MIT EL 00-004 WP

Energy Laboratory

Massachusetts Institute
of Technology

A Value Based Approach to Voltage / Reactive Power Control

May 2000

A Value Based Approach to Voltage / Reactive Power Control

Anuradha Saxena and Marija D. Ilic

Energy Laboratory Publication #
MIT EL 00-004 WP

Energy Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139-4307

May 2000

Value Based Approach to Voltage/Reactive Power Control

Marija Ilić and **Anuradha Saxena**
Massachusetts Institute of Technology
Cambridge, MA
{anuradha, ilic}@mit.edu

May 8, 2000

1 Our Vision of Power Industry Deregulation

1.1 Overview and Background

Traditionally, the power system industry has been a vertically integrated industry, consisting of three major components: *Generation, Transmission* and *Distribution.* In the last few years, due to technical, economic and environmental concerns, the need for a deregulated power system market was recognized by the government regulatory authorities, consumers and the utility industry in general. The first component to be deregulated was Generation (see [**?**]), which led to competition in generation, and creation of *forward* and *spot* energy markets. Transmission and distribution were left as regulated monopolies.

1.2 Motivation

A monopolistic transmission and distribution industry has no incentive to provide efficient and cost-effective delivery of energy to the consumers. This can only be accomplished by providing and/or designing meaningful interconnections between generators (energy sources) and consumers (energy sinks). We feel that an efficient way to ensure this is by designing and creating markets for real power reserve and wires. Our research shows that for true and real unbundling of the power industry market, it is also critically important to clearly define the responsibilities of both these market participants. Real power reserve market should be able to provide energy in case a generator fails, and the responsibility of the wires should be to provide the physical path to energy. Wires should not be responsible for stability/security of the system.

FERC/NERC has suggested a cost-based approach for transmission and distribution. However, this does not breed competition and open markets, and might under-value these services. We suggest a value-based alternative which is described in the next section.

1.3 Our Approach

This approach allows for a more complete specification of the consumer's needs and requirements than cost-based approach. Then our approach suggests creating a market for the products required by the consumers and defines community service as additional/ancillary services to ensure system's security, reliability etc. This is a value-based approach, in which the price of the "well-defined" product will be defined by supply and demand. This approach emphasizes the value of a product rather than its cost. The value of the product can be estimated by performance objective as seen by customer. The value of a good will set the price cap [2] and then price cap can be used to estimate the market performance that none of the seller exhibit technology related market power [1].

We recognize that it is a very different approach as compared to the traditional power system [2]. The main products in electricity market are:

- Real power,
- Existence of physical path for the delivery of real powe,r
- Real power reserve in case of outages (see [3]),
- Wires reserve in case of outages.

[1]This is in contrast to the conventional notion of market power, which is market share related. [**?**].

[2]Presentation of this approach was made by Dr.M.Ilic to FERC in 1997. The approach was favorabaly received by FERC

In order to provide these products efficiently, one needs to create *at least* three more markets (in addition to the existing real power markets):

1. Voltage markets,
2. Congestion markets,
3. Resereve markets.

Once the above suggested markets exist, any additional requirement is equivalent to a constraint on the power quality. Unbundling of power quality produces the following possible products:

- Frequency (PXFC) (refer [**?**]),
- Voltage,
- Harmonics (under investigation),
- Storage (Generators to stay in synchronism) (under investigation),
- .
- ..

The next section argues for the need of voltage markets.

2 Need for Voltage Markets

As deregulation of electric industry proceeds, the technical and economical feasibility of a voltage market needs to be evaluated. Currently there exists a wide range of opinion regarding the valuation of voltage support. For example, Hogan [5] suggests that when voltage control is binding, prices of reactive power can be as high as real power. On the other end are Kahn and Baldwick [6], who argue that the price of reactive power is very low when it is provided locally by capacitor banks and dispatched optimally from the generators. As

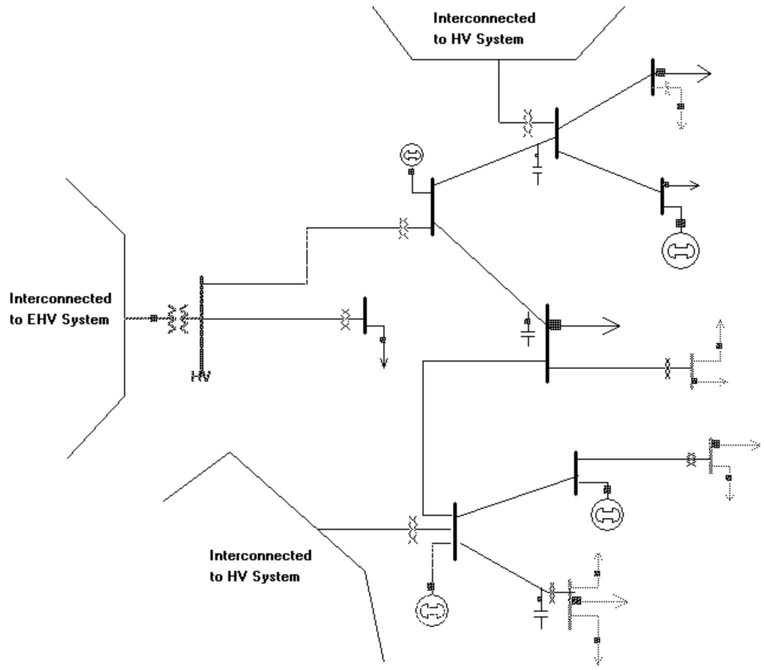

Figure 1: A Typical Distributed Utility.

market restructuring evolves, the truth will probably lie in between these extremes.

In FERC 888 order, voltage support is defined as one of the ancillary services to be provided adequately by a system operator. NERC also views voltage support as a "community" cost-based service which should be charged in proportion to the real power use [7]. However, recently it has been understood that the voltage support question is much more complex. In particular, there exists a significant difference between its cost and its value to the market. Consequently, it has become important to revisit the issues related to the voltage/reactive power support using available tools of both, power engineering as well as economics.

In the rest of the document, we analyze voltage support and conclude that a meaningful market for voltage support needs to be created, not only at the transmission level, but also at the distribution level. Our aim is to unbundle real and reactive power while keeping in view the underlying technical representation of the power system. The critical goal of suggesting such markets is to provide in the long run the right incentive to invest in voltage support technologies.

3 Existing Voltage Related Problems

The current approach of voltage control is not fool-proof as witnessed by recent distribution system failures [8]. In July 1999, the south fork of Long Island was on the verge of voltage collapse. Voltage collapse probably would have occurred if peak demand had not been reduced as a result of voluntary load curtailment. PJM grid also saw sudden and steep voltage decline in July 1999. Fortunately, it recovered without harming the system due to the emergency actions had already been put in place to control voltage, such as curtailing contractually interruptible customers, starting up emergency generation, etc.

However, in the new competitive environment, this strategy may not work. The fact that load shedding at the low voltage level to support the voltage at EHV level may not hold true any more. More importantly in the presence of distributed generators (DGs) the assumption of unidirectional power flow may not hold. Consequently, it is not necessarily true that as we move further into the distribution network the voltage reduces.

This raises the question: What are the new potential reliability and security problems at the system level and how can we solve these problems? One way to solve this problem may be by some sort of coordination between HV, MV and LV levels and changing control logics accordingly.

4 Cost Based Approach (Current Practices)

Federal Energy Regulatory Commission (FERC) proposed six ancillary services to be offered in an open access environment that they have identified as necessary for the transmission

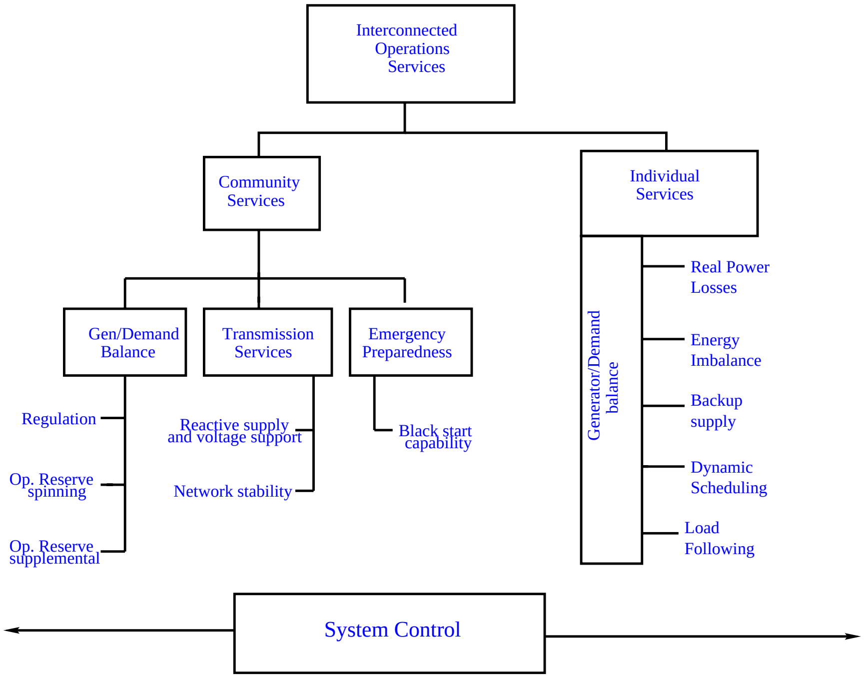

Figure 2: ISO Organization Chart.

provider to offer to transmission customers [9]. Reactive supply/voltage control is one of the six ancillary services.

Figure 2 shows the organizational chart of the IOS (refer **??**), which shows the division of responsibilities between community services and individual services. NERC states that reactive supply is provided from both, generation resources and transmission facilities, and lists it as two services distinguished by the facilities that supply them. NERC further distinguishes reactive supply services based on the source of the need for the service:

1. Reactive supply needed to support the voltage of the transmission system
2. Reactive supply needed to correct for the reactive portion of the customer's load at the delivery point.

FERC considers the cost of these facilities as part of the cost of basic transmission service. In this scenario, customers have the ability to reduce the reactive power consumption and control the voltage, which in turn will reduce the cost of transaction imposed on transmission provider. However, customers don't have any incentive to reduce reactive power consumption, even when they own generation units.

FERC concluded that since none of these customer actions entirely eliminates the need for generator supplied reactive power, the transmission provider must provide at least some reactive power from generation sources. FERC tried to exploit the customer's ability to relieve transmission providers by offering reactive supply and voltage support as a discrete service. FERC suggests that this service be charged at a flat rate charge of $x/MVAR.

Another way to look at this is as follows: Since the transmission operator will depend on the generators to provide reactive power, the right price structure of reactive power needs to be defined.

Drawbacks of the Cost-Based Approach

This approach has the following major drawbacks:

1. Uniformity in price provides no incentive to users for reducing reactive power consumption, when they can. Correct price structure will improve economic efficiency. This will also improve the ability of market participants to make intelligent decisions about energy transactions, investments and asset utilization.

2. This approach does not differentiate between technologies used to provide the voltage support. This leads to a lack of incentive for using the right technology such as FACTS control etc.

3. Presently, the generator based reactive power dispatch is seen as the primary voltage control approach. However, as the industry restructures, it is much more likely for a buyer to buy electricity from distant generator. Under these circumstances, it is not

necessarily most economical to supply reactive power from distant generators, because of high reactive power losses in transportation (as high as ten times of real power losses).

Currently, there is no notion of optimal voltage profile in the system. The current strategies to deal with voltage problem are system specific. Engineers and system operators, from their past experience and numerous off line load flow simulations, decide the voltage standards of a subsystem [10]. But if transmission providers follow the same rule then they will not be fair to all transmission users. To deal with this problem, NERC recently suggested the option of defining voltage standards, but it is difficult to impose standards for voltage starting from an industry with non-uniform standards.

5 Value Based Approach (Suggested by MIT)

FERC has recognized that the current approach is not the best. To quote footnote 359 in [9]:

> Separation of reactive supply and voltage control from transmission service also may contribute to the development of a competitive market for such service...

To suggest a market model, first, we need to identify the various options to provide voltage support in order to eliminate the market power. To achieve this systematically, following section briefly explains the simple voltage related basic concepts.

Basic Concepts of Voltage Control

Consider a two bus system with sending end voltage of $\hat{E}_s = E_s\angle\delta_s$, receiving end voltage of $\hat{E}_r = E_r\angle\delta_r$ and with the line impedance of $Z_{sr}\angle\zeta_{sr}$. The reactive power at the receiving end will be given by:

$$Q_{sr} = (E_r^2 \sin\zeta_{sr} - E_s E_r \sin(\delta_s - \delta_r - \zeta_{sr})/Z_{sr} \quad (1)$$

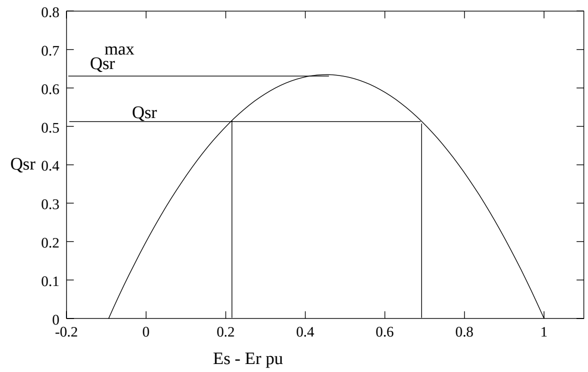

Figure 3: Reactive-Power Voltage Dependence.

The basic idea of scheduling reactive power out of generators was developed to ensure that a solution to the reactive power balance equation exists for the specified demand and the given transmission parameters. The generation based reactive power dispatch is generally implemented by changing the set point values, ${E_{G_i}}^{ref}$, of power plants. In the regulated industry, the optimum voltage set points, E_{G_i}, are obtained optimizing certain performance criterion subject to the following constraints:

1. reactive power balance constraints,
2. the load voltage acceptable limits,
3. the availability limits on the reactive power generated and
4. the limits on generator voltage.

Figure 3 shows the solution to reactive power equation 1. It demonstrates that for given transmission parameters and constant generation voltage support at a bus, it is impossible to deliver the reactive power more than ${Q_{sr}}^{max}$. Stated another way, Q_{sr}^{max} can be changed by:

1. Varying magnitude of the receiving end voltage, E_r,
2. Varying the angle of the receiving end voltge, δ_r,
3. Varying the parameters of the line, $Z_{sr}\angle\zeta_{sr}$.

So in view of this, the voltage can be controlled by:

1. Using OLTC (On Load Tap Changing Transformers),
2. Using static VAR compensators,
3. Using shunt reactors (which also works as power factor compensators) at the load (PQ) end,
4. Receiving reactive power from generator (DGs) and
5. Using smart FACTS controller.

This gives the customer many options to control voltage, and the customer can use whichever is appropriate for the specific type of load under consideration.

This leads us to suggest a *Value-Based Approach* for reactive power/voltage control [11]. This approach emphasizes on the so-called *three Rs*: Rules, Rights and Responsibilities ([**?**]) of the market and its participants.

The market structure can be visualized by decomposing the distribution network into sub-areas, served by different load serving entities. This does not preclude local utilities from entering the market. The product in this scenario would be the service for controlling voltage at the customer's node between the minimum and maximum limits specified by the customer.

5.1 Rules, Rights and Responsibilities

Market Participants in this market can be defined as: **Buyers** can be large *load serving entities*, *individual loads*, *transmission providers*. **Sellers** can be *Generators*, *wire companies* and *individual*s (using shunt capacitor/inductor (also known as shunt reactors) or FACTS controllers).

5.1.1 Rules

- **Minimum Number of Generators:** There has to be minimum number of generators in order to represent the slack bus.

- **Customer indirectly defines the product:** Customer will specify the tolerable voltage limits and its real power needs. The seller then responds by specifying:

  1. Voltage limits within which customer's real power needs can be met and
  2. Real power that the seller can supply at the customer's tolerable voltage limits.

  The customer then buys the voltage support that suits its needs.

  Note that this rule also explains clearly the events that occurred during the summer 1999 in new England area. There was ample amount of supply but it could not be delivered because of lack in voltage support, resulting from a lack of incentive to provide it.

- **No Local Transportation Costs:** If voltage support is provided locally, then no charge of transportation will be charged.

- **Customer Pays Remote Transportation Costs:** If voltage support is provided from further away, then the buyer must pay the transportation cost along with the product.

5.1.2 Rights

- **Buyers can Expect Product Delivery upon Advance Notification:** If the buyer notifies the seller in advance in case it expects some unexpected change in its demand, then the buyer has a right to expect a delivery of the product. the seller must prepare for the corrective action in advance.

- **Seller can withdarw serivces:** The seller has a right to withdraw services if buyer's load specification changes substantially.

5.1.3 Responsibilities

- **Seller must Sell:** The seller must sell the "specified" product to the buyer, if the buyers specifications do not have a large deviation from the normal operating point. In order to execute this reliably, seller also needs to have some sort of back up reactive power source like, install generation capacity or have a contract with some other utility to buy reactive power in the event of contingency. Failure of delivery of product will result in penalty.

- **Seller must Prepare in Advance:** If the seller receives advance notice of a change in demand/load from the buyer, then it has a responsibility to prepare for the corrective action in advance.

5.2 Possible Market Approaches

1. Buyers will submit the bids to buy voltage support and sellers will submit the bids to sell the voltage support and a **spot market** will be created for it.

2. Voltage support is provided/sold on a daily basis in a day ahead market through a **forward** market.

3. Buyers can make a long term **bilateral contract** with supplier.

5.3 Performance Criteria of Market Participants

- **Performance criteria of the buyers:** Performance criteria to decide how much to buy and at what price. Draw a parallel with buying real power and paying for transmission congestion max (benefit) after paying for voltage support.

  Time frame depends on the market design. Spot market is a short term and forward market is a long term. This will be analogous the problem of right technology choice in peak load pricing. In future, regulators may also decide to put a limit on consumers by which they can pollute the system, for example, shunt capacitor introduce low order harmonics in the system thereby pollute the system more as compare to FACTS controllers. But FACTS controllers are costly. The buyers using shunt capacitors may end up paying penalty.

- **Performance criteria of the sellers:** Decision making performance criteria for selling voltage support is to maximize profit after cost

  1. **Generator:** maximize (revenue - operating cost - a percent of installation cost) with constraints 1) reactive power limits does not exceed, 2) terminal voltage of the generator stays with in limits 3) load flow constraints.
  2. **Static var compensator:** maximize (revenue - maintenance cost - depreciation cost (somehow incorporate the fact of reduced life after using this time)) where maintenance cost = C(frequency of operation,installed capacity) with constraints 1) required reactive power $\leq$ installed capacity product of either wire company or individual
  3. **Shunt reactors:**
  4. **Smart FACTS controller:** Since these are costly power electronics operated devices there is large installation cost associated with it. However, these devices provide much faster and tighter voltage control. product of individual
  5. **On Load Tap Changing Transformers (OLTCs):** Its can product of wire companies.

6 Peak Load Pricing Mechanism for Voltage Markets

To show the market dynamics between different market participants, we suggest peal load pricing approach (refer [**?**]). In order to use this approach we need to identify the different operation states as OFF peak or ON Peak periods.

Normal operating conditions can be thought of as off peak period and cheap and fixed voltage support can be used ex: shunt reactors, OLTCs. then heavily loaded and lightly loaded systems can be interpreted as peak periods: for this period one can use generators, FACTS and SVCs etc of smaller capacity. The optimal combination of technologies can be found out by using peak load pricing approach of diverse technology and charge the consumer accordingly. *Question:* The main objective of the peak load pricing was to give consumer the incentive to shift their load during off peak period by charging less during off peak period. In this case an individual consumer has no direct control over system loading conditions, therefore over voltage.

7 Technical Issues Associated with Suggested Approach

This section summarizes the still unanswered technical issues which can effect voltage market directly/indirectly. It outlines the major technical research issues related with our suggested approach.

7.1 Problems with Generators as a Seller

A generator can maintain voltage only at one node. This can be achieved by aggregating the nodes until number of generators is greater than number of aggregated nodes and then each generator will maintain voltage at the aggregated node with whom it has a contract. Such large aggregation of load nodes brings the voltage control at the transmission level.

NOTE: we think that buying reactive power from a generator is an option for the voltage control at distribution level, because as more and more small distributed generator comes into market, we can move more and more towards distribution level or small aggregated nodes.

If generators supply reactive power to the load, they have to supply reactive power consumed by the load and the losses in transportation. There are two problems with this approach:

1. Estimating reactive power losses,

2. If load varies from its anticipated reactive value, how does generator compensates that?

To deal with the first problem, a few algorithms have been recently proposed [?][13]. However, these algorithms need knowledge of the entire transmission topology, its parameters and nominal operating point of the system. This type of data is not publicly available at this stage, but, some estimation of reactive power losses can be made using either state estimators or historical data. The latter problem requires some sort of communication with the buyer, which is not difficult to take place in the automated distributed system.

Need for metering: There should also be some means to measure who provided reactive power and how much? In the event of deviation from anticipated demand who pays to whom?

7.2 Will it Lead to a New System-Wide Technical Problem?

If we propose the voltage market then we need to carefully examine, the resulted technical implications, to understand system-wide voltage collapse criteria viz-a-viz specifications for necessary voltage support as individual buses. The netwrok constraints can be represented by the equation (2) in the linearized form.

$$\Delta Q = J_{Q\theta}\Delta\theta + J_{QV}\Delta V \tag{2}$$

In order to ensure the system-wide voltage stability:

$$\min Eig(J_v) > \epsilon \tag{3}$$

If the Jacobian J_v (equation 3) is near singular, then we know system will lead to voltage collapse problem, but there is no exact way to map this into bus by bus. This leaves the door wide open to another technical research question: Is there a way to identify the difficult buses? Eigenvectors or modes of the system may hold an answer to this question. If eigenvectors reveal the difficult buses then industry needs to formulate and implement those findings in order to facilitate the fair market competition. But if they don't then the bottom-up approach will make more sense. i.e. customers or LSE's will choose their voltage profile. This approach may also lead to islanding of the small subsystems.

- *Our conjecture:* If the reliability is handled "the right way" i.e. the value of wires for reliability is clear, then the probability of islanding over very long period of time (through design) is low.

- *Open Question:* Is there still a system-wide problem as one designs wires for reliability and voltage support through market mechanism (bottom up)?

7.3 Free-Rider Issue

Suggested approach also needs to deal with the issue of free-rider sooner or later. This issue can be delayed by starting the implementation of the suggested approach at the subsystem level.

7.4 Conflicting Control Logic:

There exists a possibility of conflicting control logics between market participants, in such decentralized environment. This issue highlights the need of developing smart voltage controllers.

7.5 Need of New Technical Tools

We must recognize the fact, that no method currently exists for evaluating the comparative effects of above suggested control schemes, on consumer reliability. In the absence of correct valuation of a control scheme, the pricing mechanisms which would lead to an economically optimal level of system reliability can not be formulated. Chapman J.W. suggested in his thesis [14] to use the concept of regions of attraction (ROS) of the various equilibria to determine the actual security of the system. This concept can be used to correctly value different voltage control option. However, in practice, the exact region of attraction may be difficult ot impossible to determine, even in off-line studies. More importantly, the size of the ROA is a function of the system loading and configuration.

8 Conclusion

The advantages of the approach suggested in this paper are the following:

1. As disussed above, requiring reactive power support from a far away generator is not economical because of large resulting reactive power losses. The value based approach gives an incentive to market participants to develop better and more advanced alternatives such as mini FACTS controllers etc.

2. As the present market evolves towards more open markets, the value based approach which we suggest will become more appropriate. For example, it is quite possible to introduce power quality as another product in the market. Our approach, unlike cost based approach, differentiates between voltage support technologies, leading to more efficient markets.

3. In order to get the delivery of the real power at the specified location, we need to get proper voltage support. There are no incentives to do so currently. Our approach guarantees the delivery of the real power.

4. Our approach overcomes most of the economic and social drawbacks of the cost-based approach. The arguments in favor of voltage market are overwhelming despite the problems highlighted in section **??**. We are continuing our research to solve the technical problems.

9 Future Plans

We can divide the future plan of action as following:

- Set up to show market dynamics.

- Define “value of wires” for reliability.
- Define clear performance objectives for the interconnection.
- Investigate the impact of voltage markets on system-wide engineering issues.

Following questions are worth considering:

1. Any proposal of a reactive power market, needs to consider both, the real and the reactive power reserves, because an insufficient amount of reactive power can lead to voltage collapse and security problems.

References

[1] ””

[2] “”

[3] ”Kiwan lee’s thesis”

[4] ””

[5] Hogan, W., “Markets in real electric networks require reactive prices”, *The Energy Journal*, vol.7, pp. 24-43, 1993.

[6] Kahn, E. and Baldick, R., “Reactive power is a cheap constraint”, *The Energy Journal*, vol.15, pp. 191-201, 1994.

[7] North American Electricity Reliability Council, ”Interconnected Operation Services Working Group”, *IOSWG Final Report*, March 7, 1997.

[8] “Report of the U.S. Department of Energy’s Power Outage Study Team”,*Finding and Recommendations to Enhance Reliability From the Summer of 1999.*

[9] Federal Energy Regulatory Commission, “Promoting Whole- Sale Competition Through Open Access Non-Discriminatory Transmission Services by Public Utilities: Recovery of Stranded Costs by Public Utilities and Transmission Utilities”, *FERC order 888*, April 24, 1996.

[10] Yu, C.N., Yoon, Y.T., Illic, M.D. and Catelli, A., ”On-line Voltage Regulation: The Case of New England”, *IEEE Power Engineering Society*, 1998.

[11] Illic, M.D. and Yu, C.N.,”A Possible Framework For Market-Based Voltage/ Reactive Power Control”, *IEEE Proceedings, Winter Power Meeting*, New York, NY, Feb 1999.

[12]

[13] Ilic, M. and Cordero, R., ”On providing interconnected operations services by the end user: Case of distribution losses”,*Proc. of the NSF Conference on Unbundled Power Quality Services in the Power Industry*, Key West, Fl, November 1996, pp. 28-38.

[14] Cordero, R., ”Estimation of transmission losses in a changing Electric Power industry”, *MIT EEC Thesis*, June 1996.

[15] Chapman, J.W., ”Power System Control for Large- Disturbance Stability: Security, Robustness and Transient Energy”, *MIT EEC Thesis*, May 1996.