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Aggregation of Wind Farms in Distribution Networks

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AGGREGATION OF WIND FARMS IN DISTRIBUTION NETWORKS

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ABSTRACT

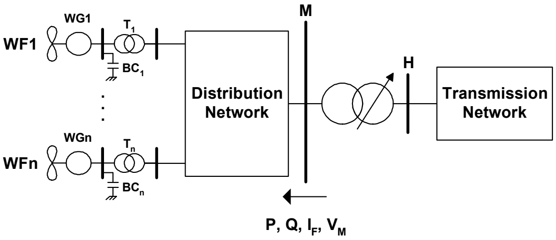
This paper presents a methodology to simplify a distribution network, which consists of a number of wind farms equipped with induction generators and MV lines. The methodology leads up to an approximate equivalent network, which consists of an equivalent wind farm and an approximate equivalent MV feeder. The proposed methodology reduces the complexity of an examined Power System and as a result accelerates the simulation time and allows various applications, such as security assessment and stability analysis, with limited resources. The validation of this methodology is examined by its application to the distribution network of Karystos in Evia Island, as well as to the whole network of Evia Island. In both examined cases, we simulate the response of both full and reduced network under the same contingency and the simulation results are commented upon and compared. The simulation is performed using a SIMULINK/MATLAB software package developed in NTUA and is appropriate for simulation and stability analysis of small interconnected or autonomous Power Systems.
Keywords: Electrical Systems, Wind Integration, Grid Equivalent

1 INTRODUCTION

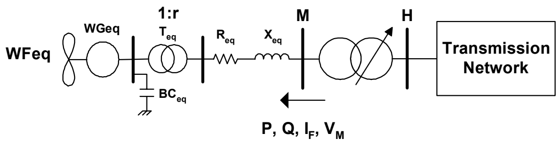
Following the favourable legislative environment for Renewable Energy Sources (RES) investments, established in Greece in 1994, a large number of applications for Wind Farms (WFs) installations (amounting to more than 3500 MW) has been filed in by Independent Power Producers (IPPs). Most of the applications are concentrated in the windy eastern coast of the mainland, especially at the areas of Evia Island and Lakonia (South Peloponnese). The legislation relative to promoting RES applications is mainly defined by the Law for regulation of electricity generation from RES (2244/94), and the newly approved Law for the de-regulation of electricity sector (2773/99).
The majority of the wind farms are (or plan to be) connected to the transmission network through radial MV feeders. The increasing wind power penetration level results in multiple WFs connected to the same HV/MV substation, thus, making the topology of the distribution network more complex.
This paper presents a technique to simplify a distribution network, which consists of a number of WFs equipped with induction generators and connected through MV lines. The methodology leads to an approximate equivalent network, which consists of an equivalent WF and an approximate equivalent MV feeder. Similar techniques from the viewpoint of wind modelling have been developed in [1-3]. The present methodology is thoroughly described in Section 2.
The applied methodology reduces the complexity of an examined Power System and as a result accelerates the simulation time and allows various applications, such as security assessment and stability analysis, with limited resources. Obviously, with the proposed simplification we cannot simulate the response of the network under disturbances occurring inside the reduced part of the network.
In the sequel, the methodology is applied to the distribution network of Karystos area in Evia Island, as well as to the whole network of Evia Island [4]. In both examined cases, the comparison between the full and the simplified network topologies is achieved by simulating the corresponding responses under the same contingency.
The simulation is performed using Wind-Hybrid System Simulation Package (WHSSP), which is a SIMULINK/MATLAB software package developed in NTUA [5], in collaboration with the University of Liege. WHSSP is using a library, which contains individual Power System models that are separately developed based on the available standard textbooks [6-11]. Such individual models refer to the transmission-distribution network, synchronous and induction machines (motors or generators), Automatic Voltage Regulators (AVR) and OverExcitation Limiters (OEL) of synchronous machines, steam, hydraulic and diesel turbines with their corresponding governors, transformers equipped with Load Tap Changer (LTC) mechanism and finally automatic Mechanically Switched Capacitors (MSC). The above-mentioned models are described through detailed algebraic and/or differential equations, as well as difference equations. Hence, this package is able to represent both short-term and long-term dynamics that occur in Power Systems, being appropriate for multi-time-scale simulation and stability analysis (small signal, frequency, voltage and transient) of small interconnected or autonomous Power Systems, which may include distributed generation, in the form of renewable energy sources.

2 METHODOLOGY DESCRIPTION

In this Section, we focus on the description of the proposed methodology and its application to a typical distribution network with wind power penetration, as shown in Fig. 1-(a).



(a) Actual network



(b) Aggregate network

Figure 1: Actual and aggregate network with wind penetration

We assume that all WFs are equipped with induction generators. Each WF is represented by an aggregate asynchronous machine. The nominal power and the active power generation of each aggregate Wind Generator (WG) are computed by summing the respective powers of all generators, which are in operation during the study period. The effect of local LV lines and cables are included in the leakage impedance of machine stator. At the terminal bus of each WF, capacitive compensation is installed in conjunction with a controller mechanism in order to keep the power factor in a desired range of values.

Each WF is considered to be connected to the transmission network through an LV/MV fixed off-nominal tap transformer (MV bus is the tap bus), radial MV feeders and MV/HV substation. The latter consists of one MV/HV transformer, which is equipped with Load Tap Changer. The role of LTC is to secure the normal operation of the WFs by keeping the substation MV bus voltage within a specified range.

The proposed methodology leads to a reduced approximate equivalent network as seen from the MV bus of the MV/HV substation, shown in Fig. 1-(b).

The reduced network consists of an equivalent WF (including power factor correction scheme), an equivalent LV/MV transformer and an equivalent MV feeder. The application of the reduction methodology requires the values of the active (P) and reactive (Q) power flow to the WFs, as well as the voltage magnitude (V_M) of the MV bus. The reduction technique consists of the following steps:

- For each WF, the tap ratio of the LV/MV transformer is considered such that WF terminal voltage is equal to nominal.
- The aggregate WG has nominal MVA (S_{WGeq}) and is generating active power (P_{WGeq}) equal to the sum of all WGs. The machine parameters correspond to the parallel combination of the individual WGs.
- Assuming nominal voltage at the terminal bus of the equivalent WG, we compute the slip and the reactive power consumption (Q_{WGeq}).
- We add the reactive compensation (power factor correction capacitors) of individual WFs, to calculate an equivalent one (BC_{eq}).
- An equivalent transformer (T_{eq}) is assumed, with its impedance calculated as the parallel combination of individual transformers.
- For the approximate equivalent network of Fig. 1-(b) we compute the current magnitude flowing through the equivalent MV feeder (I_F), according to following formula:

$$I_F = \frac{\sqrt{P^2 + Q^2}}{V_F} \tag{1}$$

and the current magnitude I_{WF} injected by the equivalent WF (including reactive compensation), according to Eq. (2).

$$I_{WF} = \sqrt{P_{WGeq}^2 + \left(Q_{WGeq} - BC_{eq}\right)^2} \tag{2}$$

The parameters of the equivalent feeder (R_{eq}, X_{eq}) are computed taking into account the active and reactive losses of the approximate equivalent network, that is:

$$R_{eq} = \frac{\left|P_{WGeq}\right| - \left|P\right| - I_{WF}^2 R_{Tr}}{I_F^2} \tag{3}$$

$$X_{eq} = \frac{\left|Q\right| + BC_{eq} - \left|Q_{WGeq}\right| - I_{WF}^2 X_{Tr}}{I_F^2} \tag{4}$$

In order to ensure nominal voltage at the terminal bus of the equivalent WF, the tap ratio r of the equivalent LV/MV transformer is computed by the division:

$$r = \frac{I_{WF}}{I_F} \quad (5)$$

3 CASE A: KARYSTOS NETWORK

In this part, the proposed aggregation methodology is applied to the distribution network of Karystos area in Evia Island. The one-line equivalent diagram of the examined system is shown in Fig. 2.

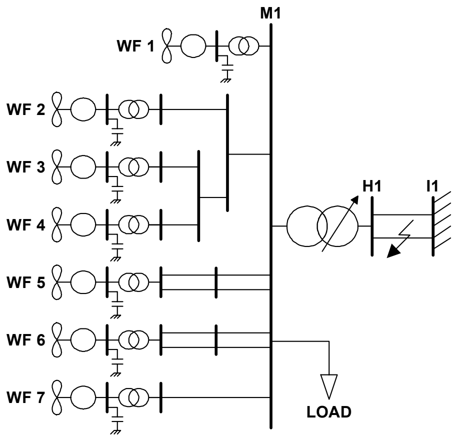


Figure 2: One-line equivalent diagram of full Karystos electrical network

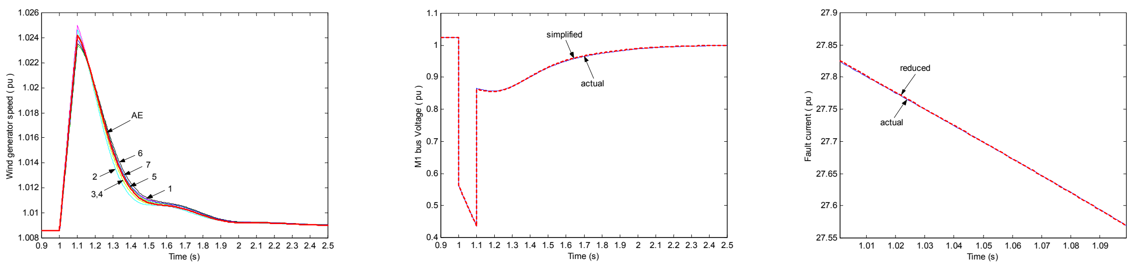
This network consists of seven WFs with total nominal generation 42.1 MW. Note that we can separate the WFs into three categories, according to the way they are connected to the MV/HV substation. The first category contains only WF1, which is connected directly without distribution line to the above substation. In the second group, WF2, WF3 and WF4 are connected to M1 bus through bifurcating distribution lines. The last category consists of WF5, WF6 and WF7, which are connected to M1 bus through single or double circuit distribution lines.

Comparison of full and reduced networks is performed by simulating a three-phase short-circuit in one circuit of the double circuit line connecting buses I1 and H1. From the simulation it was found that in case of full network, the fault critical clearing time is equal to 159 ms, while in case of simplified system the corresponding time is 164 ms. This difference is small (3%), but it should be noted that the simplified reduced model is optimistic.

At first, we consider that the fault happens at t=1 s and is cleared after 100 ms by opening the faulted line, i.e. fault clearing is quite faster than the above-mentioned critical time. The responses of wind generator rotor speeds are shown in Fig. 3-(a), together with that of the approximate equivalent WG (with bold line).

As regards the wind generators, it is clear in Fig. 3-(a) that there is an excellent match of responses between the full and the simplified network.

The voltage of bus M1 (in pu) and the short-circuit current (in pu) contributed by the WFs for both networks are shown in Fig. 3-(b) and 3-(c) respectively.



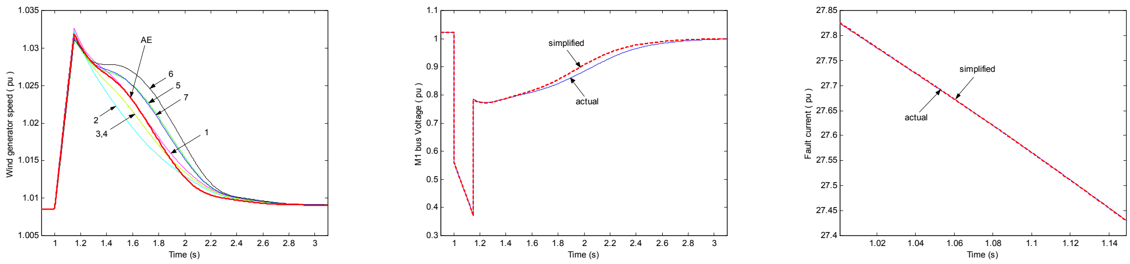
(a) Wind generator speed (b) M1 bus Voltage (c) Fault current

Figure 3: Response comparison for fault clearing time equal to 100 ms

Fig. 3-(b) and 3-(c) confirm that the approximate equivalent network response (shown with a dashed line) is accurate enough compared to the full system.

In the sequel, we assume that the examined fault is cleared after 150 ms. Concerning the wind farms, we show in Fig. 4-(a) the rotor speed (in pu) for the seven wind generators and the equivalent one (with bold line).

From Fig. 4-(a), we realize that WF response varies, according to the way they are connected to the MV/HV substation. Hence, WF2, WF3 and WF4 have similar responses, and the same happens for WF5, WF6 and WF7. WF1 is different from the others and remains close to the approximate equivalent.
For the equivalent wind farm, we note that its response combines characteristics from the three above-mentioned categories. However, it seems to withstand the examined fault more satisfactorily than the set of wind farms No 1, 5, 6 and 7, but less than WF2, WF3 and WF4. In general, there is a very good agreement between the results provided by both the individual wind farms and the equivalent one.



(a) Wind generator speed (b) M1 bus Voltage (c) Fault current

Figure 4: Response comparison for fault clearing time equal to 150 ms

The voltage of bus M1 (in pu) and the short-circuit current (in pu) for both full and simplified network are shown in Fig. 4-(b) and 4-(c) respectively.
Fig. 4-(b) shows that the simplified network is relatively less affected by the contingency than the actual system. On the other hand, the fault current of the approximate equivalent network is accurate enough compared to that of full system. Again the error is small but the problem is the optimism of the approximate model.
In conclusion, the proposed methodology results in an efficient accurate simplified network, in case we study small disturbances from the viewpoint of significance. On the other hand, if the contingency is crucial for the full network, the simplified system will provide a rather optimistic response with less accurate results.

4 CASE B: EVIA ISLAND NETWORK

In this Section, the proposed aggregation methodology is applied to the whole network of Evia Island. The examined system has been thoroughly described in Ref. [4]. The Evia Island electrical system consists of 57 buses and contains a local conventional generation unit with 2 synchronous generators of total capacity 280 MW, nineteen WFs of total capacity 200 MW and two aggregate local loads. It is interconnected to the mainland through 150 kV overhead lines and submarine cables. The WFs are located in five areas and are equipped with induction generators.
The reduced Evia network, as shown in Fig. 5, consists of 26 buses, while the number of aggregate WFs is reduced to five.

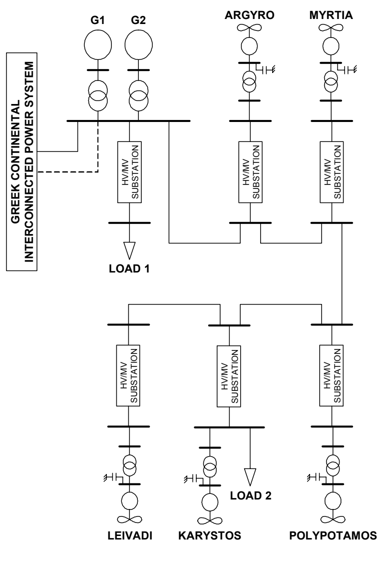
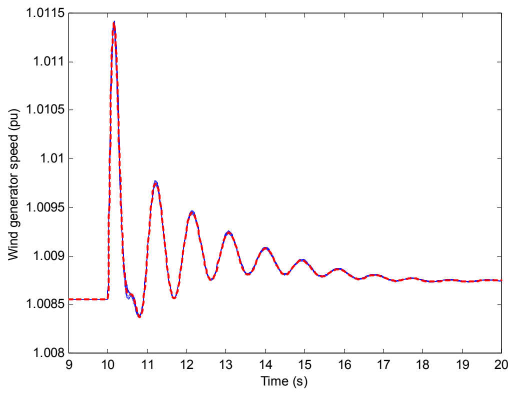


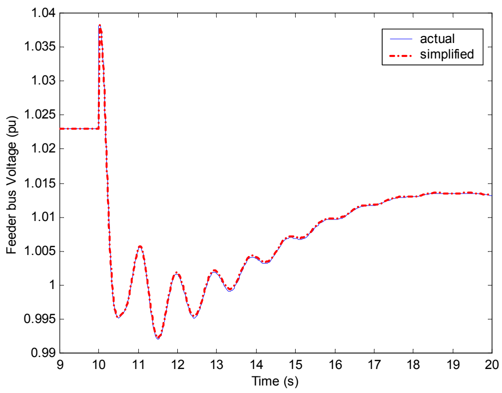
Figure 5: One-line equivalent diagram of simplified Evia Island electrical network

The local synchronous generators are equipped with Over Excitation Limiters of constant excitation type (takeover [12]) and constant time delay equal to 30 s. In addition, note that throughout the following analysis, two parallel equivalent transmission lines of 150 kV are considered to represent the interconnection of Evia Island network to the mainland.
For the operating condition under study we note that the Greek Interconnected Power System absorbs active power from the Evia Island network and supplies the latter with reactive power.
The comparison between the exact and the reduced electrical system will be achieved by simulating the network response under a single contingency and a crucial double one.
Note that during the simulation we are not taking into account any over-speed protection of the wind generators, which would activate and disconnect them from the network.

4.1 Case B1: Single Contingency
In this case, we assume that there is loss of the one parallel equivalent interconnection line (shown with dashed line in Fig. 5) at t=10 s. The simulated response of Karystos subsystem, for both full and simplified Evia Island network, is shown in Fig. 6-(a) and 6-(b).



(a) Wind generator speed



(b) Evolution of feeder bus Voltage

Figure 6: Karystos area response under single contingency (Case B1)

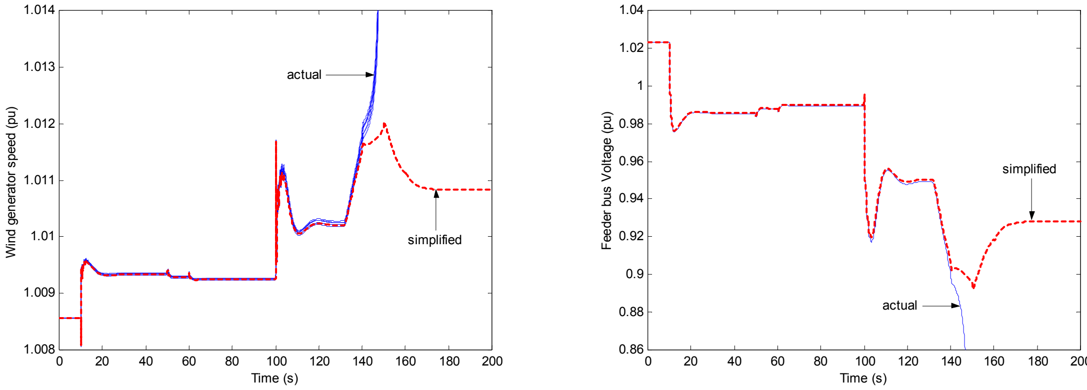
At first, note that the loss of the interconnection line reduces the imported reactive power from the mainland, leading to reduction of bus voltages. The latter reduction results in acceleration of wind generators, as shown in Fig. 6-(a). However, all wind generators reach a stable short-term equilibrium point after some oscillatories. These oscillations are due to the electromechanical mode between the synchronous generators and the external system.
Concerning the long-term response, the reduction of bus voltages activates the LTC mechanisms, which are trying to restore the respective controlled voltages. Finally, the system reaches a stable operating point.
The above figures prove that there is an excellent match of responses between the full and the simplified network. However, note that the simplified system withstands more easily the examined contingency than the full one. This comparison verifies that the proposed simplification technique provides an optimistic approximate equivalent network.

4.2 Case B2: Double Contingency
In this part we simulate the response of Evia Island network under a double contingency, which consists of the following sequential disturbances:

- At t=10 s, there is an outage of the local synchronous generator G2.
- At t=100 s, there is loss of the one parallel equivalent interconnection line.

The response of Karystos subsystem in this scenario is shown in Fig. 7-(a) and 7-(b).
At first, note that both systems withstand in a satisfactory way the local generator G2 outage and despite the voltage drop, reach firstly a stable short-term equilibrium for the wind generators and after the LTCs activation a long-term stable operating point.
As shown in the above figures, the responses of two networks under the first disturbance are close and similar enough.
Following this, the loss of the interconnection line reduces the imported reactive power from the mainland and as a result leads to a reduction of both systems' voltages. Although this fact results in acceleration of all wind generators, they reach a stable short-term equilibrium point. At the same time, the remaining local generator G1 becomes overexcited, while trying to maintain the reactive power balance of the system.
This results to the activation of the OEL system (130 sec after the beginning of simulation) that reduces the rotor current to the maximum allowed value and consequently reduces again all bus voltages. This new reduction accelerates again the wind generators. In case of full Evia Island network, no wind generator can reach a short-term equilibrium point after the rotor current limitation of generator G1, leading to system collapse.

On the other hand, in the reduced model, instability of WFs (loss of short-term equilibrium) after the OEL activation is delayed, so that a tap change at simulated time t=150 s is able to save the system. Hence, the approximate equivalent network is optimistic again.



(a) Wind generator speed (b) Evolution of feeder bus Voltage

Figure 7: Karystos area response under double contingency (Case B2)

Consequently, the validity of the proposed methodology is uncertain in cases, where the full network has reached or exceeded its stability limits.

5 CONCLUSIONS

In this paper, we presented a methodology to simplify a distribution network, which consists of a number of WFs equipped with induction generators, which are connected to the transmission network through MV distribution lines and a common MV/HV substation. The simplified system consists of an equivalent WF and an approximate equivalent MV feeder.
The proposed technique reduces the complexity of the Power System, especially in cases with distributed generation. This reduction allows faster simulation times in various applications, such as security assessment and stability analysis. However, note that with the proposed simplification we cannot simulate the response of the network under disturbances occurring inside the simplified part of the network.
The presented methodology was first applied to the distribution system of Karystos network, a subsystem of Evia Island electrical system. In cases of small disturbances, tests have shown an excellent match of responses. However, for crucial contingencies, the results are less accurate and the simplified network provides a rather optimistic response.
These conclusions were also verified in the case of whole Evia Island network. Specifically, the responses of both full and simplified networks were simulated under a single contingency a credible double one.
In the case of single contingency, the responses of both systems provide an excellent match. Hence, for not serious disturbances, the application of the proposed technique leads to accurate enough results in shorter simulation times, comparing to those required for the full network.
However, in the case of the crucial contingency, the full network was proven to be short-term unstable after the second disturbance due to wind generator over-speed, while the simplified system reached a short-term equilibrium point. This difference was focused on the fact that the full system had just met its limits, while the approximate equivalent network is being more optimistic.
Therefore, as long as the examined disturbances leave enough short-term stability margin (as measured for instance by the critical clearing time), the approximate reduced network provides a very fast and accurate way of simulating the system. However, for disturbances within for instance 10% of the critical clearing time, the aggregate model gives unduly optimistic results.
The optimism is inherent in the aggregate model, since the loss of equilibrium of one wind generator will initiate a cascade of similar events to the nearby machines. This observation must be taken into account when designing more accurate aggregate induction machine models.

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`REFERENCES

1. V. Akhmatov, H. Knudsen, "An Aggregate Model of a Grid-connected, Large-Scale, Offshore Wind Farm for Power Stability Investigations – Importance of Windmill Mechanical System", International Journal of Electrical Power & Energy Systems, Vol. 24, pp. 709-717, November 2002.
2. V. Akhmatov, H. Knudsen, A. H. Nielsen, J. K. Pedersen, N. K. Poulsen, "Modelling and Transient Stability of Large Wind Farms", International Journal of Electrical Power & Energy Systems, Vol. 25, pp. 123-144, February 2003.
3. Rui M. G. Castro, J. M. Ferreira de Jesus, "An Aggregated Wind Park Model", 13th PSCC, June 28th – July 2nd 1999, Trondheim.
4. C. D. Vournas, G.A. Manos, E. G. Potamianakis, J. Kabouris, "Voltage Security Assessment of Greek Interconnected Power System with Large Wind Penetration", EWEC, Copenhagen, Denmark, July 2001.
5. E. G. Potamianakis, C. D. Vournas, "Modeling and Simulation of Small Hybrid Power Systems", to appear in IEEE Power Tech, Bologna Italy, June 2003.
6. P. Kundur, "Power System Stability and Control", McGraw-Hill, 1993.
7. T. Van Cutsem, C. D. Vournas, "Voltage Stability of Electric Power Systems", Kluwer Academic Publishers, 1998.
8. Siegfried Heier, "Grid Integration of Wind Energy Conversion Systems", John Wiley & Sons.
9. P. C. Krause, O. Wasynczuk, S. D. Sudhoff, "Analysis of Electric Machinery", IEEE Press, New York 2000.
10. P. W. Sauer, M. A. Pai, "Power Systems Dynamics and Stability", Prentice-Hall, 1998.
11. J. Machowski, J. W. Bialek, J. R. Bumby, "Power Systems Dynamics and Stability", John Wiley & Sons.
12. C. D. Vournas, G. A. Manos, P. W. Sauer, M. A. Pai, "Effect of Overexcitation Limiters on Power Systems Long-Term Modeling", IEEE Transactions on Energy Conversion, Vol. 14, No 4, December 1999.