U.S. DEPARTMENT OF ENERGY
Electricity Delivery & Energy Reliability

Advanced Grid Modeling 2014 Peer Review

Power System Parallel Dynamic Simulation Framework for Real-Time Wide-Area Protection and Control

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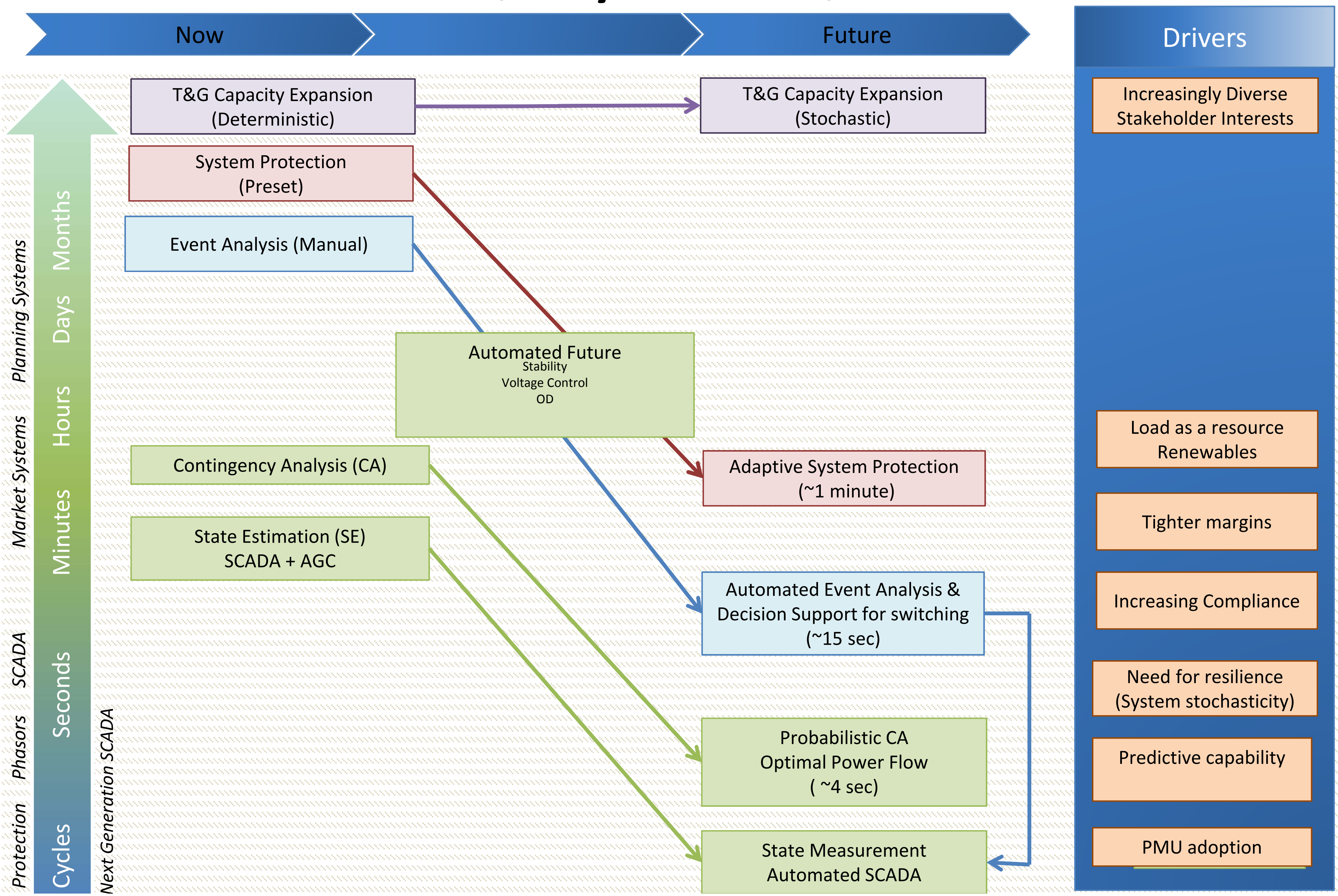
Vision – Faster, Dynamic, On-line Tools



Aligned with DOE's Advanced Grid Modeling Program Objectives

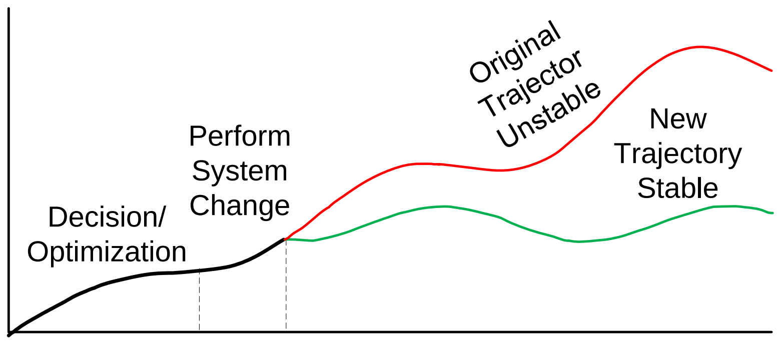
STRATEGY: Support mathematically-based power systems research to:

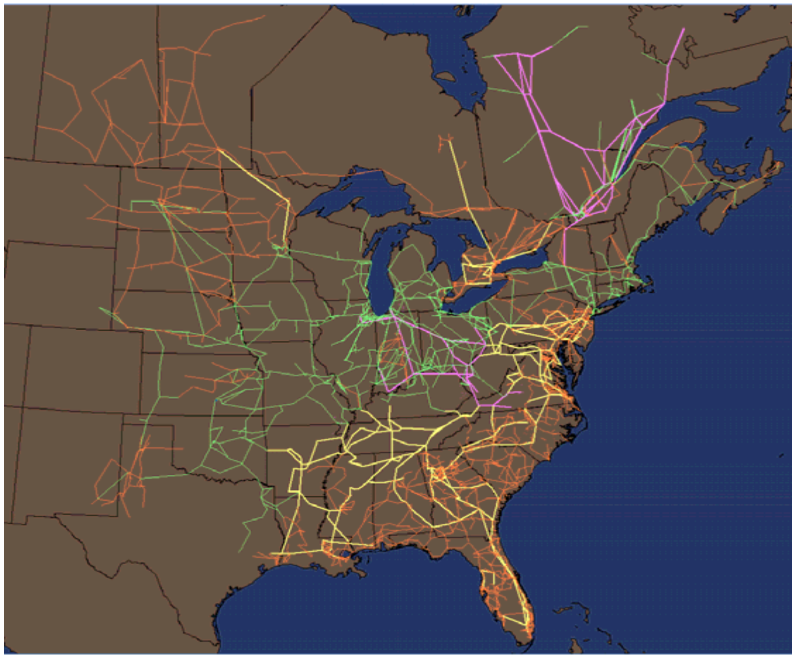
- ✓ ***Accelerate Performance –*** improve grid resilience to fast time-scale phenomena that drive cascading network failures and blackouts
  - Move from Off-line to On-line Dynamic Tools
- ✓ ***Enable Predictive Capability –*** rely on real-time measurements and improved models to represent with more fidelity the operational attributes of the electric system, enabling better prediction of system behavior and thus reducing margins and equipment redundancies
  - Goal to achieve faster than real-time & look ahead simulation

- ✓ ***Integrate Modeling Platforms (across the system) –*** capture interactions and interdependencies that will allow development of new control techniques and technologies
  - Integration of CAPE/PSSE

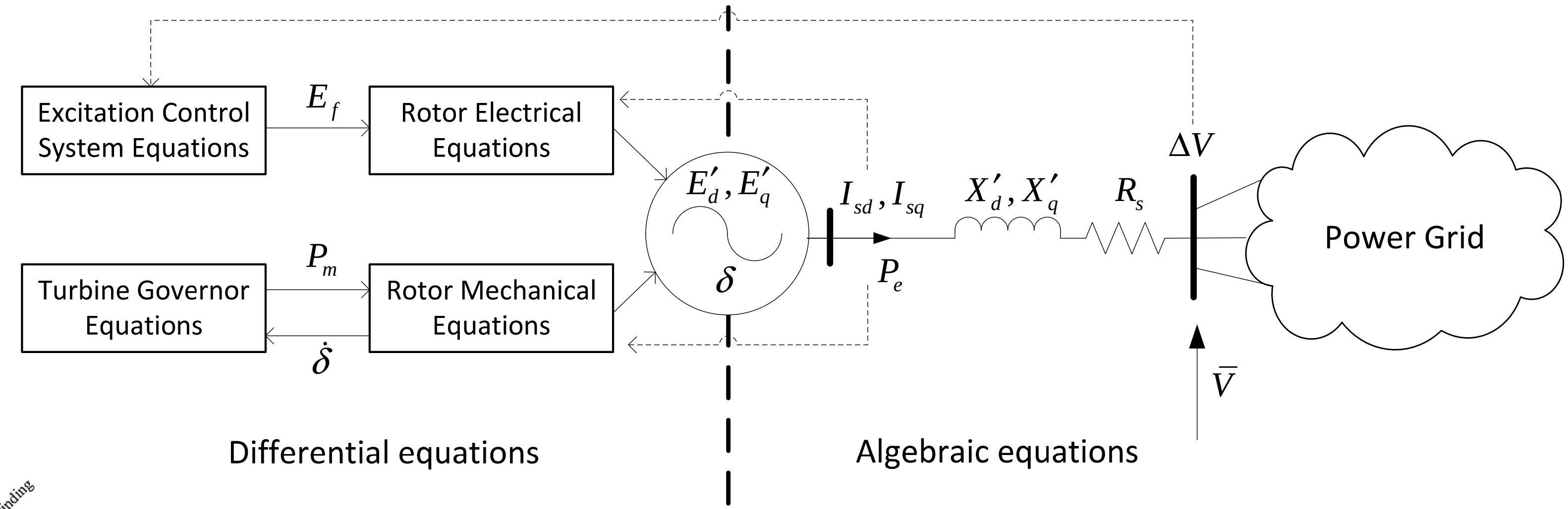
Motivation and Impact

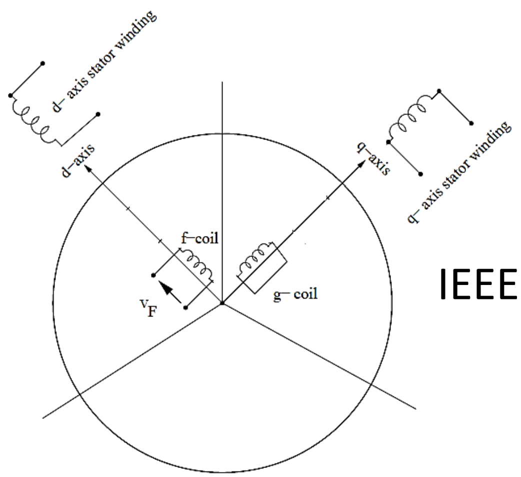
- Current state of the art software:
  - PSS®E by Siemens requires 1 minute of computation for a 1 second of real-time simulation (Eastern Interconnect → more than 60,000 buses and 8,200 generators.)
  - For predictive modeling, simulation computation will need to be an order of magnitude faster.
  - Currently performed on single CPU core.
- Technology limitations have directed focus for computation to multi-processor cores.
  - To effectively utilize multi-processor cores, parallel computation approaches must be available
- Three orders of magnitude faster is needed for look ahead simulation





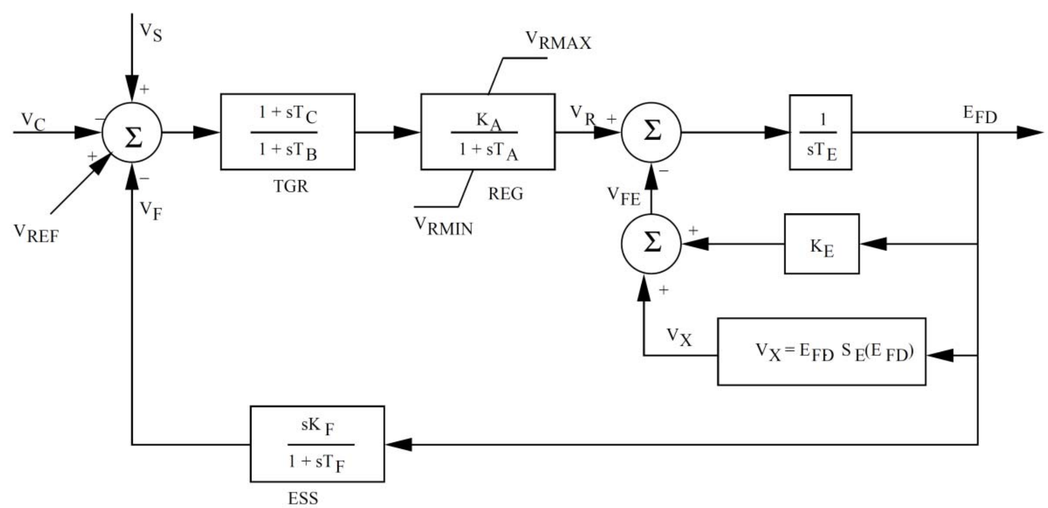
Synchronous Machine



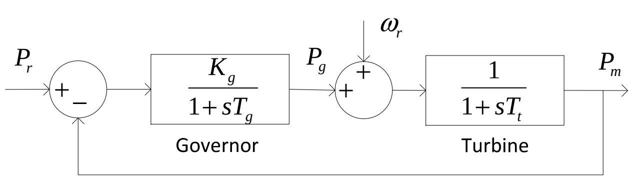


IEEE Model 1.1

Excitation control



Turbine-governor



Dynamic Model

Synchronous Machine IEEE 1.1

1 field winding on q-axis and 1 damper winding on d-axis including Transient saliency

$$\frac{d\delta}{dt} = w_B S_m$$

$$\frac{dS_m}{dt} = \frac{1}{2H}[-DS_m + T_m - T_e]$$

$$\frac{dE'_q}{dt} = \frac{1}{T'_{do}}[-E'_q + (X_d - X'_d)I_d + E_{fd}]$$

$$\frac{dE'_d}{dt} = \frac{1}{T'_{qo}}[-E'_d - (X_q - X'_q)I_q]$$

$$\frac{dE_{dc}}{dt} = \frac{1}{T_c}[-E_{dc} - (X'_q - X'_d)I_q]$$

IEEE Type 1 Excitation System

$$\frac{dE_{fd}}{dt} = \frac{1}{T_E}\left[-\left(K_E + A_E\left(e^{(B_E E_{fd})}\right)\right)E_{fd} + V_R\right]$$

$$\frac{dV_2}{dt} = \frac{1}{T_F}\left[-V_2 + \frac{K_F}{T_F}E_{fd}\right]$$

$$\frac{dV_1}{dt} = \frac{1}{T_R}[-V_1 + V_t]$$

if $T_R = 0$ then $V_1 = V_t$

$$\frac{dV_R}{dt} = \frac{1}{T_A}[-V_R + K_A(V_{ref} - V_1 - V_F)]$$

$$if\ V_R \leq V_{Rmin} \quad then \quad V_R = V_{Rmin}\ and\ \dot{V}_R = 0$$

$$if\ V_R \geq V_{Rmax} \quad then \quad V_R = V_{Rmax}\ and\ \dot{V}_R = 0$$

Governor Model

$$\frac{dP_{SV}}{dt} = \frac{1}{T_{SV}}\left[-P_{SV} + P_C - \frac{1}{R_D}S_m\right]$$

Turbine Model

$$\frac{dT_m}{dt} = \frac{1}{T_{CH}}[-T_m + P_{SV}]$$

Algebraic Equations

$$\begin{bmatrix} i_q \\ i_d \end{bmatrix} = \frac{1}{\left(R_a^2 + \acute{X}_d \acute{X}_q\right)} \begin{bmatrix} R_a & \acute{X}_d \\ -\acute{X}_q & R_a \end{bmatrix} \begin{bmatrix} \acute{E}_q - V_q \\ \acute{E}_d - V_q \end{bmatrix}$$

$$I^{DQ} = Y^{DQ} V^{DQ}$$

$$Y_{ij}^{DQ} = \begin{bmatrix} B_{ij} & G_{ij} \\ G_{ij} & -B_{ij} \end{bmatrix}; V_j^{DQ} = \left[\frac{V_{Qj}}{V_{Dj}}\right]; I_i^{DQ} = \left[\frac{I_{Di}}{I_{Qi}}\right];$$

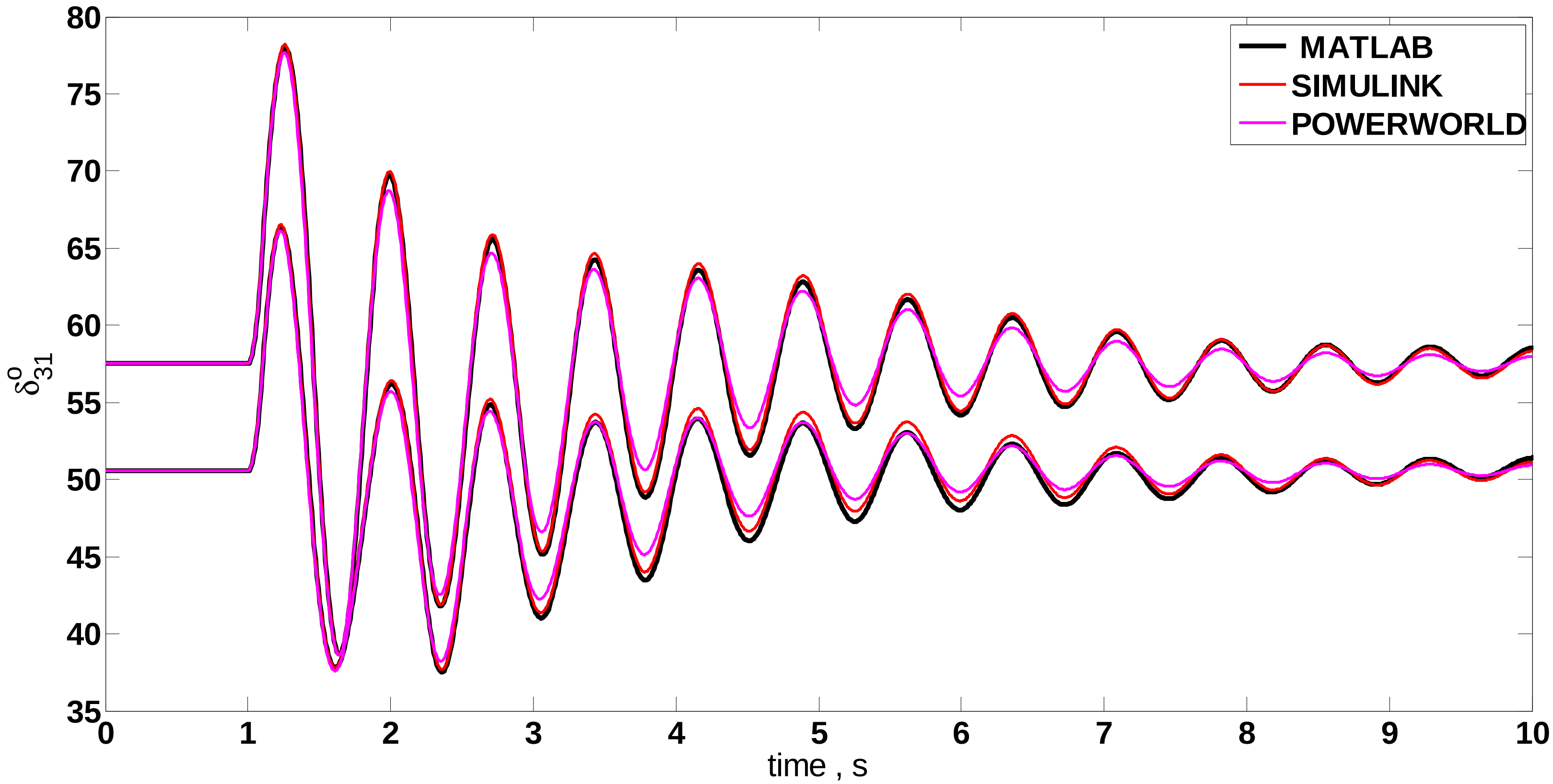
Models Built : POWER WORLD
MATLAB with generic RK4 Method
SIMULINK with inbuilt ODE15s solver

Power World uses IEEE 2.1 model for Synchronous Machines
i.e. 1 field winding, 1 damper on d-axis and 1 damper on q-axis

Power System Model Validation

3 Gen 9 Bus System

Rotor Angle Responses of GEN-2 & GEN-3 w.r.t GEN-1

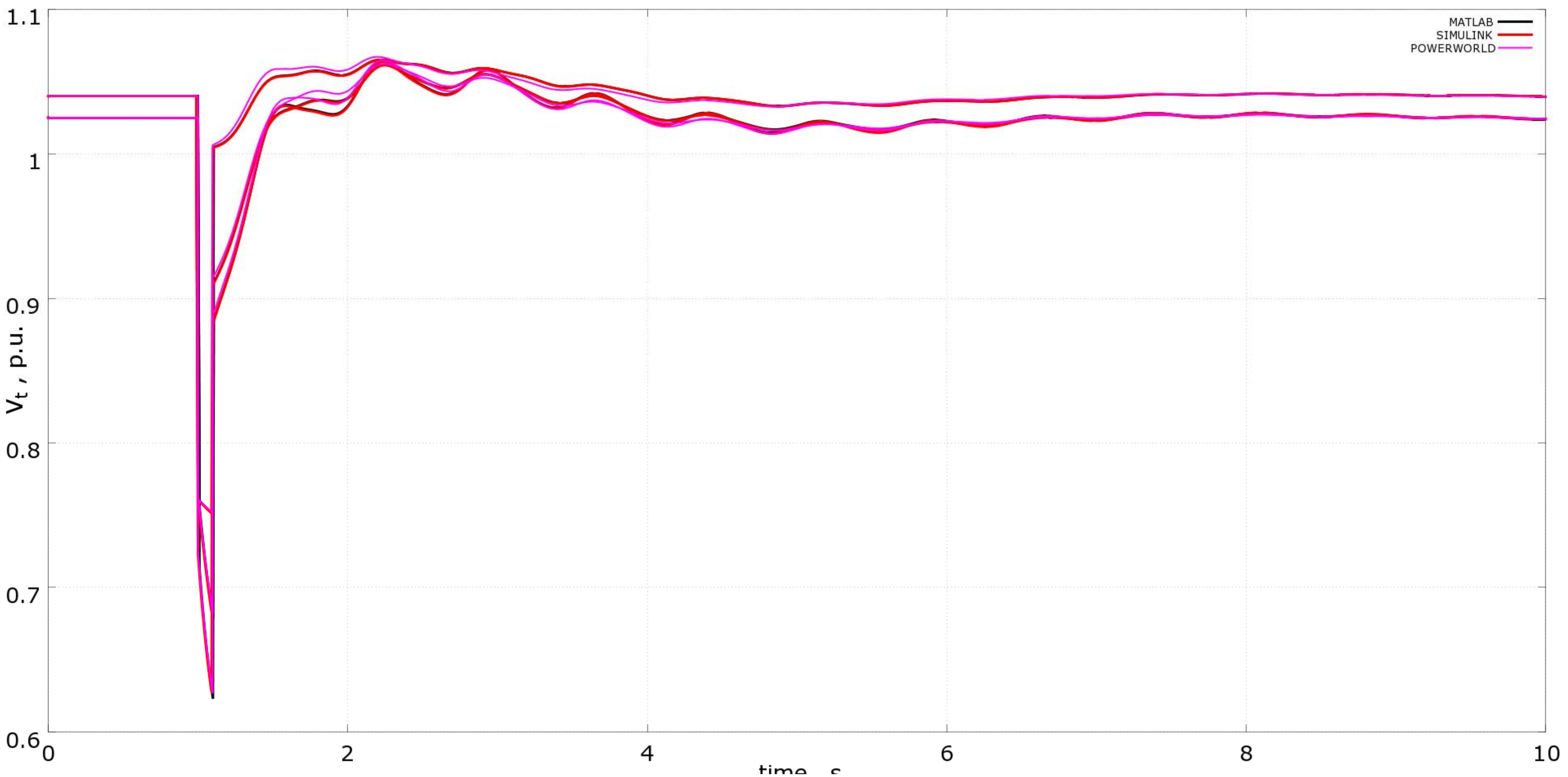


Disturbance: 3ph Fault at bus 5, Fault Duration 0.1s (6 cycles)

Dynamics of MATLAB and PowerWorld are closely matching

3 Gen 9 Bus System

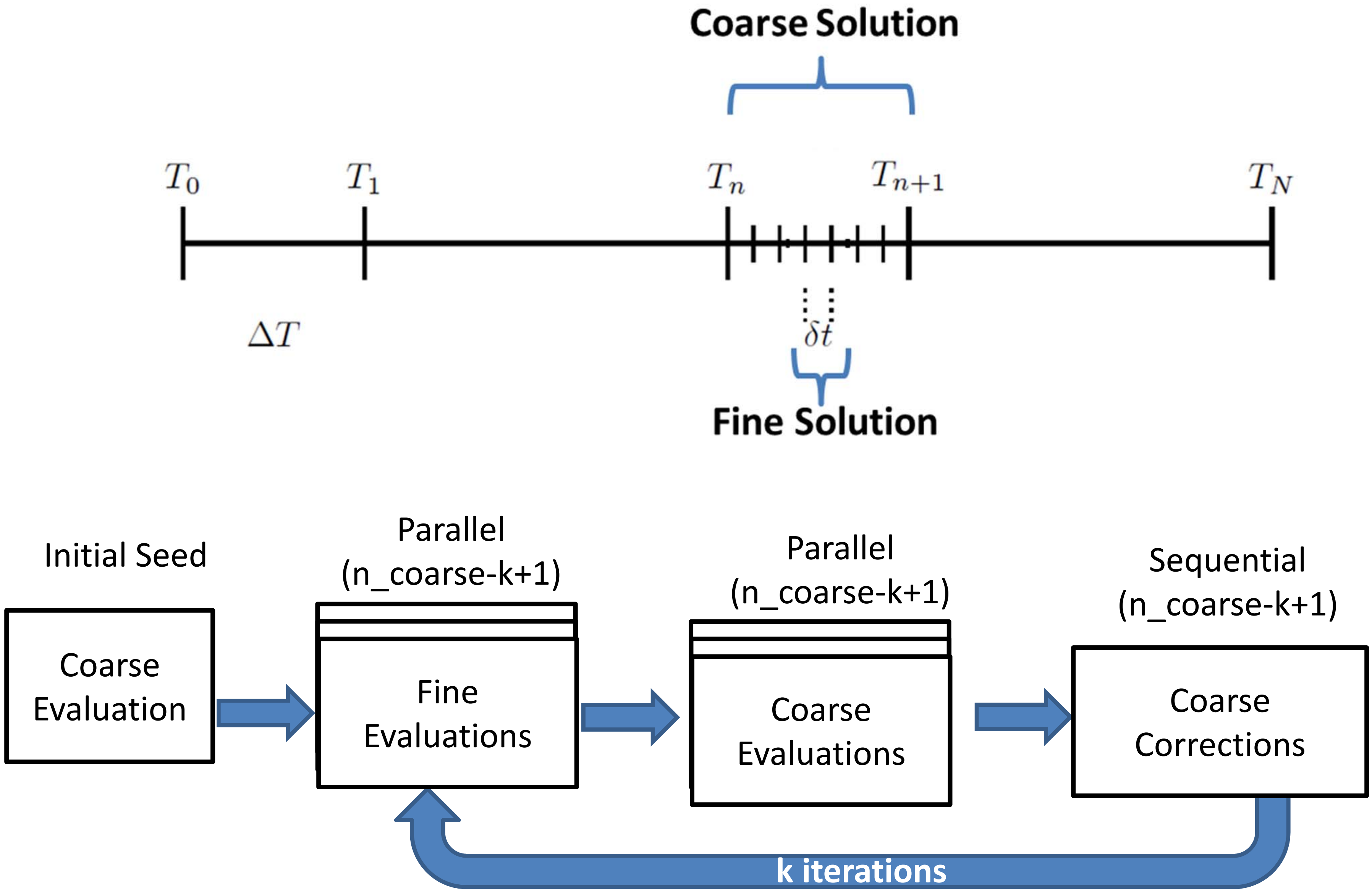
Terminal Voltage Responses



Disturbance: 3ph Fault at bus 5, Fault Duration 0.1s (6 cycles)

Parareal Time Parallel Algorithm

Parareal Algorithm

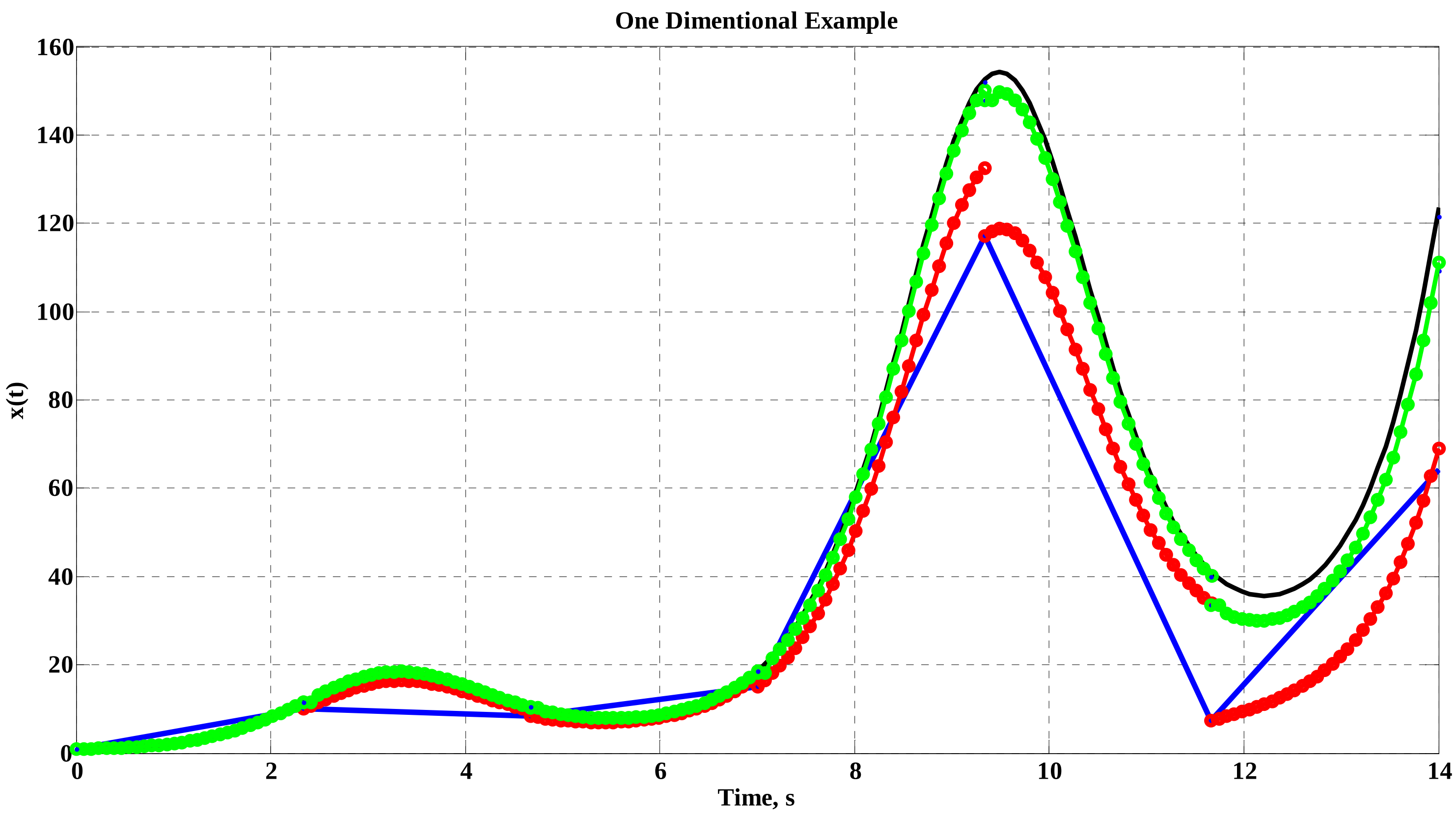


Parareal Implementation on 1&2-Dimentional Systems

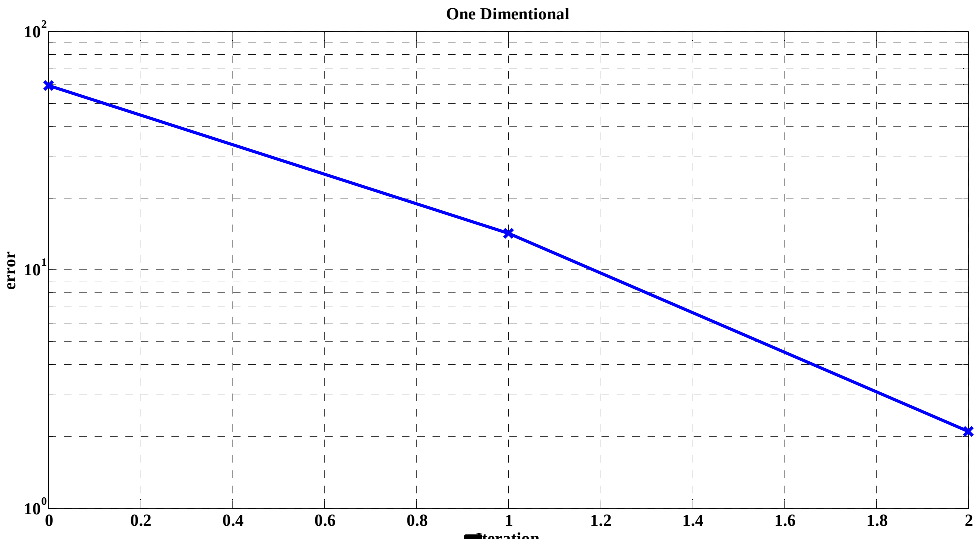
One Dimensional

$$\frac{\partial y}{dt} = \sin(t)\, y(t) + t$$

$$y(0) = 1 \quad , t \in [0, 14]$$

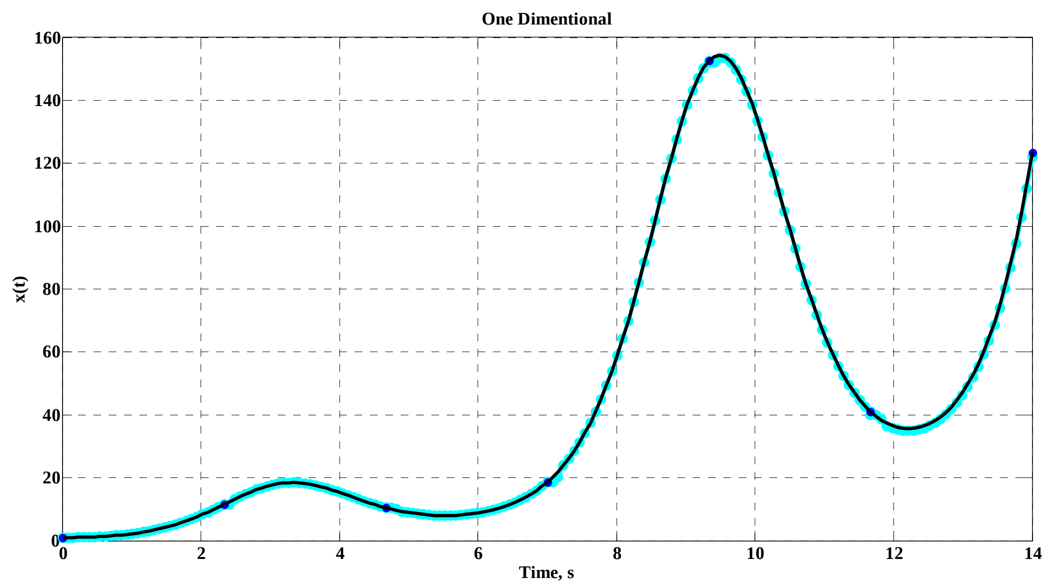


Error and Convergence



Error

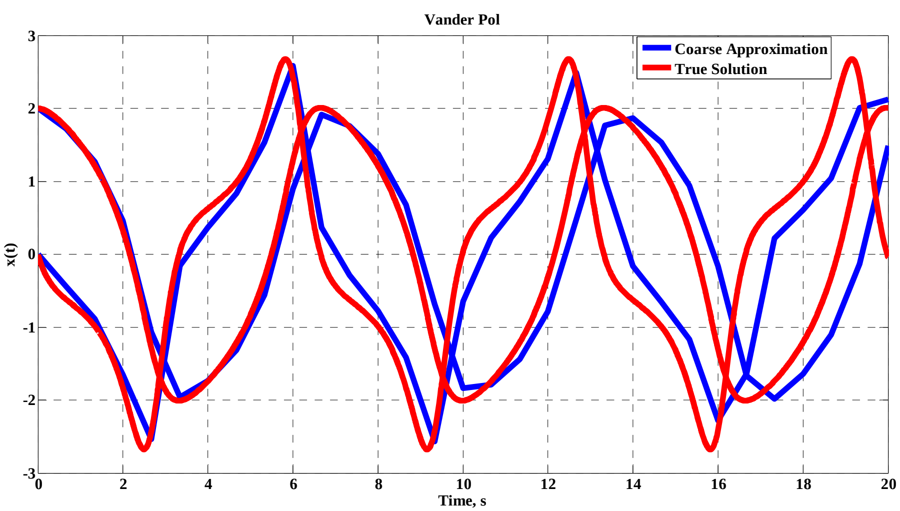
Convergence in 3 Iterations

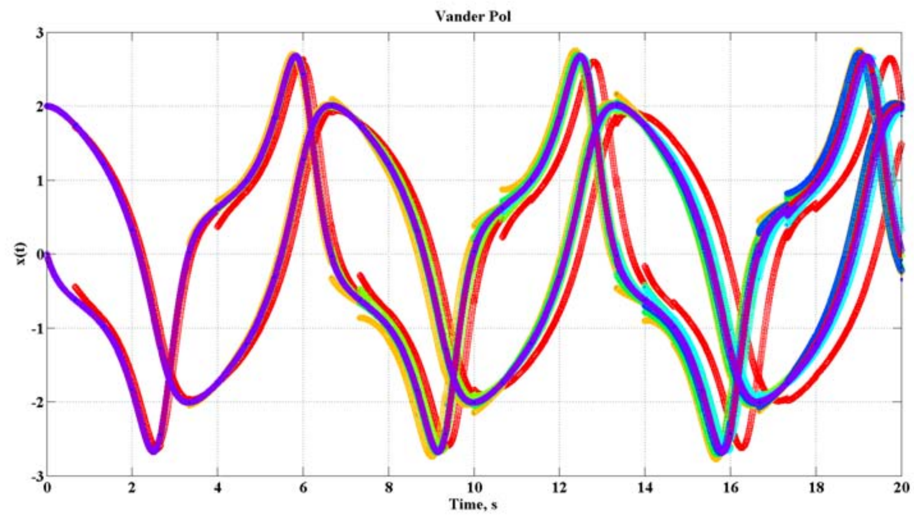


Two Dimensional System

Vander Pol Equations

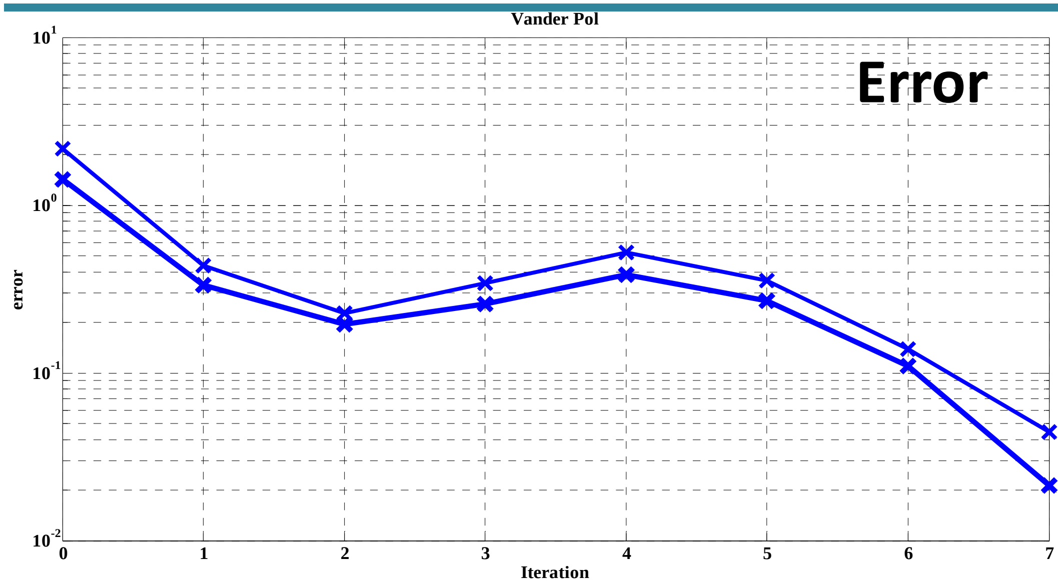
$$y_1' = y_2$$
$$y_2' = \mu\left(1 - y_1^2\right)y_2 - y_1.$$





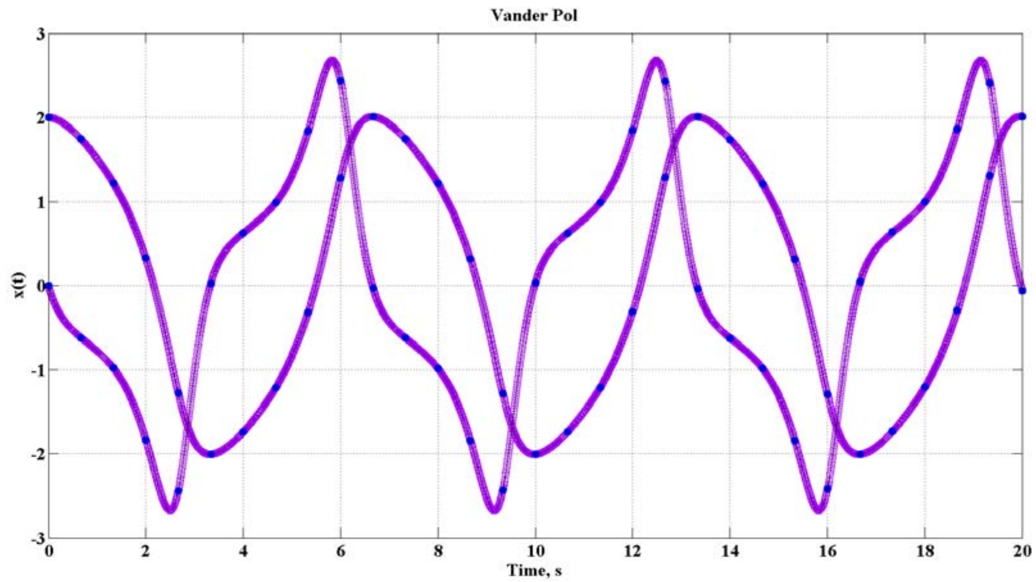
Coarse = 30; Fine = 100

Error and Convergence



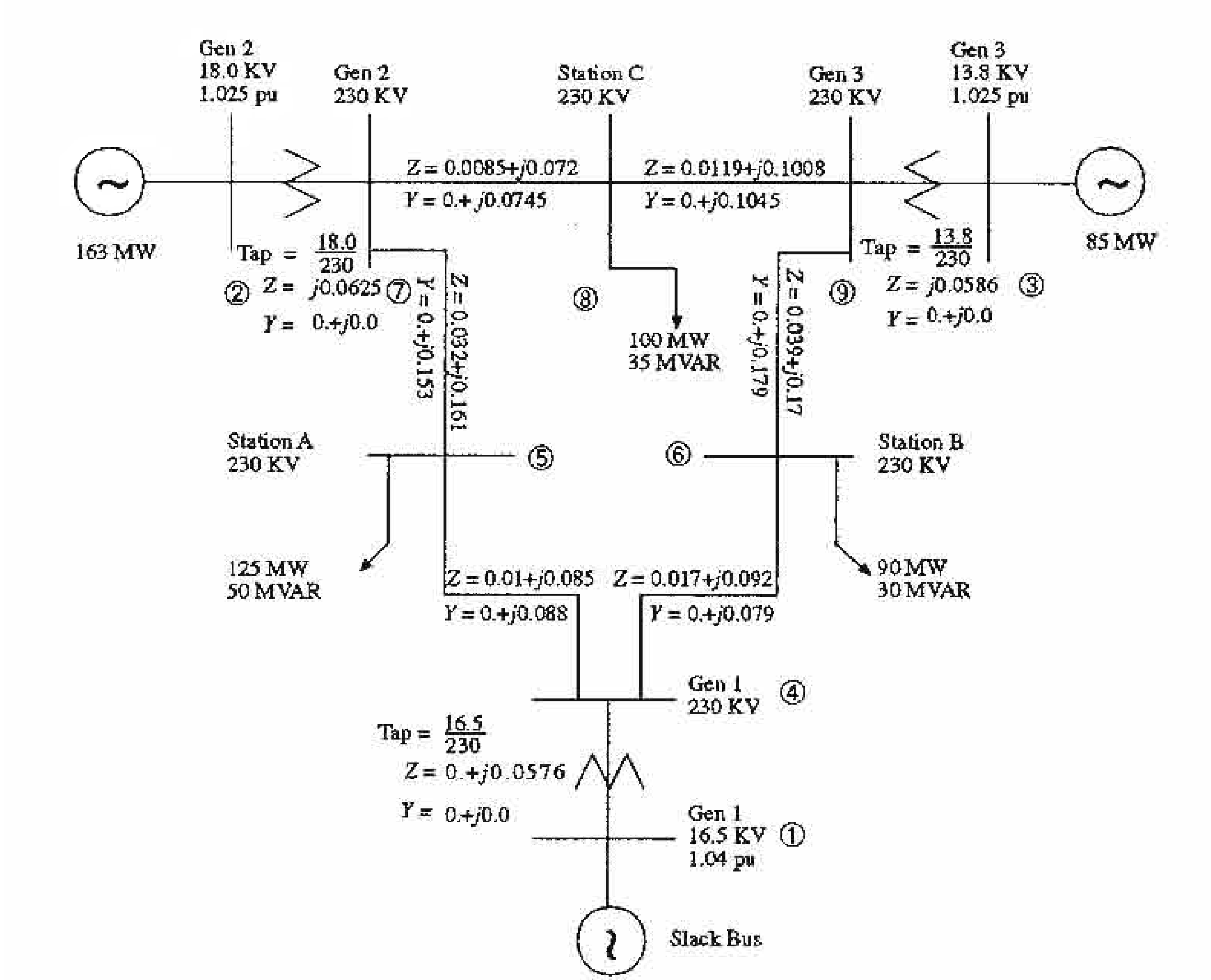
Error

Convergence in
8 Iterations

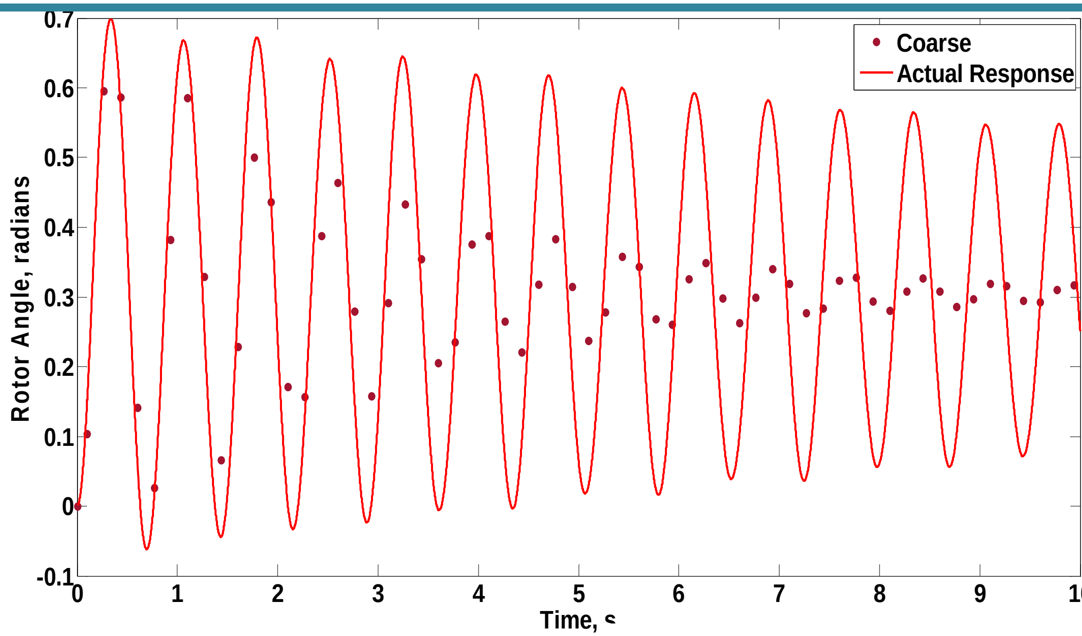


Parareal Implementation
on
Power System Classical Model

3 Generator - 9 Bus System



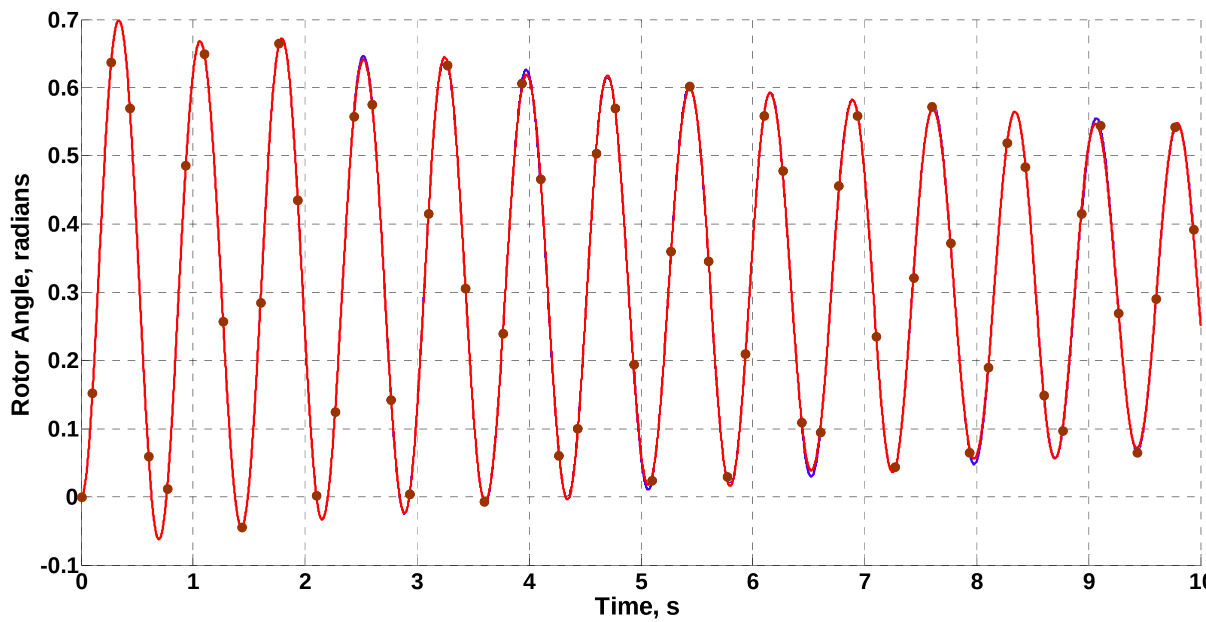
Classical Model Rotor Angle Responses – 3 Gen 9 Bus



Coarse: Classical Model with RK4
60 intervals 0.1818s

Fine: Classical Model with RK4
100 intervals 0.0018s

After 6 iterations



3 Gen 9 Bus   Both Classical Models   Coarse RK4 - Fine Rk4

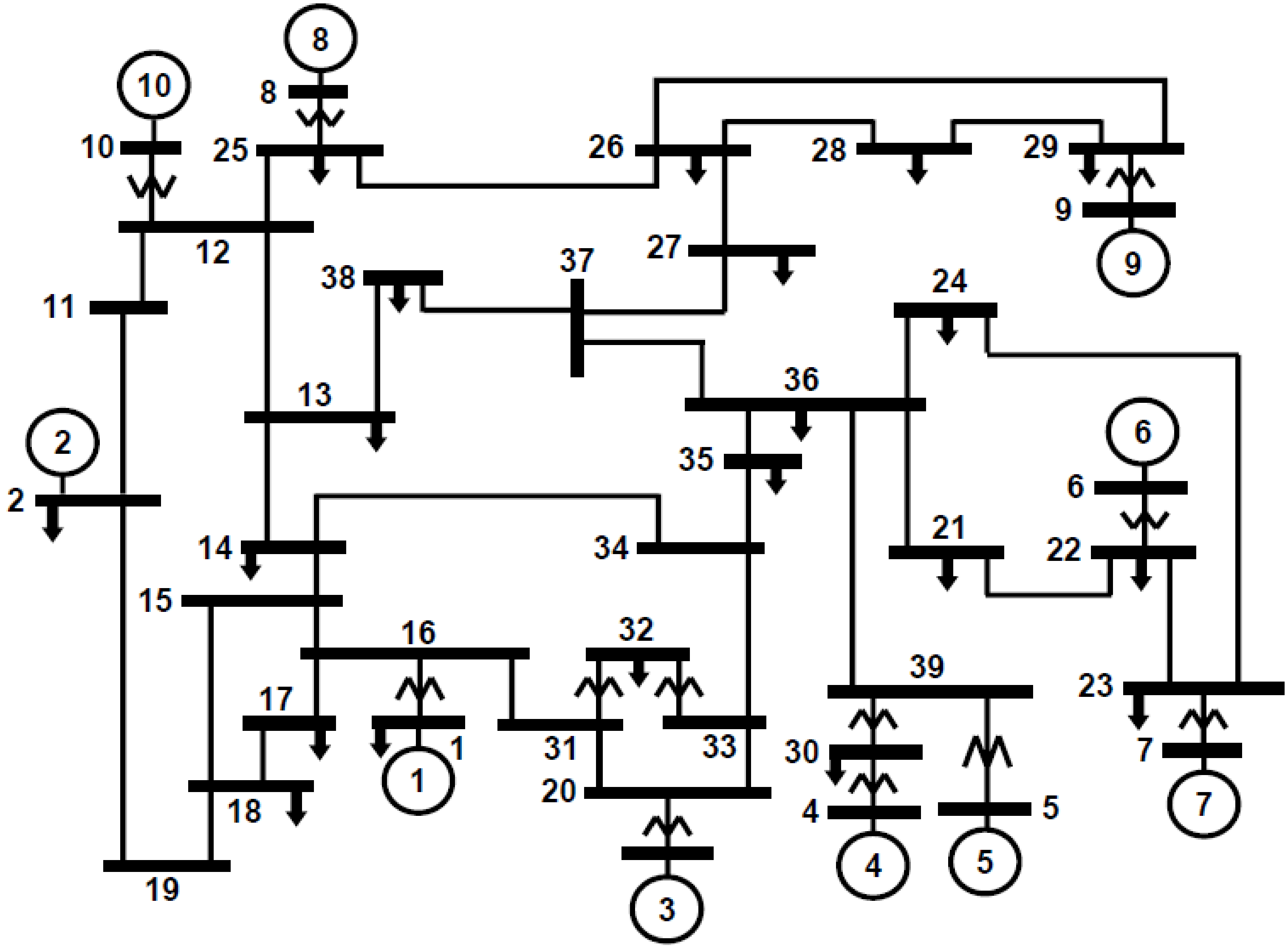
No of Fine Intervals, n_fine = 100, 0.00167s

No of Coarse Intervals, n_coarse = 60, 0.1667s

Coarse Initial	iteration k	Fine Evaluation	if Parallel		Coarse Prediction	if Parallel		Sequential Coarse Correction
	1	1.339289849	0.0223215		0.014592738	0.00024321		0.014691148
	2	1.316211219	0.02230866		0.014766918	0.00025029		0.014704129
	3	1.301405662	0.02243803		0.013325787	0.00022975		0.013452572
	4	1.272228637	0.0223198		0.013105421	0.00022992		0.01336835
	5	1.248776895	0.02229959		0.012894413	0.00023026		0.012949052
	6	1.224902533	0.02227096		0.012659558	0.00023017		0.013086705
0.033039		Total	0.13395853		Total	0.0014136	Total	0.082251957
Total Time Parareal	0.2506631							
Time for Fine Only with Fine Step	1.323156							
Speeed Up	5.27862308							

Speed Up 5.27 with the assumption of ideal Parallelization

10 Generator - 39 Bus System



Speed Up – Classical Model

Coarse – Fine	System	Achieved	Theoretical
RK4 - RK4	3 Gen-9 Bus	5.27	60/6=10
RK4 – RK4	10 Gen – 39 Bus	4.71	60/5=12

Parareal Implementation
Power System Detailed Models

Integration Methods: Trapezoidal with Midpoint rule predictor

RK4 Method

Speedup – Summary

Coarse – Fine	System	Achieved	Theoretical
Trap – Trap	3 Gen – 9 Bus	4.7	400/8= 50
Trap – RK4	3 Gen – 9 Bus	6.26	400/8=50
Trap – Trap	10 Gen – 39 Bus	5.27	400/7=57
Trap – RK4	10 Gen – 39 Bus	7.06	400/7=57
Trap – Trap	327 Gen – 2383 Bus	4.23	400/9=44
Trap – RK4	327 Gen – 2383 Bus	9.11	400/9=44

Future Work

- Hierarchical windowing approach
- Detailed IEEE 2.2 SM model
- C implementation + SUNDIALS solvers
- Initial HPC implementation to test scalability
- Benchmarking parareal on EI
- Combine system decomposition with parareal in collaboration with ANL

Acknowledgements

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