Impacts of distributed generation penetration levels on power system transient stability

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Impacts of Distributed Generation Penetration Levels on Power Systems Transient Stability

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***Abstract*—Concerns on environmental and economical issues drive the increasing developments that support small scale generators to be connected close to distribution networks, i.e. distributed generation (DG).**

When connected in small amounts, the impact of DG on the power system transient stability will be negligible, however, when the penetration of DG increases, its impact is no longer restricted to the distribution network but starts to influence the whole system, including the transmission system transient stability.

In this paper, the transmission system transient stability is investigated when a fault is applied in all possible branches (regarding the N-1 security analysis). In this studie the penetration level of DG implementation is raised in two ways: (1) a load increase is covered by DG implementation (with a constant centralized generation) or increased CG output, and (2) a reduction of centralized generation is covered by DG (with a constant load).

***Index Terms*—distributed generation (DG), power system transient stability.**

I. List of Principal Abbreviations

CG	Centralized generation
DG	Distributed generation
ASM	Asynchronous machine (Squirrel cage induction generator)
SM	Synchronous machine (generator) without grid voltage and frequency control
SMC	Synchronous machine (generator) with grid voltage and frequency control
PE	Power electronic interface of distributed generation without grid voltage and frequency control
PEC	Power electronic interface of distributed generation with grid voltage and frequency control
CG	Centralized generation

This research has been performed within the framework of the research program ‘intelligent power systems’ that is supported financially by Senter. Senter is an agency of the Dutch ministry of Economic Affairs.

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II. Introduction

Developments on distributed generation (DG) grows significantly, driven by environmental issues, e.g. as an effort to lower the carbon emission from the conventionally fossil-fueled power plants, as well as by economical issues, e.g. as an effort to substitute for transmission capacity and to respond to high electrical energy prices [2]. When DG is connected to the distribution network, the DG influences the technical aspects of the distribution grid [3]. As long as the distribution network with DG is not operated autonomously, i.e. isolated from the transmission network, the DG is part of a large power pool and the power balance can be kept by the centralized machines.

When the penetration of DG is still low, the impacts of the DG (connected at the distribution level) on the transmission system transient stability may be neglected. However when the penetration of DG increases, its impact is no longer restricted to the distribution network but starts to influence the whole system [4], including the transmission system transient stability. In this paper, the transient stability behavior of a power system with increasing penetration levels of distribution networks with DG is investigated. A previous study [1] on the implementation of DG in power systems shows that, the system transient stability is affected differently with respect to the penetration level, the DG technology, and the fault duration. In [1] a fault is simulated in one branch only and the DG penetration level is raised by increasing the load and DG in parallel (with a constant centralized generation). In this paper, the transmission system transient stability is investigated when a fault is applied in all possible branches (regarding the N-1 security analysis). The penetration level of DG implementation is raised in two ways: (1) a load increase is covered by DG implementation (with a constant centralized generation) or increased CG output, and (2) a reduction of centralized generation is covered by DG (with a constant load). In this way, a more general view of the impact of DG on the transient stability is obtained.

III. Simulation Setup

A. 39-bus New England Test System

The 39-bus New England dynamic test system [5] is used in the studies with some adjustments. Representative values for the parameters of the generators, the exciter, and the governor are taken from other sources [6], [7]. The loads are equally divided in constant impedance, constant power and constant current. Fig. 1 shows the test system used throughout the simulations in more detail and Table I lists some characteristics of the system. The 10 centralized generators in this test system are referred to as centralized generation (CG) in this paper.

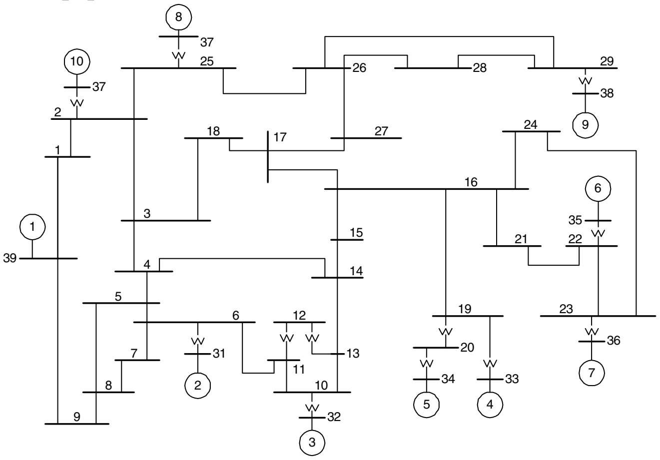


Fig.2 One-line diagram of the 39-bus New England test system [5]

TABLE I
CHARACTERISTICS OF THE NEW ENGLAND TEST SYSTEM

System characteristic	Value
# of buses	39
# of generators	10
# of loads	19
# of transmission lines	46
Total generation	6140.7 MW / 1264.3 MVAr
Total load	6097.1 MW / 1408.7 MVAr

The power system dynamics simulation package PSS/E is used to investigate the dynamic behavior of the transmission system, which alternately executes load flow and dynamic calculations [7]. In addition, MATLAB® and DELPHI are used for preparing the simulation scenarios and processing the simulation results.

IV. RESEARCH APPROACH

A. DG Technologies

Throughout the simulations, five different DG technologies are used [8], which are:

a. Asynchronous machine (Squirrel cage induction generator) – ASM
b. Synchronous machine (generator) without grid voltage and frequency control – SM
c. Synchronous machine (generator) with grid voltage and frequency control – SMC
d. Power electronic interface of distributed generation without grid voltage and frequency control – PE
e. Power electronic interface of distributed generation with grid voltage and frequency control – PEC

The squirrel cage induction generator is simulated by means of a standard induction generator model with rotor flux transients [7]. For the synchronous generator, a standard round rotor generator model with exponential saturation is used [7]. The synchronous generator with grid voltage and frequency control is equipped with a simplified excitation system model and a steam turbine governor model. The power electronic converter (uncontrolled) and the power electronic converter with grid voltage and frequency control (controlled) are modeled as a source of active power (P) and reactive power (Q), as the grid representation in power system dynamics simulation software and the typical time step used do not allow detailed modeling of power electronics [8]. Since there is no standard model available for representing power electronics in PSS/E 25.4, a so-called user-written model of a power electronic converter has been developed and integrated into this simulation program [7].

B. Simulation Scenarios

To investigate the transmission system stability under a varying DG penetration level in the system, several simulation scenarios are defined.

Firstly, a basic set up is defined, which includes:

- When DG is implemented in the test system, the DG is connected to every load bus via a j0.05 pu impedance on the 100 MVA system base.
- The DG penetration level in the system is defined as [9]:

$$\%DG_{penetration-level} = \frac{P_{DG}}{P_{DG} + P_{CG}} \times 100 \qquad (1)$$

  where P_{DG} and P_{CG} are the amount of total active power generated by DG and CG respectively.
- The transient stability of the test system is investigated by applying a fault, that is cleared after 150 ms, to any possible transmission line in the test system. That means that every line, that fulfills the (N-1) security analysis, is subjected to a fault (35 possible locations for faulty branches are then simulated whose details are attached in table A1 in the Appendix).

Secondly, in order to study the impact of the DG penetration level on the transient stability, three different groups of simulation scenarios are defined. The details of the scenarios are as follows (note that scenario I is split up in scenario I – DG and scenario I – CG):

In scenario I - DG:

- the DG penetration level is raised by increasing both the real and reactive power of all loads, which increment is covered by an equal amount of power produced by DG that is connected to each load bus. The penetration level of DG increases in steps of 3.33 % up to 33.33% (the 33.33% corresponds to a 50% increment of the load; a further increase of the load is not realistic). Thus eleven sub-scenarios are obtained with penetration levels of 0.0, 3.33, 6.67, 10.0, 13.33, 16.67, 20.0, 23.33, 26.67, 30.0, and 33.33 % and correspond with the penetration-level scenario numbers 1 to 11 (i.e. DG penetration-level scenario 1 has a 0.0% DG penetration level and serves as a reference).

- The active power generated by the large generators is kept constant, except for the active power generated by generator number 2; it acts as the swing bus.

In scenario I - CG:

- The load is increased in steps similar to that in scenario I – DG, however, the increasing load is supplied by increasing the active power output of the CG.

In scenario II:

- the DG penetration level is raised by decreasing the CG active power output in steps of 3.33 % up to 33.33%, and the implementation of DG in every load bus to cover this decrement of power. In this way, eleven scenarios of DG penetration level are obtained with penetration levels of 0.0, 3.33, 6.67, 10.0, 13.33, 16.67, 20.0, 23.33, 26.67, 30.0, and 33.33 % that correspond to the DG penetration-level scenario numbers 1 to 11.
- Centralized generator number 2 acts as the swing bus.

In scenario III:

- the DG penetration level is raised by shutting down one or more centralized generators and the implementation of DG in every load bus to cover this decrement of power. Therefore, it is not possible to decrease the amount of power generated by the CG precisely in steps of 3.33 %. As a result, eleven DG penetration level scenarios (number 1 to 11) are obtained as listed in Table II.
- Centralized generator number 2 acts as the swing bus.

TABLE II
THE SUB-SCENARIOS WITHIN SCENARIO III

Sub-Scenario number	DG penetration level (%)	# Generator(s) shut down	Bus number(s) of the shut down generator(s)
1	0.0	-	-
2	4.10	1	30
3	8.86	1	37
4	12.43	2	30,34
5	14.76	2	30,35
6	18.70	2	33,34
7	21.32	2	32,35
8	2427	2	35,38
9	28.08	3	30,33,38
10	30.51	3	32,35,36
11	33.13	3	32,37,38

C. Transient Stability Indicators

To assess the transmission system stability, two transient stability indicators are applied to quantify the rotor speed oscillations of the large generators [8], namely:

- the maximum rotor speed deviation,
- the oscillation duration.

The maximum rotor speed deviation is defined as the maximum rotor speed value achieved during the transient phenomenon. The oscillation duration is defined as the time interval between the application of the fault and the moment after which the rotor speed stays within a bandwidth of 10^{-4} pu during a time interval longer than 2.5 seconds (in the case that the particular rotor speed is stable). The rotor speed deviation is identified to be stable when the rotor speed deviation stays within a bandwidth of 10^{-5} pu longer than 5 seconds during the simulation time frame.

Fig. 3 shows the two indicators used in this paper.

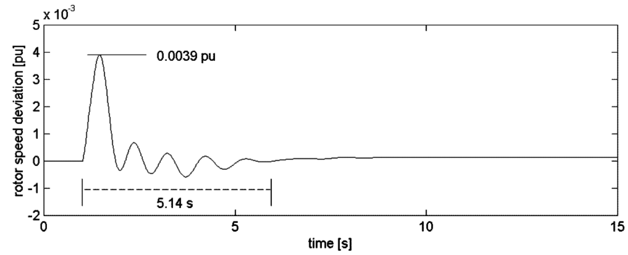


Fig. 3 Transient stability indicators: the maximum rotor speed deviation and the oscillation duration [8]

V. RESULTS

In [1], it is shown that the system transient stability is affected differently with respect to the penetration level, the DG technology, and the fault duration. In [1] a fault is simulated in one branch only and the DG penetration level is raised by increasing the load and DG in parallel (with a constant centralized generation). In this paper, the transmission system transient stability is investigated when a fault is applied in all possible branches (regarding the N-1 security analysis). The penetration level of DG implementation is raised in two ways: (1) a load increase is covered by DG implementation (with a constant centralized generation) or increased CG output, and (2) a reduction of centralized generation is covered by DG (with a constant load). In this way, a more general view of the impact of DG on the transient stability is obtained. Figs. 4 to 9 show the simulation results displaying the transient stability indicators i.e. the maximum rotor speed deviation (figs. 4, 6 and 8) and the oscillation duration (figs. 5, 7 and 9) when the penetration level of DG is increased according to scenario I – DG and scenario I – CG (figs. 4 and 5), scenario II (figs. 6 and 7), and scenario III (figs. 8 and 9). The titles of ASM, SM, SMC, PE, or PEC in a graph indicate the type of DG technology simulated. The title ‘CG’ (at the top-left graph of figs. 4 and 5) indicates the simulation result of scenario I – CG. The title ‘Reference’ (at the top-left graph of figs. 6 to 9) indicates the original case where there is no load, CG or DG increase. The x-axis of each graph represents the number of the faulted branch (see Table A1 in the Appendix). The y-axis represents the DG penetration level scenario number (0 % for the scenario nr. 1 up to 33.33% for the scenario nr. 11 in scenarios I and II, and according to Table II in scenario III). The z-axis represents the value of the stability indicator used (the maximum rotor speed deviation in per unit in figs. 4, 6, and 8, and the oscillation duration in seconds in figs. 5,7 and 9).

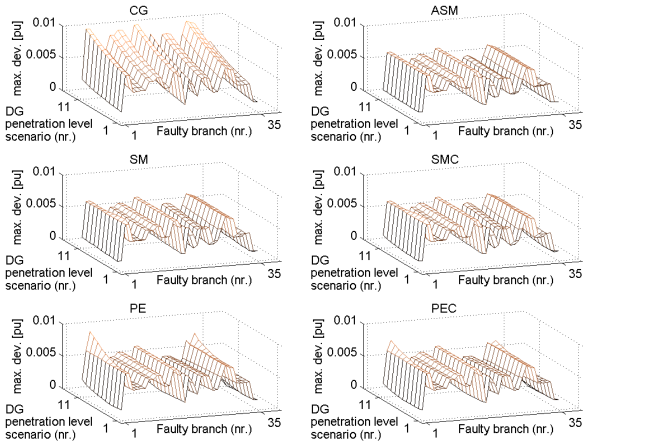


Fig. 4 Maximum rotor speed deviation when the penetration level of DG is simulated according to Scenario I – DG and scenario I - CG (See Section IV.B), and a fault is simulated in all possible branches (Table A2 in the Appendix).

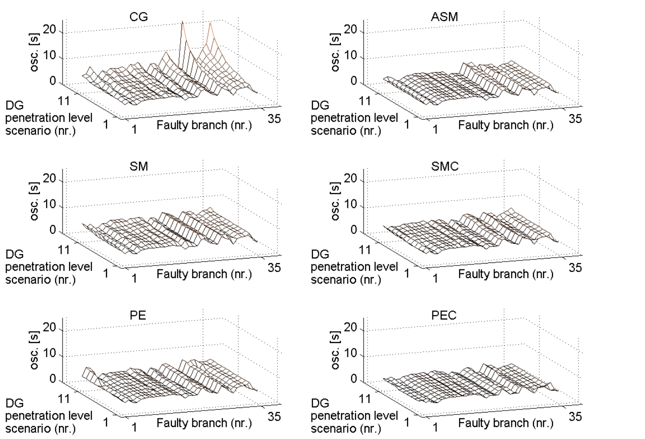


Fig. 5 Oscillation duration when the penetration level of DG is simulated according to Scenario I – DG and Scenario I - CG (See Section IV.B), and a fault is simulated in all possible branches (Table A2 in the Appendix).

When the increasing load within the test system is covered only by increasing the CG active power output (Scenario I – CG, top-left graphs of figs. 4 and 5), the indicators are generally increasing. When DG (five different technologies: ASM, SM, SMC, PE and PEC) is implemented to cover the increased load within the system, which corresponds to the raised penetration level of DG in the system, the indicators do not increase significantly.

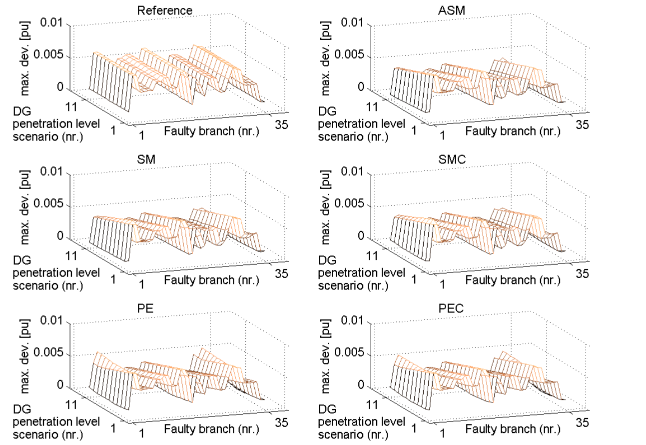


Fig. 6 Maximum rotor speed deviation when the penetration level of DG is simulated according to Scenario II (See Section IV.B), and a fault is simulated in all possible branches (Table A2 in the Appendix).

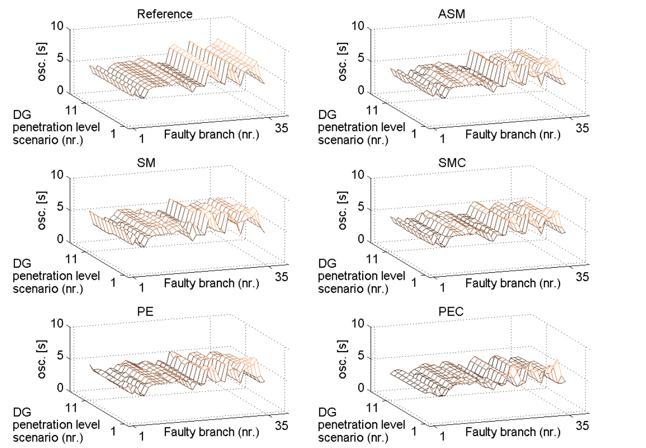


Fig. 7 Oscillation duration when the penetration level of DG is simulated according to Scenario II (See Section IV.B), and a fault is simulated in all possible branches (Table A2 in the Appendix).

When the active power output of the CG is gradually decreased and replaced by DG (five different technologies: ASM, SM, SMC, PE and PEC), i.e. an increasing DG penetration level, both the indicators decrease (figs. 6 and 7)

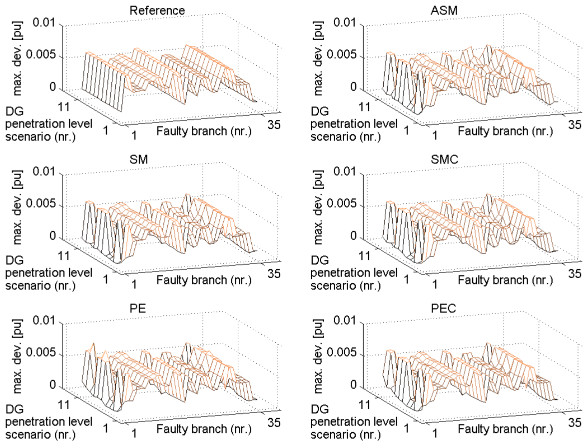


Fig. 8 Maximum rotor speed deviation of DG implementation in the test system when the penetration level of DG is simulated according to Scenario III (See Section IV.B and Table II), and a fault is simulated in all possible branches (Table A2 in the Appendix).

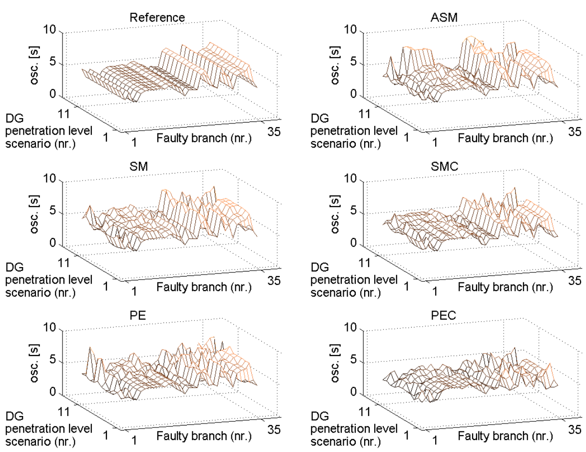


Fig. 9 Oscillation duration when the penetration level of DG is simulated according to Scenario III (See Section IV.B and Table II), and a fault is simulated in all possible branches (Table A2 in the Appendix).

No clear tendency of consistently increasing or decreasing indicators (maximum rotor speed deviation in fig. 8 and the oscillation duration in fig. 9) can be observed in the case of scenario III.

Thus, it cannot be concluded directly, as it may be suggested based on the simulation results shown in figs. 4, 5, 6, and 7, that an increasing DG penetration level in power systems will improve the transient stability of the system (represented by the decreasing indicators).

When the active power flowing in the simulated branches is displayed accordingly to simulation scenario I – CG, scenario I – DG, scenario II and scenario III, similar tendencies can be observed.

We can compare the active power flowing in each of the simulated branches (according to simulation scenarios I - CG and I - DG, II, and III, as shown in fig. 10) with the system indicators in figs. 4 to 9. It can be observed that the 'surface' of the branch power flows of scenario I – CG (upper-left graph of fig. 10) is comparable to the 'surface' of the system indicators of scenario I – CG (top-left graphs of figs. 4 and 5). The 'surface' of the branch power flows of scenario I – DG (upper-right graph of fig. 10) is comparable to the 'surface' of the system indicators of scenario I – DG (the graphs with the titles ASM, SM, SMC, PE and PEC in figs. 4 and 5). Similar results are obtained when the 'surface' of the branch power flows of scenarios II and III (lower graphs of fig. 10) are compared with the system indicators of scenarios II and III shown in figs. 6 to 9 (all graphs except the 'Reference').

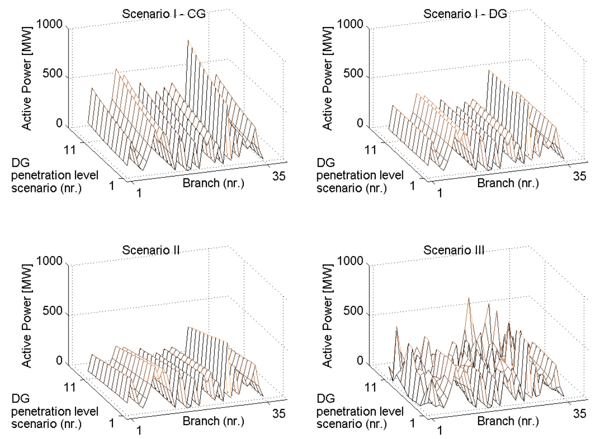


Fig. 10 Active power flowing (MW) in the simulated branches in the test system, when the DG penetration level scenario (nr.) is simulated according to scenario I, II and III. (See. Section IV)

Fig. 11 shows the total active power (MW) flowing in all simulated branches in the test system, when the DG penetration level scenario (nr.) is simulated according to scenario I (CG and DG), II and III.

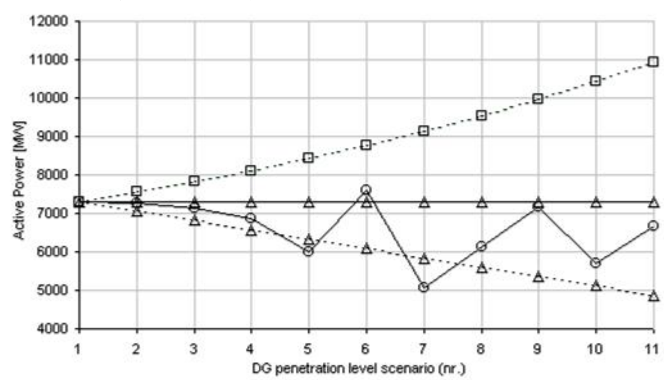


Fig. 11 Total active power (MW) flowing in all simulated branches in the test system, when DG penetration level scenario (nr. 1 to 11) is simulated according to scenario I - CG (dotted - □), I - DG (solid - Δ), II (dotted - Δ), and III (solid - O).

Large power flows have a detrimental effect on the damping of the oscillations [10]: the heavier the lines are loaded, the weaker the connections between the generators and the loads and the bigger the oscillations of the CG. Implementing DG is a natural way of 'limiting' the power flows over the transmission lines (see fig. 11).

VI. Conclusions

In this paper, the transmission system transient stability is investigated when a fault is applied in all possible branches (regarding the N-1 security analysis). In this study the penetration level of DG implementation is raised in two ways: (1) a load increase is covered by DG implementation (with a constant centralized generation) or increased CG output, and (2) a reduction of centralized generation is covered by DG (with a constant load). It is shown that large power flows have a detrimental effect on the damping of the oscillations: the heavier the lines are loaded, the weaker the connections between the generators and the loads and the bigger the oscillations of the centralized generators. Implementing DG is a natural way of 'limiting' the power flows over the transmission lines and to improve the transient stability of the transmission system.

VII. Acknowledgment

This research has been performed within the framework of the research program 'intelligent power systems' that is supported financially by Senter. Senter is an agency of the Dutch ministry of Economic Affairs.

VIII. References

[1] Reza, M., Slootweg, J. G., Schavemaker, P. H., Kling, W. L., Van der Sluis, L., "Investigating Impacts of Distributed Generation on Transmission System Stability", in *Proc. 2003 IEEE Bologna Power Tech Conference*.

[2] N. Jenkins, "Impact of dispersed generation on power systems", *Electra*, No. 199, pp. 6-13, Dec. 2001.

[3] J.A.P. Lopes, "Integration of dispersed generation on distribution networks-impact studies", in *Proc 2002 IEEE Power Engineering Society Winter meeting*.

[4] De Leon, F., Ooi, B.-T., "Damping power system oscillations by unidirectional control of alternative power generation plants", in *Proc 2001 IEEE Power Engineering Society Winter meeting*.

[5] M. A. Pai, *Energy Function Analysis for Power System Stability*, Boston: Kluwer Academic Publishers, 1989, pp. 223-227.

[6] P. Kundur, Power system stability and control, New York, US: McGraw-Hill, Inc., 1994.

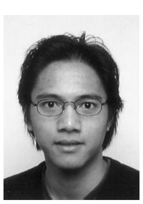
[7] PSS/E 25, On-line Documentation, Schenectady, US: Power Technologies, Inc., December 1997.

[8] J. G. Slootweg, W. L. Kling, "Impacts of Distributed Generation on Power System Transient Stability", in *Proc 2002 IEEE Power Engineering Society Summer meeting*.

[9] Donnelly, M.K., Dagle, J.E., Trudnowski, D.J., Rogers, G.J., "Impact of the Distributed Utility on Transmission System Stability", *IEEE Transactions of Power Systems*, Vol. 11, No. 2, pp. 741-746, 1996.

[10] N. Janssens, "Impact of Power Flows on Inter-Area Oscillations and Mitigation by Means of SVC's or Q-PSS", in *Proc 2002 14th Power Systems Computation Conference.*

IX. Biographies



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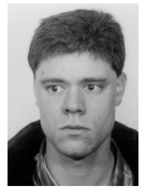

J.G. Slootweg received his M.Sc. and Ph.D. degree in Electrical Engineering from Delft University of Technology, the Netherlands, in 1998 and 2003 respectively.He also holds a M.Sc. degree in Management Science. He currently works with Essent Netwerk Noord BV, Zwolle, the Netherlands as a power systems engineer.

W.L. Kling received his M.S-degree in electrical engineering from the Technical University of Eindhoven in 1978. Currently he is (part-time) professor of the faculty of Electrical Engineering in the field of power system engineering. He is involved in scientific organizations as Cigre and IEEE.

Lou van der Sluis obtained his M.Sc. in electrical engineering from the Delft University of Technology in 1974. He joined the KEMA High Power Laboratory in 1977. In 1990 he became a part-time professor and since 1992 he has been employed as a full-time professor at the Delft University of Technology in the Power Systems Department. Prof. van der Sluis is a senior member of IEEE and convener of CC-03 of Cigre.

X. Appendix

TABLE A1
BRANCH NUMBER AND CORRESPONDING BUSES

Faulty branch (nr.)	Corres-ponding buses	Faulty branch (nr.)	Corres-ponding buses	Faulty branch (nr.)	Corres-ponding buses
1	1-2	13	8-9	25	17-27
2	2-3	14	10-11	26	21-22
3	2-25	15	10-13	27	22-23
4	3-4	16	11-12	28	23-24
5	3-18	17	12-13	29	25-26
6	4-5	18	13-14	30	26-27
7	4-14	19	14-15	31	26-28
8	5-6	20	15-16	32	26-29
9	5-8	21	16-17	33	28-29
10	6-7	22	16-21	34	1-39
11	6-11	23	16-24	35	9-39
12	7-8	24	17-18		