Induction Generator Models
In Dynamic Simulation Tools

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Abstract: **For AC networks with large amounts of induction generators - e.g. in the case of windmills - the paper demonstrates a significant discrepancy in the simulated voltage recovery after fault and fault clearing in weak networks, when comparing result obtained with dynamic stability programs and transient programs.**
The reason for the discrepancies are explained, and it is shown that the phenomenon is important when the machine inertia H is small. It is shown that it is possible to include a transient model in dynamic stability programs and thus obtain correct results also in dynamic stability programs.
A preliminary investigation indicates that the shape of the voltage recovery curve also is very much dependent on how the rotating system is represented. There are remarkable discrepancies in the first second following a fault clearing, depending on whether the shaft model is a lumped model or consists of two or more separate masses connected by a shaft.

Keywords: Induction machines, transient models, dynamic models, PSS/E, EMTP, ATP, windmills, shaft models.

I. INTRODUCTION

Wind power has gained importance in Denmark over the last years, and in the years to come it is going to become even more important. Today, in the east Danish system there is a total installed capacity of 300 MW, and the expected installed capacity in the year 2008 is approx. 1000 MW. The long term perspective is above 2000 MW in the year 2030. The major part of the expected new wind power capacity will be in the form of new off-shore wind farms.

The mentioned amounts of power should be seen relative to the peak load in the system on a typical winter week day, which - today - is approx. 3000 MW, and relative to the low load on a typical summer week night, which is approx. 750 MW.

Because of this expected enlargement of the installed wind power capacity it is necessary to perform extensive system studies to make sure that all dimensioning criterias are going to be fulfilled also in the future. And in order to perform such studies it is obviously necessary to have good models of both the windmills, the windmill generators, and of the AC network to which they are going to be connected.

II. MODELLING CONSIDERATIONS

The work described in this paper is only a part of a larger windmill model development effort. This paper will focus on the development and implementation of a transient induction generator model for dynamic stability simulation programs. However, for the sake of completeness a quick overview of the entire windmill model is also given here.

A windmill - when seen all the way from the incoming wind and to the 3-phase connection point to the AC network - can be represented by the modular block diagram in Fig. 1. Each block represents a part of the entire windmill construction, which - except for the shown connection points - can be represented independently from the other parts.
The first block represents the relation between the incoming wind, the rotational speed of the wind turbine, the pitch angle of the wind turbine blades (optional), and the mechanical shaft torque from the wind turbine.
The second block represents systematic disturbances arising from the mechanical construction of the windmill. The most important of these are the tower shadow effect, and (what is considered to be) mechanical oscillations of the blades.
The third block represents the mechanical shaft of the wind turbine, the gear, and the generator rotor mechanical system, including the connecting shaft pieces.
The fourth block represents the generator. Depending on the choice of technology they can be either synchronous or induction generators. In Denmark – as in many other countries – induction generators are traditionally used.

Depending on the kind of studies being performed some of these blocks may be either omitted or reduced, if they do not have any impact on the phenomena under consideration.

In [1] an empirical model of the windmill itself is described. That model basically covers all the mechanical parts of the windmill, from the incoming wind to the mechanical shaft torque; i.e. the first three blocks in Fig. 1.
This paper will focus on the rest of what is in the diagram; i.e. modelling of the generator itself.

III. CHOICE OF GENERATOR TYPE

In the south-eastern part of Denmark 3 off-shore wind farms of each about 150 MW, totally 450 MW, are going to be commissioned in the years 2002, 2005, and 2008.

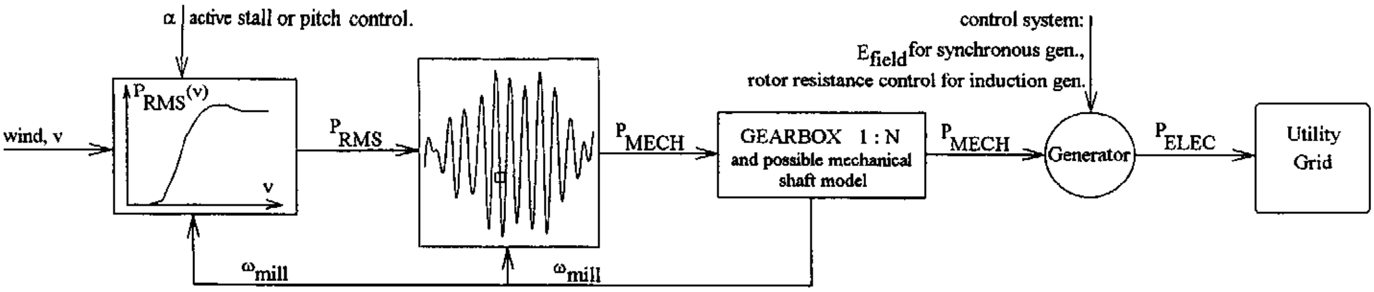

Fig. 1: Windmill model block diagram.

As there is a strong wish only to use robust, low-maintenance, and well-known technology in these first off-shore projects the generators in these windmills are going to be induction machines, connected via step-up transformers and sea cables to the nearby 132 kV transmission network.

IV. FORESEEABLE PROBLEMS

Since this region is a relatively long distance away from the main production and load centres in the north of the east Danish power system, the windmills are going to feed into a relatively weak network, where the short circuit capacity is in the order of up to 3000 MVA; i.e. an approximate ratio of 3000 MVA / 450 MW ≅ 6.7.

Preliminary studies have indicated, that the combination of a weak AC network and a high amount of power from the windmills will make voltage collapse following faults and fault clearings in the 132 kV net the predominant dimensioning factor in this region in the years to come.

V. MODELLING PROBLEMS

Since comparisons between simulation results from a traditional dynamic stability program (in our case PSS/E) and measurements on real induction machines had hinted at some discrepancies in the reactive power consumption of the machines under abnormal voltage conditions it was decided to undertake a comparative study between a dynamic model (CIMTR3 in PSS/E) and a full transient model (UM3 in ATP) using a very simple AC network consisting of an infinite source, a line, and an induction generator; see Fig. 2. The induction machine MW rating was 0.5 MW, and the short circuit capacity in the connection point was 4.0 MVA; i.e. an approximate ratio of 4.0 MVA / 0.5 MW ≅ 8.

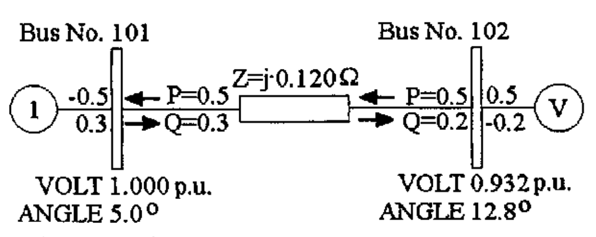

Fig. 2: Simple AC network.

The simulated event was the same in the two programs; a 100 ms fault applied at the terminals of the induction machine, and the 3-phase rms terminal voltage before, during, and after the fault was monitored. The simulation results for this are shown in Fig. 3a and 3b.

The results were quite disturbing. As can be seen the voltages are quite different, when focusing on:

a) the voltage immediately following the fault clearing - 0.745 p.u. vs. 0.767 p.u.
b) the voltage dip after the fault clearing - 0.064 p.u. vs. 0.02 p.u., and
c) the recovery time, until normal voltage had been restored - 600 ms vs. 400 ms.

The discrepancies were so remarkable, that continued system planning investigations based on the traditional dynamic induction machine models were put on hold, until a closer investigation had been performed.

VI. CAUSE OF THE PROBLEM

Investigations and discussions performed together with the supplier of the dynamic simulation program made it clear that the discrepancies were due to the fact that the DC offset in the stator - and the thereby associated braking torque immediately following the fault - are ignored in the machine models for dynamic stability programs. To our knowledge this is a general problem in induction machine models in most dynamic stability programs.

The reason for ignoring DC offset and other stator transients are given in e.g. [2], and can be outlined as follows:

In a dynamic stability program the instantaneous phase values have been replaced with fundamental frequency phasors which - during a dynamic simulation - only change relatively slow when compared to the period time of the fundamental frequency. However if DC offset were included in machine models then they would appear as a fundamental frequency variation of the phasors, thus making it necessary to have a much smaller time step in the simulations. For that reason it is desirable to disregard stator transients.

Since the effect of a DC offset is that the additional DC current gives an accelerating torque in one half-period of the fundamental frequency and a decelerating torque in the next half-period then the net effect is almost nil. Therefore it is an acceptable assumption to disregard DC offset.

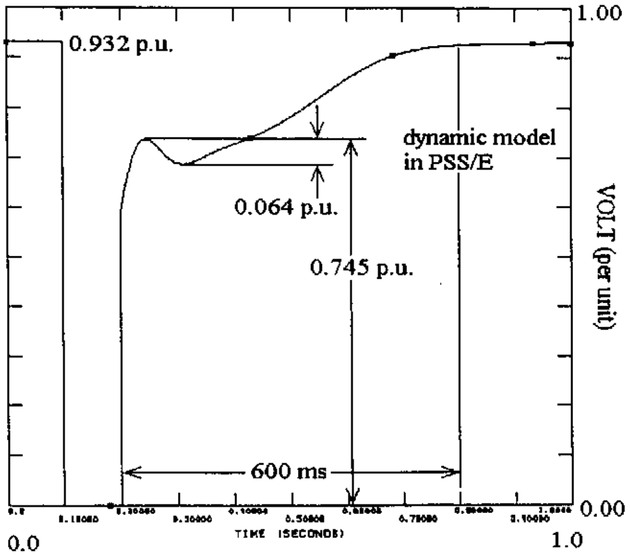

Fig. 3a: RMS voltage with standard dynamic stability program induction generator model.

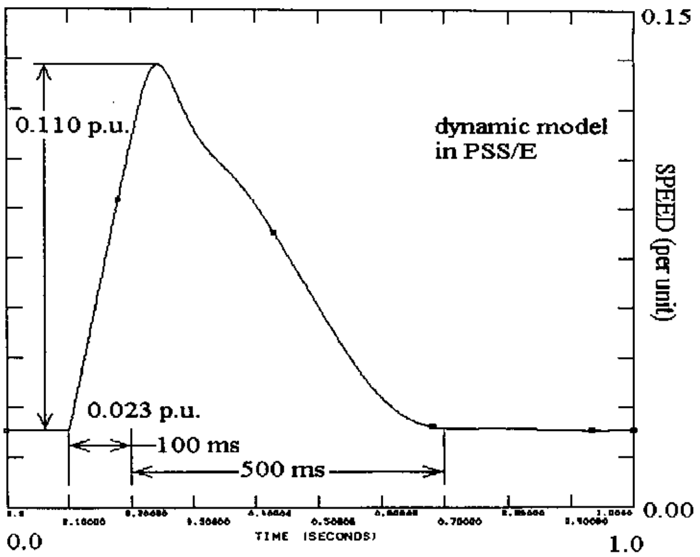

Fig. 4a: Speed variations with standard dynamic stability program induction generator model.

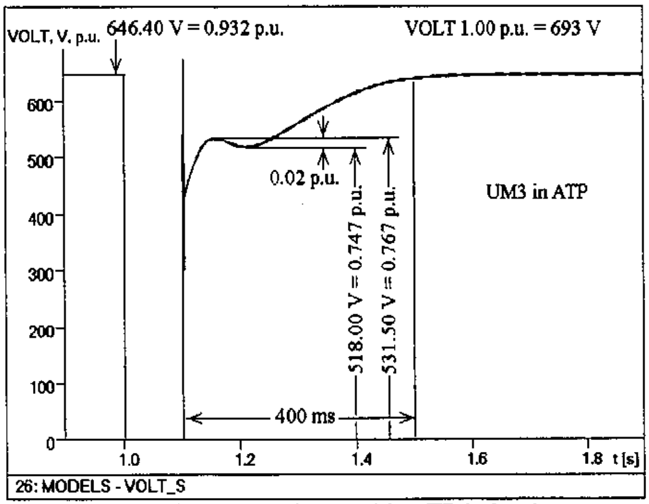

Fig. 3b: RMS voltage with ATP induction machine model (UM3).

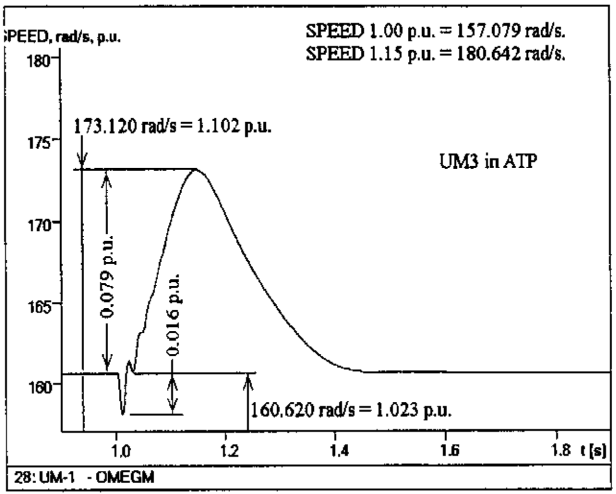

Fig. 4b: Speed variations with ATP induction machine model (UM3).

Now, this reasoning has been derived for synchronous machines, for which there is no doubt that it is correct. It is basically an evaluation of the average speed variations and thereby of the active power coming out of the machine.
However when proceeding to implementing induction machine models in dynamic stability programs the same assumptions seemingly has been accepted without further questions. At least according to [2] there is no indication that additional considerations have been made; the same assumption of disregarding the stator transients has been applied without further explanations.

The effect of disregarding the stator transients is quite clear when looking at the rotor speed curves in Fig. 4a and 4b. The consequence of the initial braking torque is that the machine enters the transient with a speed, which is different than the speed which is obtained when using the classical induction machine model in a dynamic stability program.

Considering the fact that the reactive power consumption of an induction machine is dependent on the slip then it is hardly surprising that ignoring a component which has an effect on the speed can lead to remarkable discrepancies in the voltages; especially when the AC network is weak.
The same explanation also explains why this problem only is relevant for induction machines; synchronous machines have a separate source of excitation, so for synchronous machines the reactive power is much less dependent on the instantaneous speed of the machine rotor.

VII. SOLUTION TO THE PROBLEM

Because of the discrepancy in the simulation results between the dynamic and the transient model it was decided to implement a transient model of an induction generator in a dynamic stability program. The model was described directly 'by the book' in accordance with e.g. [2], and was implemented in PSS/E using MODELS [3].

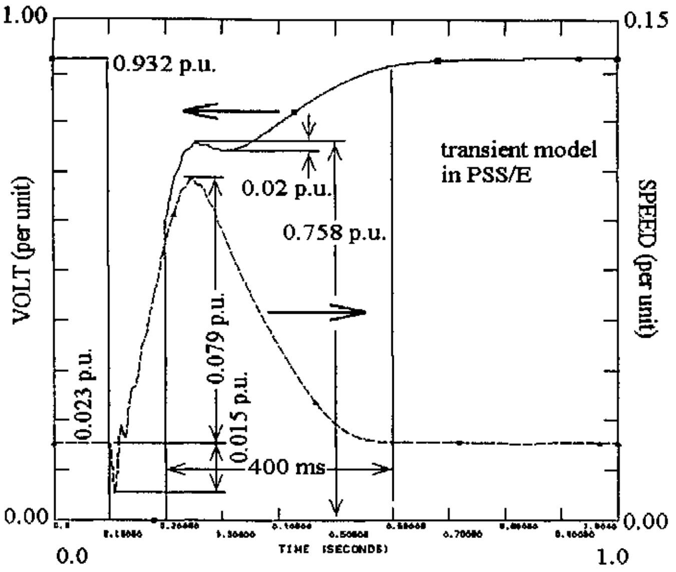

Fig. 5: RMS voltage and rotor speed with new induction machine model (ASGEN2).

When interfacing a transient model into a dynamic stability program, it was necessary to acknowledge the constraint of dynamic stability programs, where stator transients must be ignored. The reason for this is that the network solution in each time step is a load flow solution, which is based on the assumption, that all electrical transients in the network are extinguished. Thus the stator transients are only represented internally in the machine model, but this is also enough to secure that DC offsets are taken correctly into account.
A simulation of the same event with this new model resulted in an almost perfect agreement with the ATP results; see Fig. 5.

VIII. SIGNIFICANCE OF DC OFFSET

Now, having a valid model of an induction machine with correct representation of DC offset the next step was to estimate the significance of the phenomenon. For that purpose a simplified equivalent (10 nodes and 4 generators) of the east Danish network was established, and a large induction generator, representing a wind farm, was connected to the remote end of the system, parallel to an (equivalent) 1400 MVA unit. The short circuit capacity of the rest of the network was approx. 4000 MVA.
The size of the induction generator was increased in steps from 100 MW to 600 MW in such a way that the sum of the powers, respectively the MVA ratings of the induction generator and the synchronous generator together was kept constant at 1100 MW, respectively 1400 MVA. The inertia constant of the induction generator was assumed to be 0.48 s, corresponding to a typical value of an induction machine rotor.

The results are shown in Fig. 6 and 7, and as can be seen the new model shows that - in this network configuration - it is possible to connect an induction generator with a generating capacity of between 100 and 150 MW more than what would have been shown by the traditional model.

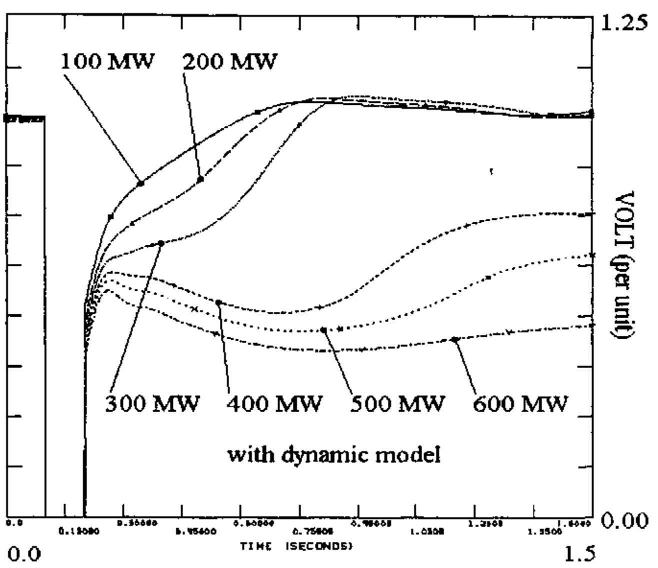

Fig. 6: Standard model.

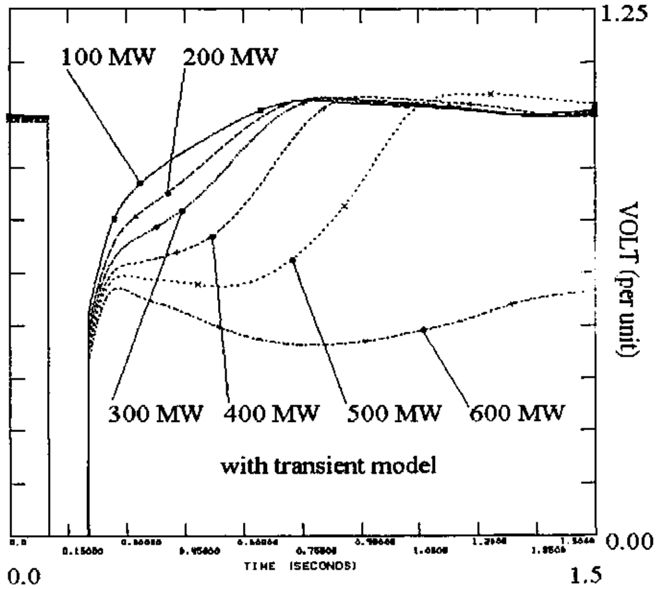

Fig. 7: New model with DC offset.

IX. SIGNIFICANCE OF INERTIA CONSTANT

The previous investigation showed that when only the inertia of the induction machine rotor itself is considered then the impact of including or ignoring DC offset is quite large. Now, in most cases the rotating system consists of more than just the rotor, and since the main reason that the DC offset causes a difference voltage response is the initial difference in the rotor speeds, as shown in the Fig. 4a and 4b, then the differences must be expected to become less distinct when the inertia becomes larger, and the initial speed difference thereby becomes smaller.
Therefore the same test as before was used with a power of 500 MW, which with the classical model caused a voltage collapse, but which recovered (slowly) with the transient model. The test was to increase H, thus decreasing the speed change caused by the initial DC offset torque, and observe at

what value of H the two voltage curves would start to converge. For comparison, typical inertia constants for windmills are in the range around 2.5 s, so - when including the generator rotor - the total inertia is somewhere around 3 s.

As can be seen in Fig. 8 the curves starts to converge when H reaches approx. 1 s and is almost fully converged when H is around 3 s. This means that in most practical applications where there is a - when compared to the induction machine rotor inertia H_{rot} - relatively heavy rotating mass connected to the machine shaft, the classical model will produce almost correct results. It is only when the inertia becomes rather low - 1 s or less - that it is necessary to use a detailed model.

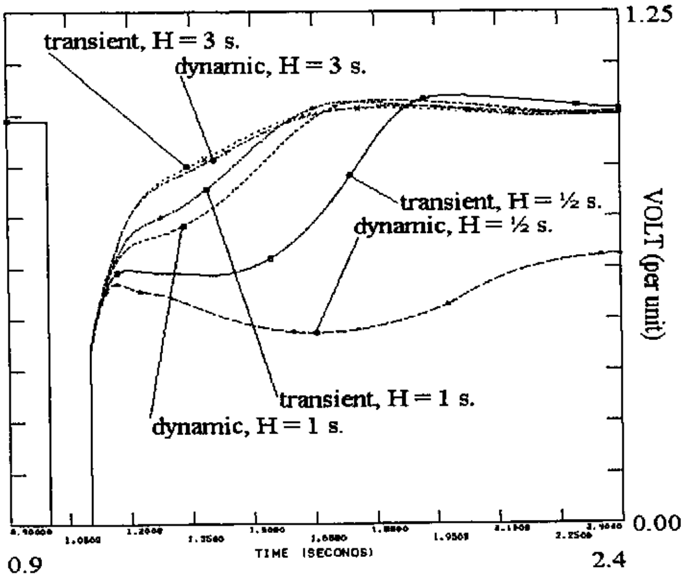

Fig. 8: Model comparison - with varying inertia constants.

X. SIGNIFICANCE OF SHAFT MODEL

In all the investigations performed so far, only a lumped element representation of the inertia of the rotating system has been considered. However, all rotating shaft systems are divided into sections, and - as the typical numbers above showed - for windmills it is the mill itself which is quite heavy, whereas the machine rotor is light. And since the rotor is light then it might still go through large speed variations when there is a large disturbance occurring in the AC network, even though the windmill itself maybe is not accelerated very much. It is only the stiffness of the shaft connecting these two rotating masses which limits the speed deviations between the rotor and the windmill.

The shaft has a finite stiffness. As mentioned in [1] typical values of the eigenfrequencies of such systems are in the range 1-2 Hz, and for a specific Danish windmill the eigenfrequency is known to be 1.67 Hz. Using this value together with the known inertia constants it is possible to calculate the shaft stiffness k_{shaft}.

The MODELS code of the induction generator model was easily modified to accommodate a multi-mass rotor system, and - going back to the simple network equivalent of Fig. 2 - the same fault event was simulated again, but this time with a lumped mass with H = 3 s, respectively with a shaft system with two lumped masses of H_{rot} = 0.5 s, H_{mill} = 2.5 s, and k_{shaft} = 0.27 pu/rad. The results in terms of terminal voltages and rotor speeds are as shown in Fig. 9a and 9b.

As can be seen the differences in voltage is quite remarkable, and since stability is often either lost or maintained in the first short periods following a disturbance then these differences may be quite important when performing network stability studies with large amounts of wind power in the network. However further investigations on this topic have not been performed so far.

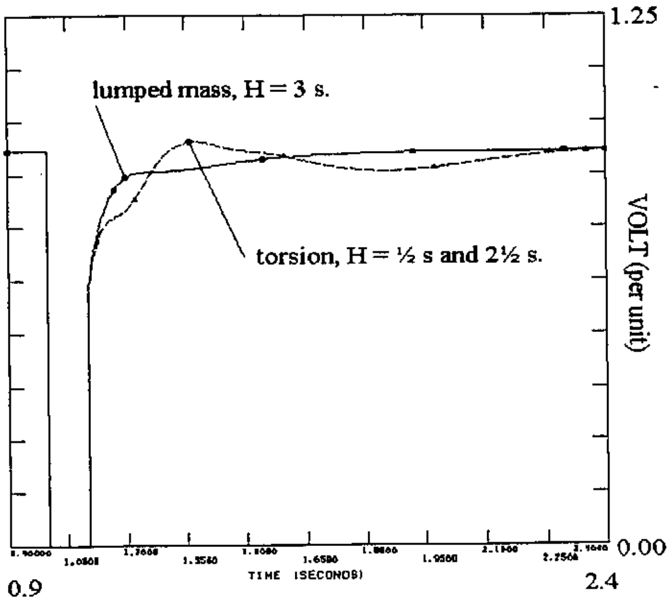

Fig. 9a: Significance of shaft model – voltages.

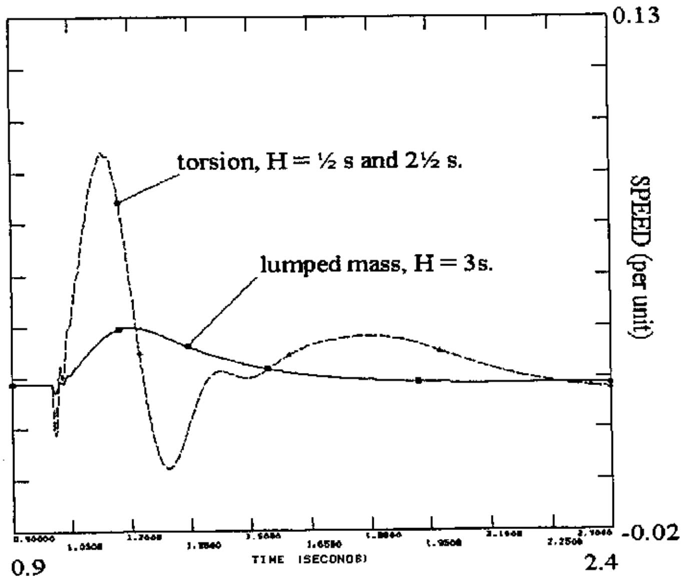

Fig. 9b: Significance of shaft model - speeds.

XI. CONCLUSIONS

Investigations have shown that DC offset in an induction machine is significant for a correct representation of the rotor speed and thereby also for reactive power consumption and machine terminal voltage during and after disturbances in the network. The significance is larger the smaller the inertia constant H is. For values of H larger than 3 s it seems to be almost without importance, whereas for values of H below 1 s it is very important.
When the inertia constant H is large the classical induction machine model in dynamic stability programs is valid, but not for the reasons normally assumed. Those reasons only apply to synchronous machine models, and the method for synchronous machine modelling seems to have been applied for induction machine models as well without further considerations.

Note also that all the above examples have assumed generator operation of the induction machines, because the main topic of the studies was stability studies for future wind farms. In these cases disregarding the initial braking torque of the DC offset can be considered to be a conservative assumption, since the stability was better when the DC offset was included; but, on the other hand, if motor operation were to be assumed then disregarding of the DC offset is actually an optimistic assumption.

Finally it is noted that the voltage response of an induction generator with a torsional shaft model seems to be remarkably different from the same generator with a lumped mass model, when simulating disturbances in the vicinity of the induction machine.

Further investigations are needed to decide whether or not this phenomenon has an impact on system stability in networks with large amounts of induction machines.

In conclusion it should be said that when using simplified models - such as e.g. a classical induction machine model or a lumped mass model of a shaft system - then great care should be taken in verifying that the assumptions, under which the simplifications are valid, indeed are fulfilled in the situation at hand.

Otherwise a lot of simulation work may - at best - be wasted, and - at worst - be more or less misleading. And, if these assumptions are not known, then it may be better to use full transient models - with typical data, if the actual data are not available - just to make sure that the work is not worth-less because of unfulfilled basic assumptions.

XII. REFERENCES

[1] V. Akhmatov & H. Knudsen,'Dynamic modelling of windmills.', IPST'99, International Power System Transients, 1999, Budapest, Hungary.

[2] P. Kundur, 'Power System Stability and Control', McGraw-Hill Inc., ISBN 0-07-035958-X

[3] L. Dube, 'User Guide to MODELS in PSS/E', DEI Simulation Software, August 1998.