

Study of the Influence of Induction Motor Models on Dynamic Stability of a Power System

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Abstract: The influence of power system load on dynamic stability is significant. However the load is not sufficiently modeled yet because of its complex nature. It is known that a major portion of load is induction motors. Thus induction motor is sometimes used as the dynamic part of load model. In this research, induction motor model suitable for dynamic stability study is investigated. The induction motor implemented in rotor speed based frame has been newly utilized instead of commonly used frequency based frame. A comparative study of the transient and steady-state stability of the power system has been performed under different model application. It is clarified that third order model implemented in rotor speed based frame is the most suitable one for dynamic stability studies. In addition, some requirements for load model are clarified.

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Chapter 1 Introduction

The catastrophic consequences of the blackouts have necessitated the proper planning and operation of the power systems to ensure the stability. Stability analysis is the key for power system planning. The results of the stability studies depend on the accuracy of the load models used.

Load modeling is very difficult task as the loads are characterized by their randomness, their statistical nature and different timescale properties. The load models should be updated according to the growth of the loads and the changes in the system configurations. The dynamic part of the load models are represented by the induction motor dynamics. Although a number of induction motor models are available, the properness of the available models still needs to be investigated.

This research primarily investigates on the selection of the best induction motor model for the analysis of power system stability. The discontinuity problem associated with the induction motor models based on system frequency based frame (ω_e -frame model) has been pointed out and alternatively, the utilization of model in rotor speed based frame (ω_r -frame model) has been proposed. The fifth order, third order and the first order models have been compared in terms of power system stability assessment. The results show that the lower order models give more optimistic results. In addition some load model requirements are discussed.

Chapter 2 Comparative Study of Induction Motor Models Using Singular Perturbations

The three models of the induction motors have been compared i.e. the fifth order, the third order and the first order models. The fifth order model has set of five dynamic equations; two for stator d, q axis voltages, two for rotor voltages and one for rotor inertia. The third order model has two rotor dynamic equations and one rotor inertia dynamic equation. The stator flux dynamics is neglected and the stator voltage equation is represented by algebraic equations. The first order model has the dynamics of the rotor inertia only. The stator and rotor voltage equations are the algebraic equations. The responses of these three models are obviously different.

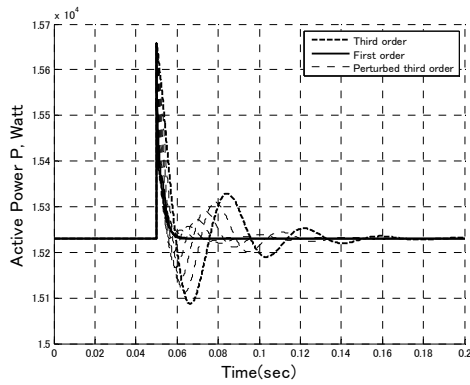


Fig 1: Perturbation to Third Order Model

The timescale properties of the stator flux dynamics, rotor flux dynamics and the rotor inertia dynamics are different. So, the singular perturbation theory can be applied to the approximation of induction motor model. We define a perturbation parameter ϵ that changes the timescale of the dynamics.

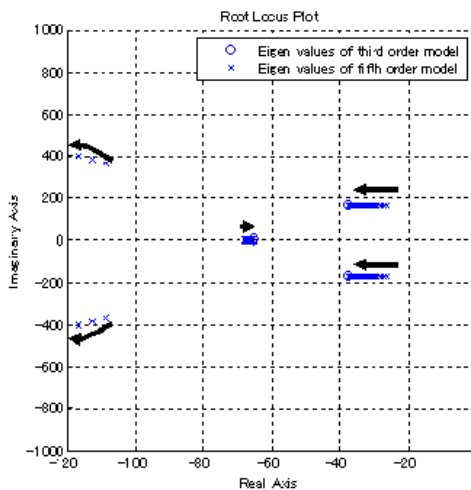


Fig 2: Root-locus for perturbation applied to the fifth order model

The responses of the fifth order model approach that of the third order model as the perturbation parameter approaches zero. Similarly, the responses of the third

order model approach that of first order model as the perturbation parameter approach zero. The case for the voltage disturbance is shown in Fig 1. Going from the higher order to the lower order model, eigenvalues shift towards the left in root-locus plane confirming the optimistic nature of lower order models as shown in Fig 2.

Chapter 3 Models of Induction Motor for Stability Studies

Many researchers have utilized the ω_e -frame induction motor model for stability analysis. However, this model has a problem of discontinuity of state variables if the phase angle of the system changes in step manner (Fig 3). This is the result of the improper definition of the coordinate system. To eliminate this problem, the utilization of model in ω_r -frame, which is the coordinate system based on the rotor speed of induction motor, is proposed. This implementation would be similar to the implementation of synchronous machines (Fig. 4).

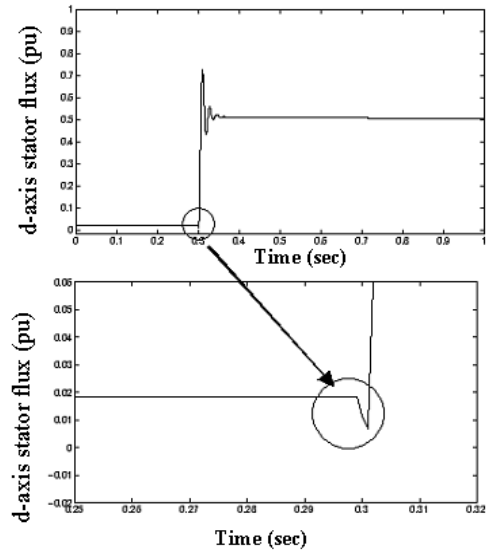


Fig 3: Discontinuity of flux

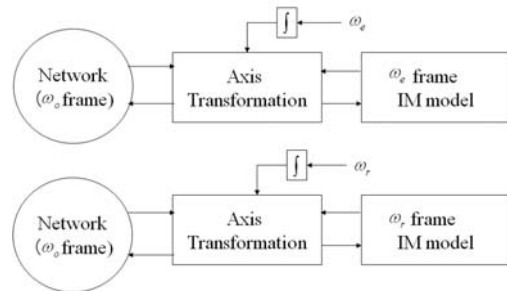


Figure 4: Implementation of ω_e and ω_r frame models

It is common practice to neglect the effect of the system frequency variation on the network elements. For stability analysis, the generators and the induction motor models are built on constant system frequency framework. The ω_e and ω_r frame models under study are approximated by the constant system frequency. These models have been compared with the ω_e -frame

model without approximation i.e. the model under variable frequency framework. The coordinate system is defined as shown in Fig 4. The comparison is shown in Fig 5. The 1% disturbance in frequency is applied at 0.3 [s]. The response of the rotor speed is observed. It is obvious that the ω_r -frame model has the similar response with the ω_e -frame model without approximation. The approximated ω_e -frame model has steady state deviation in the rotor speed. This error arises due to the mismatch of the coordinate system of the ω_e -frame model and the deviated system frequency. This confirms the superiority of ω_r -frame model over the ω_e -frame model.

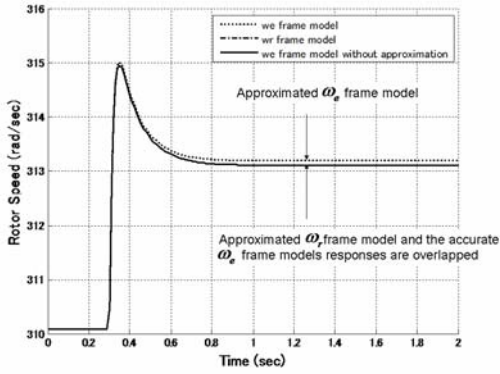


Fig 5: Comparison of ω_e and ω_r frame models

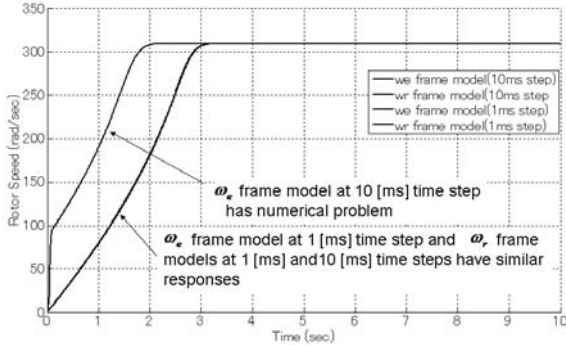


Fig 6: Comparison of ω_e and ω_r frame models with different time steps

For the small time steps (1 [ms]), the startup responses of ω_e and ω_r frame induction motor models are similar. Fig 6 shows the comparison of the startup responses of ω_e and ω_r frame models with 10 [ms] time step and then ω_r -frame model with 1 [ms] time step. The responses of ω_r -frame model with both the 1 [ms] and 10 [ms] time-step are same. But, the response of ω_e -frame model with 10 [ms] time step is different. So, ω_r -frame model is invariant of the time step chosen. So, ω_r frame model is more accurate than ω_e frame model over the varying simulation conditions.

Chapter 4 Construction of Stability Simulator

A three machine nine bus system has been selected for the model comparison. There are three load buses. Each load bus is loaded by static loads and induction

motor loads in varying proportion. The synchronous generators are implemented as Norton's current injectors into the system. The stator flux dynamics of the generators are neglected. Due to the difference in the values of d and q axis inductances, there are dynamic variations of the generator transient impedances as seen from the network. The effect is called sub-transient saliency, which is fully considered in the simulation. In addition to the current injection, dynamic transient admittances are also updated into the network subsystem. The transmission lines and the static loads are modeled by equivalent Y-bus.

The simulation is carried out in MATLAB/SIMULINK package. The initialization tasks are done by using MATLAB script file. The step-by-step simulation is carried out by SIMULINK model. The integration method chosen is Dormand-Prince method and the time-step chosen is 10 [ms].

Chapter 5 Comparative Study of the Power System Stability

The responses of the bus voltages for the implementation of different induction motor models have been compared. The responses are obviously different. As the proportion of the induction motor increases, there are further differences among the responses. The transfer capability of the line is measured in terms of loading level. The transfer capability of the line is decreased if the ratio of motor loads is increased (Table 1). The implementation of the lower order model gives the higher loading level than the implementation of the higher order models. Furthermore the presence of induction motor loads degrades the voltage stability of the bus. The bus voltage goes unstable even if the generator rotor angle is within stability limit.

Table 1: Load Levels for stability limit

	Load Level	
Model	30% Motor	50% Motor
Fifth Order	1.073	0.750
Third Order	1.198	0.869
First Order	1.271	0.882
Static Loads	1.781	

The steady state stability has been assessed by the comparison of eigenvalues. The eigenvalues that have poor damping and the significant oscillatory frequency are significant for stability analysis (Fig 7). These eigenvalues have been computed for the load level of 100% and the induction motor ratio of 30%.The comparison shows that the higher order models have more poorly damped oscillations. The first order model implementation gives the most optimistic stability solution. The eigenvalues of the third order model shows the stability margin similar to the fifth order model. It should be noted that the static load model results in the most conservative result.

The nonlinear behavior of the induction motor in

power system stability has been studied by comparing the maximum loading level of the line with various motor ratios. The result is shown in Fig 8. It can be observed that the lower order models show the higher loading level of the line. The relationship between the loading level and the motor ratio is nonlinear. Also the nonlinearity of the third order model and the fifth order model is very similar. The first order model shows the similar behavior up to certain motor ratio after which it gives comparatively more optimistic result.

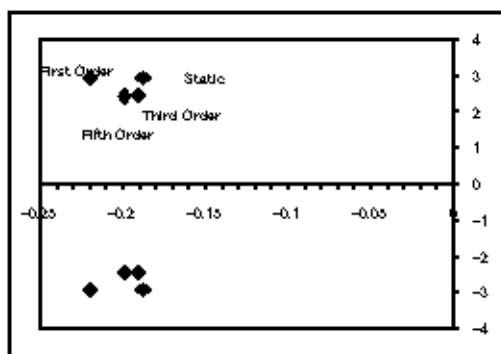


Fig 7: Comparison of eigenvalues

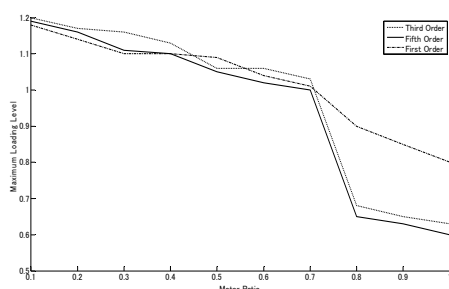


Figure 8: Comparison of nonlinearity of the induction motor loads

The comparison of transient responses, the eigenvalues and the nonlinearity of the induction motor loads shows the third order model is the best model for stability studies. As compared with the first order model, the third order model has very similar response with the fifth order model. Fifth order model is the most accurate one as it employs the least approximations in the modeling.

Chapter 6 Load Modeling Considerations

The survey of literatures on load modeling shows that there are two kinds of load models used in practice. The first one is the “Induction Motor Based Load Model” in which a motor in combination with the ZIP or exponential load is used. The other is the “General Load Model” based on the measurable bus quantities. This model is expressed in the form of mathematical subsystem, e.g. transfer functions. This model is built by measurement data. Since power engineers prefer to play with the measurable bus quantities such as voltage, frequency, active power and reactive power, the general load model is widely preferred.

Conventionally single input load model is being used in power system stability simulations. However, some dynamic response is observed for $\Delta\delta$ input in the third order model of induction motor as explained in Chapter 3. We propose to use the Two-Input load model with voltage magnitude and angle input so as to achieve a proper model of induction motor. Regarding the choice of the best model, we recommend to use the third order model as it can be modeled for two-input. The third order induction motor model is implemented as Norton’s equivalent (Fig 9).

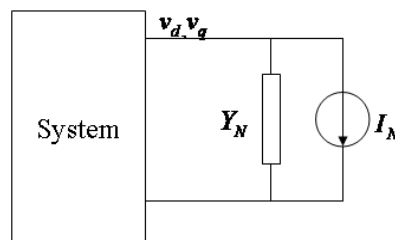


Fig 9: The implementation of third order model

Chapter 7 Conclusion and Future Works

The comparative study of the first order, third order and the fifth order models of induction motor have been performed under the stability simulation framework. The responses of the three models are obviously different from each other. The three models can be ‘connected’ and the lower order models can be justified under singular perturbation framework. The root-locus analysis shows that the lower order model implementation gives more optimistic stability result. When implemented in power system, the higher order model gives less power transfer capability than the lower order models. The lower order models give the more optimistic transient stability results. Also, the higher order model implementation gives more poorly damped oscillations. The steady state stability assessment results are more optimistic for the lower order models.

Another important conclusion of this study is the superiority of implementing the ω_r -frame model over the ω_e -frame model. The effect of the system frequency change on the coordinate system can be well represented by ω_r -frame. This eliminates the possible discontinuity of the state variables. The comparison in the steady state and startup responses also confirms the superiority of ω_r -frame models numerically.

In the future, the difference between ω_r -frame and the ω_e -frame model can be studied in more depth to find the all possible causes of the differences. The modeling of the induction motor models only does not complete the dynamic load modeling. The outcomes of this research can be utilized to prepare the data for the power system load modeling. In addition, nonlinear nature of induction motor could be incorporated in the load model. As explained in chapter 6, the two input load model may be developed for better load model.