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

Shrirang Abhyankar, Barry Smith, Hong Zhang
Argonne National Laboratory

Alexander Flueck
Illinois Institute of Technology

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Algorithms, computing resources, and software tools need to be up to date with the market operational demands.
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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
Research on parallel power system applications

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,...
Parallel computing in Power Systems

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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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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

- ODE Integrators
- Visualization
- Nonlinear Solvers
- Interface
- Linear Solvers
- Grid Management
- Preconditioners + Krylov Methods
- Object-Oriented
- Matrices, Vectors, Indices
- Profiling Interface
- Computation and Communication Kernels
  - MPI, MPI-IO, BLAS, LAPACK
Flow control of a PETSc application

Main Routine

- Timestepping Solvers (TS)
- Nonlinear Solvers (SNES)
- Linear Solvers (KSP)
- Preconditioners (PC)

PETSc

- Application Initialization
- Function Evaluation
- Jacobian Evaluation
- Postprocessing
## PETSc Numerical Components

### Parallel Numerical Components of PETSc

<table>
<thead>
<tr>
<th>Nonlinear Solvers</th>
<th>Time Steppers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newton-based Methods</td>
<td>Euler</td>
</tr>
<tr>
<td>Line Search</td>
<td>Backward Euler</td>
</tr>
<tr>
<td>Trust Region</td>
<td>Pseudo-Time Stepping</td>
</tr>
<tr>
<td>Other</td>
<td>Other</td>
</tr>
</tbody>
</table>

### Krylov Subspace Methods

<table>
<thead>
<tr>
<th>GMRES</th>
<th>CG</th>
<th>CGS</th>
<th>Bi-CG-Stab</th>
<th>TFQMR</th>
<th>Richardson</th>
<th>Chebychev</th>
<th>Other</th>
</tr>
</thead>
</table>

### Preconditioners

<table>
<thead>
<tr>
<th>Additive Schwarz</th>
<th>Block Jacobi</th>
<th>Jacobi</th>
<th>ILU</th>
<th>ICC</th>
<th>LU (sequential only)</th>
<th>Other</th>
</tr>
</thead>
</table>

### Matrices

<table>
<thead>
<tr>
<th>Compressed Sparse Row (AIJ)</th>
<th>Block Compressed Sparse Row (BAIJ)</th>
<th>Block Diagonal (BDiag)</th>
<th>Dense</th>
<th>Other</th>
</tr>
</thead>
</table>

### Vectors

<table>
<thead>
<tr>
<th>Indices</th>
<th>Block Indices</th>
<th>Stride</th>
<th>Other</th>
</tr>
</thead>
</table>
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
  - MUMPS, Spoolso, SuperLU, SuperLU_Dist, UMFPack, pARMS
  - PaStiX, BLOPEX, FFTW, SPRNG
  - HYPRE, ML, SPAI
  - Sundials
  - HDF5, Boost
  - Packages can be directly downloaded and installed at configure time
    --download-<packagename>=1
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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
  - New
    ./ex -snes_type <ls,tr,test> -ksp_type <gmres,cg,bicg,preonly> -pc_type <lu,ilu,icc,jacobi> -mat_type <aij,baij,sbaij>
- Debugging [gdb, dbx]
  - Automatic generation of trace back
  - Attach debugger at start, on error, to a subset of processes
  - Valgrind
- Check jacobian correctness
  - -snes_type test -snes_test_display
- Profiling
  - Logs Time, Memory usage, Calls, Flops, MPI messages, user code (stages, events)
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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]

\[
\begin{bmatrix}
A & D \\
C & D
\end{bmatrix}^{-1}
\begin{bmatrix}
A & D \\
C & D
\end{bmatrix}^{-1}
\begin{bmatrix}
A & 1 \\
1 & 1
\end{bmatrix}^{-1}
\left(1 - \begin{bmatrix}
A & B \\
C & D
\end{bmatrix}\begin{bmatrix}
A & D \\
C & D
\end{bmatrix}^{-1}ight)
\]

- Gauss-Seidel inspired, works when fields are loosely coupled

- Factorization: `-pc_fieldsplit_type schur`

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

\[
\begin{align*}
    x_{TS}(t_{N+1}) - x_{TS}(t_N) - \\
    \frac{\Delta t_{TS}}{2} (F(t_{N+1}) + F(t_N)) &= 0 \\
    G(t_{N+1}) &= 0 \\
    x_{EMT}(t_{n+1}) - x_{EMT}(t_n) - \\
    \frac{\Delta t_{EMT}}{2} (f_1(t_{n+1}) + f_1(t_n)) &= 0 \\
    i_{bdry}(t_{n+1}) - i_{bdry}(t_n) - \\
    \frac{\Delta t_{EMT}}{2} (f_2(t_{n+1}) + f_2(t_n)) &= 0 \\
    x_{EMT}(t_{n+2}) - x_{EMT}(t_{n+1}) - \\
    \frac{\Delta t_{EMT}}{2} (f_1(t_{n+2}) + f_1(t_{n+1})) &= 0 \\
    i_{bdry}(t_{n+2}) - i_{bdry}(t_{n+1}) - \\
    \frac{\Delta t_{EMT}}{2} (f_2(t_{n+2}) + f_2(t_{n+1})) &= 0 \\
    &\vdots \\
    x_{EMT}(t_{n+k}) - x_{EMT}(t_{n+k-1}) - \\
    \frac{\Delta t_{EMT}}{2} (f_1(t_{n+k}) + f_1(t_{n+k-1})) &= 0 \\
    i_{bdry}(t_{n+k}) - i_{bdry}(t_{n+k-1}) - \\
    \frac{\Delta t_{EMT}}{2} (f_2(t_{n+k}) + f_2(t_{n+k-1})) &= 0
\end{align*}
\]
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

<table>
<thead>
<tr>
<th>System size</th>
<th>Simulated time (sec)</th>
<th>TS3ph</th>
<th>EMT</th>
<th>Only TSEMT</th>
<th>TS3ph-TSEMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 bus</td>
<td>3</td>
<td>0.13</td>
<td>4.96</td>
<td>5.46</td>
<td>0.41</td>
</tr>
<tr>
<td>118 bus</td>
<td>3</td>
<td>0.36</td>
<td>30.1</td>
<td>4.87</td>
<td>0.53</td>
</tr>
</tbody>
</table>
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!!
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