Simulation of Small Signal Stability of Single Machine Connected to an Infinite Bus System

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Electrical Engineering Gadjah Mada University

Abstract—Power system small signal stability is very important subject on studying of power system planning and power system operation. The study of this kind of stability is done continuously in order to avoid failure in the system. The aim of this research is to identify factors that influence stability of single machine connected to an infinite bus and how control system affect the stability. The generator model which is used on this research is Heffron-Phillips model. The stability is known by observing the eigenvalues of generator in a certain condition. According to the result of this research, it can be known that stability of generator is affected by generator loading, the reactance of transmission, and the tuning of control system such as AVR and PSS. Increasing of generator loading and transmission reactance will lead instability. However control system will improve stability if it’s tuned correctly. Incorrect tune of control system will not lead to stability improvement, moreover can lead instability. On heavy loading, the addition of high gain AVR is prohibited. However high gain AVR addition is allowed on low loading. The addition of PSS can be done either in high loading or low loading.

Keywords—Power System Stability, Heffron- Phillips’s Model, Automatic Voltage Regulators (AVR), Power System Stabilizers (PSS)

I. PRELIMINARY

A. Background

Power system comprise of components which is integrated called interconnection. The component can be generator, transformers, transmission lines, etc. Each of these component develop in order to meet development of load.

This development makes power system operation more complicated. It’s easier for the system exposed by disturbance. Though system must persistent in its stability in order to meet load demand. If the system is unstable, it will make load demand unserved. Of course it’s a disadvantage for power system company. That’s why it’s important to investigate power system stability.

Because of a lot of constraint, usually power station located away from the load. It’s needed a transmission line which varies on its length. The longer transmission line, the bigger impact to stability.

In steady state condition all of the generators have to work in same speed which called synchronous operation. This condition affected by either small or big disturbance. System stable if after subjected to these disturbance is able to return to either previous or new condition.

B. Basic Theory

B.1 Type and Stability Definition

Power system stability denotes the ability of power system, for a given initial operation, to regain a state of operating equilibrium after being subjected physical disturbance with most of system variables bounded so that system integrity preserved. System integrity is preserved when all of the system is intact with no tripping generators or load except tripping in order to keep system operation. Stability is balance condition between oposing forces. Instability happen when disturbance leads to sustained imbalance between opposing force. Power system stability categorized into some kind shown in Figure 1. In general stability categorized into :

a) Rotor Angle Stability

Rotor angle stability denotes the ability of interconnected synchronous machines of power system to remain in synchronous condition in normal operation and after being subjected disturbance. It depends on the ability of the system to restore balance condition between electromagnetic torque and mechanical torque in every synchronous machine of the system. Instability can occur in form of increasing
angular swing in some generators leading loss of synchronism with other generators.

b) Voltage Stability

Voltage stability is concern with the ability of power system to maintain voltage in all of it's buses in normal condition and condition after being subjected disturbance. Instability may occur in form of either increasing or fall of voltage in certain busses. The impact can be in form of loss of load in particular area where voltage can't be tolerated or loss of it's integrity.

c) Frequency Stability

This kind stability denotes the ability of power system to maintain stability against big or small disturbance cause unbalance between generation and load. This kind stability depend on the ability of system to regain between this difference at minimum loss of load.

B.2 State Variable Model

Any kind of system can be represented into state variables:

\[
\begin{align*}
\dot{x}(t) &= Ax(t) + Bu(t) \\
y(t) &= Cx(t) + Du(t)
\end{align*}
\]

Where:

- \(x(t)\) = State space vector = vector of state space for \(n\)-order system
- \(A\) = System matrix
- \(B\) = Input matrix
- \(u(t)\) = Input vector = vector which comprises input function of the system
- \(y(t)\) = Output vector = Vector formed from determined output
- \(C\) = Output matrix (\(n \times p\)). Direct coupling between input and output

Using Laplace transform on state space equation, the equation will be in form:

\[
\begin{align*}
sX(s) - x(0) &= AX(s) + BU(s) \\
Y(s) &= CX(s) + DU(s)
\end{align*}
\]

Figure 1. Classification of power system stability

The system is stable if all of its eigenvalues located at Left half plane of imaginary axis. This method investigate system stability in "s" plane. Another way to know system stability is to convert state variable equation to differential equation. The differential equation is solved using numerical method such as Euler, Runge-kutta, etc. System is stable if all of it’s variable convergent to certain value.

2. IMPLEMENTATION

Implementation of small signal stability single machine connected to an infinite bus requires computer softwares such as MATLAB 7.0.4 and SIMULINK. The dynamic data of machine are taken from [5] page 263. Using Heffron-Phillips's model, simulation are done for the generator equipped by either AVR or PSS. Simulation also covered generator without AVR and PSS. For this three circumstances, can be draw model in state form:

A. Generator Without AVR

\[
x = [A]x + [B](\Delta E_d)
\]

Where:

\[
x' = \begin{bmatrix} \Delta \delta \\ \Delta \delta_m \\ \Delta E_q \end{bmatrix}
\]

\[
[A] = \begin{bmatrix}
0 & \omega_0 & 0 & 0 \\
-\frac{R_s}{2} & -\frac{L_s}{2} & -\frac{R_s}{2} & 0 \\
-\frac{L_s}{2} & 0 & -\frac{1}{r_m} & \frac{1}{r_m} \\
r_m & 0 & -\frac{1}{r_m} & \frac{1}{r_m}
\end{bmatrix}
\]

\[
[B]' = \begin{bmatrix} 0 & 0 & \frac{1}{r_{do}} \\
0 & 0 & 0
\end{bmatrix}
\]
B. Generator Equipped by AVR

\[ x = [A]x + [B](\Delta V_{ref}) \]  

(4)

Where:

\[ x' = [\Delta \delta \Delta S_m \Delta E_q \Delta E_{fd}] \]

\[ [A] = \begin{bmatrix} 0 & \omega_b & 0 & 0 \\ -\frac{k_s}{2\beta} & -\frac{k_s}{2\beta} & -\frac{k_s}{2\beta} & 0 \\ 0 & 0 & -\frac{k_s}{\tau_m} & -\frac{1}{\tau_m} \\ -\frac{k_s}{\tau_e} & \frac{k_s}{\tau_e} & 0 & -\frac{1}{\tau_e} \end{bmatrix} \]

\[ [B]' = \begin{bmatrix} 0 & 0 & \frac{V_F}{\tau_e} \\ 0 & 0 & \frac{V_F}{\tau_e} \end{bmatrix} \]

C. Generator Equipped by PSS

\[ x = [A]x + [B](\Delta V_{ref}) \]  

(5)

Where:

\[ x' = [\Delta E_q \Delta \delta \Delta S_m \Delta E_{fd} \Delta x] \]

\[ [B]' = \begin{bmatrix} 0 & 0 & \frac{V_F}{\tau_e} \\ 0 & 0 & \frac{V_F}{\tau_e} \end{bmatrix} \]

\[ [A] = \begin{bmatrix} -\frac{1}{\tau_m} & -\frac{k_s}{\tau_m} & 0 & \frac{1}{\tau_m} & 0 \\ 0 & 0 & \omega_b & 0 & 0 \\ -\frac{k_s}{2\beta} & \frac{k_s}{2\beta} & -\frac{k_s}{2\beta} & 0 & 0 \\ \frac{k_s}{\tau_e} & \frac{k_s}{\tau_e} & 0 & -\frac{1}{\tau_e} & \frac{k_s}{\tau_e} \\ -\frac{k_s}{\tau_e} & \frac{k_s}{\tau_e} & 0 & -\frac{1}{\tau_e} & 0 \end{bmatrix} \]

System will be in stable condition if all of its eigenvalues on left half plane. The values of K1 to K6 are obtained from calculation of initial condition.

3. SIMULATION RESULT

A. Generator Without AVR

This simulation is done by varying either generator loading (Pe) or transmission reactance (x_p). Generator loading range from 0.3 to 1.7. The result is illustrated on Figure 2.

According to Figure 2, the loci of eigenvalues pole 1 (dashed-line style) and pole 2 (point-line style) remain on left half plane. However pole 3 (thick-line style) is on the left half plane up to Pe = 1.5. After this value pole 3 will cross imaginary axis toward right half plane along real axis. This movement cause system become unstable. Pole 3 has only real part so instability is in form monotonic instability.
B. Generator Equipped by AVR

Among the consideration on addition AVR is the value of K5. The addition AVR when K5 has positive value make enhancement on damping torque. In other hand this addition also make reduction on synchronizing torque. For example at \( P_e=0.5 \). The result is in table I:

<table>
<thead>
<tr>
<th>( P_e=0.5 )</th>
<th>Pole 1 and Pole 2</th>
<th>Pole 3 and Pole 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>without AVR</td>
<td>-0.11852(\pm)j 5.9301</td>
<td>-0.22593 dan 0</td>
</tr>
<tr>
<td>AVR</td>
<td>-0.15121(\pm)5.5406</td>
<td>-10.08(\pm)14.381</td>
</tr>
<tr>
<td>K5</td>
<td>0.049957</td>
<td></td>
</tr>
</tbody>
</table>

At negative K5, the addition AVR has opposite effect if be compared to positive K5. The effect are reduction on damping torque and enhancement on synchronizing torque which can be seen in table 2 describes condition at \( P_e=0.7 \):

<table>
<thead>
<tr>
<th>( P_e=0.7 )</th>
<th>Pole 1 dan Pole 2</th>
<th>Pole 3 dan Pole 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without AVR</td>
<td>-0.153(\pm)6.4201</td>
<td>-0.157dan 0</td>
</tr>
<tr>
<td>AVR</td>
<td>0.14141(\pm)6.617</td>
<td>-10.373(\pm)12.767</td>
</tr>
<tr>
<td>Nilai K5</td>
<td>-0.034</td>
<td></td>
</tr>
</tbody>
</table>

On negative value of K5, the addition of high gain AVR lead instability. However instability occur in form oscillatory instability well described by table 3

<table>
<thead>
<tr>
<th>( P_e=1.6 )</th>
<th>Pole 1 dan Pole 2</th>
<th>Pole 3 dan Pole 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without AVR</td>
<td>-0.2541(\pm)5.5165</td>
<td>0.04524 dan 0</td>
</tr>
<tr>
<td>AVR</td>
<td>-11.785(\pm)11.704</td>
<td>1.554(\pm)7.7305</td>
</tr>
<tr>
<td>Nilai K5</td>
<td>-0.296</td>
<td></td>
</tr>
</tbody>
</table>

C. Effect of AVR's Gain Variation on Stability

This experiment is done either at positive K5 or negative K5. AVR gain is varied from 0 to 401.

On positive K5, the result of experiment can be seen on Figure 4 where locus goes further to left as gain increases. At the loci change its direction to right and will be in stable until

![Figure 4](image)

Meanwhile at negative K5 the experiment result can be seen in Figure 4. System will be stable only before , after this value loci crosses imaginary axes and system becomes unstable. Further increasing lead loci move to right and turn left at

![Figure 5](image)

D. Generator Equipped by PSS

Experiment is done on same circumstances with generator equipped AVR which is at positive and negative K5. Using PSS is tuned using procedure at [8] pages 273.
As the result at positive K5 using that procedures can be obtained PSS constant:

\[
G(s) = 22.13 \begin{pmatrix} 1 + s0.053 \\ 1 + s0.027 \end{pmatrix}
\]

The eigenvalues is on table 4

<table>
<thead>
<tr>
<th>Table IV</th>
<th>COMPARISON BETWEEN SYSTEM WITH AVR, WITHOUT AVR, AND WITH PSS AT PE=0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pe=0.5</td>
<td>Pole 1 dan Pole 2</td>
</tr>
<tr>
<td>Without AVR</td>
<td>-0.118529/j 9.9301</td>
</tr>
<tr>
<td>AVR</td>
<td>-0.151124/j 5.5406</td>
</tr>
<tr>
<td>K5</td>
<td>0.049957</td>
</tr>
</tbody>
</table>

Meanwhile on negative K5, can be obtained PSS constant:

\[
G(s) = 22.13 \begin{pmatrix} 1 + s0.2 \\ 1 + s0.15 \end{pmatrix}
\]

The eigenvalues is on table 5

<table>
<thead>
<tr>
<th>Table IV</th>
<th>COMPARISON BETWEEN SYSTEM WITH AVR, WITHOUT AVR, AND WITH PSS AT PE=1.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pe=1.1</td>
<td>Pole 1 dan Pole 2</td>
</tr>
<tr>
<td>Tanpa AVR</td>
<td>-1.1792/j 6.3998</td>
</tr>
<tr>
<td>Dengan AVR</td>
<td>0.7062/j 7.3532</td>
</tr>
<tr>
<td>Dengan PSS</td>
<td>-1.3404/j 13.3190</td>
</tr>
</tbody>
</table>

According to the experiment can be drawn conclusion that PSS will enhance damping either on positive and negative K5. Positive K5 usually happen at low loading of generator and short transmission line. Negative K5 happen at relative high loading and long transmission line.

4. CONCLUSION

1. Every system will has different response for different state of operation. It's caused by difference of eigenvalues.
2. Control equipment such as AVR and PSS will enhance stability if it is correctly tuned. Incorrect tuned lead instability.
3. Control equipment have miscellaneous effects on stability. By adding AVR at negative K5 will reduce damping torque and synchronizing torque. At positive K5 the effect is inverse above. Meanwhile addition PSS will increase damping torque at either positif K5 or negatif K5.
4. Base on this experiment the stability of generator is affected by generator loading, transmission reactance, and tuning of control apparatus.

REFERENCE

The Penang Bridge (Jambatan Pulau Pinang) connects Gelugor on the Island of Penang and Seberang Prai on the Malaysian mainland.

Penang Bridge, opened to traffic on 14th September 1985 as a 6.2 km dual-carriageway toll bridge plus a 2.2km three lane central span, has since August 2009 operated as a full three lane carriageway.

*The bridge can withstand an earthquake up to 7.5 on the Richter scale*
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Professor in the Faculty of Engineering
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KEYNOTE PRESENTATIONS

ANDAMAN BALLROOM

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Conference Chairman
Professor Dr. Ismail bin Daut

9.15 - 9.30  OPENING ADDRESS  
Deputy Vice Chancellor (Academic) UniMAP
Professor Dr. Sazali Bin Yaacob

9.30 - 10.30  KEYNOTE 1  
Professor Emeritus Dr. Joachim Holtz
"Digital versus Quasi-Analog Control of Servo Drives"

INTERVAL  coffee  (pre-cocktail area)

11.00 - 12.00  KEYNOTE 2  
Professor Dr. Khalid bin Mohamed Nor
"Education and Research on Power System Engineering Challenges and Opportunities in Malaysia"

12.00 - 1  KEYNOTE 3  
Professor Dr. Muhammad H. Rashid
"Advances in Power Electronics and Applications in Renewable Energy"

LUNCH  (Tamarind Brasserie)
TECHNICAL PROGRAMME

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**TRACK 3b: POWER SYSTEMS: Dynamics and Control**

**CHAIR:** cik Ernie binti Chemid

**T3b.7 73-97237** Pricing of Dynamic Reactive Power Support Based on MW Shipment Assessment using PSO.
A. Pirayesh, M. Seyed Yazdi: 
Shahid Beheshti University, Tehran, Iran.

**T3b.8 73-23884** Simulation of Small Signal Stability of Single Machine Connected to an Infinite Bus System.
Husni Rois Ali, Sasongko Pramonohadi, M. Ismaeni BS, Suharyanto: 
Gadjah Mada University, Indonesia.

**T3b.9 73-68636** Study of Asynchronous Wind Turbine Effects on Weak Grid by using Small Signal Modeling.
H. Kazemi Karegar: 
Shahid Beheshti University, Tehran, Iran.
A. Derakhshan: 
Azad University, Tehran, Iran.

**T3b.10 73-86631** Two Novel Proposed Controllers for a Wind Energy Conversion System.
M.S. Toulabi, B. Sobhani, M. Sedighizadeh, A. Rezazadeh: 
Shahid Beheshti University, Tehran, Iran.