A Practical Approach for Faster Power System Transient Simulation

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Outline

• Motivation

• Numerical Integration Method
  – Explicit method: Second Order RK method
  – Multi-rate method

• Practical problem definition

• Proposed Method

• Case study

• Conclusion
Motivation

- Power system dynamic simulation involves a wide range of different time constants [stiff]
- In order to avoid numerical instability, explicit integration methods require very small time steps for stiff power systems
- Only a small fraction of system states shows fast dynamics
- Therefore, simulation of an entire power system with small integration time steps is not efficient
- This work aims to reduce the transient simulation time by removing fast modes from a system.
**Numerical Integration**

**Explicit method: Second Order RK method**

\[ x_n = x_{n-1} + h \left( \frac{1}{2} k_1 + \frac{1}{2} k_2 \right) \]

where

\[ k_1 = f(x_{n-1}, t_{n-1}) \]

\[ k_2 = f(x_{n-1} + k_1, t_{n-1} + h) \]

**Region of Stability**

\[ hl = \frac{r(z)}{s(z)} = 1 + z + \frac{1}{2} z^2 \]

\[ |z| < 1 \]

Stable Region

\[ -2 < hl < 0 \]

if \( l = -2400 \)

\[ h < 0.05 \text{cycle} \]
Multi-rate Method

1. At each macro step (H), the slow variables ($y_s$) are integrated.
2. Interpolate the slow variables to provide approximation for each micro step (h).
3. Fast variables can be found using the interpolated slow variables as needed.

Practical Problem: Big negative eigenvalues

- WECC case (17,710 buses) SMIB result
  - Bus # 42711
    - Min. eigenvalue: -2601.8
    - SMIB Participation factor
      - EXST1 exciter model
        - NEED Very Small Time Step
When two lead-lag compensators are neglected, 

\[
T(s) = \frac{V_1}{V_2} = \frac{K_A (1 + sT_F)}{T_A T_F s^2 + (T_A + T_F + K_A K_F)s + 1} = \frac{K_A (1 + sT_F)}{T_A T_F (s - p^+) (s - p^-)}
\]

where 

\[
p^\pm = \frac{-(T_A + T_F + K_A K_F) \pm \sqrt{(T_A + T_F + K_A K_F)^2 - 4T_A T_F}}{2T_A T_F}
\]
**EXST1 and its reduction of small eigenvalue**

\[
T(s) = \frac{V_1}{V_2} = \frac{K_A(1 + sT_F)}{T_AT_F(s - p^+)(s - p^-)}
\]

\[
T_{\text{reduction}}(s) = \frac{V_1}{V_2} = \frac{K_A(1 + sT_F)}{T_AT_F(-p^-)(s - p^+)} = \frac{K_A(1 + sT_F)}{1 - s/p^+}
\]

When the exciter input voltage shows only low frequency range, the reduced model can be used.

Only abrupt voltage change introduces high freq. component.

Voltage change is dependent on fault given.
Fault Type Dependency

- Generator or Load fault
- Bus or Line to ground fault

Bus 1 Voltage Magnitude

- When Gen ID 1 open at bus 1
- When Load 1 open to ground fault
- When Bus 1 to ground fault
- When Line 1-2 to ground fault
Fault Type Dependency

Single-Sided Amplitude Spectrum

FFT results of voltage magnitude

- Bus to Ground fault
- Line to Ground fault
- Generator Outage
- Load Outage
Bus Fault Location Dependency

When Bus to ground fault at Bus 5,

Electrically Far

Bus 1

Electrically Close

Bus 5

Voltage Magnitude at different bus location

FFT results of voltage magnitude

Single-Sided Amplitude Spectrum
Proposed Approach I
: Fault Dependent Model Reduction
Case Study: GSO 37 bus Case

1. JO345 Gen ID1 OPEN
2. DEMAR69 Solid Bus to Ground fault
3. JO345 Solid Bus to Ground fault

JO345 EXST1 exciter
min. eigenvalue: -2102
GSO 37 bus Case: Simulation results

Generator Outage

JO345 Gen ID1 OPEN

Bus Voltage when JO345 ID=1 Generator Outage

Voltage Magnitude [pu]

Time [sec]

1.02
1.025
1.03
1.035

Original Model
Reduced Model

Bus Voltage Magnitude at JO345

JO345 ID2 Gen MW output

Generator MW Terminal [Mvar]

Time [sec]

0 1 2 3 4 5 6 7 8 9 10

Original Model
Reduced Model

JO345 ID2 Gen Mvar output

Generator Mvar Terminal [Mvar]

Time [sec]

-10 -8 -6 -4 -2 0 2 4 6 8 10

Original Model
Reduced Model
GSO 37 bus Case: Simulation results

Bus Fault - FAR

DEMAR69 Solid Bus to Ground fault

Bus Voltage when DEMAR69 Bus Fault

Voltage Magnitude [pu]

Original Model
Reduced Model

Time [sec]

Voltage Magnitude at JO345

J O345 ID1 Gen MW output

Original Model
Reduced Model

Time [sec]

Bus Voltage when DEMAR69 Bus Fault

J O345 ID1 Gen Mvar output

Original Model
Reduced Model

Time [sec]
## GSO 37 bus Case: Computation Time Benefits

### Bus Fault - FAR

**DEMAR69 Solid Bus to Ground fault**

**Simulation Time: 10 sec**

<table>
<thead>
<tr>
<th>Exciter Model</th>
<th>Numerical Integration</th>
<th>Max. Time Step (cycle)</th>
<th>Time to Solve (sec)</th>
<th>Max. Angle Difference (deg.)</th>
<th>Total Newton Solutions</th>
<th>Total Newton Iterations</th>
<th>Number of Jacobian Factorizations</th>
<th>Number of Forward/Backward Substitutions</th>
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</thead>
<tbody>
<tr>
<td>Original</td>
<td>Single Rate</td>
<td>0.05</td>
<td>47.99</td>
<td>26.854</td>
<td>13975</td>
<td>12773</td>
<td>40</td>
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<td>Multi Rate</td>
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<td>2.4</td>
<td>1.08</td>
<td>27.011</td>
<td>443</td>
<td>433</td>
<td>40</td>
<td>433</td>
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<tr>
<td>Reduced</td>
<td>Single Rate</td>
<td>2.4</td>
<td>1.01</td>
<td>26.901</td>
<td>431</td>
<td>404</td>
<td>36</td>
<td>404</td>
</tr>
</tbody>
</table>

**Newton Solution Results**

- Total Newton Solutions
- Total Newton Iterations
- Number of Jacobian Factorizations
- Number of Forward/Backward Substitutions
GSO 37 bus Case: Simulation results

**Bus Fault - CLOSE**

**JO345 Solid Bus to Ground fault**

**Bus Voltage Magnitude at JO345**

- **JO345 ID1 Gen MW output**
  - Original Model
  - Reduced Model

- **JO345 ID1 Gen Mvar output**
  - Original Model
  - Reduced Model
EXST1 eigenvalues are changed

JO345 Solid Bus to Ground fault

**EXST1 eigenvalue = -2102**

**EXST1 eigenvalue = -1102**

**EXST1 eigenvalue = -501**

**EXST1 eigenvalue = -261**

**EXST1 eigenvalue = -27**
Right eigenvector

\[ D x(t) = \sum_{i=1}^{n} \lambda_i f_i c_i e^{i \lambda t} = \sum_{i=1}^{n} \lambda_i y_i D x(0) e^{i \lambda t} \]

<table>
<thead>
<tr>
<th>State \ Eigenvaleue</th>
<th>-2102</th>
<th>-1102</th>
<th>-501</th>
<th>-261</th>
<th>-27</th>
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<tbody>
<tr>
<td>Machine Angle</td>
<td>3.19E-10</td>
<td>-2.20E-09</td>
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<td>0</td>
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<td>Exciter Va</td>
<td>0.999999991</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>0.999728538</td>
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<td>Exciter VF</td>
<td>0.000119065</td>
<td>-0.00023</td>
<td>-0.00016</td>
<td>-0.00031</td>
<td>0.003303785</td>
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<td>Governor Filter Output</td>
<td>-1.71E-11</td>
<td>1.19E-10</td>
<td>1.28E-09</td>
<td>9.17E-09</td>
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<td>Governor Desired Gate</td>
<td>5.42E-15</td>
<td>-7.20E-14</td>
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<tr>
<td>Governor Gate</td>
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<td>Governor Turbine Flow</td>
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</tbody>
</table>
Revised Approach
Conclusion

• Practical approach is proposed in order to reduce a computational burden for power system transient simulation

• The method dynamically switches to original EXST1 or to reduced one depending on **SMI B analysis and right eigenvector information**

• The approach shows quite good performance in simulation time and accuracy. While maintaining the accuracy, the method reduces the simulation time about 98%
Questions ?
My mistake was

\[ T(s) \]

<EXST1 Exciter model>

Limiter block function is neglected

<SEXS Exciter model>

Figure from PowerWorld Manual
EXST1 model is used to define the reduced model transfer function by changing model parameters.
Questions ?
QSS (Quasi-Steady-State) approximation

• Replaces short-term dynamics with their equilibrium conditions
• Thus transform the differential equations to algebraic ones that are solved together with network equations
Numerical Integration

- Approximate computation of an integral using numerical techniques

\[ x = f(x, y, t) \]

\[ 0 = g(x, y, t) \]

**Explicit Method**

[Forward Euler]

\[ x_n = x_{n-1} + h \cdot f(x_{n-1}, y_{n-1}, t_{n-1}) \]

**Implicit Method**

[Backward Euler]

\[ x_n = x_{n-1} + h \cdot f(x_n, y_n, t_n) \]

For solving a stiff ODE,

Need very small time step

Larger time step is okay, But computational burden