<http://kth.diva-portal.org>

This is an author produced version of a paper published in *IEEE Innovative Smart Grid Technologies-Asia (ISGT Asia)*, 2012.

This paper has been peer-reviewed but does not include the final publisher proof-corrections or proceedings pagination.

© 2012 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

Citation for the published paper:

A. Nasri, M. Ghandhari, R. Eriksson.

Appropriate placement of series compensators to improve transient stability of power system

IEEE Innovative Smart Grid Technologies-Asia (ISGT Asia), 2012.

Access to the published version may require subscription.

Published with permission from: IEEE

Appropriate Placement of Series Compensators to Improve Transient Stability of Power System

Amin Nasri, *Member, IEEE*, Mehrdad Ghandhari, *Member, IEEE*, Robert Eriksson, *Member, IEEE*,

Abstract—Trajectory sensitivity analysis is used to find the best places for installation of thyristor controlled series capacitors (TCSC) to improve transient stability of the power system. Based on the rotor angles of generators, an equivalent angle (δ_{eq}) is defined by determining accelerating and decelerating machines, and then using trajectory sensitivities of this angle with respect to the impedances of the transmission lines in the post-fault system, appropriate locations for placing TCSC will be found. Severity of the faults is also considered in this calculation. This method is applied to the IEEE 3-machine 9-bus test system to find the priorities of the transmission lines for installation of TCSC. Simulation with industrial software verifies the obtained results.

Index Terms—Trajectory sensitivity analysis (TSA), Thyristor Controlled Series Capacitor (TCSC), Transient Stability, Critical Clearing Time (CCT).

I. INTRODUCTION

ELECTRICAL power systems are being more and more complicated every year and proportionally their analysis will also become more difficult. So, there is an intense need to use more efficient methods for power system analysis. One of the most important topics in power system is the inspection of the transient stability when power system being subjected to a contingency. Transient stability is the ability of power system to keep its synchronism when a large disturbance, like three phase short circuit, occurs in the system. Several factors like the initial condition of the power system, type, severity and location of the fault affect the transient stability. The maximum duration that one fault can remain in the power system without causing instability is the critical clearing time (CCT) of that fault. CCT of a fault can be used as a power system stability index for that fault. Due to nonlinear nonsmooth nature of dynamic behaviour of power system, transient stability assessment can be an extremely massive calculation especially when the goal is to check the stability margin in each iteration of an algorithm which intends to improve the transient stability [1].

Simulation of power system usually provides information about a single scenario and each change to the power system needs another simulation which leads to repetitive simulation and high computational cost [2]. Trajectory sensitivity analysis (TSA) is one of the most advantageous methods, since it linearizes the system around the nominal trajectory instead of one operating point and provides information to calculate the variation of trajectory due to changes in the parameters of

the system. [3] developed a new method for power system stabilizer (PSS) design based on trajectory sensitivities of power system with respect to (PSS) parameters. TSA is also able to give insight information about the distance of power system from instability [4], [5].

As the instability of the power systems may create several expensive and hazardous follow-ups, system operators really like to improve the transient stability of their systems. Series compensators like thyristor controlled series capacitors (TCSC) equipped with the proper controller can be used to compensate the reactance of transmission line in a way to enhance the transient stability. Using these devices most effective on the transient stability, it is vital to find the best locations for installation of these TCSCs. Reference [6] used corrected transient energy margin (CTEM) as a transient stability index and calculated the effects of putting a TCSC in the transmission lines using this index. For allocation of TCSC from transient stability viewpoint, sensitivity coefficients β based on the change of the generator electric output due to the change of the compensation ratio were defined in [7] and were calculated for different locations of TCSC. In [8] an estimation of TSA has been used to study the effects of series and shunt Flexible AC Transmission system (FACTS) devices on the transient stability. A stability index based on the estimation of trajectory sensitivities of rotor angles of the generators with respect to the clearing time of the faults was calculated for different locations of FACTS devices. Stability index defined in [8] is not suitable for optimal placement of FACTS devices since it is not accurate and also leads to repetitive simulation of power system

In this paper, the precise analytical trajectory sensitivities of rotor angles of the generators to the impedances of transmission lines are calculated for the post-fault system. Based on the obtained trajectory sensitivities of rotor angles and definition of equivalent angle (δ_{eq}), trajectory sensitivities of the δ_{eq} to the impedances of the transmission lines are computed. An algorithm is proposed to use these calculated trajectory sensitivities to find the optimal locations of series compensators for improving transient stability of power system. This proposed algorithm is implemented in MATLAB®10b using IEEE 3-machines 9-buses test system. Finally, the obtained results is applied to the industrial software SIMPOW®11 for verification [9]. It should be mentioned that the existing methods need to move the compensator to all the available locations and each time simulate the system to investigate its impact on the transient stability while the proposed method which is based on the trajectory sensitivity analysis calculate all the required information with just one simulation and will reduce significantly the computational cost.

A. Nasri, M. Ghandhari and R. Eriksson are with the Department of Electric Power Systems, School of Electrical Engineering at KTH Royal Institute of Technology, Sweden, e-mail: (see <http://www.kth.se/en/ees/omskolan/organisation/avdelningar/eps/abouteps>).

II. POWER SYSTEM MODELING AND TRAJECTORY SENSITIVITY ANALYSIS

As explained comprehensively in [10], power systems can be modeled by the following differential algebraic equations

$$\dot{x} = f(x, y; \lambda) \quad (1)$$

$$0 = \begin{cases} g^-(x, y; \lambda) & s(x, y; \lambda) < 0 \\ g^+(x, y; \lambda) & s(x, y; \lambda) > 0 \end{cases} \quad (2)$$

$$x(t_0) = x_0, y(t_0) = y_0 \quad (3)$$

Where x are the dynamic states, y are the algebraic states and λ are the parameters of the system. Rotor angles of the generators (δ), magnitude and angle of bus voltages and impedances of the transmission lines are the examples of the dynamic states, algebraic states and parameters of the power system, respectively. x_0 and y_0 are initial conditions of dynamic and algebraic states and based on the above notations, events in the system like faults occurs when $s(x, y; \lambda) = 0$.

To write the equations in a more organized way, vectors of $\underline{x}$ and $\underline{f}$ are defined as follows

$$\underline{x} = \begin{bmatrix} x \\ \lambda \end{bmatrix} \quad \underline{f} = \begin{bmatrix} f \\ 0 \end{bmatrix} \quad (4)$$

And therefore

$$\dot{\underline{x}} = \underline{f}(\underline{x}, y) \quad (5)$$

$$0 = \begin{cases} g^-(\underline{x}, y) & s(\underline{x}, y) < 0 \\ g^+(\underline{x}, y) & s(\underline{x}, y) > 0 \end{cases} \quad (6)$$

To calculate the trajectory sensitivities analytically, the derivatives of (5), (6) are calculated with respect to $\underline{x}_0$

$$\dot{\underline{x}}_{\underline{x}_0} = \underline{f}_{\underline{x}}(t)\underline{x}_{\underline{x}_0} + \underline{f}_y(t)y_{x_0} \quad (7)$$

$$0 = g_{\underline{x}}(t)\underline{x}_{\underline{x}_0} + g_y(t)y_{x_0} \quad (8)$$

The system is assumed to be away from the events. It is clear that the initial value for the trajectory sensitivities of dynamic states is an identity matrix. Using this matrix the initial values for the trajectory sensitivities of algebraic states can be also computed.

$$\underline{x}_{\underline{x}_0}(t_0) = I \quad (9)$$

$$y_{x_0}(t_0) = -(g_y(t_0))^{-1}g_{\underline{x}_0}(t_0) \quad (10)$$

$\underline{f}_{\underline{x}}$, $\underline{f}_y$, $g_{\underline{x}}$ and g_y are time varying functions which are calculated along the system trajectories. When an event like a short circuit fault occurs in the power system, jump condition should be derived for computation of the trajectory sensitivities which is fully described in [10]. To find the trajectory sensitivities, the differential algebraic equations (5), (6), (7) and (8) should be solved simultaneously with the initial conditions described above.

III. TRANSIENT STABILITY ASSESSMENT USING TRAJECTORY SENSITIVITY ANALYSIS

The result of transient instability appears in the form of increasing rotor angles of some generators which leads to their loss of synchronism with other generators. So, monitoring angular swings of generators (dynamic states δ) could be one way to check the transient stability. To improve the transient stability, power system parameters can be controlled (if applicable) in a way to have positive effects on the variation of rotor angles of generators when the system is subjected to a fault and prevent power system from being unstable. Impedance of transmission line is one of these parameters which can have a considerable effect on the stability of power system with controlling power flows in the transmission lines. Nowadays with the presence of FACTS devices like TCSC, it is possible to control the impedance of transmission lines and improve transient stability of power system. Due to heavy cost of these devices, it is not economical to install several TCSCs in a power system, and therefore, the optimal locations for installation of these devices should be determined instead. In this paper, TSA is used to determine the trajectory sensitivities of rotor angles of generators to the impedances of transmission lines. So, the matrices of power system parameters and trajectory sensitivities of dynamical states for this study are as follows

$$\lambda = [x_{L_1} x_{L_2} \dots x_{L_{n_l}}] \quad (11)$$

$$\begin{bmatrix} \frac{\partial \delta_1}{\partial x_{L_1}} & \frac{\partial \delta_1}{\partial x_{L_2}} & \dots & \frac{\partial \delta_1}{\partial x_{L_{n_l}}} \\ \frac{\partial \delta_2}{\partial x_{L_1}} & \frac{\partial \delta_2}{\partial x_{L_2}} & \dots & \frac{\partial \delta_2}{\partial x_{L_{n_l}}} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial \delta_n}{\partial x_{L_1}} & \frac{\partial \delta_n}{\partial x_{L_2}} & \dots & \frac{\partial \delta_n}{\partial x_{L_{n_l}}} \end{bmatrix} \quad (12)$$

where x_{L_i} is the impedance of i^{th} transmission line, n_l is the number of transmission lines, δ_j is the rotor angle of j^{th} generator, and n is the number of generators.

A. Definition of equivalent angle

In this part, an equivalent angle is defined and the trajectory sensitivity of this angle to the impedances of transmission lines is introduced for appropriate placement of series compensators. To define this angle, machines are separated to two groups named accelerating (A) and decelerating (D) groups with respect to their rotor angles (δ) in center of inertia (COI) reference and, then this two-machine equivalent is replaced by a single machine equivalent system. The equivalent angle includes all the rotor angles and is defined as follows [11]

$$M_A = \sum_{i \in A} M_i, \quad M_D = \sum_{j \in D} M_j \quad (13)$$

$$\delta_A = M_A^{-1} \sum_{i \in A} M_i \delta_i, \quad \delta_D = M_D^{-1} \sum_{j \in D} M_j \delta_j \quad (14)$$

$$\delta_{eq} = \delta_A - \delta_D \quad (15)$$

where M_i and δ_i are the inertia and rotor angle of i^{th} generator, respectively. According to this definition, the trajectory sensitivity of the equivalent angle to the impedances of transmission lines is as follows

$$\frac{\partial \delta_{eq}}{\partial x_{L_i}} = \frac{\partial \delta_A}{\partial x_{L_i}} - \frac{\partial \delta_D}{\partial x_{L_i}} \quad (16)$$

where

$$\frac{\partial \delta_A}{\partial x_{L_i}} = M_A^{-1} \sum_{i \in A} M_i \frac{\partial \delta_i}{\partial x_{L_i}} \quad (17)$$

$$\frac{\partial \delta_D}{\partial x_{L_i}} = M_D^{-1} \sum_{j \in D} M_j \frac{\partial \delta_j}{\partial x_{L_i}} \quad (18)$$

B. The proposed algorithm

- 1) Most important faults with clearing time close to their CCT are selected.

$$t_{cli} = t_{cc_i} - \varepsilon \quad (19)$$

where t_{cli} and t_{cc_i} are the clearing and critical clearing times of the i^{th} fault respectively, and ε is a positive small number.

- 2) For each fault:

- a) (5), (6), (7) and (8) are solved simultaneously using the above λ vector and all the dynamic and algebraic variables and their trajectory sensitivities with respect to the parameter vector λ are calculated. Simulation time does not need to be so long.
- b) Based on the obtained data for the rotor angles (δ) of the generators, generators are divided to accelerating and decelerating groups which oscillate against each other.
- c) The matrix of trajectory sensitivities of dynamical states (12) is prepared and based on the definition of δ_{eq} , trajectory sensitivities of δ_{eq} with respect to the impedances of transmission lines are computed.
- d) The maximum peak to bottom value of trajectory sensitivity of δ_{eq} to each transmission line and its sign after occurrence of fault are determined.
- e) The values obtained in (d) are normalized to their maximum value and are divided to the clearing time of the fault.

- 3) Finally

- a) for each transmission line, sum of normalized trajectory sensitivities of δ_{eq} to the impedance of that line for different faults is calculated considering their sign of variation after being subjected to those faults (data from step 2). These results show how effective each transmission line is for improvement of transient stability.
- b) The transmission line which has most positive effect is chosen for installation of TCSC.

IV. SIMULATION AND RESULTS

A. Proposed method implementation

The IEEE 3-machine 9-bus system shown in Fig. 1 is used to evaluate the proposed algorithm, the system data is available in [12]. The reactances of transformers are included in transient reactances of generators. Table I shows list of selected faults which will be applied to the test system.

Fig. 1. Modified IEEE 3-machines test system.

TABLE I
List of selected faults

Name	Type	Clearing Time	Fault Location
Fault 1	Three phase short circuit	143 ms	Bus 1
Fault 2	Three phase short circuit	142 ms	Bus 2
Fault 3	Three phase short circuit	129 ms	Bus 3
Fault 4	Three phase short circuit	202 ms	Bus 4
Fault 5	Three phase short circuit	195 ms	Bus 5
Fault 6	Three phase short circuit	191 ms	Bus 6

When a fault occurs in the system, generators are divided to two groups as mentioned before. Fig. 2 shows the rotor angles of generators in center of inertia reference for fault 6. It is clear that generators 2 and 3 are more critical and oscillate against generator 1. For this fault, generator 1 is selected as decelerating group and generators 2 and 3 as accelerating group, and equivalent rotor angle is calculated based on this classification and is also depicted in Fig. 2. The trajectory sensitivities of δ_{eq} with respect to the impedances of transmission lines are calculated and shown in Fig. 3. For more clarification, first cycle of variation of trajectory sensitivities is also depicted in Fig. 4. This figure shows that the signs of trajectory sensitivities of δ_{eq} with respect to the impedances of transmission line after fault 4 and 5 are negative but for the others are positive. Line 4, line 5, line 6, line 3, line 2 and line 1 have the largest absolute peak to bottom value of

trajectory sensitivities, respectively.

The most important issue here is to understand the meaning of these absolute peak to bottom values and their signs after occurring faults. It can be written based on the trajectory sensitivities

$$\Delta\delta_{eq} \approx \left(\frac{\partial\delta_{eq}}{\partial x_{L_i}}\right)\Delta x_{L_i} \quad (20)$$

As TCSC is going to be installed in the transmission lines, Δx_{L_i} will be negative and since δ_{eq} will also increase rapidly after occurring fault which is visible from Fig. 2, the value of trajectory sensitivity of δ_{eq} with respect to the impedance of the transmission line should be positive to decrease δ_{eq} and enhance transient stability of the system. Absolute peak to bottom value of trajectory sensitivity shows how sensitive δ_{eq} is to the impedances of the transmission lines and its sign determines if putting TCSC in that line has positive or negative effect on the transient stability. So, installing TCSC at transmission line 4 and 5 not only does not improve transient stability for this fault but also has a very large negative effect because of its large negative peak to bottom value. Between the transmission lines with positive effects, line 6, line 3, line 2 and line 1 have better impact on the transient stability of the system, respectively.

The same calculations are done for the other selected faults

Fig. 2. Rotor angles of generators and equivalent angle.

and results are given in Table II. For each fault, computed peak to bottom values of trajectory sensitivities for different transmission lines are normalized to their maximum value. Each column corresponding to each fault shows these normalized trajectory sensitivities of δ_{eq} . It can be seen that one of the trajectory sensitivities is equal to 1 for each column. The next step is to consider clearing time of each fault. For this purpose, all the digits of each column are divided to the clearing time of its corresponding fault. Table III shows the final trajectory sensitivities considering duration of faults. Final step is to calculate the sum of positive and negative effects of each transmission lines on transient stability for all the selected faults and decide about the best location for installing TCSC.

Fig. 3. Trajectory sensitivities of δ_{eq} to impedances of transmission lines (5 seconds duration).

Fig. 4. Trajectory sensitivities of δ_{eq} to impedances of transmission lines (first cycle).

According to the obtained results shown in Table IV, Line 3 and 6 are the best locations for installing TCSC, Line 2 and 1 do not affect transient stability so much, finally Line 4 and 5 may have negative effects on transient stability.

TABLE II
Normalized trajectory sensitivities of δ_{eq} for different faults

	Fault 1	Fault 2	Fault 3	Fault 4	Fault 5	Fault 6
Line 1	-0.01890	0.43240	0.52750	-0.59440	0.53420	0.31290
Line 2	-0.03930	0.75390	0.32540	0.59000	-0.34170	0.42550
Line 3	1.00000	0.99700	0.82010	-0.46440	1.00000	0.49280
Line 4	0.27750	-0.18650	-0.17540	0.19100	0.33520	-1.00000
Line 5	0.13260	-0.40570	0.17670	0.04690	0.31500	-0.99810
Line 6	0.69490	1.00000	1.00000	1.00000	-0.44130	0.62590

TABLE III
Weighted and normalized trajectory sensitivities of δ_{eq} for different faults considering duration of each fault

	Fault 1	Fault 2	Fault 3	Fault 4	Fault 5	Fault 6
Line 1	-0.13217	3.02378	4.05769	-2.92808	2.72551	1.62969
Line 2	-0.27483	5.27203	2.50308	2.90640	-1.74337	2.21615
Line 3	6.99301	6.97203	6.30846	-2.28768	5.10204	2.56667
Line 4	1.94056	-1.30420	1.34923	0.94089	1.71020	-5.20833
Line 5	0.92727	-2.83706	1.35923	0.23103	1.60714	-5.19844
Line 6	4.85944	6.99301	7.69231	4.92611	-2.25153	3.25989

TABLE IV
Sum of positive and negative effects of each transmission lines on transient stability

	Line 1	Line 2	Line 3	Line 4	Line 5	Line 6
Sum	8.37642	10.87946	25.65452	-3.27011	-3.91082	25.47923

Fig. 5. TCSC steady-state circuit series with a transmission line

B. Simulation with industrial software

To verify the results, industrial software SIMPOW@11 is used to simulate the test system in the presence of TCSC. Fig. 6 shows a transmission line equipped with a TCSC. The active power flow through transmission line between bus i and bus m when impedance of line is just a reactance is equal to

$$P_{im} = \frac{U_i U_m}{X_{eff}} \sin(\theta_{im}) \quad (21)$$

$$X_{eff} = X_{line} - X_{TCSC} \quad (22)$$

Where, X_{eff} is the value of effective reactance of the transmission line between Bus i and Bus m , X_{line} is the reactance of the transmission line, X_{TCSC} is the reactance of TCSC, U_i and U_m are the voltage magnitude of Bus i and Bus m , and θ_{im} is the angle difference between Bus i and Bus m . Since the transmitted active power is inversely proportional to X_{eff} , variation of X_{eff} (due to the TCSC) results in variation of the power flow in the line. Therefore, TCSC can be used as a powerful means for controlling power flows in the transmission lines and for improving transient stability and power oscillation damping in power systems. X_{TCSC} is

$$X_{TCSC} = X_{TCSC_0} + \Delta X_{TCSC} \quad (23)$$

where X_{TCSC_0} is the TCSC steady state reactance and ΔX_{TCSC} is the stability control modulation reactance. Controller which is used in this paper is based on the control lyapunov functions defined in [13]. According to these functions

$$\Delta X_{TCSC} = k_{TCSC} \sin(\delta_{eq}) \omega_{eq} \quad (24)$$

where k_{TCSC} is a positive gain and ω_{eq} is the equivalent speed of generator. Equivalent speed can be calculated based

on (13)-(15) using generator speeds instead of rotor angles. After implementing TCSC in the industrial software, TCSC is placed in different transmission lines. For each location, CCTs in the presence of TCSC for all the selected faults are calculated. Table V shows the best and worst CCTs and their corresponding locations of TCSC for each selected fault which exactly match with the calculated trajectory sensitivities in Table III. As it was expected, the transmission line with

TABLE V
CCTs before and after installing TCSC for the best and worst locations

	CCTs without any TCSC (ms)	CCTs with one installed TCSC (ms)			
		Best Location	CCT	Worst Location	CCT
Fault 1	144	Line 3	150	Line 2	144
Fault 2	143	Line 6	152	Line 5	142
Fault 3	130	Line 6	136	Line 4	132
Fault 4	203	Line 6	218	Line 1	197
Fault 5	196	Line 3	216	Line 2	194
Fault 6	192	Line 6	206	Line 4	178

the largest positive value of trajectory sensitivity of δ_{eq} can improve transient stability significantly while the transmission line with a negative value can have a negative effect on the transient stability.

C. Best location for installing next series compensators

It is also important to be mentioned here that when a transmission line is chosen as the best location for installing TCSC, it means that it has the most positive overall effect on the transient stability considering all the selected faults. So, putting TCSC in the chosen line could also have a negative effect on the transient stability for a few numbers of faults. Anyway, this is the best achievable improvement of transient stability that can be obtained by installing one TCSC in this system. To eliminate this negative effect, more series compensators should be added to the power system and be placed in the best possible locations. The best way to find the appropriate places for installing next series compensators is to check again the calculated trajectory sensitivities of equivalent angle with respect to the impedances of transmission lines for the fault with a negative effect of first compensator. For instance in the studied test system, although line 3 has the most positive overall effect on the transient stability (Table IV) but considering only fault 4, it has a slightly negative effect on it (Table III). So, another series compensator can be installed in the system to remove this negative effect. Fifth column of Table III shows computed trajectory sensitivities corresponding to fault 4 and it is clear that line 6 has the largest positive impact on the transient stability for this case. Table VI shows the new critical clearing times of the selected faults after installing second TCSC at line 6. It can be seen that for all the selected faults transient stability has been improved.

V. CONCLUSION

In this paper, trajectory sensitivity analysis has been used as a tool to determine the effect of changing impedances

TABLE VI
CCTs without any TCSC and after installing two TCSCs

	CCTs without any TCSC	CCTs with two installed TCSCs
Fault 1	144 ms	153 ms
Fault 2	143 ms	158 ms
Fault 3	130 ms	138 ms
Fault 4	203 ms	219 ms
Fault 5	196 ms	211 ms
Fault 6	192 ms	220 ms

of different transmission lines on the trajectory of rotor angles of generators when a fault occurs in a power system. It has been clarified for the first time why putting series compensators in the transmission lines does not always improve the transient stability of power system. A method was proposed to determine the appropriate places to install series compensators for improving transient stability of power system. The method has been applied to the IEEE 3-machine 9-bus system using thyristor controlled series compensator. MATLAB®10b has been used for implementation of the proposed method and finally results have been verified using industrial software SIMPOW®11.

ACKNOWLEDGMENT

Amin Nasri has been awarded an Erasmus Mundus PhD Fellowship. The authors would like to express their gratitude towards all partner institutions within the programme as well as the European Commission for their support.

REFERENCES

- [1] G. A. Maria, C. Tang, J. Kim, "Hybrid transient stability analysis [power systems]," *IEEE Trans. on power systems*, vol. 5, pp. 384-393, May 1990.
- [2] I. A. Hiskens, M. A. Pai, "Sensitivity analysis of power system trajectories: recent results," *2004 International Symposium on Circuits and Systems*, vol. 3, pp. 439-443, August 2002.
- [3] Zhou. Baorong, D. Z. Fang, T. S. Chung, "Computation of trajectory sensitivities of power systems with respect to parameters of PSS," *2004 International Conference on PAdvances in Power System Control, Operation and Management*, vol. 1, pp. 280-284, November 2003.
- [4] M. A. Pai, T. B. Nguyen, "Trajectory sensitivity theory in nonlinear dynamical systems: some power system applications," *Control engineering series*, Birkhauser, Boston, 2003.
- [5] D. Z. Fang, Qin. Yi. Fei, "A new trajectory sensitivity approach for computations of critical parameters," *Electric Power System Research* 77, pp. 303-307, 2007.
- [6] R. Moslemi, H. A. Shayanfar, "Optimal location for series FACTS devices to transient stability constrained congestion management," *10th International Conference on Environment and Electrical Engineering (EEEIC)*, pp. 1-4, May 2011.
- [7] R. Shizawa, K. Nishida, T. Ohtaka, S. Iwamoto, "Allocation of TCSC from Transient Stability Viewpoint," *2004 International Conference on Power System Technology - POWERCON 2004*, vol. 1, pp. 216-221, November 2004.
- [8] D. Chatterjee, A. Ghosh, "Transient Stability Assessment of Power Systems Containing Series and Shunt Compensators," *IEEE Trans. on power systems*, vol. 22, no. 3, August 2007.
- [9] SIMPOW: Simulation of Power System, <http://simpow.com/index.html>
- [10] I. A. Hiskens, M. A. Pai, "Trajectory sensitivity analysis of hybrid systems," *IEEE Trans. circuits and systems*, vol. 47, no. 2, February 2000.
- [11] M. Pavella, D. Ernst, d. Ruiz-Vega, "Power System System Transient Stability Analysis and Control," *Kluwer Academic Publishers*, 2000.
- [12] M. A. Pai, "Energy Function Analysis for Power System Stability," Appendix A, 2007.
- [13] M. Ghandhari, G. Andersson, M. Pavella, D. Ernst "A control strategy for controllable series capacitor in electric power systems," *Automatica* 37, pp. 1575-1583, 2001.

Amin Nasri received his M.Sc. degree in Electrical Engineering from the Sharif University of Technology, Tehran, Iran, in 2008. He is pursuing the Erasmus Mundus Joint Doctorate in Sustainable Energy Technologies and Strategies (SETS) hosted by Comillas Pontifical University, Spain; the Royal Institute of Technology, Sweden; and Delft University of Technology, The Netherlands. He is currently a Ph.D. Student in the Division of Electric Power Systems, School of Electrical Engineering at KTH Royal Institute of Technology.

Mehrdad Ghandhari received the M.Sc., Tech. Lic. and Ph.D. degrees in Electrical Engineering from Royal Institute of Technology, Stockholm, Sweden, in 1995, 1997, and 2000, respectively. He is currently Associate Professor at KTH Royal Institute of Technology.

Robert Eriksson received his M.Sc., Tech. Lic. and Ph.D. degrees in Electrical Engineering from KTH Royal Institute of Technology, Stockholm, Sweden, in 2005, 2008 and 2011 respectively. He is currently a Postdoctoral researcher in the Division of Electric Power Systems, School of Electrical Engineering at KTH Royal Institute of Technology.