nowa technologia oparta na zaawansowanych rozwiązaniach energoelektronicznych w półprzewodnikach wysokiej częstotliwości przełączania, teorii sterowania i technologii mikroprocesorowej, jako Tyrystorowy Kompensator Szeregowy (TCSC), Kompensator Statycznych Warstw Statycznych (SVC), te sterowniki urządzeń statycznych przeznaczone do konsolidacji wydajności sieci, niezawodności, sterowalności, wysokiej jakości zapotrzebowania i zdolności przenoszenia mocy systemów przesyłowych prądu przemiennego*. (***Sterowanie i modelowanie wielomaszynowego stabilizatora systemu elektroenergetycznego za pomocą FACTS***)

Keywords: Flexible AC transmission system devices, Multi-machine network system, Power system stabilizer,.
Słowa kluczowe: FACTS, system wielomaszynowy, DFIG, stabilność systemu.

Introduction

The electric power industry is being relentlessly pressured by governments, politicians, large industries, and investors to privatize, restructure, and deregulate. A new deregulation in the power industry meant new challenges and huge changes. However, despite changes in different structures, market rules, and uncertainties, the underlying requirements for power system operations to be secure, economical, and reliable, sustainable remain the same [1]. Modern power systems are highly complex and expected to fulfil the growing demands of power wherever required, with acceptable quality and costs [2]. The Economic and environmental factors necessitate the location of generation at places away from load centers. This problem can be effectively tackled by introducing of the high power electronic controllers for the regulation of power flows and voltages in interconnected networks [3-4]. The new technology of thyristor valves and digital controls was initially extended to the development of static var compensator for load flow compensation and voltage regulation in long transmission lines [5]. In 1988, G. Hingorani introduced a new concept of Flexible AC Transmission Systems by incorporating power electronic controllers to enhance power transfer in AC transmission lines, improve voltage regulation [6]. The FACTS device refer to controlling and modelling of multi-machine network as Thyristor controlled series capacitor, static var compensator, and newer controllers based on voltage source converters such united power flow controller [7-8].

I. Modelling of multi-machine system

A. Power System Dynamic Model

A modern power system consists of a number of components for example the generators and their excitation systems, power system stabilizers (PSS), FACTS devices such as TCSC, loads, transmission network etc. A perfect modelling of each of these components is fundamental to study the dynamic behaviour of a power system multi-machine. The dynamic behaviour of the components and its governing equations are obtainable as follows [9].

B. State Matrix For Fifth Order Dynamic *Model*

1. Electricals equations

(1) $$\frac{dE'_{di}}{dt} = \frac{1}{T'_{qoi}}\left[-E'_{di} - \left(x_{qi} - x'_{qi}\right)i_{qi}\right].$$

(2) $$\frac{dE'_{qi}}{dt} = \frac{1}{T'_{doi}}\left[E_{fdi} - E'_{qi} + (x_{di} - x'_{di})i_{di}\right].$$

(3) $$\frac{dE''_{di}}{dt} = \frac{1}{T''_{qoi}}\left[E'_{di} - E''_{di} - \left(x'_{qi} - x''_{qi}\right)i_{qi}\right].$$

(4) $$\frac{dE''_{qi}}{dt} = \frac{1}{T''_{doi}}\left[E'_{qi} - E''_{qi} + (x'_{di} - x''_{di})i_{di}\right].$$

(5) $$E_{di} = E''_{di} + x''_{q}i_{qi}.$$

(6) $$E_{qi} = E''_{qi} - x''_{di}i_{di}.$$

2. Mechanical Equations

(7) $$\frac{d\delta i}{dt} = (\omega_{ri} - \omega_{si}) = \Delta\omega_{ri}$$

(8) $$\frac{d\Delta\omega_{ri}}{dt} = \frac{1}{2H}(p_{mi} - p_{ei} - D\Delta\omega_{ri})$$

Where i the number of generator is varies from 1 to16.

The algebraic equations defining the stator voltages and generator electrical real power is given by (9-10), assuming the generator armature resistance is negligible.

(9) $$E_{di} = \frac{x''_{qi} - x_{\sigma si}}{x'_{qi} - x_{\sigma si}}E'_{di} - \frac{x'_{qi} - x''_{qi}}{x'_{qi} - x_{\sigma si}}\varphi_{2qi} + x''_{qi}i_{qi}$$

(10) $$E_{qi} = \frac{x''_{di} - x_{\sigma si}}{x'_{di} - x_{\sigma si}}E'_{qi} - \frac{x'_{di} - x''_{di}}{x'_{di} - x_{\sigma si}}\varphi_{1di} - x''_{di}i_{di}$$

(11) $$E_{ti} = \sqrt{{E_{di}}^2 + {E_{qi}}^2}$$

(12) $$p_{ei} = E_{di}i_{di} + E_{qi}i_{qi}$$

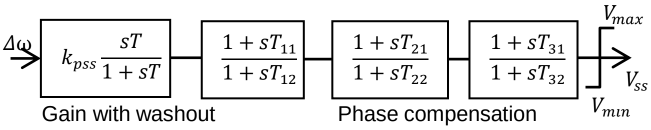
3. Excitation Systems Equation: The differential equations governing the operation of the excitation system are given by:

(13) $$E_{fd} = K_A(V_{ref} + V_{ss} - V_r);\ E_{fd}min \le E_{fd} \le E_{fd}max$$

4. *Power System Stabilizers (PSSs):* Besides the excitation control of generators, we use PSSs as supplements to damp the local modes. The dynamic equation of the PSS is given by:

(14) $$Vss = Kpss\frac{sT_w}{(1+sT_w)}\frac{(1+sT_{11})}{(1+sT_{12})}\frac{(1+sT_{21})}{(1+sT_{22})}\frac{(1+sT_{31})}{(1+sT_{32})}S_m$$

Power System Stabilizer Block Diagram is given by:



5. Network Interface and Network Equations

While writing the algebraic network balance equations, we need to work in a common reference frame of the network, instead of the rotating reference frame of the generators. For that reason the generator currents and voltages need to be rotated by the rotor phase angle δ, the Network Interface and Network Equations are given by:

5.1 П-equivalent circuit of transmission line

(16) $$I_{Qi} + jI_{Di} = (I_{qi} + jI_{di})e^{j\delta_i}$$

(17) $$V_{gi} = V_{Qi} + jV_{Di} = (V_{qi} + jV_{di})e^{j\delta_i}$$

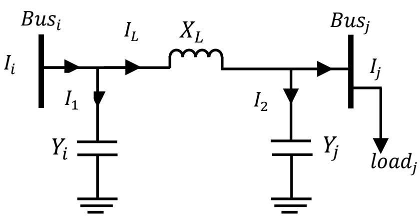


Fig.1. π-equivalent circuit of transmission line

5.2 Network Equations

(18) $$S_i = V_i^* * I_i = P_i - jQ_i = V_i^* \sum_{k=1}^{n} Y_{ik}V_k$$

(19) $$V_i^* = V_i e^{-j\delta_i}$$

(20) $$Y_{ik} = G_{ik} - jB_{ik} = Y_{ik}e^{-j\theta_{ik}}$$

(21) $$P_i = \sum_{k=1}^{n} V_iV_kY_{ik}cos(\delta_{ik} - \theta_{ik})$$

At the same

(22) $$Q_i = \sum_{k=1}^{n} V_iV_kY_{ik}sin(\delta_{ik} - \theta_{ik})$$

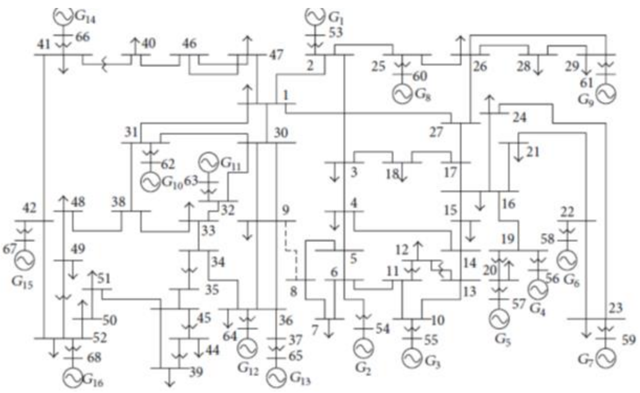


Fig.2. Multi-machine power network England reference.

***C.* The Topology of Multi-machine Power Network**

The 5-area, 16 Synchronous Generators, 68 Bus System for R. Graham system represented on Fig.2 Shows the one-line diagram of the test system, nonlinear simulation of the test is done on *MATLAB* by using Power System Toolbox. The proposed agglomerative hierarchical clustering algorithm is to be applied for a data set consisting of the time-domain responses of all generators during and following a disturbance [10]. A typical time domain response of a group of interconnected synchronous generators to a disturbance or a change in the operation conditions of the power network is similar to the one shown in Fig.2 [11].

II. TCSC steady state behavior

The TCSC is one of the most important and greatest known series FACTS controller devices, it has been in use for many years to increase line power transfer as well as to enhance system stability [12]. Basically a $TCSC$ consists of three components: capacitor banks$C$, bypass inductor L and bidirectional thyristor. The firing angles of Thyristors are controlled to adjust the $TCSC$ reactance in accordance with a system control algorithm, According to the variation of the thyristor firing angle α or conduction angle σ, this process can be modeled as a fast switch between corresponding reactance offered to the power system.

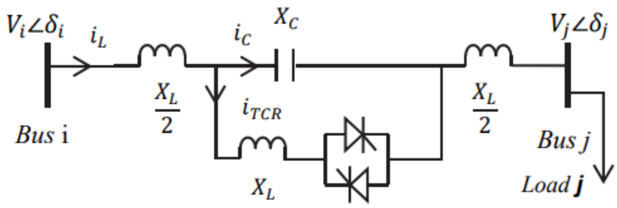


Fig.3. complete equivalent circuit of TCSC

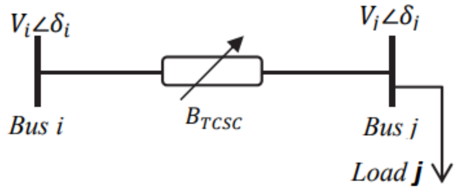


Fig.4. simplified equivalent circuit of TCSC susceptance model

The equivalent reactance at the fundamental frequency can be represented as a variable reactance X_{TCSC} . There exists a steady-state relationship between α and the reactance X_{TCSC} . This relationship can be described by the following equation.

(23) $$X_{TCSC} = -X_c + k_1\{2(\pi-\alpha) + sin[2(\pi-\alpha)]\} - k_2cos^2(\pi-\alpha)\{\rho tg[\rho(\pi-\alpha)] - tg(\pi-\alpha)\}$$

For a differential variation, the derivative value of the $TCSC$ impedance characteristic.

$k_1 = \frac{X_C+X_{LC}}{\pi}$; $k_2 = \frac{4X^2{}_{LC}}{\pi X_L}$; $\rho = \frac{\omega_0}{\omega} = \sqrt{\frac{X_C}{X_L}}$; $X_{LC} = \frac{X_C*X_L}{X_C-X_L}$; $\omega_0{}^2 = \frac{1}{LC} = \omega^2\frac{X_C}{X_L}$;

The impedance of the TCSC was adjusted based on machine rotor angle and the magnitude of the speed deviation [10].In addition, different control schemes for a TCSC were proposed such as variable structure controller, bilinear generalized predictive controller, the neural networks and fuzzy logic controller have been proposed for TCSC-based stabilizer design [13]. The damping characteristics of the designed stabilizers have been demonstrated through simulation results on a multi-machine power system, robust nonlinear coordinated control approach to excitation and TCSC for transient stability enhancement [14].

III. NONLINEAR SIMULATION RESULT

A. Nonlinear simulation result- TCSC without PSS

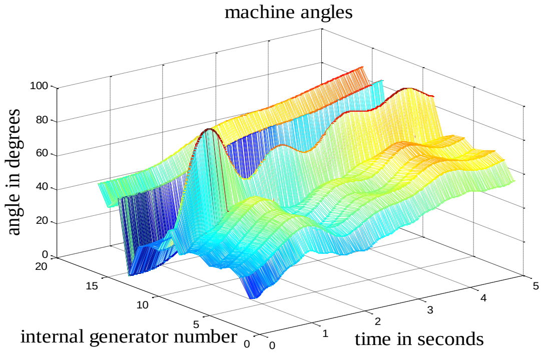


Fig.5. rotor angle machine oscillation in 3D

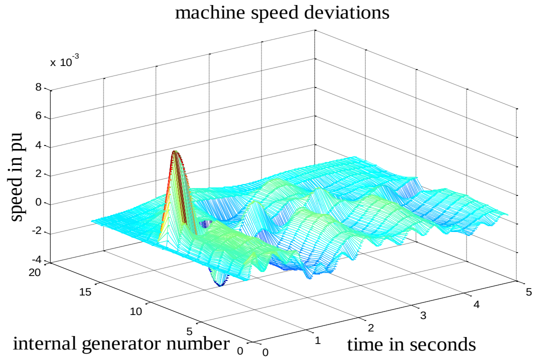


Fig.6. machine speed in pu in 3D

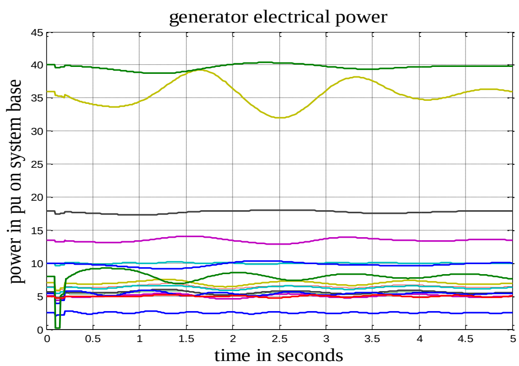


Fig.7. generator electrical power

B. Discussion about Simulation Result TCSC without PSS

The dynamic simulation quantities (ω_r, δ, p) are being observed in Fig.5 to Fig.7 are the rotors, angle and speed oscillation signals following a system commotion.

As can be seen in previous the event of avoidance, rotors angle and speed deviations of all generators are indicating stable operation of the generators, when electrical power is being delivered as Fig.7, at constant rotor speeds and constant rotor angles following a disturbance, the rotor angles interchange to meet the new condition of operating, these fluctuations in the operating outcome in developed of oscillations which can be seen as sudden speed deviation on the rotors angles and rotors speeds. The oscillations continue over a period of time, if there isn't damping forces in the system FACT without PSS.

C. Nonlinear simulation result - TCSC with PSS

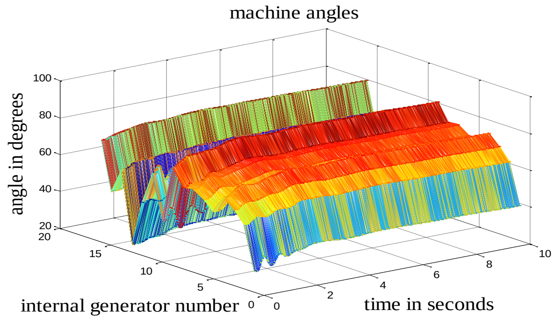


Fig.8. machine angle in 3D

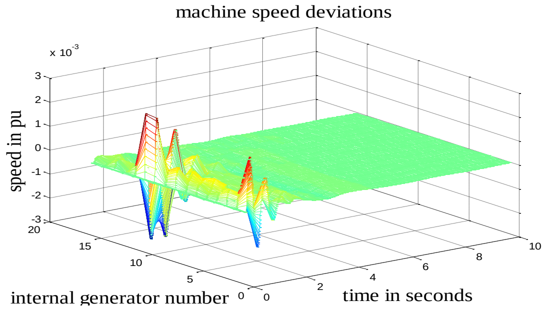


Fig.9. machine speed in pu in 3D

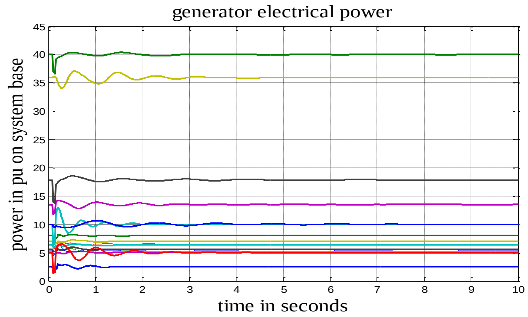


Fig.10.generator electrical power

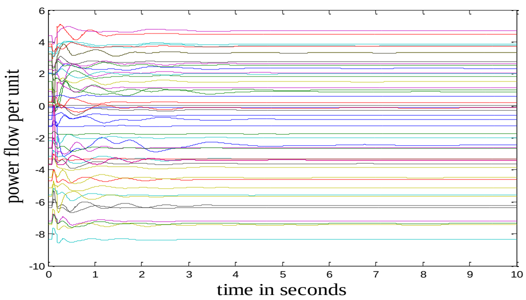


Fig.11. power flow unit

D. Discussion about Simulation Result TCSC with PSS

The dynamic simulation quantities (ω_r, δ, p) are being observed in Fig.8 to Fig.11 are the rotors angle and rotor speed oscillation signals following a system disturbance. As can be seen at the moment of disturbance, angle and speed deviations of all generators rotor are indicating stable operation of the generators where electrical power is being delivered, the variation of rotor angle meet the new operating condition. These fluctuations in the operating outcome in developed oscillations which can be seen as a deviation on the rotor angle and rotor speed. The oscillation signals continue for a short period of time then decay, if there are enough damping forces in the system FACT-PSS.

Conclusion

The Multi-machines power system is a highly nonlinear system that operates dependently with inters generators parameters, loads demands, changing environment, and topology. A typical modern Multi-machines power system is thus a very high-order Multivariable process and dynamic performance. The stability of power system is highly influenced by the dynamics of generator rotor speed and power-angle relationships. The basic structures of FACTS-PSS devices and their potential to increase system controllability and stability are having various functions to civilizing power system quality.

The abbreviation parameter

T''_{do}: d-axis sub-transient open-circuit time constant.
T'_{do}: d-axis transient open-circuit time constant.
T''_{qo}: q-axis sub-transient open-circuit time constant.
T'_{qo}: q-axis transient open-circuit time constant.
E''_q: q-axis sub-transient emf.
E'_q: q-axis transient emf.
E''_d: d-axis sub-transient emf.
E'_d: d-axis transient emf.
x''_q: q-axis sub-transient reactance.
x'_q : q-axis transient reactance.
x''_d: d-axis sub-transient reactance.
x'_d: d-axis transient reactance.
x_d: d-axis reactance.
x_q: q-axis reactance.
H: generator inertia time constant.
$\Delta\omega_r$: rotor speed deviation.
δ: rotor angle.

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