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# Fewer Prices than Zones

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## Steven Stoft, February 6, 1998


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**This paper does not represent the views of the FERC or of its Office of Economic Policy.**

Nodal energy spot prices induce a least-cost dispatch in a competitive market. But it is clear that most of the country will not, at least initially, adopt nodal pricing. There is an alternative approach which might also lead to optimal pricing. In this approach scarce transmission resources are priced explicitly instead of implicitly through nodal energy price differences. Pricing transmission congestion explicitly requires a new set of prices and an extra market, but it may have advantages. Unfortunately, there is still no completely specified system of explicit congestion pricing with the efficiency properties of nodal pricing, but this article brings us a step closer to that goal.

Several schemes for explicit congestion pricing are already on the table, including proposals by Chao and Peck, IndeGO, and CCEM.[1] Each of these makes a contribution, but none describes a pricing system with the coherence of nodal pricing.

In this article I will demonstrate the simplicity of Chao-Peck (CP) prices but will also suggest a substitute for their complex market mechanism that greatly simplifies life for the average power trader. I will show that CP prices can be easily extended to CP+Hub prices which provide a complete nodal energy spot market. Even including the hub price, there are fewer CP+Hub prices than zonal prices in networks that can be successfully zoned. Finally I will argue that, although the necessary market mechanism has not been fully developed, there is reason to hope this task is manageable. We will also take note of the progress that NERC has made in developing the calculating engine that is the necessary basis for such a market.[2]

## I. The Pricing Scheme

### Chao-Peck Prices

Unlike "nodal pricing" which prices energy, "explicit congestion pricing" prices the use of scarce transmission resources. For simplicity we will think of these resources as lines. The challenge of explicit congestion pricing is then to determine the correct prices for these lines and to allocate their use according to these prices. I will now present an example of correct explicit congestion pricing, and will then explain the derivation of these prices.

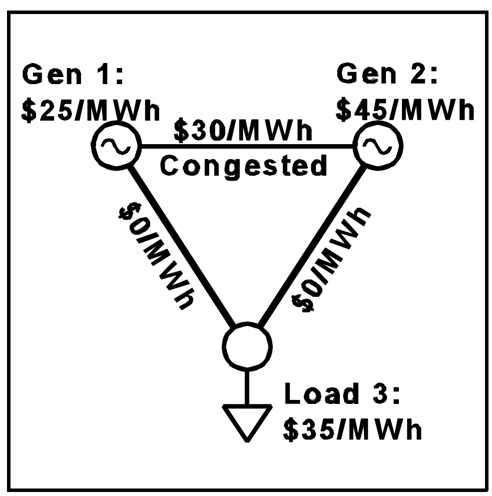


**Figure 1. CP Prices**

Assume, as shown in Figure 1, a three-node, three-line lossless grid in which all lines have equal impedance (non-technically, impedance is resistance to power flow). Assume that nodes 1 and 2 have $25/MWh and $45/MWh generators respectively and that there is load at node 3.

Also assume that only the line, from 1 to 2, is a scarce resource. We then know from nodal pricing theory that the energy price at node 3 is \$35/MWh.[3]

These nodal energy prices are completely uncontroversial. In spite of the dispute between the pure "bilateralists" and the "poolco/bilateral" advocates, all agree that these are the only energy prices that induce a least-cost, efficient dispatch. Because of this we know that the explicit congestion prices, shown in Table 1, must in some sense be in complete agreement.

These prices can be calculated from nodal prices as follows. Find the congested lines. In this case only line 1-2 is congested. Compute how much power would flow on this line if 1 kW were injected at one end and withdrawn from the other, and call this the line's "flow factor" (F). In this case F = 2/3, because 1/3 of the power would flow from 1 to 3 to 2, a path which has twice as much "resistance to power flow" and thus receives half as much flow as line 1-2. The explicit congestion price is then given by the formula:

| | |
|---|---|
| Line 1-->2 | \$30/MWh |
| Line 1-->3 | \$0/MWh |
| Line 2-->3 | \$0/MWh |

**Table 1. CP Prices**

$$P_{12} = (P_2 - P_1)/F$$

Since the other two lines are not congested, i.e., are not limiting the dispatch, they receive a price of zero.

These prices are not a new concept. They are in fact exactly the prices for "transmission capacity rights for links" generated by Chao and Peck's proposed bilateral trading scheme.[4] So from now on I will refer to them as Chao-Peck (CP) prices. They have also been discussed by Wu and Varaiya, and have been part of the nodal-pricing calculation since Schweppe introduced it.[5]

**Pricing Contradiction?**

Note that for line 1-2, the nodal congestion price is \$20 while the new (CP) congestion price is \$30. Which is right? Both are. But they must be used differently. The congestion cost of injecting a MW at 1 and withdrawing it at 2 is \$20 according to nodal congestion pricing. But, this injection-withdrawal pair cause a flow of 2/3 MW on line 1-2, so CP-pricing also charges it \$20, 2/3 of \$30/MW. CP congestion prices have two appealing properties that nodal congestion prices lack. First, lines that are not used to their capacity limit have a zero congestion price and second, congested lines always have a positive congestion price in the direction of the flow.

### Using CP Prices

CP prices are used to compute the charge to bilateral traders for their use of scarce transmission resources, in this case for line 1-2. Thus, when the generator at node 1 sells to the load at node 3, it is charged the CP price of line 1-2 times the amount of power that it ships over that line. If it trades Q MW, it will be charged $Q \times P_{12} \times DF$, where DF is its distribution factor on line 1-2 for a trade from node 1 to node 3. These distribution factors are based on standard engineering methods and are something that you can already download (by the thousands) from NERC's internet site.[6] In our example DF = 1/3, so the cost is $30×(1/3) per MWh, or $10/MWh. Consequently the load can pay $35 and give $10 of this to the ISO and $25 to the generator at node 1. In this way, the outcome is identical to that obtained under nodal pricing, and thus sends the right price signal to the generator.

But what about the trade from Gen 2 to the load? It seems that it will be charged just as much and will thus be unable to trade with the load as is needed for a least-cost dispatch. The trick is that DFs are directional and so is the congestion price. $P_{12}$ is the price to flow from node 1 to node 2 but Gen 2's contribution to flow goes from 2 to 1, so its DF is negative. Gen 2's flow reduces congestion. Thus Gen 2 pays $Q \times P_{12} \times DF$, which equals Q×($30)(-1/3). In other words Gen 2 is ***paid*** $10/MW for its use of line 1-2. This allows it to make the efficient trade with the load. (Remember, by transmitting power to the load, Gen 2 allows Gen 1 to increase its transmission. Thus generation by Gen 2 is necessary for an optimal dispatch, even though it is expensive.)

**The Simplification of CP Pricing**

In a meshed network with 1000 buses and one congested line, there will be 1000 different nodal prices, but only one non-zero CP price. In a network with *K* congested lines, there will be *K* non-zero CP prices. Because the number of congested lines is typically *much* smaller than the number of buses in a network, Chao-Peck pricing can be expected to produce vastly fewer prices in most real-world networks. This has its advantages.

**The Complication of CP Pricing**

Of course since the relatively few CP prices are economically equivalent to the full complement of nodal spot prices, there must be some large set of adjustment factors to accompany the CP prices. These are of course the distribution factors. In fact we need nearly $K \times N$ of these where $N$ is the number of nodal prices and $K$ is the number of congested lines.[7] Although this may seem to be an overwhelming complication it must be remembered that any given transaction will use only *K* of these factors, and that NERC has already computed them for purposes of grid security.

**The Benefit of CP Pricing for Hedging**

Traders want price certainty. This is true in every market. But just as there is no certainty about next year's corn prices, so there will be no certainty about next year's congestion prices. That's the nature of markets. So what's a farmer to do? The answer, tried and true, is to sell corn futures now and lock in your price. Someday this will be possible with congestion, but futures markets need liquidity just to thrive. Buy concentrating congestion pricing on a few physically congested links, CP-pricing can provide the volume of trade necessary to produce liquidity.

For the sake of concreteness, I will hazard a guess that under a CP pricing regime 90% of the congestion revenues from the entire U.S. market will be collected at ten points of congestion (congested NERC "flowgates"). CP prices will focus the financial market's attention on a few crucial bottlenecks and will provide perfect indexes on which to base purely financial futures contracts. Once there is a well-defined, public market price, there is really no reason for futures markets to get mixed up with physical delivery; they can operate just like the S&P500 futures market.

Of course this form of hedging cannot reproduce the perfect hedge offered by owning the correct TCC (nodal transmission congestion contract), but CP-price congestion futures will have a liquidity advantage, and TCC's may not be available in all markets.

## II. The Market Mechanism

**Why Decentralized CP Pricing Doesn't Work**
In order to make use of these prices we need to find a market mechanism that will generate them. (I am ***not*** proposing that CP prices be computed from nodal prices as was done in example 1.) Chao and Peck have proposed such a mechanism, though they did not insist on it. In fact, their proposed mechanism was given such a preeminent position in their presentation that the CP prices themselves have received little attention. The mechanisms that they have proposed have been decentralized. This means that when one trader wants to buy the transmission rights to support a trade, she must buy more than *N* separate rights, one for each line that her power will flow on. But recall that some of it will flow on every line in the network.[8] This trading requirement seems far more burdensome than nodal pricing.

But in my experience, it is not the complexity decentralized trading, but its market power problems that have caused most people to overlook the importance of CP prices. First note that if any one person owns all of a transmission line, that person has monopoly power over all users of the grid, for each and every user must use every line to some extent in order to make any trade. Thus every bilateral trader making one trade will be faced with buying thousands of transmission rights, with each one purchased from a monopolist.

One suggested mitigation is to require universal divestiture to the point that no transmission owner owns more that 20% of any line. But even this would leave transmission owners with enormous market power because demand for minor lines will be very inelastic. A suggestion that seems to have more promise is to require line owners to sell the entire capacity of each line. Supposedly this would drive the price of any line with unused capacity to zero. But this market still seems to provide lucrative opportunities for anyone wishing to corner the market. There are thousands of markets (one for each line), and cornering any one gives you control over all power trades. Possibly we could police all traders to see that none attempts a corner and each buys only the transmission that they "really need."

But at this point it seems easier to conclude that a decentralized market may not be the only goal worth pursuing. Perhaps power traders would be willing to give up decentralization in return for vast simplification plus a total short-circuit on the transmission owner's market power. Perhaps the ideology of decentralization can be balanced with a desire for practicality. The centralized NY stock exchange, for example, seems to work just fine. In fact it has lower transaction costs (the real transaction costs are in the spread) and fewer scandals than the decentralized NASDAQ market.

**The Centralized Path to CP Prices**

In their original article (JRE, July 1996), Chao and Peck list "three alternative implementation plans," the first of which is that "the electricity prices and the transmission charges are determined jointly by a central agency ... ." This clearly indicates early consideration of an approach similar to what we will now consider, though it does include the concept of transmission bids. In fact a footnote explains that this "plan is essentially the same as the approach advanced by Hogan [based on energy bids] ... However it differs from Hogan's approach in how the economic rents are allocated to individual transmission asset owners."

In December of 1995, I discussed with the WEPEX Transmission Team a "hybrid transmission/Inc/Dec auction" with transmission bids defined to "pay up to x¢/kWh for y MW from i to j." The centralized approach I will now present combines this type of transmission bid with CP prices. This completes the definition of a "central agency" approach to CP pricing. Chao has indicated he is now also focusing on a centralized approach which, designed by himself and Robert Wilson, is ~~now~~ being tested by Charles Plott at Cal Tech.[9] I will now return to the development of a centralized market mechanism.

Auctions centralize the process of trading and in doing so can reduce trading costs. They can provide a more liquid and thus more competitive market. (I am not claiming they always do this.) In this case an auction would look as follows. At some date well before "real-time," say one week in advance, all interested traders would submit bids for transmission rights. For example a trader might request the right to transmit 100 MW from A to B during a 1 hour period and offer to pay up to $\$P_{AB}$/MW for that right.

The outcome of the auction would be a list of accepted bids and a price per MW for each congested line. Each accepted bid would be charged for the power flow it caused on the congested lines (determined by the DFs) according to the congestion price on each line. For accepted bids this would always be less than or equal to the amount bid. Bidders would end up with a right from A to B, and not a set of rights on congested lines. This insures that their right to flow power from A to B remains valid even if some new line becomes congested.

The initial auction would be followed either by a series of auctions, or if feasible, by a bid-ask market in which transmission rights are traded continuously up until real time. Of course any trader who wishes to buy or sell a right or fraction thereof for transmitting from A to B may do this outside of the centralized bid-ask market if he can. But when a trader wants to buy a right from A to Z and no such right is available, that trader would submit a bid to the ISO (or whomever runs the auction). Similarly traders that have purchased rights can submit orders to sell to the ISO. The ISO will use these bids to create a market in transmission rights. Even if a continuous bid-ask market is computationally infeasible, the ISO should be able to process zero-cost transactions in real time. These include requests for rights on paths that are not congested and requests for reconfiguration of existing rights. (Of course a reconfiguration will often produce an unused remnant that needs to be sold at the next auction.)

## III. Expanding CP-Pricing to Cover Energy Trades

**Adding Nodal Prices**

There are many good reasons to allow both bilateral and nodal trading to go on simultaneously and without discrimination. But the best argument for this slightly complex arrangement may be that we should let the market choose which way it prefers to trade, instead of having the decision made on very shaky theoretical and ideological grounds. Unfortunately it has been difficult to create such a level playing field. In order to use CP prices in such a non-discriminatory market, we need to extend them to cover nodal prices.

So far we have $K$ CP prices corresponding to the $K$ congested lines, but we know that nodal pricing requires $N$ more nodal prices. Or does it? On this point we have genuinely good news. A complete nodal-pricing market can be synthesized from the CP pricing structure by adding only one (1) more price for a total of only $K$+1 prices.

To see how this works, pick any bus in the network and declare it to be the "hub." The one price we add is simply the standard nodal price at the hub. Call this the hub price.

So how do we find the nodal price at some other bus given these $K$+1 prices? The answer is easy. Pretend the ISO is located at the hub and engages in bilateral trade with the buyer or seller. The trader's nodal price is simply the hub price plus the congestion price of trading with the ISO.

This is best understood by example. Say a load at bus A wants to buy energy from the ISO. The ISO sells from the hub, so first the buyer must pay the hub prices $P_H$. Then the buyer must pay for the congestion caused by an injection at H and a withdrawal at A. Say there is only one congested line with a CP price of $P_C$, and that the flow H→A has a DF of 50% on that congested line (since the DF is positive, flow H→A increases congestion). Thus the buyer must also pay 50% of $P_C$, for a total price at bus A of $P_H + 0.5 \times P_C$.

Now consider a seller at bus A. The seller will receive the hub price $P_H$, but will have to pay the congestion charge for getting the power to the hub. This charge is $DF \times P_C$. But for a flow to the hub (direction still matters) the DF is -50%. So the seller pays a negative charge, i.e. the seller receives a congestion payment in addition to the hub price. Thus the seller's price at bus A is $P_H + 0.5 \times P_C$, exactly the same as the buyer's price. This is just the standard spot price at bus A. Note that for the market to determine the hub price, energy bids will have to be included in the auction.

Now if the hub happens to be very far from bus A, we will still get the right answer, but the calculation might involve heavier use (plus or minus) of distant more congested lines. This makes hedging congestion more complicated. Consequently it could be useful to have more than one hub. This could also be useful in case the hub ever had to be taken out of service. A second hub will of course have its own nodal price which will simply provide redundancy. All nodal prices can be computed from either hub and you will get the same answer.

A final complication arises with the incorporation of losses. But the correct solution to this problem is well known. Traders should be charged for their marginal contribution to losses, times the power traded, times the price of energy. Power engineers have no trouble computing the power injection at the hub that would be needed to cover an extra kW of power shipped in a bilateral transaction. Thus adding the hub price makes possible the proper treatment of losses.

**CP Pricing vs. Zonal Pricing**

In the Jan./Feb., 1997 issue of the *Electricity Journal* I showed that some (very few) networks could use zonal pricing without any price distortion, while others could not.[10] The distinction between these two types of networks can be expressed even more clearly using the CP-pricing / DF framework that we have just developed.

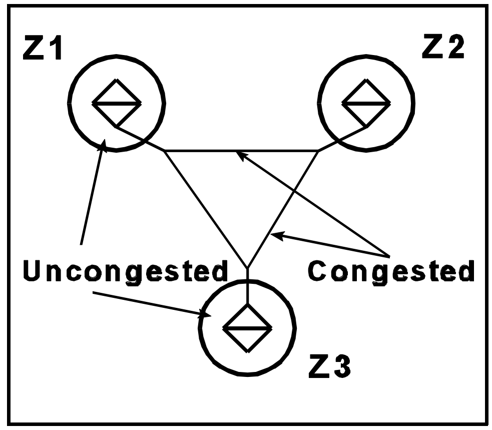


**Figure 2. A Zonable Grid**

For a zone to support a uniform energy price, every bus in that zone must have exactly the same set of distribution factors (DFs) on all congested lines. Thus for zone 1 to have a uniform energy price it must be the case that sending power from bus A in zone 1 to bus X in some other zone has the same distribution factor on every congested line as sending power from bus B, C or D (also in zone 1) to bus X.

Now it might seem that such a coincidence is simply impossible in any real network, but that is not the case. Certain network topologies produce this coincidence. Figures 2 and 3 show two different networks in which ***the intra-zonal lines are all uncongested***, but the inter-zonal lines can be congested. All buses in each zone shown in Figure 2 have the same DFs on the inter-zonal lines. Thus if only the inter-zonal lines are congested, the zones will have uniform prices. We call such a grid "zonable." But notice that the A-X flow distribution factors on the inter-zonal lines will be different than the D-X flow distribution factors. Consequently we call the grid in Figure 3 non-zonable. This means that marginal costs of energy in the uncongested Z1 region are not uniform.

In a zonable network, that is, one in which zones really do have uniform energy prices, there can be congestion only on the inter-zonal lines. This limits the number of CP prices to 1 plus the number of interzonal lines. In fact there is a lower limit. For a zonable network, the number of CP+Hub prices, $K$+1, will never be greater than the number of different zonal prices. It will sometimes be much less. If there is only one congested line in Figure 2, there will be three different zonal prices, but the number of CP+Hub prices is $K+1 = 2$. With Z zones you can have Z different zonal prices while at the same time having only 2 CP+Hub prices.

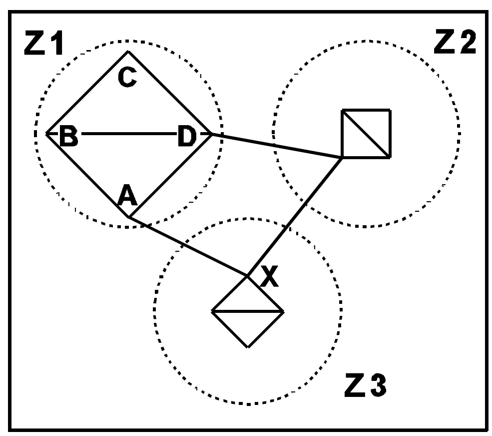


**Figure 3. A Non-Zonable Grid**

Thus CP+Hub pricing often has fewer (and never has more) prices than zonal pricing. CP+Hub pricing also has the advantage of working correctly in any network, not just in the limited set of zonable grids.

## VI. The Unsolved Problem

While the CP+Hub pricing system has much to recommend it, there is still the crucial outstanding problem of designing a market mechanism that discovers these prices reliably and quickly. As argued above, our best bet seems to lie with an auction, but designing such an auction, and the algorithm for evaluating the bids quickly, may be difficult. In fact some expert mathematical programmers claim it is, while others claim it is not. Time will tell. But the central feature of this pricing system is encouraging. For a system with only a few congested lines at any given time, the auction algorithm needs to discover very few prices. If there are, say, only 10 points of congestion, once we find these the program needs to solve for only 11 numbers besides the thousands of DFs computed in an ordinary power flow. This would seem to be doable, even with the following complications.

The first complication is that real networks are non-linear; they are not DC approximations. This means that DFs depend not only on the grid's geometry, but also on the level of power flows. First it should be noted that this complication does not invalidate anything that has been described above. All that is needed to carry the above discussion into the AC world is to define the distribution factors (DFs) as marginal DFs. (In the non-linear case these are different than average DFs, while in the DC approximation they are the same.) That said, non-linear programs do take much longer to solve.

Other complications lies in the nature of the grid's constraints. Voltage constraints can be highly non-linear, stability constraints can apply to many lines at once, and first-contingency constraints can multiply the number of physical constraints. These complications will complicate a centralized auction, but they would also complicate a decentralized auction. Contingency constraints will increase the number of congestion prices that need to be hedged, but CP-Hub pricing will still produce vastly fewer prices than nodal pricing (though the nodal prices are still implicit). NERC could provide a sound basis for attacking these market design problems by simply publishing a list of constraints that were binding during the last year and the hours during which they were binding.

## V. Conclusion

The CP-Hub pricing system consists of a centralized market in which two types of bids can be submitted, energy bids and transmission bids. Each type of bid specifies a quantity and price. The price part of the bid indicates a limit on what the bidder will pay or accept, but the bidder my receive a better price. The auction produces one price for every congested line and one price for energy at whichever bus has been declared the "hub." These prices together with power-transfer distribution factors (DFs) are use to compute how much accepted bidders must pay. Energy bidders pay (receive) the hub price plus congestion costs and loss charges on an assumed trade with the hub. Transmission bidders pay congestion prices times their flows on the congested lines plus loss charges.

The essential point is that the economics of an optimal dispatch can represented in two ways, either as N (1000s of) nodal prices or as $K$+1 (10s of) CP+Hub prices accompanied a power flow. These representations are equivalent in the sense that every energy trade costs the same under either system. Nodal prices can be computed from CP+Hub prices and the optimal power flow. But it also requires the use of a power-flow calculation to derive CP prices from nodal prices, so a financial market cannot be expected to do this. Thus even if the nodal price representation is used it may be useful to publish CP prices for use by private hedging markets.

CP-pricing is as simple from the trader's point of view as any bilateral trading method yet proposed, but it has the added advantage of being efficient. It is efficient in the sense that if the traders do not have market power and if they are good enough profit maximizers, the CP prices will lead them to the least-cost dispatch.

In spite of this, it should be noted that the process by which a bilateral market discovers a optimal dispatch is considerably more intricate that the process by which a nodal energy market discovers the same dispatch. Traders in a nodal market trade at their node and need only discover their own cost function in order to make bids that cause the market to clear at the optimal dispatch. Bilateral bidders, however, must set energy prices for their bilateral trades, prices and quantities for congestion bids, and find an appropriately overlapping set of trading partners so that both energy and transmission markets can clear. Some have "faith" that the free market will always come within a hairs breadth of solving this problem optimally, others fear it will miss the mark by a mile. Since we have little to go on but the faith and fear, allowing spot-energy traders and bilateral traders equal access to the market would seem to be cheap insurance. Such a system would allow the market to determine the most efficient method of trading. CP+Hub pricing has the advantage that it creates such a level playing field.

I cannot yet conclude that CP-pricing should actually be implemented because the market mechanism necessary for arriving quickly and reliably at the CP-prices has not yet been designed. The design of this mechanism (probably an auction) would extremely useful, and I would urge a cooperative effort among electricity-market theorists.

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1.Hung-po Chao and Stephen Peck describe their proposal in three papers: "A Market Mechanism for Electric Power Transmission," *Journal of Regulatory Economics* 10(1) July 1996. "An Institutional Design for an Electricity Contract Market with Central Dispatch," *Energy Journal*, Vol. 18, No. 1, January 1997. "Reliability Management in Competitive Electricity Markets," EPRI working paper, July 8, 1997. The Coalition for a Competitive Electric Market's proposal is most clearly delineated in "Auctionable Capacity Rights and Market-based Pricing," by Tabors Caramanis & Associates with contributions from Robert Wilson, April 1997, available at http://www.tca-us.com/misc.htm. Draft documents describing IndeGO's proposal are available at http://www.idahopower.com/ipindego1.htm.

2.The NERC "IDC" calculator was initially developed by GAPP and in particular Ontario Hydro.

3.The cheapest way to supply an extra MW to bus 2, is to supply a half MW from both generation buses at an average price of $35. Any greater reliance on the cheap generator will overload the congested line.

4.In their July 1996 JRE article, Chao and Peck say "Let us denote by $\pi_{ij}$ the price of the transmission capacity right for link (i,j)."

5.Wu, F., and P. Varaiya. 1995 "Coordinated Multilateral Trade for Electric Power Networks: Theory and Implementation." UCEI working Paper, PWP-031. Schweppe, F.,M. Caramanis, R.

Tabors, and R. Bohn. 1988. *Spot pricing of Electricity*. Kluwer Academic Publishers.

6.http://www.nerc.com/~filez/dftf.html

7.By using superposition and a reference bus, it is only necessary to compute $N$ DFs for each congested line.

8.In many flow-based schemes there is a 1% or 5% cutoff, which means that not all users have to buy rights on all lines. But, this can leave considerable power flow unaccounted for because there are so many 5% flows.

9.In his paper "Auctions of Transmission Capacity Reservations," December 1996, Wilson advocates and centralized FCC style auction and suggests that a "so-called Vickrey auction," similar to the one presented in this paper, is "expensive to develop and complicated to administer."

10.I also argued in that article that from only $K$+1 nodal prices all the rest can be found from the power flows alone, without any knowledge of bids. This led me to search for an efficient pricing system using $K$+1 prices that could be used in place of inefficient zonal pricing. While considering the use of NERC's IDC calculator as the basis of a congestion auction I stumbled on the present system but soon realized that these prices had been employed by Chao and Peck years ago.