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Using PETSc as a Testbed for Developing and Benchmarking Parallel Power System Applications

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October 24, 2012

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Need for parallelizing power system algorithms

- Next-generation power grid
 - PMUs, smart meters, Distributed Generation, Plug-in hybrid vehicles, Smart and Micro-grids, Power electronics, Increased communication
- Resultant Computational challenges
 - Data explosion, Real-time simulation requirements, Larger or denser network, Multi-scale (temporal, geographical)
- Next-generation computing architecture
 - Multicore, Manycore machines.
 - GPGPUs

Parallel computing in Power Systems

- Research on parallel power system applications
 - Power Flow, Optimal Power Flow, Transient Stability, Contingency Analysis, State Estimation, Electromagnetic transients simulation.
- Survey papers
 - “Parallel processing in power systems computation” (IEEE Task Force)
 - “High Performance Computing in Power Systems” (D. Falcao)
- Many parallel algorithms showed significant time savings yet hesitancy in commercial adoption
 - Specific algorithms tested for on a specific architecture using a specific topology and operating conditions.
 - Parallel algorithms are hard to program: synchronization/communication, partitioning, parallel linear, nonlinear solvers, reductions, debugging,...

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Parallel computing in Power Systems

- Need to develop and benchmark parallel algorithms on **different** computing architectures on **different** topologies under **different** power system operating conditions.
 - Benchmark existing parallel algorithms.
 - Develop and benchmark new ones.

This a lot of work!!!

High performance libraries, such as PETSc, can aid in the rapid development and benchmarking process:

- Rapid development of parallel applications.
- Portable to variety of computing architectures.
- Wide array of tested for linear, nonlinear, and time-stepping solvers.
- Reduce the experimentation time and effort.

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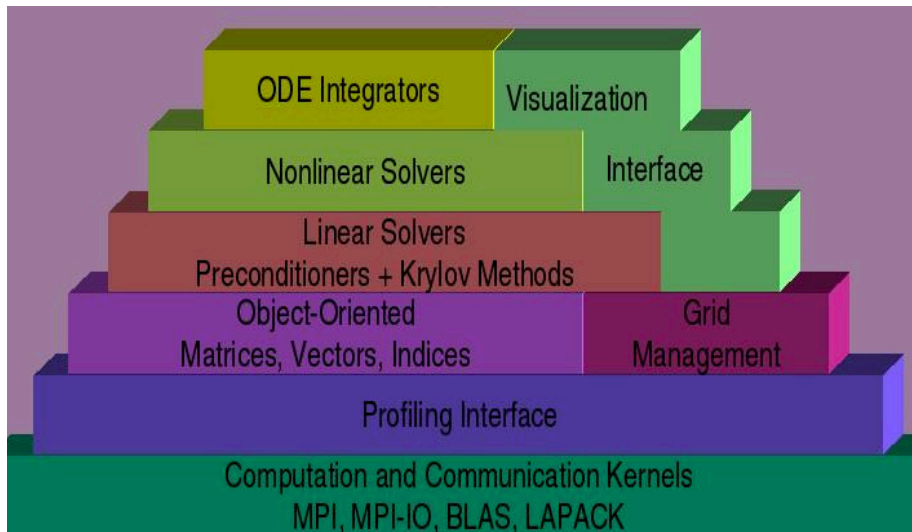
Portable Extensible Toolkit for Scientific Computation

- What is PETSc?
 - Library for developing large-scale parallel applications.
 - Provides parallel numerical solvers (time-stepping, nonlinear, linear) and basic building blocks (parallel matrices, vectors, communication objects) for rapidly developing parallel applications.
 - Mostly used by researchers in PDE applications.
 - Free for anyone to use including industrial users.
 - Top 100 R & D award in 2009, Cited as DOE's top 10 advancements in computational science accomplishments in 2008.
- What can PETSc handle ?
 - PETSc has run implicit problems with 1 billion unknowns
 - PFLOTRAN for flow in porous media
 - PETSc has run on over 224,000 cores efficiently
 - UNIC on the IBM BG/P at ANL
 - PFLOTRAN on the Cray XT5 Jaguar at ORNL

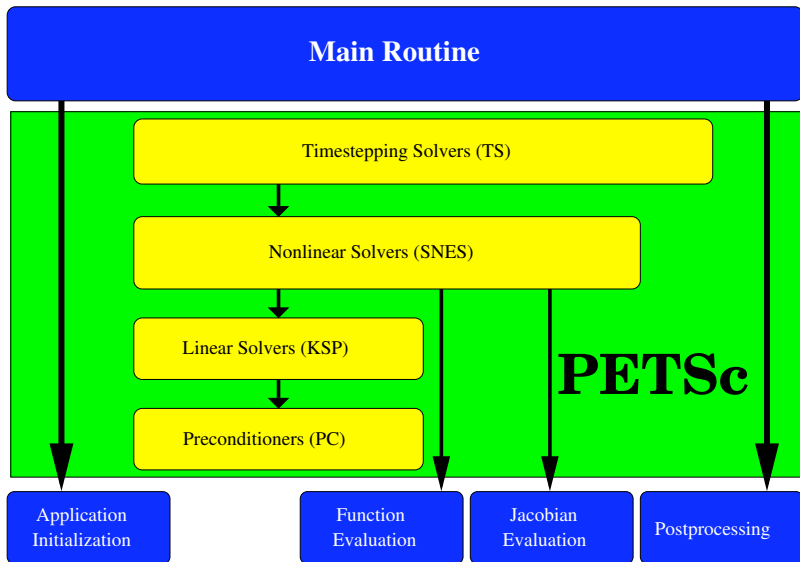
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PETSc Organization

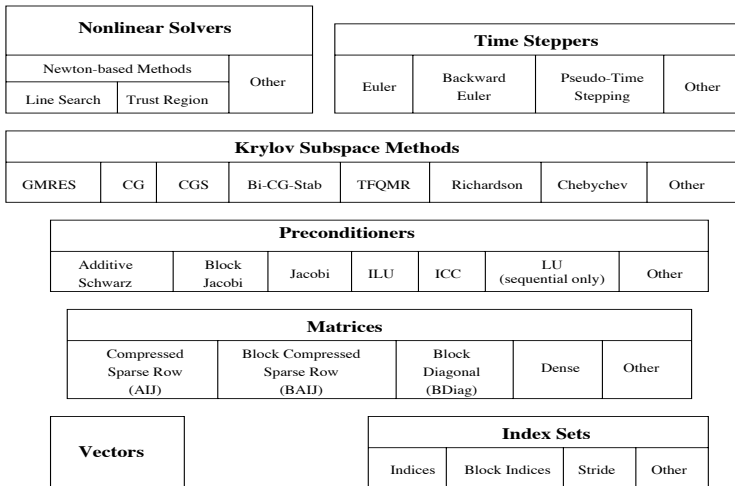


Flow control of a PETSc application



PETSc Numerical Components

Parallel Numerical Components of PETSc



PETSc features

- Free for anyone, including industrial users
- Portability
 - Unix, Linux, MacOS, Windows
 - Tightly/loosely couple architectures
 - 32/64 bit ints, single/double/quad precision, real/complex
 - C, C++, Fortran, Matlab, Python (petsc4py)
- Extensibility
 - BLAS, LAPACK, BLACS, ScaLAPACK, PLAPACK
 - MPICH, MPE, Open MPI
 - ParMetis, Chaco, Jostle, Party, Scotch
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PETSc features

- Abstract linear algebra interface (Vectors, Matrices, Index Sets, etc.)
- Consistent user interface.
- Keep MPI opaque to the user.
- Flexible run time options
 - Old
Modify. Make. Run. Modify. Make. Run
 - New
`./ex -snes_type <ls,tr,test> -ksp_type
<gmres,cg,bicg,preonly> -pc_type <lu,ilu,icc,jacobi>
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- Debugging [gdb, dbx]
 - Automatic generation of trace back
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Support for GPGPUs and Multicore architectures

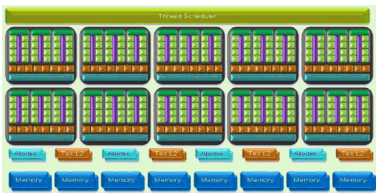


Figure: NVidia GTX 280 GPU architecture

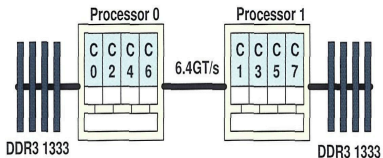


Figure: Intel Nehalem

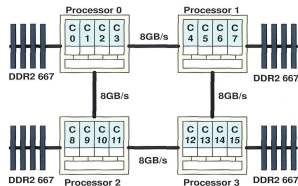


Figure: AMD Barcelona

Splitting for Multiphysics

Efficient solvers for coupled multiphysics applications

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} f \\ g \end{bmatrix}$$

- Relaxation: `-pc_fieldsplit_type`
[additive,multiplicative,symmetric_multiplicative]

$$\begin{bmatrix} A & \\ & D \end{bmatrix}^{-1} \quad \begin{bmatrix} A & \\ C & D \end{bmatrix}^{-1} \quad \begin{bmatrix} A & \\ & \mathbf{1} \end{bmatrix}^{-1} \left(\mathbf{1} - \begin{bmatrix} A & B \\ & \mathbf{1} \end{bmatrix} \begin{bmatrix} A & \\ C & D \end{bmatrix}^{-1} \right)$$

- Gauss-Seidel inspired, works when fields are loosely coupled
- Factorization: `-pc_fieldsplit_type schur`

$$\begin{bmatrix} A & B \\ & S \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{1} & \\ CA^{-1} & \mathbf{1} \end{bmatrix}^{-1}, \quad S = D - CA^{-1}B$$

List of power system applications that can be developed using PETSc

- Linear (using KSP)
 - DC Power Flow, Sensitivity factors
- Nonlinear (using SNES)
 - AC Power Flow, Contingency analysis, Continuation power flow
 - Distribution power flow, Combined Transmission-distribution power flow
- Time-stepping (using TS)
 - Transient stability, Electromagnetic transients
 - Combined transient stability-electromagnetic transients (hybrid simulation)
- Optimization (using TAO package)
 - SCOPF, LMP calculations
- Eigen-value analysis (using SLEPc package)
 - Small signal stability analysis

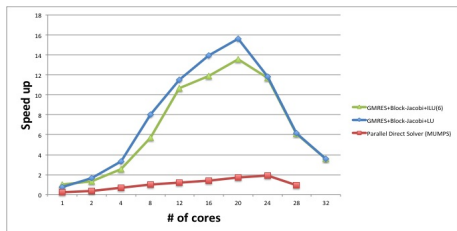
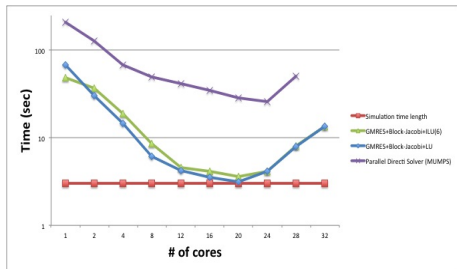
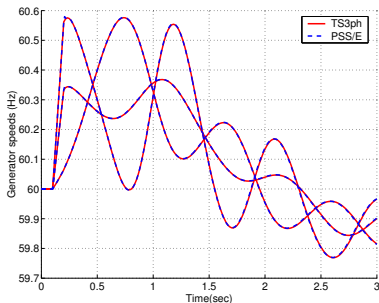
Real-time electrical power system dynamics

- Nonlinear differential-algebraic power system model

$$\dot{x} = f(x, y)$$

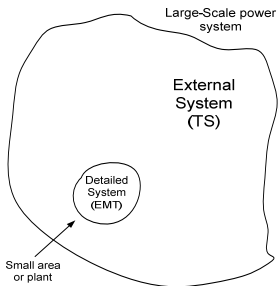
$$0 = g(x, y)$$

- Three-phase network
- Spatial decomposition in parallel



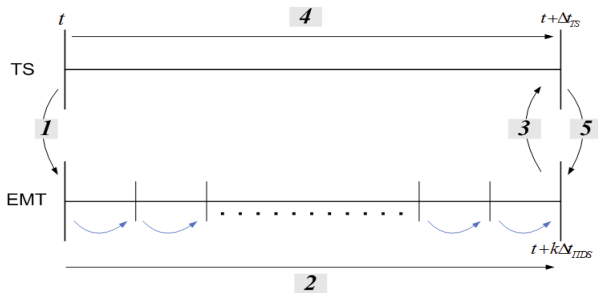
* Scalability results of 2360 bus, 4670 branches, 1080 generator system

Combined Electromechanical and Electromagnetic Transients Simulation



- Capture “global” slow dynamics and “local” fast dynamics
- Use TS globally and EMT locally
- Need interface for
 - Time step
 - Network modeling
 - Waveform

Existing “explicit” hybrid simulation approach



- Make separate TS and EMT programs talk to each other
- Explicit approach
- No iterations between TS and EMT
- Diverges for large changes in voltages/currents
- Limited parallelism

Proposed “Implicitly-coupled” hybrid simulation approach

- Combine TS and EMT at the equation level rather than at the application level
- Solve TS equations and coupled-in-time EMT equations for each TS time step together
- More robust than the explicit approach
- Allows an integrated parallel implementation

$$x_{TS}(t_{N+1}) - x_{TS}(t_N) - \frac{\Delta t_{TS}}{2}(F(t_{N+1}) + F(t_N)) = 0 \quad (4)$$

$$G(t_{N+1}) = 0 \quad (5)$$

$$x_{EMT}(t_{n+1}) - x_{EMT}(t_n) - \frac{\Delta t_{EMT}}{2}(f_1(t_{n+1}) + f_1(t_n)) = 0 \quad (6)$$

$$i_{bdry}(t_{n+1}) - i_{bdry}(t_n) - \frac{\Delta t_{EMT}}{2}(f_2(t_{n+1}) + f_2(t_n)) = 0 \quad (7)$$

$$x_{EMT}(t_{n+2}) - x_{EMT}(t_{n+1}) - \frac{\Delta t_{EMT}}{2}(f_1(t_{n+2}) + f_1(t_{n+1})) = 0 \quad (8)$$

$$i_{bdry}(t_{n+2}) - i_{bdry}(t_{n+1}) - \frac{\Delta t_{EMT}}{2}(f_2(t_{n+2}) + f_2(t_{n+1})) = 0 \quad (9)$$

$$\vdots$$

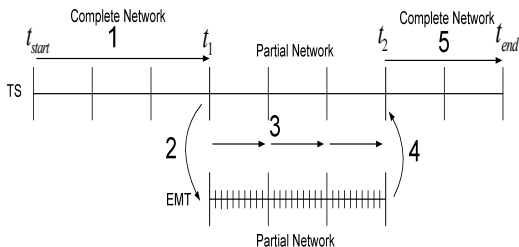
$$\vdots$$

$$x_{EMT}(t_{n+k}) - x_{EMT}(t_{n+k-1}) - \frac{\Delta t_{EMT}}{2}(f_1(t_{n+k}) + f_1(t_{n+k-1})) = 0 \quad (10)$$

$$i_{bdry}(t_{n+k}) - i_{bdry}(t_{n+k-1}) - \frac{\Delta t_{EMT}}{2}(f_2(t_{n+k}) + f_2(t_{n+k-1})) = 0 \quad (11)$$

Multi-scale dynamics simulation strategy

- Only run the implicitly coupled simulator in the presence of fast dynamics, run TS for all other times

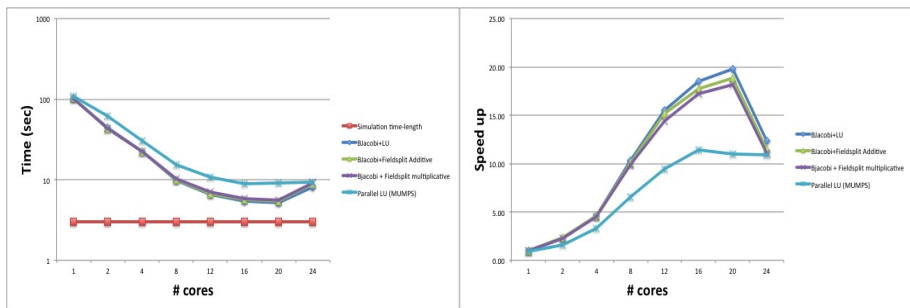


- Time-comparison of different dynamic analyses

System size	Simulated time (sec)	TS3ph	EMT	Only TSEMT	TS3ph-TSEMT
9 bus	3	0.13	4.96	5.46	0.41
118 bus	3	0.36	30.1	4.87	0.53

Parallel implementation and performance results

- Partition TS network in space and EMT network in time
- Each processor gets equations for
 - TS subnetwork
 - EMT equations for multiple time-steps



*2360 buses total, 4 buses, 3 transmission lines and 4 loads in EMT network

*Using GMRES + Block-Jacobi + LU + Very Dishonest preconditioning

PETSc use in the example applications

- **Easy parallel implementation**
- Partitioning (using ParMetis)
- Tune Linear solvers (using KSP and PC libraries)
- Nonlinear solver (SNES library)
- Portable code
- Reduced experimentation time
 - Selecting different algorithms at run-time!!

Wrapping up...

*Developing parallel, nontrivial applications that deliver high performance is still difficult and requires months (or even years) of concentrated effort. PETSc is a toolkit that can ease these difficulties and reduce the development time, but it is not a black-box solver, nor a **silver bullet**. – Barry Smith*

PETSc can help power system applications

- to solve algebraic and DAE problems
- benchmark with different numerical solvers.
- rapidly develop efficient parallel code, can start from examples
- develop new solution methods and data structures
- debug and analyze performance
- advice on software design, solution algorithms, and performance
 - `petsc-{users,dev,maint}@mcs.anl.gov`