Scalability of ELISIMS: Comprehensive Detailed Simulation of the Electric Power Industry

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Abstract

We conduct an experimental analysis to identify the most computational time consuming fragments of software and hardware that will likely be an integral part of power exchanges in a deregulated environment. The empirical analysis provides insights into the scalability of the system as a function of branch congestions, excess/scarcity of power, average size of multi-lateral contracts, topology and size of networks. Additionally they yield insights into the reliability, security and stability of electric networks.

1 Introduction

At present, the electric power industry in the US and worldwide is undergoing restructuring largely in the form of deregulation of generation and re-regulation of the transmission and distribution functions from centralized utility-company style operation to a decentralized market driven operation. This transformation is motivated by changes in the political and regulatory environments in which it has become reasonable to consider inducing competition. Large state and region-wide electric price differences provide additional motivation. The electric power system has developed over decades under the regulated monopoly paradigm yielding the system we have today, with its stability and security. The system will evolve, however, in response to new market imperatives, producing a system that will be quite different. Importantly, market-driven initiatives toward distributed generation and bilateral and multilateral contracts could lead to a more efficient but a less robust transmission interconnection than we have today.

Because of large number of interacting parts in the electric power system, it is extremely difficult to deduce the effect of changes in the system without resorting to computational simulation. At Los Alamos we are currently developing ELISIMS, an acronym for Electric Industry Simulation System. The goal is to build a *comprehensive, detailed* simulation based analysis tool to understand the varied effects of the deregulation process on the power industry:
(1) *Comprehensive* in that we propose including the whole North American continent because that is becoming the scale of tight interconnection.
(2) *Detailed* in that we propose to include each significant element at the level of generators, transmission, varied control elements, and load distribution buses.
(3) *Industry* in that we intend to include the regulatory, financial, and market factors that interact with the engineering elements.

The basic architecture of the simulation is described in [3] and is not discussed here in detail due to space considerations. The main point to note in the present context is that it is a multi-layer the architecture. Each layer captures a certain level of time resolution and specific functionality. Two important layers germane to this paper are: (i) the market layer and the (ii) the physical layer and the interaction between these two layers. The two layers are coupled; we briefly describe the prototype market layer below. The design of this layer will be substantially modified in the coming years; nevertheless the current design has certain essential features that provide useful insights.

2 The market

For our simulation tool we have chosen to implement the so called *continuous nodal market*. It is a market with nodal prices as opposed to markets with zone prices. We designed the market as a 24 hour forward market with no possibility of spot trading. The market allows only bilateral contracts which are processed in the order they come. The power price at each node is a function of the power

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price for the given hour and given generator, and transmission cost. The transmission costs are based on congestion. We came out with a mathematical function that computes these fees. The costs are based on *contract paths* which serve as a first order approximation of real costs incurred.[4] The contract paths are computed as the shortest path from a generator to a customer. To compute shortest path we use Dijkstra's shortest path algorithm (see [2]).

Next, we describe mechanisms of our market to make you accustomed with the interplay among all the market entities: customers, power producers (generators), system operator, and power exchange. System operator is an entity which is responsible for stability and security of the grid; it runs the network from the physical point of view, i.e., it operates buses, branches, controls grid network limits etc. It does not have any obligations against customers or producers, and actually it should be completely independent from all other entities. On request from the power exchange it gives answers on whether a new contract is going to preserve all security and stability parameters of the network. Power exchange is an entity that runs the market itself. It collects orders from customers and producers, and tries to fulfill them.

Suppose you are a customer willing to buy some power to satisfy your needs. You try to find a generator that is able to provide you with the power of required volume at the lowest possible price. You submit your request to the power exchange that will run the Dijkstra's algorithm, and find the closest generators (not necessarily with enough power to fulfill your request in whole). The weights that we assign to branches for every run of the shortest path algorithm are current congestions. Then the power exchange submits this request to the system operator that takes a generator-customer couple, runs the power flow code, and finds out about feasibility of such a trade. If this trade is feasible, i.e., it does not exceed any branch limits, it will signal this fact to the power exchange. If it is the case that the generator has less power than the volume that the customer is willing to buy, we close the trade for this contract, and the customer repeats the whole procedure again for the remaining power.

ELISIM is written in ANSI/ISO C/C++ for UNIX environment. The tool is capable of using two kinds of power flow codes. First of the two is the power flow code developed at the University of Texas at Arlington, which is a well tested non-linear power flow code. The other one is a linearized version of power flow code developed at the Los Alamos National Laboratory. Due to the necessity to start the simulation from zero loads and power generation (i.e. black start), we found the linearized version easier to use. The computational error of the linearized version is, in the case of electric power market, acceptable.

We note that running power flow code of any kind is the most computational time consuming procedure in our simulation. It can consume 85–95% of used processor time. In our case the used hardware was a PC based on an Intel Pentium III 500 MHz processor and 256MB of memory. Running the simulation on the ERCOT network took us 2 hrs 12 min to simulate one real-time hour[5] (i.e. 52 hrs 48 mins to run the whole 24 hrs market). 88% of this time was spent to run the power flow code.

3 Experiment setup

The goal of the experiments below is to provide some initial data on scaling characteristics of future electric power exchanges, e.g., scaling of running time of electric power exchanges with number of nodes, topology of networks, size of contracts, demand/available power ratio, or capacity of lines. Under running time of an power exchange we understand time within which the exchange is able to clear the whole market for a single business day (24 hrs). Besides running time we also studied the criticality of branch capacities and demand/available power ratio to proper functioning of power exchanges.

In accordance with known simulation techniques we identified parameters that we believed are of the greatest importance to the future reasoning about behavior of power exchanges. We divided these parameters into independent and dependents variables. Independent variables are those which constitute input of the system, and vice-versa dependent variables are those which constitute output. Changing the value of a chosen independent variable we tried to identify the impact of this variable on the dependent variables. During this process we kept the remaining independent variables constant.

We have chosen the independent variables as follows:

Topology – we have chosen to study three topologies: tree (with random degree of nodes between 2 and 5), near grid (a grid network with 25% of edges removed, and random topology which is supposed to approximate the topology of real networks. We have considered a tree with random degree of nodes and 10% of random edges added to be a good candidate. If one takes a careful look at a real

[4] A number of papers in the literature discusses why one should not consider a simple path based cost calculation. This is an important issue and we discuss it further in our technical report.

[5] This was with the linear power flow code. Parameters of the network were: topology = ERCOT, number of buses = 4,527, size of contracts = 6.2MW, capacity of branches = ERCOT, demand/power available ratio = 0.86. Number of branches for ERCOT is 5,412. Number of contracts necessary to settle one real time hour was approximately 5,700.

network, it does not take long to realize that by removing a certain percentage of lines the networks becomes a tree.
Number of buses – running time is largely determined by this parameter. It comes from the fact that running time of the power flow code scales up with this parameter.
Size of contracts – this parameter also influences the running time. Unlike the above two parameters the value of this one is not given from the beginning. Smaller contracts mean more power flow code runs. To achieve efficiency, future power exchanges will allow its participants to take part in various forms of gaming. This activity can severely influence size of contracts, and thus throughput of exchanges.
Demand/available power ratio – we studied the impact of scarcity and excess of power, and its influence on functioning of the market.
Capacity of branches – congested branches force everybody to find alternative suppliers to avoid hefty transportation fees.
Next, we list the dependent variables:
Simulation time (running time) – we ran the simulations on a PC computer (Intel Pentium III 500MHz processor, 256 MB RAM).
Ratio approved/disapproved contracts – less disapproved contracts mean in some sense better market.
Satisfied demand and power sold – fundamental parameters of power markets.
Number of contracts – we studied this parameter in order to obtain some idea about how many contracts we need to clear the market under different circumstances.

Further, we note that we constructed all the networks so that around 10% of all buses were generator buses, and complementary 90% of buses were load buses.

4 Results

We have chosen to use the linear power flow code since this one is much easier to run.

Experiment 1 – We tested the dependence between number of nodes and running time of our simulated power exchange for different topologies. Surprisingly, we found out that the topology with the longest running time is our random graph. The second slowest topology is our near–grid graph, and the fastest topology is our tree graph. This fact is depicted in Figure 1. This outcome stems from the way we store sparse matrices, and the way we search within them. The linear power flow code itself runs in polynomial time[6]. As we have mentioned above 85–95% of running time are accordind to our experiments spent in power flow code. This would be well noticeable if we ran the experiment with only the power flow code being fed with data. The result would be almost identical with Figure 1.

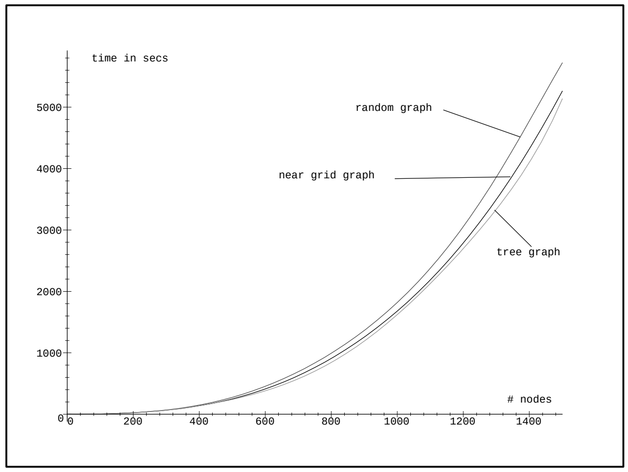

Figure 1: Figure showing the relationship between running time of a power exchange and number of nodes for different topologies. The uppermost curve depicts the random graph, followed by the near–grid graph, and the tree graph coming as the last one. We have set the independent variables to the following values: size of contracts = 16.66MW, demand/available power ratio = 0.75 (i.e. an excess of power), capacity of branches = 500MVA. We were iterating through number of buses 100–1,500, and through topologies.

Experiment 2 – We studied what influence has scarcity, or excess of power on proper functioning of power exchanges. In Figure 2 we depict relationship between power sold and satisfied demand (in percentage points), and changing demand/available power ratio. Increasing ratio means less power. We see that power sold, or saturated demand are approximately linearly increasing, or decreasing, respectively. Due to no information exchange among market entities (exchange, customers, producers), the maximum satisfied demand reaches about 93% even in the case of a huge excess of power. Vice-versa, in the case of huge scarcity of power, the power sold reaches 98%. To improve these performance data, we would need to come closer to the optimum economic dispatch scenario, but this we consider infeasible without better information flow among the participating entities. A solution to this problem we perceive the loading vectors as suggested in [9].

[6] For details refer to [7]. For storage of sparse matrices we used the row-wise, upper, ordered representation (RR(U)O) as of p. 23. Further, we used algorithm of p. 265 for numerical triangular factorization, and algorithm of p. 269 for solution of the related linear system. These constitute the most computationally expensive chunks of code within the linear power flow code.

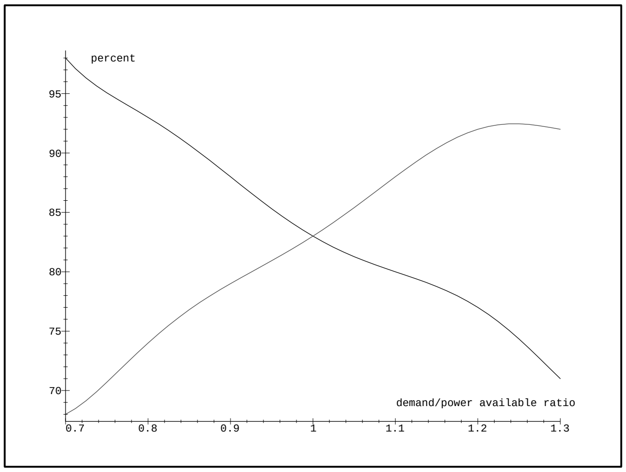

Figure 2: Figure showing the relationship between satisfied demand and power sold, and demand/available power ratio. The increasing curve for power sold, and the decreasing curve for demand satisfied. Independent variables set to the following values: topology = random graph, number of buses = 1,000, size of contracts = 16.66MW, capacity of branches = 500MVA. We iterated through the demand/available power ratio 0.7–1.3.

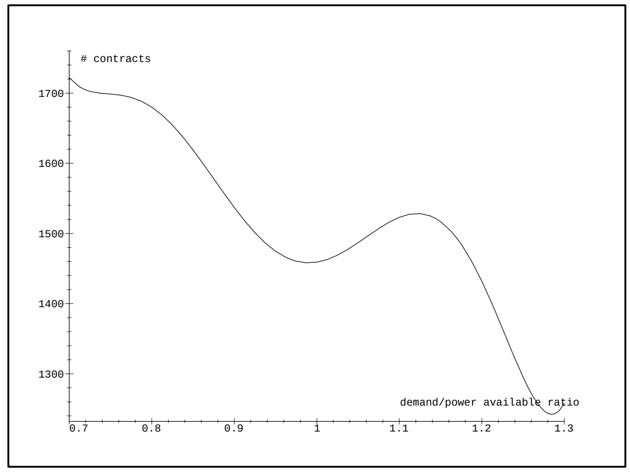

Figure 3: Figure showing the relationship between the number of contracts necessary to clear the market and demand/available power ratio. Independent variables set to the following values: topology = random graph, number of buses = 1,000, size of contracts = 16.66MW, capacity of branches = 500MVA. We iterated through the demand/available power ratio 0.7–1.3.

Experiment 3 – We studied the influence of excess/scarcity of power on the number of contracts that are necessary to clear the market. The relationship is depicted in Figure 3. Less contracts are needed to clear the market when there is not enough power. This fact may be slightly contraintuitive, but clearly logic since less power also means less power to be sold with its direct impact on the number of required contracts. In this setup, we can clearly see that excess/scarcity of power provided the network throughput is not at its boundaries does not constitute a serious threat to the functioning of the market. Around its equilibrium point the exchange need approximately 1,500 contracts to clear the market whereas in the the case of excess power something over 1,700. This numbers should not be taken as measure sticks, however, they show the trends that a power exchange designer has to count with. Also we should remember that this is only in the case when the capacity of branches is far from its limit.

Experiment 4 – We tried to get some idea on the influence of branch congestions on the functioning of power exchanges. In Figure 4 we draw the relation between the time of simulation and branch capacities. On the x axis we are uniformly changing the branch capacities from 50MVA to 300MVA. We can see that if it is the case that the network starts to reach its transportation capabilities, in our case around 200MVA, situation dramatically changes. At 50MVA we need 80,000 secs to clear the market and at 300MVA we need one fourth of it, i.e., something over 20,000 secs. However, we have to point out that in this case we were unable to keep the average contract size constant, at least not without changes in the market mechanisms, which would then skew our results in another, yet more difficult to track way. Actually, the average size went as low as 7.5MW for 100MVA branches and 1.5MW for 50MVA branches. The fact that a network reaches its transportation capabilities may be caused by a heat wave, cold wave, or technical problems where some of the branches have to be temporarily put off-line. In any case we might need computational capabilities four times higher that in the case when the network is operating in a stable state. This is of course only an estimate based on our particular setup, and the reality can be much scarier.

Experiment 5 – In Figure 5 we draw the relationship between saturated demand, power sold and percentage of approved contracts and branch capacities. In this case we can see as the network is reaching its capabilities, the percentage approved contracts plummets alongside with saturated demand and power sold. It would be certainly possible to improve this situation by extending information flows among the market entities, but the overall image will probably not change significantly. We recommend this problem to focus on in the future, because in case of stock exchanges there are mechanism how to deal with problems like this, e.g., stopping of the market, but it is unclear how to do it in case of trading with continuous commodities.

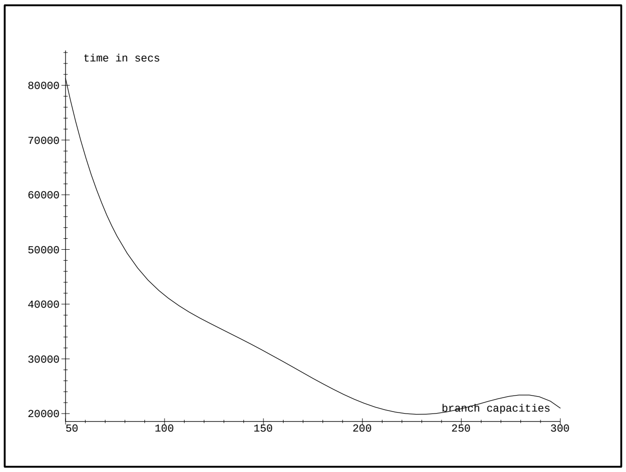

Figure 4: Figure showing the relationship between simulation time, and branch capacities. Independent variables set to the following values: topology = random graph, number of buses = 1,000, size of contracts = 1.5–16.66MW, demand/available power ratio = 0.75. We iterated through branch capacities 50–300MVA.

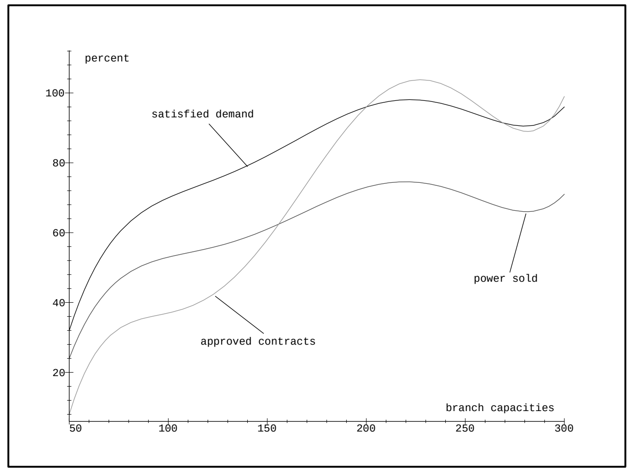

Figure 5: Figure showing the relationship between percentage of approved contracts, satisfied demand and power sold, and branch capacities. Independent variables set to the following values: topology = random graph, number of buses = 1,000, size of contracts = 1.5–16.66MW, demand/available power ratio = 0.75. We iterated through branch capacities 50–300MVA.

Experiment 6 – We tried to give some answers on the impact of size of contracts on running time of exchanges. This task showed to be an uneasy one, since it would not be possible to do so without tweaking certain mechanism inside of our power market simulator. However, we indirectly know that the response of the power flow code to any customer-generator couple for a given topology and number of nodes is constant. Also, we learned that the computational burden lies heavily on the power flow code. From this facts we can derive that any halving of the average contract size will cause doubling of necessary running time, i.e., the dependence is linear up to small amount of time spent outside of the power flow code.

5 Conclusions

We presented some facts that we have learned from running a series of simulations on the LANL designed tool for simulating electric power market: ELISIMS. We reached several conclusion, the most important one might be that functionality of any future electric power market will be dominated by its computational capability to run a power flow code which is of huge importance for ensuring security and stability of the electric grid. Without this the exchange (system operator) would be unable to find out whether the contract currently submitted for approval is going to keep all grid parameters in its limits. We have found out that around 85-95% of computational time of any electric power exchange is likely to be spent in running the power flow code. This figure can however run much higher depending on the power flow code used. Our experience says that if one tries to use a non-linear power flow code there can be severe problems when trying to guarantee the power flow code to converge for an arbitrary customer-generator contract. In fact, as the running of the power exchange requires a "black start" for each simulated hour this task can be near impossible. This is one of the reasons we used a linearized power flow code throughout out simulation. Other results include some initial information on scaling of power exchanges with branch congestions, excess/scarcity of power, and average size of contracts. We identified that branch congestions can cause a serious problem to proper functionality of electric power exchanges. The remaining three factors probably will not cause significant problems, or they will only scale linearly. These results need to be intepreted ith care; rather than exact numbers they show trends that an electric power exchange designer can learn from. Additionally the results are valid only in case of use of sequential algorithms to run power exchanges. We have recently completed a parallel design and implementation of the power flow algorithm.

Our results were achieved with a market that does not allow any information flows among its entities (except between power exchange and system operator). Part of our next research is to introduce such information flows and reason about their impact. However, at present, there is no general agreement what information flows should be allowed, and which not. In the mean time, we have completed an initial implementation of the "loading vectors" idea of Wu and Varaiya (see [9]). This enhancement allowed us to decrease running time of ERCOT from roughly 54 hrs to 30 minutes (PC, Pentium III, 500MHz, 256MB, 24 hrs market). Another problem of our current market implementation is that we only allow bilateral contracts at the moment. It can be shown that this fact holds the market away from reaching an optimum economic dispatch. Introducing n-lateral contracts will put additional burden on power exchanges. It will probably enhance capabilities of market players, and that will lead to extended gaming.

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