# REDUCING GENERATOR MODELS DEPENDING ON FAULT POSITION

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**Abstract – This study presents a generator model reduction technique for use in transient stability analyzes. One-machine system tests showed that the other side of the transmission line connecting a generator to system was electrically distant away enough to model it with single winding model. This result implied that in a multi-machine system the generators electically close to study generator can be modelled with that model with sufficient accuracy. Tests on Turkey system verified this result.**

## I. INTRODUCTION

An important step in power system planning is the examination of dynamic and transient stability characteristics of alternative system designs. This examination generally involves the time simulation of the behaviours of many generators and their controls using a digital computer stability program. The computation cost of this process is a function of the complexity with which the power system elements are modelled.

The influence of generator modelling complexity on the accuracy of stability study results varies with many factors. The dynamic behaviour of a generator varies in a non-linear way with the electrical load on the generator. Therefore, a model chosen to represent the generator must be accurate over a wide range of operating conditions. A generator's dynamic performance also varies with the transmission system to which it is connected and the electrical proximity between it and others of comparable size in the system.

Most stability programs neglect network transients (the (d$\psi$) / (dt) terms) and their inclusion is studied in reduced order models of generator [1 – 2]. Some studies create improved reduced order models, which take into account neglected transients in amortisseur windings [3 – 4]. And some other studies clarify mathematically the underlying assumptions in model order reduction and present its theory [5 - 7].

There exist also experimental studies investigating the effect of machine modelling on the accuracy of generator swing [8 – 10]. [9] Reveals that increased model did not always result in increased accuracy of results when standard generator data used. Also, accuracy of the results between complete model and approximate models increases as the excitation level increases, and inclusion of only larger time-constant transients, $(T'_{do}, T'_{qo})$ appears to give sufficiently accurate results for use in transient stability studies.

Accuracy of approximate modeling behaviour of a generator depends on many factors, and especially on the proximity and severity of the disturbance. Therefore, the full-order model of generator is recommended under critical conditions, where the fault is very close to the machine under study, or the machine is under-excited.

In literature, many aspects of generator model reducing have been investigated, and dependence of model order choice on generator's distance to the fault has been underlined. However, a measure has not been clarified, which recommends the simplest approximate model with sufficient accuracy in case of a large disturbance at any bus.

A generator tends to be modelled in more detail as its electrical distance to the disturbance decreases. Therefore, we dealt with the generator model reduction problem relating it to the electrical distances of generators to the disturbance.

Our studies on one-machine system which was operating on the stability limits and electrically remote from the infinite bus it was connected indicated that after a disturbance on the other side of the transmission line, a generator could be represented by its 3$^{rd}$ order model which considers only those transient states in the field winding. One consequence of this result was that strongly coupled generators with the study generator which is electrically very close to the disturbance could be represented by their 3$^{rd}$ order models and other generators by their simple models. And the applications on Turkey 380 kV Interconnected System verified this.

Results showed that the rank correlation between generators, which was computed from the coherency distances we defined, was a proper measure for model reduction of generators.

## II. METHOD

In this study, we assumed that the generators were lightly over-excited, in order the excitation not to mask model order reducing behaviour of generators.

In a practical system, governor and automatic voltage regulator effects must not be neglected, but as inclusion of their effects would tend to mask the difference between the models, they were omitted for this study. For the same reason damping of the machines were also omitted.

### One-machine-infinite bus test system

A one-machine-infinite bus system, shown in Figure – 2.1, was used to investigate the effects of generator modeling of different complexity depending on the disturbance of varying electrical distance from the generator.

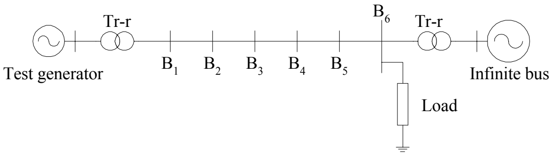


Figure – 2.1 One machine infinite bus system

The test generator was connected to the system through a transmission line of reactance fourty percent on machine's MVA base, which is a nominal line rectance for a remote generator from the system. Line reactance between two subsequent buses is 2.5 %, which corresponds a line reactance less than the shortest line in a practical system. The transformer reactance was chosen as ten percent on machine's MVA base, since short circuit voltage of a transformer is generally around twelve percent. Generator was loaded at 85 % of its rated MVA. Under these conditions the generator operates near to the critical stability limits. Critical clearing time was determined incase of a three-phase short circuit fault on the high voltage side of the transformer.

Generator behaviours of high order and approximate models were compared as follows:

Swing curves of different models of the generator were obtained upon a three-phase short circuit fault on the buses B1 – B5, respectively. Errors between the two-second curves were computed according to the following equation.

$$\varepsilon\% = \frac{\int_{t=0}^{t=2} \left|(\delta_{full}(t) - \delta_{approx.}(t))\right| dt}{\int_{t=0}^{t=2} \left|\delta_{full}(t)\right| dt} * 100 \qquad (2\text{-}1)$$

### Generator models

Generator models studied, shown in Figure – 2.2, were from the most complex to the simplest as the following:

High order model (model 3): This model included two rotor circuits in each axis. It is the most complex model used in most power system stability programs. It consisted of the field circuit plus one amortisseur in the d-axis and two amortisseurs in the q-axis.

Intermediate order model (model 2): This included a field circuit and a single quadrature axis rotor circuit.

Simple model (model 1): This model had no q-axis rotor circuits and represented by only the field circuit.

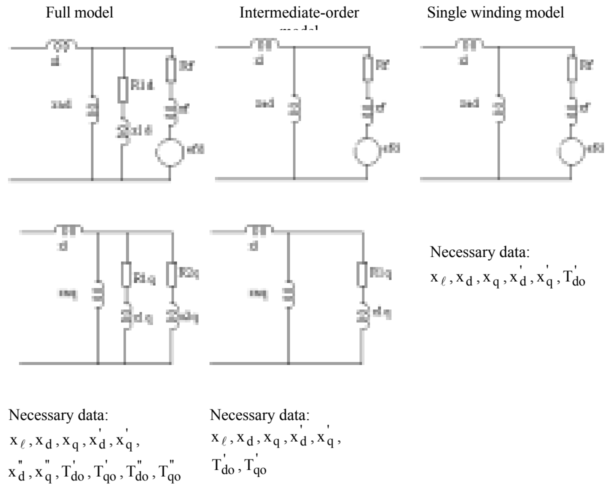


Figure – 2.2 Generator models used in this study

### Generator data

In one-machine-infinite bus system tests two turbogenerators were used, whose standard data were given in Table 2 – 1. Rated MVA of one of the machines was chosen much larger than the other in order to consider the effect of the size of the machine on the accuracy of the results.

### Determination of the degree of electrical proximity

We used the coherency measure that we developed in a companion paper to identify the generators to be modelled in varying modelling complexities. Since an electrically close generator to the disturbance tends to be modelled in detail, we developed a measure, rank correlation coefficient between any two buses, to determine the degree of electrical proximity of a generator to the disturbance. This measure was calculated from bus admitance matrix of the system.

### Coherency Distance

We define the 'coherency distance' between two generators as

$$B'_{ij} \stackrel{\Delta}{=} B_{ij} * \min\left[H_i \; H_j\right] / \max\left[H_i \; H_j\right] \qquad (2\text{-}2)$$

Where $B_{ij}$ is the corresponding term to the generator i and generator j in the reduced admittance matrix of the system and $H_i$ is the inertia of the generator i. The matrix $B^{'}$, which is comprised of all $B_{ij}$'s was named as 'coherency distance matrix'.

Depending on this definition we determine the tendency of two generators to swing together by simply measuring the correlation between those two corresponding columns, or rows, in this matrix.

**Rank Correlation Function and Coherency Measure**

The most widely used measure of association between variables is the linear correlation coefficient:

$$r = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2 \sum_i (y_i - \bar{y})^2}} \qquad (2\text{-}3)$$

where $\bar{x}$ is the mean of $x_i$'s, $\bar{y}$ is the mean of $y_i$'s for at least 20 measurements, where $x_i$'s and $y_i$'s represent generator distances between each other in this study.

However, r is a poor statistic for deciding whether an observed correlation is statistically significant, or whether one observed correlation is significantly stronger than another [11].

The uncertainity in interpreting the significance of the linear correlation can be overcome by nonparametric or rank correlation, where value of each $x_i$ is replaced by the value of its rank among all the other $x_i$'s in the sample that, is, 1, 2, 3, ...N.

Let $R_i$ be the rank of $x_i$ among the other $x_i$'s, $S_i$ be the rank of $y_i$ among the other $y_i$'s, then the rank-order correlation coefficient is defined to be the linear correlation coefficient of the ranks,

$$r_s = \frac{\sum_i (R_i - \bar{R})(S_i - \bar{S})}{\sqrt{\sum_i (R_i - \bar{R})^2 \sum_i (S_i - \bar{S})^2}} \qquad (2\text{-}4)$$

is the measure of the degree of the 'coupling' or 'coherency' of two generators, or any two buses, where $R_i$ and $S_i$ correspond to the ranks of magnitutes of their coherency distances to other buses.

Using the relation (2-4) the degree of coupling between generator i and generator j can be defined as

$$C(i,j) \overset{\Delta}{=} r_s\left[B'(:,i), B'(:,j)\right] \qquad (2\text{-}5)$$

And corresponding matrix can be named as 'coherency matrix' whose dimensions were determined by the number of the generators in the system.

Table – 2.1 Generator data

| | Generator 1 | Generator 2 |
|---|---|---|
| Rated power (MVA) | 699.0 | 126.0 |
| Rated voltage (kV) | 20.0 | 10.5 |
| H (seconds) | 28.8 | 2.7 |
| $x_d^{'}$ | 0.0460 | 0.1070 |
| $x_q^{'}$ | 0.1310 | 0.2380 |
| $x_d$ | 0.2240 | 1.6270 |
| $x_q$ | 0.2210 | 1.1910 |
| $r_a$ | 0.0000 | 0.0001 |
| $T_{do}^{'}$ | 5.1400 | 3.0400 |
| $T_{qo}^{'}$ | 1.5000 | 1.5000 |
| $x_\ell$ | 0.0290 | 0.0790 |
| Saturation factor | 0.3030 | 0.4000 |
| $x_d^{''}$ | 0.0360 | 0.0950 |
| $x_q^{''}$ | 0.0350 | 0.1590 |
| $T_{do}^{''}$ | 0.0440 | 0.0220 |
| $T_{qo}^{''}$ | 0.1410 | 0.1000 |

## III. RESULTS

Table – 3.1 presents the model reduction errors, and Figure – 3.1 – 2 swing curves of the test generators used in the one-machine infinite bus system. The disturbance is a three-phase short circuit at the front side of the transformer.

Table – 3.1 Model reduction errors of the test generators used in the one-machine system

| Faulted bus | Generator 1 model reduction error (%) | |
|---|---|---|
| | Model 3-Model 2 | Model 3-Model 1 |
| B1 | 10.4 | 12.8 |
| B2 | 6.0 | 8.0 |
| B3 | 4.0 | 5.6 |
| B4 | 3.2 | 4.3 |
| B5 | 2.7 | 3.6 |
| Faulted bus | Generator 2 model reduction error (%) | |
| | Model 3-Model 2 | Model 3-Model 1 |
| B1 | 8.9 | 14.3 |
| B2 | 3.9 | 7.7 |
| B3 | 2.3 | 4.9 |
| B4 | 1.3 | 3.2 |
| B5 | 1.2 | 2.5 |

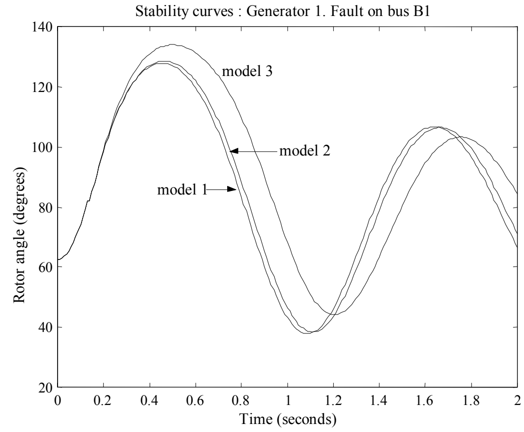


Figure – 3.1 (a) Model reduction behaviour of generator 1 after a 0.13 second short circuit at bus B1

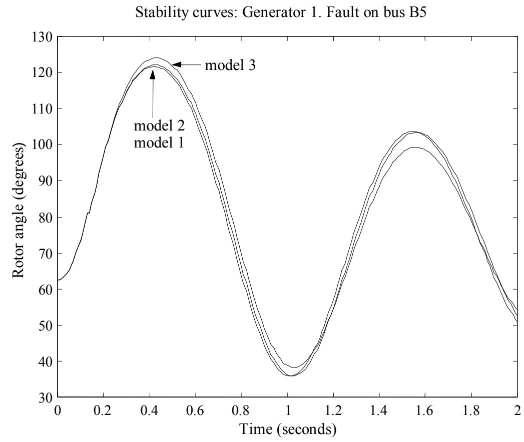


Figure – 3.1 (b) Model reduction behaviour of generator 1 after a 0.13 second short circuit at bus B5

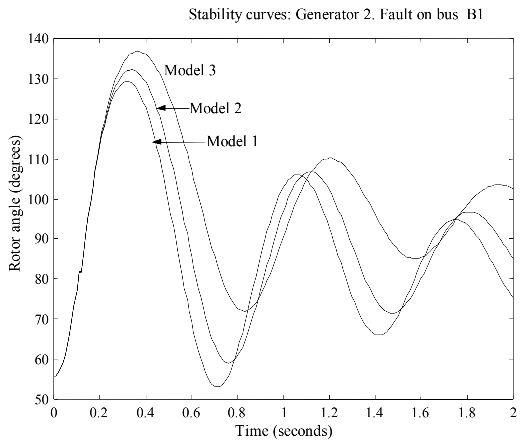


Figure – 3.2 (a) Model reduction behaviour of generator 2 after a 0.11 second short circuit at bus B1

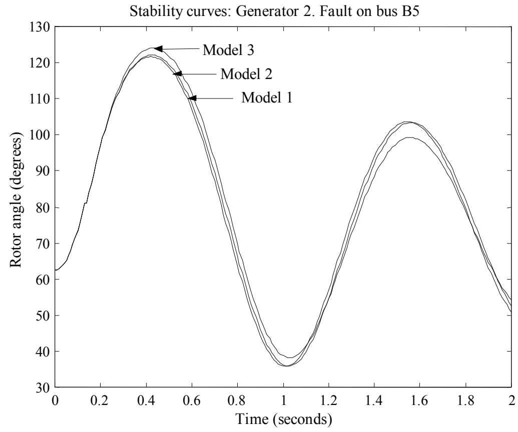


Figure – 3.2 (b) Model reduction behaviour of generator 2 after a 0.11 second short circuit at bus B5

Table – 3.2 presents the correlation values of the generators under study in Turkey system shown in Figure – 3.3, which were computed according to (2-3).

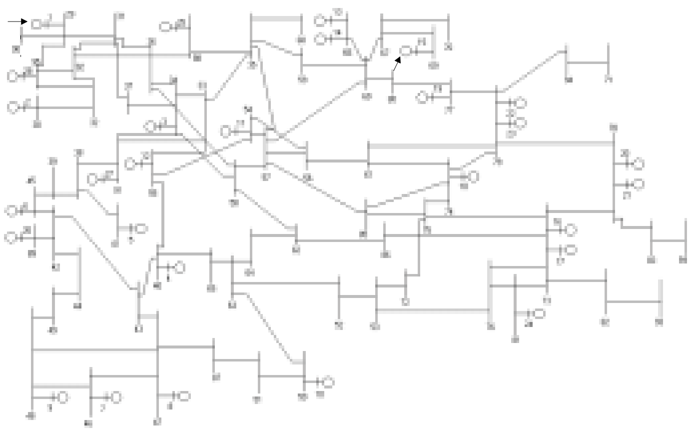

Figure – 3.3 Turkey 380 kV interconnected system

Table – 3.2 Correlation values of study area generators in Turkey system.

| | 6 | 7 | 8 | 9 | 10 | 26 |
|---|---|---|---|---|---|---|
| 6 | 1.00 | | | | | |
| 7 | 0.93 | 1.00 | | | | |
| 8 | 0.93 | 0.99 | 1.00 | | | |
| 9 | 0.91 | 0.99 | 0.98 | 1.00 | | |
| 10 | 0.65 | 0.84 | 0.85 | 0.86 | 1.00 | |
| 26 | 0.98 | 0.98 | 0.97 | 0.96 | 0.75 | 1.00 |

Generator 6 in Turkey system was chosen to investigate the model reduction behaviour upon a 0.12 second three-phase short circuit at the front side of its transformer. Figure – 3.4 gives the swing curves of the generator 6 for the following cases:

Case 1: All the 28 generators are modelled with full model.

Case 2: The generators other than those generators, which are closely coupled with the generator 6, are modelled with simple model.
Case 3: Generators 7, 8, 9, 10 are modelled with 3rd order model.
Case 4: Generators 7, 8, 9, 10 are modelled with simple model.
Case 5: Generator 26 is modelled with 3rd order model.
Case 6: All the generators except the generator 6 are modelled with simple model.

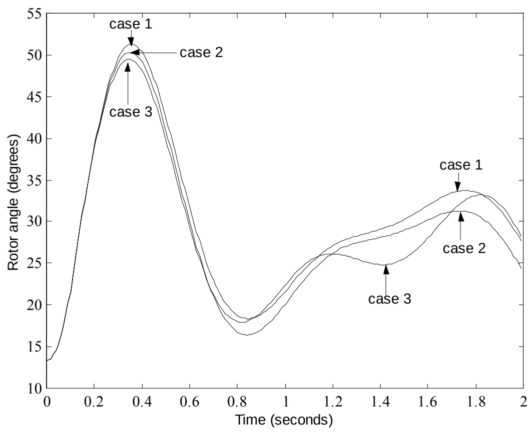


Figure – 3.4 (a) Swing curves of generator 6

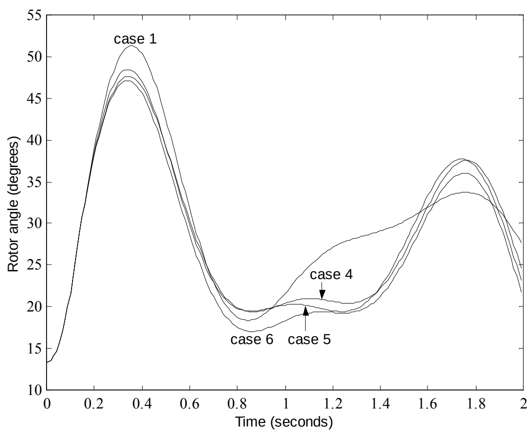


Figure – 3.4 (b) Swing curves of generator 6

And, Table – 3.3 present the model reduction errors of the generator 6 for the above cases.

Table – 3.3 Model reduction errors of generator 6

| | Case2 | Case3 | Case4 | Case5 | Case6 |
|---|---|---|---|---|---|
| Errors (%) for different cases | 4.7 | 5.4 | 9.1 | 8.8 | 11.0 |

## IV. CONCLUSIONS

Tests on one-machine system show that the other side of its transmission line is electrically distant away enough to model a generator with 3rd order model.

When applied to a multi-machine system this result means that the generators that are strongly coupled with the study generator can be modelled with the 3rd order model, and the rest of these generators with simple model.

## V. REFERENCES

[1] Sauer, P.W.; Ahmed-Zaid, S.; Pai, M. A. Systematic Inclusion of Stator Transients in Reduced Order Synchronous Machine Models. IEEE Transactions on Power Apparatus and Systems. Vol. PAS-103, No: 6; 1984
[2] Mayer, J. S.; Wasynczuk, O. An Efficient Method of Simulating Stiffly Connected Power Systems with Stator and Network Transients Included. IEEE Transactions on Power Systems. Vol. 6, No: 3; August 1991
[3] Sauer, P.W.; Ahmed-Zaid, S.; Kokotovic, P. V. An Integral Manifold Approach to Reduced Order Dynamic Modeling of Synchronous Machines. IEEE Transactions on Power Systems. Vol. 3, No: 1; February 1988
[4] Xu, X.; Mathur, R.M.; Jiang, J.; Rogers, G. J.; Kundur, P. Modeling of Generators and Their Controls in Power System Simulations Using Singular Perturbations. IEEE Transactions on Power Systems. Vol. 13, No: 1; February 1998
[5] Krause, C.; Nozari, F.; Skvarenina, T. L.; Olive, D, W. The Theory of Neglecting Stator Transients. IEEE Transactions on Power Apparatus and Systems. Vol. PAS-98, No: 1; Jan/Feb 1979
[6] Ahmed-Zaid, S.; Sauer, P. W.; Pai, M. A.; Sarıoğlu, M. K. Reduced Order Modeling of Synchronous Machines Using Singular Perturbation. IEEE Transactions on Circuits and Systems. Vol. CAS-29, No: 11; November 1982
[7] Sauer, P. W.; LaGesse, D. J.; Ahmet-Zaid, S.; Pai, M. A. Reduced Order Modeling of Interconnected Multimachine Power Systems Using Time-Scale Decomposition. IEEE Transactions on Power Systems. Vol. PWRS-2, No: 2; May 1987
[8] Dineley, J. L.; Morris, A. J. Synchronous Generator Transient Control: Part I-Theory and Evaluation of Alternative Mathematical Models. IEEE Transactions on Power Apparatus and Systems. June 1971
[9] Dandeno, P. L.; Hauth, R. L.; Schulz, P. Effects of Syncronous Machine Modeling in Large Scale System Studies. IEEE Transactions on Power Apparatus and Systems. May 1972
[10] Alden, T. H.; Nolan, P. J. Evaluating Alternative Models for Power System Dynamic Stability Studies. IEEE Transactions on Power Apparatus and Systems. Vol. PAS-95, No: 2; March/April 1976
[11] Press, W. H.; Flannery, B. P.; Teukolsky, S. A.; Vetterling, W. T. Numerical Recipes
In C. Cambridge University Press; 1988