VOLTAGE QUALITY OF SUPPLY INCORPORATED SPOT MARKET MODEL: A MARKET EFFICIENCY PERSPECTIVE

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Abstract

This paper explores the potential to enhance economic efficiency by incorporating network attributes into an electricity spot market. Various network models are available, but the only AC load flow model can properly reflect voltage quality effects. In particular, market designs incorporating two versions of the AC load flow model are compared in this paper. One is 'technical regulation approach' and the other is 'voltage value function (VVF) approach'. The industry benefits resulted from energy trading are used as a main indicator of market efficiency.

1. INTRODUCTION

An electricity market has been implemented in many countries as a centerpiece of an electricity restructuring process. Even though some electricity markets have worked well, others have not and there remain many difficulties in incorporating network effects into an electricity market. In particular, due to the technical nature of electric energy, the important issue of quality of supply has been dealt with outside the electricity market. This separate treatment is one of key reasons for market inefficiency.

Ideally, the physical network features should be fully reflected in an electricity market for maximum market efficiency. From an engineering perspective, three alternative network models are available for incorporation into an electricity spot market; Transport model, DC load flow model and AC load flow model.[1] However, only the AC load flow model correctly represents voltage-related network effects [3]. In previous research, two alternative ways to incorporate AC load flow models into nodal spot market models have been suggested [7]. One is based on traditional centralized decision-making, whereas the other one is based on decentralized decision-making, in which voltage magnitude is managed by market participants' preferences.

The decentralized model assumes that each market participant expresses its willingness to accept off-nominal voltages as part of its bids or offers via a voltage value function (VVF) [7]. Bids and offers thus become functions of nodal voltages at the participants' points of connection, which are then reflected in the nodal energy spot prices calculated using a nodal market model that incorporates an AC load flow model of the network. This approach also allows nodal prices for reactive power to be determined and for decentralized decisions to be made about operating and investing in reactive power resources.

This paper explores the potential to enhance economic efficiency by incorporating network attributes into an electricity spot market.

2. ENERGY MARKETS AND MARKET BOUNDARY ISSUES

Electricity industry restructuring usually involves vertical and horizontal disaggregation of the pre-existing integrated monopoly industry. After structural reform, decision-making is decentralized by introducing a competitive market place. As a result, decision-making becomes dominated by commercial behavior rather than equipment physical behavior. For this purpose, important aspects of physical power system behavior must be abstracted into an economic model of power system behavior.

A suitable economic model of power system behavior can be constructed from four different markets, which cover different forward looking time horizon: ancillary service market (quality of supply), spot market (energy market), technical forward market and financial futures market [5]. Given that the forward markets are derivative markets based on the other two markets, the following overview description is restricted to the ancillary service and spot market.

2.1 Ancillary Service Market

The purpose of ancillary service market is to address uncertain short-term physical phenomena having time scale variation shorter than one trading period such as

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[1] DC load flow and Transport model are simplified version of AC load flow. The DC load flow model assumes that voltage magnitude is fixed, whereas the Transport model regards both fixed voltage magnitude and voltage angle as fixed.

power frequency, supply availability, voltage magnitude and waveform purity. These issues have traditionally been addressed by implementing ‘technical standards’ and ‘code of conduct’. However, it might be possible to address some quality of supply attributes using a commercial approach as will be illustrated in this paper [5].

The requirement for ancillary service fundamentally arises because the spot market is solved at discrete intervals (e.g. 30 minutes), which is an abstraction from continuous power system operation. Also, it is difficult to commercialize some aspects of ancillary services, which broadly include [6]: (1) implementing the outcomes of commercial transactions, to the extent that these lie within acceptable operating boundaries, (2) maintaining availability and quality of supply at levels sufficient to validate the assumption of commodity-like behavior in the main commercial market.

More specifically, ancillary services are closely relevant to short-term system operation and could include following services:

- Supporting spot market implementation, mainly short-term energy balancing and maintaining system frequency.
- Supporting quality of supply other than system frequency, mainly voltage magnitude and system security.
- Supporting system restoration from black out or island of power systems.

2.2 Spot Market

The spot market implements energy trading for the next spot market interval, typically 30 minutes or one hour. Ideally, the spot market for one interval should be solved independently for all other market intervals of the spot market. Therefore, the spot market algorithm should be a set of algebraic rather than differential equations. As well explained in [4, 9], the spot energy market could be organized based on economic market equilibrium. Each participant would submit offers to sell energy or bids to buy energy in the next half hour. Then, these offers and bids would be processed to derive an equilibrium point, in which supply and demand intersect.

The price setting process for a given market interval is illustrated by drawing the aggregated supply and demand curves in price-quantity plane. The aggregated supply curve is obtained by summing up all individual producer supply curve. An individual producer supply curve is a schedule showing the quantity that a producer would be prepared to sell at each level of price. Fig. 1 is a simple example of market equilibrium.

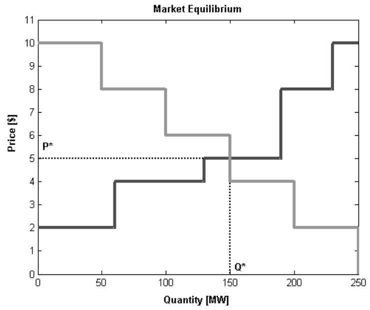

Fig.1 Market Equilibrium

The equilibrium curve could show how the industry benefits are created by the trading. Suppose that the supply curve intercepts the demand curve at point (Q^*, P^*). This point is called competitive equilibrium, at which a stable quantity and price of commodity in the market is defined. In the figure, the area bordered by the vertical axis at Q^*, horizontal axis and the demand curve is the total potential benefits obtained by demand sides. The area below the supply curve and the vertical axis at Q^* is the total possible cost expended in the production process. Accordingly, the industry benefits are the difference between total demand benefits and total supply cost.

2.3 Market Boundary

The spot energy market solution determines the target energy transactions of buyers and sellers, which the power system operator then attempts to achieve through the use of ancillary services, such as automatic generation, frequency and voltage control. Security considerations may also constrain permissible spot market outcomes. Thus, there is a two-way interface between ancillary services and spot market. There are also inevitable overlaps. Thus, the energy spot market and ancillary service markets should be coordinated in order to achieve economic efficiency and physical feasibility.

One possible approach for overcoming the market boundary is to more fully integrate network phenomena into the energy spot market. For this purpose, Nodal Auction Model (NAM) is originally proposed in [5], in which power system network can be modeled by using a load flow formulation as a means of network incorporation into spot market.

3. NETWORK EMBEDDED SPOT MARKET

The AC load flow model accurately represents physical network characteristics, whereas more simplified network representation such as the DC load flow model or Transport flow model cannot address voltage quality related network effects. Therefore, only the AC load flow model will be discussed here.

3.1 Network System Representation

Even though a wave equation representation might be needed to model a network exactly, the π-equivalent circuit model for medium length transmission line is normally used in an AC load flow model. The 2-node π-equivalent circuit for a transmission line appears in Fig. 2. The π equivalent circuit of transmission is expressed by self-admittance (Y_k, Y_j) and mutual admittance (Y_{kj}).

Assume that each node (node k) is connected to every node (node 1,2,3,·····,n) in the network by one or more transmission lines.

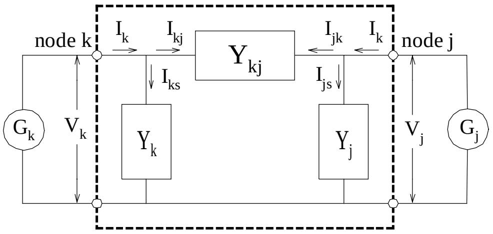

Fig.2 π-Equivalent Circuit

For an n-bus system, the electric power flow at node k in polar form is shown in Equation (1).

$$\begin{aligned} P_k &= V_k \sum_{j=1}^{n} V_j (G_{kj} \cos\theta_{kj} + B_{kj} \sin\theta_{kj}) \\ Q_k &= V_k \sum_{j=1}^{n} V_j (G_{kj} \sin\theta_{kj} - B_{kj} \cos\theta_{kj}) \end{aligned} \tag{1}$$

where, k=1,2,·····,n. G_{kj} and B_{kj} are the real and imaginary parts of mutual admittance Y_{kj} between node k and j respectively. θ_{kj} is voltage angle difference between k and j. Moreover, the network loss (P_{kj}^L, Q_{kj}^L) in the line between k and j is shown in Equation (2):

$$\begin{aligned} P_{kj}^{L} &= G_{kj} (V_k^2 + V_j^2 - 2 \cdot V_k V_j \cos\theta_{kj}) \\ Q_{kj}^{L} &= B_{kj} (-V_k^2 - V_j^2 + 2 \cdot V_k V_j \cos\theta_{kj}) \end{aligned} \tag{2}$$

For the purposes of considering line thermal rating, attention is focused on the apparent power flow and the apparent power flow is used as a criterion of network flow limit. Thus, the apparent power on network line between node k and node j should be more than minimum line limit as well as less than maximum line limit. Given that line limit is considered at steady state thermal limit (P_{kj}^C), the minimum limit and maximum limit have same magnitude and opposite sign. (P_{kj}^{Cmax} =-P_{kj}^{Cmax} = P_{kj}^C). Thus, network flow constraint function is shown in Equation (3).

$$P_{kj}^{C\,max} \le S_{kj} (= P_{kj} + jQ_{kj}) \le P_{kj}^{C\,max} \tag{3}$$

3.2 Network Embedded Market: Nodal Auction Model (NAM)

Since electric energy is governed by the laws of physics rather than commercial contract, the existence of network should be properly reflected in setting market prices, thus, network incorporated spot market framework is suggested as a form of Nodal Auction Model (NAM) [5]. In particular, spot market mechanism of nodal auction model that is based on auction mechanism has strength to avoid the physical inconsistency of bilateral trading mechanism, which could not comply the law of physics.

An auction algorithm is used to establish a set of nodal prices for each energy market period. Market participants submit a number of bids and offers, each of which consists of a price, a minimum quantity and maximum quantity such as (p_i, q_i^{min}, q_i^{max}). These bids are then dispatched so that the net total value of the accepted bids is maximized, subject to network losses and flow constraints. If a bid is submitted by a consumer, then the consumer is indicating a wiliness to consume any quantity x_i such that $q_i^{min} \le -x_i \le q_i^{max}$ if the price to be paid is p_k or less. Most consumers will submit bids with $q_i^{min} \le 0$ and $q_i^{max}=0$. Meanwhile, if the bid is submitted by a generator, then the generator is indicating a wiliness to generate any quantity x_i such that $q_i^{min} \le x_i \le q_i^{max}$ if the price to be paid is p_k or more. Most generators will submit bids with $q_i^{min}=0$ and $q_i^{max} \ge 0$.

Assume that the network model in the auction process has N nodes and bids (S_i, B_i) are submitted by generators and consumers located at various nodes. Then, network incorporated optimal dispatch of bids is achieved by following mathematic model at node k [5].

$$\begin{aligned} & max\ f(x,\sigma) = [x_i]^T \cdot [P_{x_i}] \\ & s.t \\ & g(\sigma,x) + \sum_{\beta_i \in S_i \cup B_i} x_i = 0 \\ & h(\sigma,x) \le 0 \\ & 0 \le x_i \le q_i \quad \text{if } i \in Seller \\ & -q_i \le x_i \le 0 \quad \text{if } i \in Buyer \end{aligned} \tag{4}$$

where σ is network state vector such as voltage magnitude and voltage angle, x_i is optimal active power dispatch for market participant i, $g_k(\sigma,x)$ is real valued function of network state vector, expressing sum of power flow into node k on each transmission line incident on node k and $h_k(\sigma,x)$ is vector valued function of the network state vector and the bids x_i, expressing constraints on the operation of the electricity industry such as line power flow.

The mathematic form of above optimal dispatch for active power becomes a constrained nonlinear program (NLP) and is quite similar to generic optimal power flow. However, even though the mathematic feature is very similar to classical optimal power flow (OPF), its solution algorithm is quite different. The most obvious distinction is that the nodal auction model regards demand as changeable, whereas the optimal power flow takes demand as a fixed system requirement.

4. VOLTAGE QUALITY OF SUPPLY INCORPORATED SPOT MARKET MODEL

The nodal auction model covers the time frame from very short-term quality issues. A quality attribute can be incorporated into the $h_k(\sigma,x)$ function only if it can be expressed in terms of voltage angle and magnitude. Here, we should keep in mind that if the quality valued function expressed by state variables is not incorporated into nodal auction model, the established shadow price of that quality attribute is never the market clearing price. This implies that we need a proper quality attribute value function in order to get the correct competitive market price.

4.1 Voltage Quality of Supply Arrangement

Electrical equipment is designed on the basis of certain expectations of quality of supply. In commercial terms, quality defines the tradable commodity and purchasers will have certain expectations of quality of supply.

Traditionally, voltage quality has been maintained by technical standards and codes of conduct. Accordingly, one possible approach for voltage quality arrangement is to retain technical standard and rules of conduct for voltage quality of supply. Intuitively, it is recommended that the technical standard method be used in initial stage of competitive electricity industry. Moreover, some proper cost allocation process is required in implementing the technical standard in order to recover the cost of voltage quality supplier.

In addition, market-based approach could be considered for setting targets for voltage quality. As a market-based approach, instead of using voltage constraint in nodal auction algorithm, the voltage quality expressed by voltage magnitude and angle, which is called as ‘voltage value function (VVF)’, is incorporated into the optimization algorithm by relaxing voltage constraint. The voltage value function method is originally suggested in [5], and a plausible function model is featured in [7]. The voltage quality is maintained by market participants in the suggested VVF based market model. A detailed description of voltage value function will be described in next subsection.

Unfortunately, market-based voltage quality embedded market never means that real time system operation is no more required. Even though market-based voltage quality attribute is incorporated into spot market, short-term technical control would still be required for the time scale shorter than the spot market period.

4.2 Voltage Value Function (VVF)

If the reactive element of network impedance is ignored in Fig.2, the approximate power loss P_{Loss} between node k and node j is given by

$$P_{Loss} \approx \frac{P_j^2 \cdot r_{kj}}{V_j^2} \tag{5}$$

Assume that the voltage technical regulation is relaxed and power demand P_j at node j is fixed for implementing market-based voltage quality approach. Then, the system voltage tends to be maintained as high as possible in order to decrease the power system loss. However, electrical equipment is designed to operate within an allowed voltage range that market participants may wish to specify in the form of ‘allowable voltage range’. Accordingly, if the nodal voltage magnitude is outside the allowable voltage range, it may cause some additional cost due to insulation degradation and higher voltage or current related losses. The additional cost as a function of voltage magnitude can be incorporated into the participants bidding functions.

By incorporating VVFs into bidding functions, market participants can express their willingness to buy or sell electric energy as a function of voltage. Sellers would expect a higher price to compensate for the additional risk of damage to their facilities if the voltage became either lower or higher than their equipment’s allowable voltage range, whereas the buyer would be not be willing to pay as much if their electrical facilities are exposed to voltage either lower or higher than their equipment’s allowable voltage range. Thus, the price outside the allowable voltage range could be expressed as relative price with respect to the price of inside boundary using ‘additional cost’ and ‘reduced payment’, which is depended on voltage magnitude as follow.

$$\begin{array}{ll} p^* [1 + p(V_k)] & \text{for seller} \\ p^* [1 - p(V_k)] & \text{for buyer} \end{array}$$

where, p^* is market participant's price for inside of boundary and $p(V_k)$ is the additional cost and reduced payment at node k.

The price difference between inside boundary and outside boundary could be used as a voltage quality preference of market participants. This preference is revealed as tolerance factor to auction center by market participants along with other bid data. In particular, the tolerance factor will provide important role to protect the extremely voltage increase caused by the relaxation of voltage limits.

Given that the voltage value function is used as objective function of electricity trading, the function modeling is inevitably limited to twice-differentiable continuous function in order to be used in a constrained nonlinear programming problem. Taking into this limitation, the following voltage value function of market participant *i* is suggested in [7].

$$
\begin{aligned}
p_i(V_k) &= p_i^* \cdot \pi_i(V_k) \\
&= p_i^* \cdot \pi_i(V_k) \left| \begin{array}{ll} 1+\alpha_i \cdot (V_i^{min} - V_k)^3 & if,\ V_k < V_i^{min} \\ 1 & if, V_i^{min} < V_k < V^{max} \\ 1+\gamma_i \cdot (V_k - V_i^{max})^3 & if,\ V_k > V_i^{max} \end{array} \right.
\end{aligned}
\tag{6}
$$

As discussed above, market participants reveal their quality preference using tolerance factor α_i, and γ_i properly, and the value of tolerance factor should have opposite sign for seller and buyer. Thus, many different type of voltage value function could be given by just changing parameters (V_i^{min}, V_i^{max}, α_i, and γ_i).

For illustration of voltage value function, the Case 4 model in the Table 3 is given in Fig. 3. In Case 4, the voltage value function (VVF) is approximately modeled as follow; seller is elastic to lower voltage (α_i= 4000, V_i^{min} = 0.95[p.u.]) as well as to upper voltage (γ_i = 4000, V_i^{max} = 1.05[p.u.]). Similarly, buyer is elastic to lower voltage (α_i = -4000, V_i^{min} = 0.95[p.u.]) as well as upper voltage (γ_i = -4000, V_i^{max} = 1.05[p.u.]). The VVF curves are illustrated with \$2/kwh for seller and \$4/kwh for buyer within range price, respectively.

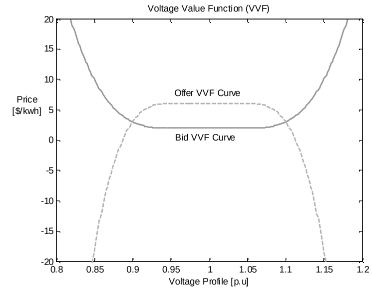

Fig. 3 Voltage Value Function (VVF) Curve

4.3 Mathematic Modeling

Based on the Nodal Auction Model (NAM) discussed above, the network related constraints to be incorporated into the basic algorithm of nodal auction model as form of equation (4) should include active power balance, reactive power balance, nodal voltage limit, reactive power generation limit and network flow limit [1, 7].

Regarding active power balance, the injected active power by both supplier and buyer should be equal to active power outlet to network system with respect to every node. In addition, dispatched active power should not exceed the quantity that market participants revealed in bidding process.

$$\sum_{j=1}^{n} V_k V_j (G_{kj} \cos\theta_{kj} + B_{kj} \sin\theta_{kj}) + \sum_{\beta_i \in S_i \cup B_i} x_i = 0 \tag{7}$$

where, x_i is bid active power by seller (S_i) and buyer (B_i). Similar to active power balance, the reactive power provided by a supplier such as a generator or reactive power compensator (y_k) and absorbed by a buyer should be equal to reactive power outlet to network system with respect to every node. In demand side, reactive requirement is modeled by the affine function [2], which is proportional to active power as well as load power factor (φ_i).

$$\sum_{j=1}^{n} V_k V_j (G_{kj} \sin\theta_{kj} - B_{kj} \cos\theta_{kj}) + y_k + \sum_{\beta_i \in B_i} \varphi_i \cdot x_i = 0 \tag{8}$$

Moreover, since a reactive power supplier could either produce or absorb reactive power, its reactive production is managed between negative (absorption) maximum and positive (production) maximum limit.

$$Q_k^{min} \le Q_k \le Q_k^{max} \tag{9}$$

At nodes where voltage value functions are not implemented (e.g. technical standard), nodal voltage should be kept within an appropriate range.

$$V_k^{min} \le V_k \le V_k^{max} \tag{10}$$

The flow on a line should not exceed its allowable capacity set by a security constraint. Nor should the line flow exceed the steady state thermal limit. In practice, if power flow from node k to j, S_{kj}, is positive and its magnitude is limited by a thermal capacity (P_{kj}^{Cmax}), then the opposite power flow from node j to node k, S_{jk}, should not exceed the steady state thermal limit with the opposite sign. Therefore, the lower limit of line flow is same as upper limit with opposite sign. The constraint equation could be given by equation (3).

As a result, basic nodal auction algorithm formulation, equation (4) could be re-modeled as follow using both voltage value function and network constraint equations at node k.

$$
\begin{aligned}
& max\ f(x,\sigma) = [x_i]^T \cdot [P_{xi}] = \sum_{\beta_i \in S_i \cup B_i} x_i \cdot P_i^* \cdot \pi_i(V_k) \\
& s.t \\
& \sum_{j=1}^{n} V_k V_j (G_{kj} \cos\theta_{kj} + B_{kj} \sin\theta_{kj}) + \sum_{\beta_i \in S_i \cup B_i} x_i = 0 \\
& \sum_{j=1}^{n} V_k V_j (G_{kj} \sin\theta_{kj} - B_{kj} \cos\theta_{kj}) + y_k + \sum_{\beta_i \in B_i} \varphi_i \cdot x_i = 0 \\
& V_k^{min} \le V_k \le V_k^{max} \\
& Q_k^{min} \le Q_k \le Q_k^{max} \\
& 0 \le x_i \le q_i \qquad\qquad if\ i \in Seller \\
& -q_i \le x_i \le 0 \qquad\quad if\ i \in Buyer \\
& P_{kj}^{C\,max} \le S_{kj} \le P_{kj}^{C\,max}
\end{aligned}
\tag{11}
$$

where, x_i is optimal active power dispatch for market participant i, y_k is optimal reactive dispatch at node k, σ is network state vector (V,θ), $\pi_i(V_k)$ is voltage value function for market participant i, α_i is lower voltage tolerance if $V_k<V_i^{min}$, γ_i is upper voltage tolerance if $V_k>V_i^{min}$, p_{xi} is willingness to buy or sell active power if $V_k^{min}<V_k<V_k^{max}$, V_k^{min} and V_k^{max} are participants' minimum and maximum preferred voltage located at node k respectively, V_k is network voltage at node k and β_i is bidding data from seller and buyer.

4.4 Computation Algorithm

The computation task for auction process depends on the network representation, which is expressed by $g_k(\sigma,x,y)$ and $h_k(\sigma,x,y)$. Since $g_k(\sigma,x,y)$ and $h_k(\sigma,x,y)$ include nonlinear equations, the mathematic model should be computed by a nonlinear optimization technique. In this paper, the optimization computation is implemented by MATLAB embedded function, which is based on sequential quadratic programming (SQP) [10, 11].

The solution algorithm of SQP consists of three major steps as follow. The first is to find a search direction and then a design value x for the current iteration through a Quadratic Programming (QP) subprogram. In this subprogram, the step size is determined by an appropriate line search direction. Secondly, the current iteration design value produced by QP subprogram is used to test convergence to the optimal value. Finally, the Hessian matrix is updated using quasi-Newton updating method for the next iteration if the solution of current iteration does not satisfy feasibility and optimality. Each step is described in detail as follow.

- *Quadratic Programming Subprogram*: given that finding an optimal solution is mainly based on the search technique, the QP subprogram that yields search direction as well as step size is at the heart of the SQP. The QP subprogram is based on expanding the objective function quadratically as well as constraint function linearly. Thus, QP subprogram becomes a simple nonlinear program with linear constraints. This is why we call this algorithm Sequential Quadratic Programming.

If current iterated design value does not satisfy the optimization, it is required to get the design value of next iteration, $x^{k+1} = x^k + \omega \cdot d$ in which ω is an optimal step size at k^{th} iteration. For this, the search direction vector *d* is firstly calculated, then, the step size has to be calculated. The step size calculations are based on simultaneously decreasing the objective value as well as improving the constraint satisfaction.

- *Convergence Check*: once design value is obtained at each iteration, the value is checked to see if it satisfies the KT conditions as well as all constraint conditions. Obviously, calculating Lagrange multiplier is required to verify the KT condition as well as other additional operations such as setting up merit function, metric replacement of Hessian matrix. After then, the optimal value and constraint value are checked to see if they have converged within pre-determined error.

- *Updating the Hessian Matrix*: if the design value at the current iteration does not satisfy the convergence error, the main SQP algorithm should implement another iteration including QP subprogram. The most important information for moving one location to another in optimization problem is whether the selected direction is guaranteed to minimizing objective value. This information for minimizing direction could be given by the second order derivative of objective function (Hessian). The actual Hessian defined in QP subproblem is not used due to its complication in real implementation. Instead, the metric Hessian updated at each iteration is used.

As discussed, the nature of mathematic formulation is based on classical optimal power flow due to similar network constraint conditions. Thus, the main optimization scheme of the suggested voltage quality incorporated nodal auction algorithm is implemented with well verified OPF package [12] except that OPF program is modified to implement Nodal Auction Model.

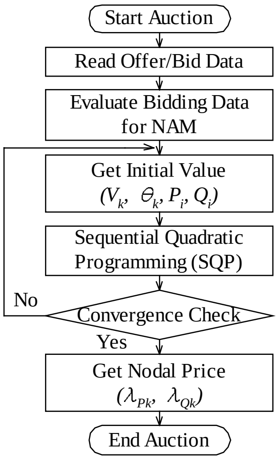

Fig. 4 Computation Algorithm of NAM

5. NUMERICAL TEST AND RESULTS

5.1 System Model: 5-Bus System

The simulation is implemented based on 5 bus system, which was used in [8]. The tested 5-bus system consists of two generator nodes and three load nodes as Figure 5.

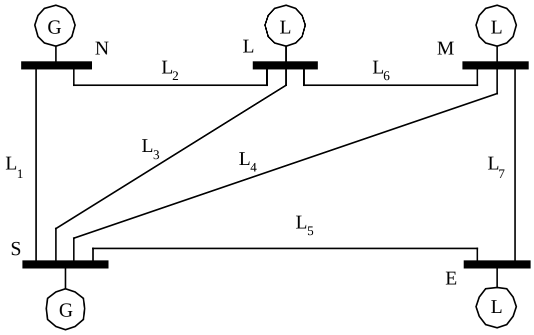

Fig.5 5-Bus System Model

The parameters of transmission network are given in following Table 1, which is based on 100[MVA].

Table 1. Transmission Data

Line Name	From	To	R [p.u.]	X_L [p.u.]	X_C [p.u.]
L_1	N	S	0.02	0.06	0.06
L_2	N	L	0.08	0.24	0.05
L_3	S	L	0.06	0.18	0.04
L_4	S	M	0.06	0.18	0.04
L_5	S	E	0.04	0.12	0.03
L_6	L	M	0.01	0.03	0.02
L_7	M	E	0.08	0.24	0.05

For market-based simulation, it is assumed that each node submits offers and bids data to the auction center to reveal the willingness to buy or sell electric energy with associated voltage value functions. As seen in Table 2, we have assumed that market participants have two equal blocks of generation and demand for this simple simulation. Note that reactive power generation of seller is given by lower and upper boundary, whereas the reactive consumption of buyer is expressed by means of power factor.

5.2 Market Data

The following market data is submitted to the auction center as a bid data. Voltage lower and upper limit are only used in technical regulation simulation, whereas voltage tolerance factors (α, γ) are only used in VVF model-based simulation. Another three VVF model cases are implemented by just changing the voltage tolerance factor of offers and bids. Each offer and bid is represented as an independent generator unit at the concerned node.

Table 2. Offers and Bids Data (VVF Model Case 1)

Offers

Name	Bus	V^{min}	V^{max}	α	γ	q	p	Q^{min}	Q^{min}	P.F
N1	N	0.95	1.05	40	40	0.75	2	-0.8	0.8	-
N2	N	0.95	1.05	40	40	0.70	4	-0.6	0.6	-
S1	S	0.95	1.05	40	40	0.40	3	-0.3	0.3	-
S2	S	0.95	1.05	40	40	0.20	6	-0.3	0.3	-

where, V^{min}, V^{max}, Q^{min}, Q^{max} , q is in [p.u.] and p is in [$/kwh].

Bids

Name	Bus	V^{min}	V^{max}	α	γ	q	p	Q^{min}	Q^{min}	P.F
L1	L	0.95	1.05	-40	-40	0.30	7	-	-	0.98
L2	L	0.95	1.05	-40	-40	0.15	6	-	-	0.98
M1	M	0.95	1.05	-40	-40	0.25	8	-	-	0.98
M2	M	0.95	1.05	-40	-40	0.15	7	-	-	0.98
E1	E	0.95	1.05	-40	-40	0.40	9	-	-	0.98
E2	E	0.95	1.05	-40	-40	0.20	8	-	-	0.98

5.3 VVF Model Validation

The purpose for proposing voltage value functions is to replace the existing ‘technical standard method’ with ‘market based method’ with respect to voltage quality of supply. Thus, results for the two methods are compared by means of the resulting nodal voltage profile in order to allow comparison.

The technical method is simulated by applying the same voltage constraint at every node ($0.95 \leq V \leq 1.05$). Then, four VVF-based cases are simulated by changing voltage quality tolerance factor. Unlike the technical method, voltage limit at node is relaxed in VVF model cases, and thus nodal voltage regulation relies only on market participants’ voltage quality preferences.

As can be observed in Table 3, even though the voltage profile in VVF model tends to give a little higher voltage than technical method, it is very impressive that both results by Case 2 and Case 4 have quite similar level of voltage profile with technical method. This implies that if well estimated voltage tolerance factors are given, the voltage profile at nodes could be well self-regulated by means of market-based method in restructured electricity industry.

Table 3 Nodal Voltage Profile [p.u.]

Model Case	**N**	**S**	**L**	**M**	**E**
Technical Method $[0.95 \leq V \leq 1.05]$	1.050	1.041	1.018	1.016	1.009
VVF Method (Case 1) $[\alpha_S=40, \gamma_S=40]$ $[\alpha_B=-40, \gamma_B=-40]$	1.078 **(2.67%)**	1.068 **(2.59%)**	1.047 **(2.85%)**	1.045 **(2.85%)**	1.038 **(2.87%)**
VVF Method (Case 2) $[\alpha_S=4000, \gamma_S=4000]$ $[\alpha_B=-40, \gamma_B=-40]$	1.053 **(0.29%)**	1.044 **(0.29%)**	1.021 **(0.29%)**	1.020 **(0.39%)**	1.012 **(0.30%)**
VVF Method (Case 3) $[\alpha_S=40, \gamma_S=40]$ $[\alpha_B=-4000, \gamma_B=-4000]$	1.078 **(2.67%)**	1.068 **(2.59%)**	1.047 **(2.85%)**	1.045 **(2.85%)**	1.038 **(2.87%)**
VVF Method (Case 4) $[\alpha_S=4000, \gamma_S=4000]$ $[\alpha_B=-4000, \gamma_B=-4000]$	1.053 **(0.29%)**	1.044 **(0.29%)**	1.021 **(0.29%)**	1.020 **(0.39%)**	1.012 **(0.30%)**

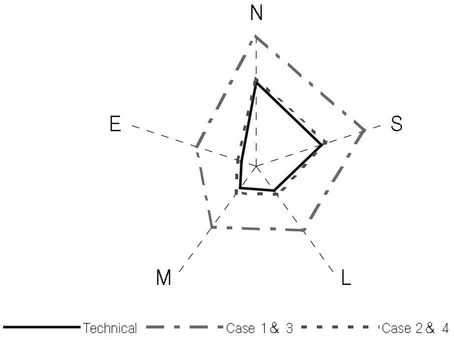

Fig. 6 Nodal Voltage Profile

5.3 Market Efficiency by Market Participants

The industry benefit is used as a key market efficiency indicator that can be used to explore the effect of changing the voltage quality preference of market participants. Given the same technical standard as in Table 3 and buyer's tolerance factors are set by α_B= -4000 and γ_B= -4000, then the trading benefits produced by seller's response are shown in Table 4.

Table 4 Trading Benefits by Sellers' Participating [$]

Benefits	**Technical**	α_S**=40,** γ_S**=40**	α_S**=400,** γ_S**=400**	α_S**=4000,** γ_S**=4000**
Supplier	4.063	4.053	4.059	4.062
Consumer	11.250	11.250	11.250	11.250
Network	0.672	0.601	0.648	0.663
Industry	**7.187**	**7.190** **(Δ 0.04%)**	**7.191** **(Δ 0.06%)**	**7.188** **(Δ 0.01%)**

As a buyer's response case, there are two possible methods for buyers to change their voltage preferences; (1) change of V^{min}, (2) change of bid price. In this simulation, the former method is adopted. If seller's tolerance factors are set to α_S= 4000, γ_S= 4000 and buyer's tolerance factors are set to α_B= -4000, γ_B= -4000, then the effect on trading benefits by changing buyers' V^{min} is shown in Table 5.

Table 5 Trading Benefits by Buyers' Participating [$]

Benefits	**Technical**	$\mathbf{V^{min}}$ **(0.98)**	$\mathbf{V^{min}}$ **(0.99)**	$\mathbf{V^{min}}$ **(1.00)**
Supplier	4.063	4.062	4.062	4.062
Consumer	11.250	11.250	11.250	11.250
Network	0.672	0.663	0.663	0.663
Industry	**7.187**	**7.188** **(Δ 0.01%)**	**7.188** **(Δ 0.01%)**	**7.188** **(Δ 0.01%)**

According to the two results, even though the magnitude of benefit increase is not prominent, it obviously tends to enhance the industry benefits in the market-based approach. This implies that given more precise tolerance factor are developed, market-based method for voltage quality of supply might be more efficient than technical standard method.

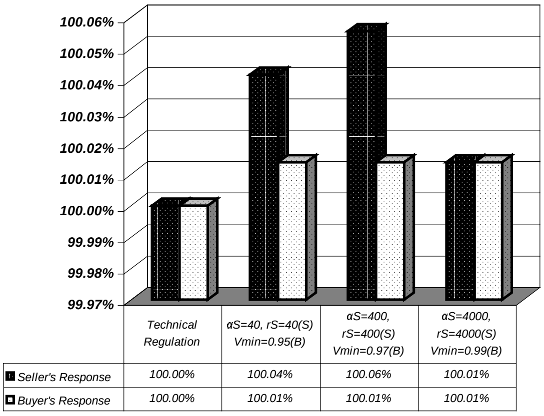

Fig. 7 Effect on Industry Benefits by Participants

5.4 Market Efficiency by Network Effects

Voltage related network issues include network losses, voltage constraint and reactive power consumption. Accordingly, various network effects might be simulated in terms of network aspects such as line power flow limit, network loss, control source scarcity and nodal voltage magnitude. In this paper, the network effect by voltage control source scarcity is reviewed.

Let assume that tolerance factor of N-node and S-node be equally elastic source with α_S= 4000, γ_S= 4000, and all buyer node respectively has α_B= -40 and γ_B= -40 for lower and upper voltage tolerance factors. In a non-scarcity case, since reactive capacity at S node is enough to supply the system reactive power requirement, the reactive power located at S-node could properly supply the reactive power requirement.

As a scarcity case, assume that the reactive capacity at S-node is reduced under the total system reactive requirement. Moreover, the power factor of load is changed from 0.98 to 0.965 in order to increase the system reactive power demand, which could exceed the capacity of Q_S. The market result with respect the change of reactive capacity at S node is shown in Table 6.

Table 6 Market Result by Capacity Scarcity at S node

Q_S	**60**	**30**	**25**	**20**	**15**	**10**	**5**
Q_N	-8.2	-8.2	-3.9	1.2	6.4	11.6	16.8
MP	3.99924	4.00055 **(∆ 0.10%)**	4.00053 **(∆ 0.13%)**	4.00055 **(∆ 0.16%)**	4.00057 **(∆ 0.19%)**	4.00059 **(∆ 0.23%)**	4.00061 **(∆ 0.26%)**
IB	7.185	7.185 **(∆ 0.00%)**	7.185 **(∆ 0.00%)**	7.185 **(∆ 0.00%)**	7.184 **(∇ 0.01%)**	7.183 **(∇ 0.04%)**	7.181 **(∇ 0.10%)**

where, Q_S is Reactive capacity at S node [MVar], Q_N is Reactive capacity at N node [Mvar], MP is Marginal price [\$/MW] and IB is industry benefits [\$].

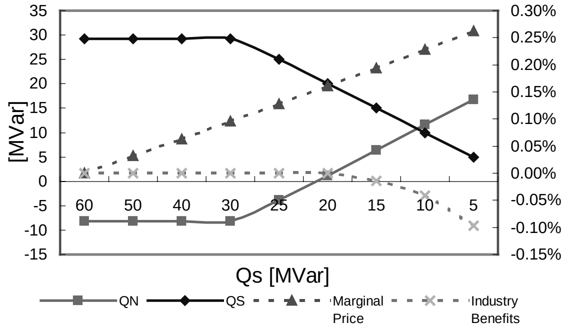

Fig. 8 Market Outcomes for Capacity Scarcity

As the Qs is reduced, the decreased capacity is replaced by Q_N. This leads to increase the marginal price of reactive power at S-node, and could boost up the active nodal marginal price. As a result, the industry benefits are obviously decreased as the capacity scarcity is more increased.

6. CONCLUSION

Electricity industry restructuring is a complex process that involves the replacement of traditional engineering functions by commercial trading. However, this is not always possible, so that a mix of commercial and engineering functions remains. This paper has explored the conversion of one of those engineering functions, voltage control to a commercial process. It has demonstrated that the inclusion of voltage value functions in an energy spot market is feasible in principle. However, more work is required before these ideas could be applied in practice.

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