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Integrated State Estimation and Contingency Analysis Software Implementation using High Performance Computing Techniques

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Abstract: Power system simulation tools are traditionally developed in sequential mode and codes are optimized for single core computing only. However, the increasing complexity in the power grid models requires more intensive computation. The traditional simulation tools will soon not be able to meet the grid operation requirements. Therefore, power system simulation tools need to evolve accordingly to provide faster and better results for grid operations. This paper presents an integrated state estimation and contingency analysis software implementation using high performance computing techniques. The software is able to solve large size state estimation problems within 1 second and achieve a near-linear speedup of 9,800 with 10,000 cores for contingency analysis application. The performance evaluation is presented to show its effectiveness.

Keywords: Energy Management Systems (EMS), Situational Awareness, High Performance Computing, State Estimation, Contingency Analysis

1. INTRODUCTION

The power grid has experienced an unprecedented transition as it saw many changes over the last decade. Some examples of these changes include the deployment of new smart grid technologies, the increased penetration of renewable energy in power systems, and the application of other emerging technologies. This transition poses significant challenges in power grid operation and management. Central to this transition, power system computation needs to evolve accordingly to provide fast results for power grid operation.

Current power system simulation tools are mainly implemented based on sequential algorithms and optimized for single core environments. This includes widely used energy management system (EMS) functions in control centers, like state estimation (SE) and contingency analysis (CA) functions. In today's practice, the typical state estimation program runs every 20-30 seconds, which is not fast enough to accurately capture the system state, especially in the case of a severe disturbance. For example, in the September 2011 Pacific Southwest blackout, there were events that occurred less than 10 seconds apart. If system states can be obtained in near real-time, say 1 second, the cascading event sequence, similar to the mentioned blackout, might be able to be mitigated earlier and the loss could be minimized.

Similar situations apply to the contingency analysis function. As a result of the heavy computational burden involved and the limitation of computational resources in today's control center, a certain number of pre-selected contingency cases are analysed. The pre-selection is based on off-line studies. This set of contingencies includes mainly *N*-1 contingencies, i.e., one power grid element is in contingency, and a few "*N-x*" contingency cases, i.e., multiple power grid elements are in contingency. This limited number of contingencies cannot guarantee coverage of all critical contingencies for different operation points with different generation and load patterns. This is especially true for the cases of running multiple contingencies with the new "*N-x*" North American Electric Reliability Corporation (NERC) standard. Considering the new stochastic behavior introduced by variable energy resources, as well as the requirement of look-ahead unit commitment for market operation, the current contingency analysis function needs to be greatly improved in computational time. Reducing the computation time enables the contingency analysis to meet the requirements of future grid operation and enhance the reliability and efficiency of power grid operation.

Power system researchers understand that operations need appropriate analysis tools available to quickly run simulations to help them make timely decisions. There are many researchers working on improving power system computation by taking advantage of high-performance-computing (HPC) techniques to accelerate power grid applications. Because state estimation and contingency analysis are two typical EMS functions whose outputs are critical for subsequent analysis, this paper focuses on improving their computational speed. The approach in this paper utilizes HPC techniques to handle the substantial computational burden for better state awareness.

There are numerous publications in the area of parallel state estimation with different parallelization techniques. For instance: Wallach et al. (1981) used Alternating Sequential/Parallel system, Abur and Tapadiya (1990) used sparse vector techniques, and Dag and Alvarado (1997a, b)

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applied the preconditioned conjugate gradient (PCG) method to develop parallel state estimation approaches. In the area of parallel and distributed state estimation, Seidu and Mukai (1985) developed a parallel multi-area state estimation algorithm based on multipartitioning techniques. Falcao et al. (1995) applied coupling constraints optimization techniques for parallel and distributed state estimation. Nordman and Lehtonen (2005) proposed an agent-based distributed state estimation concept. All algorithms discussed in these papers were not tested on practical systems. Ebrahimian and Baldick (2000) applied auxiliary problem principal to develop a distributed state estimator and tested the approach on practical systems. A better computational speed was observed than the centralized state estimators, which helped highlight the practical scalability of distributed or parallel state estimation.

In the area of parallel contingency analysis, most research is focused on *N*-1 contingencies with a small-medium size model. For instance, Alves and Monticelli (1995) discussed using parallel computers and distributed networks to solve contingency analysis. Santos, et al. (1999) discussed a distributed client-server scheme for fast decoupled load flow-based contingency analysis. Balduino and Alves (2004) implemented parallel contingency analysis on a cluster of microcomputers with parallel virtual machine (PVM) and message passing interface (MPI) systems. Morante, et al. (2006) proposed a pervasive grid middleware to split contingency cases automatically according to a master-slave model. All these researchers are mainly focused on *N*-1 contingency analysis and with a small-to-medium size model. Mittal et al. (2011) presented a scalable parallel implementation of a probabilistic contingency analysis scheme for *N-x* contingency analysis with IEEE 300- and 118-bus model, scaled up to 8192 cores with a speedup of 6513 and 5630, respectively. Khaitan el al. (2013) presented a technique to combine the advantage of proactive task scheduling and stealing with the simplicity of massive-slave scheme, and tested on a 13,029-bus system. A speedup of 30.37 was obtained with 32 cores. The latter two examples highlight the significant gains and improving speedup characteristics HPC techniques can bring to large-scale contingency analysis.

The authors have also conducted extensive research in the area of parallel state estimation and massive contingency analysis. For state estimation, the authors did a series of studies with different solver techniques. For instance, a Preconditioned Conjugated Gradient (PCG) algorithm with the Hypre solver (Hypre online) was applied to in-house parallel state estimation software and tested with the Western Electricity Coordinating Council (WECC) 2005 planning case; a solution time of ~5 seconds was achieved (Chen, et al. 2012c). This parallel state estimation software with the Hypre solver was further validated with 47 real snap shots from the Bonneville Power Administration (BPA) system. The average solution time was 3.66 seconds, which is about 2 seconds faster than a commercial EMS tool (Chen, et al. 2013a, 2014). Recently, the authors achieved sub-second computations with the BPA data (Chen et al., 2015), which is more than 10 times faster than today's commercial tools. Further performance was gained with the NICSLU solver (Chen. et al.. 2011, 2012b, 2013b).

The discussion of the benefits of fast state estimation can be found in Elizondo et al. (2012). For example with fast state estimation, operators have more time to apply corrective control actions to increase the chances of arresting a cascading failure or mitigating its impact.

For contingency analysis, the authors developed a counter-based dynamic load balancing scheme to obtain optimal speedup for massive contingency analysis, utilizing the SuperLU direct linear solver (SuperLU online). A computational time of 31 seconds for 20,000 *N*-1 contingency cases was obtained using 512 cores, resulting in a speedup of 462 (Huang et al. 2009). The authors proposed multi-counter based dynamic load balancing schemes and provided guidance on selecting different schemes based on MATLAB simulation (Chen et al. 2010), The different schemes were evaluated on over 10,000 cores using the WECC 2005 model (Chen et al. 2012b). The speedup of 7877 with 10240 cores was obtained for 1 million *N*-2 cases for the WECC 2005 model. The best computational time of 66.9 seconds was reached with two-counter based dynamic scheme and 10240 cores.

To allow better flexibility and make the software more functional, the authors made further contributions to integrating the parallel state estimation and massive contingency analysis software together with an option of selecting many popular sparse linear solvers. The new software is called SECA, which comes from a combination of SE and CA. It allows the utilization of the power of advanced computing techniques with the capability of performing in-depth analysis. This paper focuses on implementation of the SECA software, and the new performance of state estimation and contingency analysis functions with the new solvers on the WECC 2005 test case.

With further penetration of smart grid technologies and the need for more frequent grid operation changes to accommodate the rapid changes from intermittent energy resources, the complexity of the power system problems will increase quickly. The developed SECA software is expected to help meet the requirements of the grid operations, as well as enable higher efficiency and reliability.

This paper is organized as follows: Section 2 describes the overall information of the integrated SECA software, followed by Section 3 on the performance of parallel state estimation and massive contingency analysis. Finally, Section 4 presents concluding remarks with future work.

2. SECA SOFTWARE INTRODUCTION

The SECA software is able to run power flow, state estimation and contingency analysis, individually or together. The software has a config file to select different options for power flow, state estimation, and contingency analysis, such as the location of required input files and outputs files, the violation thresholds, and linear solver options. This config file provides flexibility to users for testing different power system conditions with different solvers and quickly identifying the solver with best performance.