Current Issues In Reactive Power Management: A Critical Overview

Contribution to the panel
"Reactive Power Management and Payment Mechanisms in Competitive Electricity Markets"

Gianfranco Chicco, *Member*, *IEEE*, and George Gross, *Fellow*, *IEEE*

Abstract **– This paper reviews specific issues and challenges in reactive power management within the competitive electricity market context and increasing requirements of system security. The basic aspects refer to the specific constraints introduced by the capability curves of the generating units, the notion of opportunity costs and the questionable role of obligation to serve concerns. Other key issues are related to the responsibilities of the grid operator in transmission networks, the mechanisms for reactive power procurement with critical concerns about the use of optimization procedures, the importance of obtaining meaningful indicators and suitable sensitivity information to characterize the power system operation, and the needs for developing specific calculations based on the value of reactive support during normal operation and in dynamic conditions.**

Index Terms **– reactive power, voltage support, reactive power and voltage support ancillary service, independent grid operator, pricing, lost opportunity costs, obligation to serve, generator capability curve, system security.**

I. Introduction

Reactive power and voltage support is an essential service to ensure secure power system operations. In the competitive electricity market environment, the provision of such a service must take into account the economics in addition to the technical and physical considerations and so depends on the market players and the electricity market rules. Reactive support and voltage control from *generation sources* is deemed to be an ancillary service [1] in the England and Wales system and is one of the six specified ancillary services in the FERC Order No. 888 [2]. In light of the experience to date, the discussion on the role of reactive power supply includes all aspects of the service from economic issues to security [3-5]. The detailed analysis of characteristics and procurement and pricing of reactive power issues [6] summarizes many conceptual aspects and current practices, points out various deficiencies in the reactive power procurement in the US markets and provides recommendations for, and lists a number of challenges in the reactive power supply and usage area. Basically, there are many problems with the lack of transparency and consistency in reactive power planning and procurement mechanisms and the rather weak incentives to supply reactive power.

The strongly local nature of reactive power restricts its ability to be transmitted over electrically large distances. As such, the reactive power procurement depends on the availability of local reactive power sources [7]. More importantly, such characteristics imply that reactive power cannot be treated as a commodity of the same type as active power or active energy. Many reactive power management issues concern the static and dynamic aspects of the operating conditions. In fact, the key use of reactive power is primarily to maintain a specified voltage profile under normal operating conditions and to avoid system collapse under emergency by ensuring the existence of adequate dynamic reactive power reserves. The *valuation* of the reactive support provided is a rather challenging problem whose effective solution is yet to be determined.

The very local nature of reactive power provision renders the economics of reactive power and voltage support to be challenging and makes highly questionable the feasibility of setting up a workable market structure for reactive power procurement. Moreover, the development of pricing mechanisms able to provide appropriate incentives to stimulate suitable investments in areas lacking in reactive power supply capability remains a major challenge.

This paper provides a critical overview of a number of issues related to the procurement and management of reactive power and voltage support services. Section II discusses the fundamental limitations arising from the generator capability curves, the notion of opportunity costs and the practical means to discharge the *obligation to serve* requirements. Section III describes some system-wide aspects of reactive power management, including the role and responsibilities of the transmission system operator, the appropriate incorporation of reactive support issues in the formulation of optimization formulations, the definition of meaningful indicators for characterizing the effectiveness of the reactive power management and the discussion on the worth of reactive power support. The last section contains concluding remarks on the numerous challenges ahead.

II. Basic Issues

We discuss in this section some key aspects of the reactive power and voltage support service.

G. Chicco is with the Dipartimento di Ingegneria Elettrica, Politecnico di Torino, corso Duca degli Abruzzi 24, I-10129 Torino, Italy (e-mail gianfranco.chicco@polito.it).

G. Gross (gross@uiuc.edu) is with the Department of Electrical and Computer Engineering at the University of Illinois at Urbana–Champaign, Urbana, IL 61801, USA.

II.1. Capability curves

The classical description of the operational limits of a synchronous generator is obtained from the capability curve, representing the region of feasible operation on the active power/reactive power plane [8]. In many studies, the capability curve is approximated by using linear segments, in order to simplify the inclusion of the capability curve into the formulation of analysis or optimization problems. At the present stage of the research, it becomes essential to characterize the actual operational behavior of the generators. Hence, the use of such approximations could be no longer sufficient. In the perspective of providing useful insights to the study of the technical aspects concerning the reactive power production and its limits, the capability curve description should include more details. In particular, the dependence of the capability curve on the voltage settings should be taken into account. In certain cases, even the possibility of extending the feasible region inside the capability curve by providing more efficient cooling [9] could be considered as a viable option. With the purpose of providing additional voltage support in transient conditions, additional margin can be obtained by taking into account the overloading capability curve, in which the capability limits are partially relaxed. In addition, for power system studies it is important to take into account the model of the whole set of components (generator, step-up transformer and possible local reactive power compensation) forming the *generation unit* connected to the transmission system nodes, with explicit inclusion of the generator capability limits. Alternatively, a comprehensive *capability chart* of the whole generation unit at the transmission system interconnection [10,11] has to be identified and included in the model. The capability chart has to be drawn by taking into account the impact of possible variations of the *control variables* (generator set point voltage, the tap position of the ULTC or the set point of other compensation devices) on the capability limits of the generators [12]. In order to make it possible to carry out the technical assessment of the power system operation, the information concerning the technical characteristics of the generation unit components have to be provided to the IGO and as such cannot be considered to be private information. By using these information, the IGO is enabled to determine the suitable control variables to be imposed in order to satisfy the operational objectives under the IGO responsibility.

II.2. Opportunity costs

The operating point of the power system depends on the structure, loading level and control settings of the whole network. For a generator, the control variables are the active power and the voltage magnitude. The active power can be determined as a result of bilateral contracting or competitive auctions in the energy market. Once imposing the active power quantities, one or more generators could reach its/their reactive power limits on the capability curve in normal operating conditions. If the reactive power limits were reached, the reactive power support requirements could be satisfied by curtailing a portion of the active power generation. This would result in foregone profits for the generator, namely, the *opportunity costs* [7,13] representing the value of the opportunity the generator gives up to provide the reactive power support required by the system would be lost. To exemplify, let us consider a seller submitting a *MW* offer to the energy market, with maximum power offered P_o and with a stepwise bid structure for different amounts of power offered. The energy market clearing followed by congestion management defines the quantity of the accepted offers and the market price. At the node to which the generator is connected, the market price is assumed to be defined by the *locational marginal price* or *LMP* [14]. In particular, it is possible to distinguish among a *marginal* generator, for which the accepted *MW* offer P_c determining the *LMP* can be lower than the submitted MW offer P_o, and a *non-marginal* generator, for which the accepted *MW* offer P_c equals the submitted *MW* offer P_o. With reference to IGO requirements for the reactive power and voltage support ancillary service, the generator could be unable to provide sufficient reactive power to maintain the active power generation at the quantity P_c. We illustrate the notion in graphical terms in Fig. 1 showing a portion of the capability curve of a generator, which is required to provide reactive power at its real power output P_c at the point *B*. The generator operation at the power level P_c cannot meet the reactive support at the corresponding limiting value at the point *A*. The IGO determines a technically feasible solution through the variation of some voltage control set points so as to transition the operation from point *B* to point *C* along some direction such as that given by line *r* in Fig. 1. This necessitates the reduction of the active power generation to P_r to attain an acceptable operating condition at the point *C*. The power reduction has associated with it the opportunity costs due to the foregone profits of the reduced output and corresponding revenues. Fig. 2 shows the filled area corresponding to the lost opportunity costs for a marginal generator.

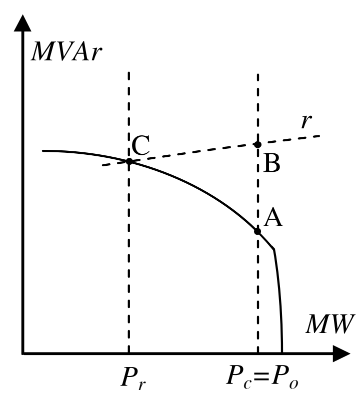

Fig. 1. Portion of the generator capability curve.

The opportunity costs depend on the reduction in the active power (and thus energy) production, valued at the clearing price of the energy market. Hence, they are of the same order of magnitude as the profits of the generator. The costs of the provision of reactive power at any operating point inside the capability region are negligibly small with respect to the costs of generation of active power due to energy losses. As such, the opportunity costs represent the *dominant component* of the cost structure concerning the provision of reactive power support in normal operating conditions [7] and are widely recognized as essential elements for setting up reactive power pricing or market schemes [15]. However, *a priori* quantification of the lost opportunity costs is very difficult due to the strong dependence on the operating conditions of the system.

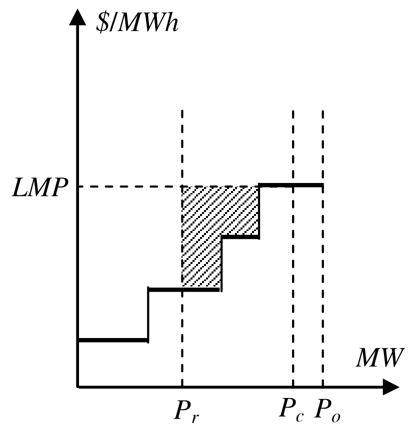

Fig. 2. Graphical representation of the opportunity costs for a marginal generator.

II.3. Obligation to serve

The economic treatment of the operating points lying inside the generator capability curve (for pricing or market purposes) has been subject to various interpretations during the last years. According to some regulations, such as the FERC Order No.2003 [16], the producer should not be compensated when its operating point is located within a region of the capability curve bounded by two established power factor values (e.g., from 0.95 leading to 0.95 lagging), while it should or could be rewarded outside that region. The notion of a power factor-based region within which no economic compensation is given raises *obligation to serve* concerns with various technical and economic ramifications. Among them is the "imprecise interconnection standards" of [6] since the standards requiring obligations to serve for the generation units within prescribed power factor limits do not specify on which side of the step-up transformer the power factor has to be measured. However, such an obligation to serve is economically and from a policy perspective highly questionable. In fact, there is no guarantee that each generator output lies within the specified power factor limits and so the application of the standards introduces a lack of uniformity in a pricing scheme allowing a generator to be compensated only when it is outside the obligation to serve region. This situation is not consistent with the fact that all reactive power providers should be paid on a non-discriminatory basis. In addition, the network structure considerations imply that a generator may need to produce or absorb reactive power, at a different level to maintain the specified voltage profile under low-loading or no-load conditions than when loaded more fully.. This is true due to the *intrinsic* reactive power support required from generators to maintain the specified voltage profile even in the absence of active power requirement, as discussed in [17]. Indeed, compliance with the reactive support requirement for operation within the power factor-based obligation to serve region under low-load conditions, may be infeasible or overly difficult. Since the operating point also depends on the voltage control set points, their specification by the IGO imposes an additional challenge for constructing an equitable non-discriminatory solution.

An even more questionable situation occurs under the hypothetical presence of a reactive power market in which the generator owners, acting as sellers, would be able to associate price offers to the operating points lying outside the *obligation to serve* region. Again, the presence of the network would constrain the solution of any reactive market clearing procedure, in such a way to give some sellers an effective dominant position with possible monopoly or oligopoly and potentially extensive market power. The limits of the *obligation to serve* region may serve for specifying the boundaries for setting up procedures aimed at minimizing the reactive power procurement costs. However, in this case the boundary would may be viewed as discriminatory since the generators must operate outside the boundary. It follows from this discussion that the attempt to force the reactive power outputs to remain within a prescribed region has no reasonable rationale. As such, the inner region of the capability curve needs to be viewed uniformly in terms of the pricing criterion, with no distinction given to an *obligation to serve* region.

III. System-Wide Aspects of the Reactive Power Provision and Management

This section covers a set of issues related to the reactive support required in the transmission system, its procurement and valuation considering the normal system operation and the effects of taking into account voltage security aspects.

III.1. Reactive support responsibilities of the IGO

The strongly interconnected meshed network structure of the power system requires the coordinated control of the network by a single centralized entity. This entity is responsible for determining the controls required to facilitate transactions and ensure transmission system reliability and security. Here we denote such an entity with the generic term *independent grid operator* (IGO), encompassing various terms such as independent system operator, regional transmission organization or transmission system operator in use in different jurisdictions. Among its functions, the IGO has to provide the acquisitions of all unbundled ancillary services [9]. In the competitive market, the IGO does not own the reactive power sources and has to procure them from the generators or other sources. As defined in FERC Order No. 888, the reactive power and voltage support service is an ancillary service only when provided by a generator or a load. All services from other devices are considered as part of the basic transmission service. While there is growing interest in the deployment of capacitors, reactors, static VAr compensators (SVCs), flexible AC transmission systems (FACTS), and other devices, the provision of reactive power by these components of the transmission network cannot providing an ancillary service. These components are in general privately owned, and in principle their operation could be managed locally and independently of the IGO. However, local resource management would be driven by different objectives with respect to the ones pursued by the IGO. In a competitive market environment, conditions of major benefit or opportunities for any market player could occur by modifying the power flows in the system. An example is the setting up of circulating reactive power flows through the imposition of specifically determined voltage settings, as recalled in [18]. Another example, is the case of reactive support leaning, in which a generator could reduce its share of reactive power support to lean on other generators, by changing its voltage setting point and thereby withholding part of its reactive power output [7]. This could induce other generators to produce more reactive support, leading to lost opportunity costs. Such a behavior thus overrides the outcomes of the competitive energy market. It is, therefore, important to set up appropriate rules to prevent such behavior to manipulate markets. The management of locally produced reactive power must therefore remain under the central authority of the IGO.

III.2. Optimal procurement of reactive power and voltage support

The IGO must adopt a transparent and non-discriminatory procedure to procure the reactive power support. In principle, this procedure may use the optimal power flow (*OPF*), typically based on a loss minimization objectives. But, in the competitive environment, such a strategy is less meaningful since no single entity pays for the losses and, as long as a scheme to allocate them exists, is of less impact than in the conventional vertically integrated structure. Some caution is required in the application of the *OPF* for addressing the reactive power support procurement. In general, the minimization of the production costs is not a viable objective within a market-based framework, in which the production costs constitute private information of each seller. Furthermore, criteria of maximization of the loadability margin and loss minimization may conflict with a generator's interests, since the costs incurred nor the value of the reactive support services are taken into account. An *OPF* with the net social surplus as the objective function may be more suitable for electricity market applications with the reactive power prices explicitly represented through dual variables. Additional aspects may include voltage security costs in the *OPF* formulation [19].

There is a need for the definition of an appropriate objective function that is able to explicitly account for the value of reactive support under normal operating conditions, the opportunity costs [20] and the value of security [21]. The representation of the local nature of reactive support is a complicating factor. As such, the minimization of the total cost of reactive support provision may not be appropriate [22], since the local aspects would not be appropriately represented. Local issues are handled by introducing the concept of minimum reactive power needs for the generators, associated to the cost curves [23]. In the application of this concept, a generator producing reactive power above minimum needs has to be remunerated, since otherwise reactive power support is required from the network and the entity receiving that support has to pay for it. Bus voltage profiles have major impacts on the reactive power production. The presence of voltage constraints may lead to high reactive power prices [24] and, therefore, nodal prices for reactive power may be highly volatile. The reactive power support may vary significantly for different technically acceptable solutions, making it difficult for the *IGO* to set up control strategies that ensure equity of treatment of the resources under disparate ownership. Incorporation of contingencies and security aspects in the *OPF* has to reflect the value, not the costs of the reserves, including the so-called *VAr* reserves. The relationships between the effective reactive power limits under specified system conditions, which need be the reactive power limits of the generator, and the set of contingencies under consideration.

The formulation of an appropriate objective function is not the only complication. Even with a suitable objective function, the formulation of a specific reactive-side *OPF* for reactive power support, the resulting voltage control settings may not resolve all the voltage security issues. In fact, the outcomes of such an *OPF* may required to be coordinated with the results of the energy market clearing and congestion management. Furthermore, the incorporation of voltage control, security-based and energy-based objectives in a multi-objective OPF may be less than satisfactory. In fact, the multi-objective formulation solution represents a compromise among the different objectives, thereby blunting the possibility of satisfying each objective to an acceptable extent. A better way may be the formulation of a single *OPF* by the IGO, with a clear and widely agreed objective and to introduce all the relevant aspects as constraints. This task is an important challenge in future research.

III.3. Reactive support share and sensitivity information

The local nature of the reactive power and voltage support calls for a specific quantification of the actual availability of the reactive power sources throughout the system. More specifically, for enhancing the effectiveness of the reactive power support, it is not sufficient to install a relatively high reactive power capacity at a given location. It is indeed necessary to verify that the installed capacity can be effectively used when needed. This depends on the actual amount of reactive power that can be provided to follow a specific trajectory of evolution of the system operating points. In practice, for evaluating the effectiveness of the reactive support at a certain location in the network, it is possible to resort to suitable *sensitivity* information.

On the static analysis standpoint, the relevant issues are the load variations, expressed in terms of specified directions in the space of active/reactive power load parameters and active power generations, and the variations of the voltage setpoints. Suitable sensitivity indicators can be provided in different ways. For a given loading and generation pattern, the *reactive support share* definition proposed in [25] takes into account the network structure, the location of the reactive power sources and the changing characteristics of the demand. From another point of view, marginal information concerning the transmission losses (*MW/MVAr*) and the cost reduction (*$/MVArh*) associated to the availability of a reactive resource at a specific can be obtained from a conventional optimal reactive power flow program [24,26].

The evaluation of the reactive support share and of the related sensitivity information can be carried out without introducing any quantity referred to the possible creation of a reactive power market [27-29]. However, the information obtained are anticipatory of possible conditions of market power that could occur if a reactive power market would exist [30]. Indeed, considering a given location in the system and a specific moment in time, the existence of a reactive support share mainly limited to a few generators is a remarkable reason for avoiding the creation of a reactive power market with time-dependent (e.g., hourly) prices determined by auction-based mechanisms. Such a situation occurs frequently, in particular in large networks, even after partitioning the network in different voltage control areas.

III.4. Security aspects and the value of reactive support

The concept of *value* of the reactive support has to be considered in different contexts. The main distinction occurs among operational and emergency conditions. In the operational framework, the value could be referred to unused capacity issues. Possible evaluations could be envisioned according to the reactive support share concept [25] by calculating the related sensitivity coefficients. In emergency conditions, introducing the notion of value instead of cost of the reactive support is essential. In fact, on the one hand even a relatively inexpensive reactive power source would be ineffective in providing support at electrically remote locations. On the other hand, the incalculable value of avoiding the occurrence of severe dynamic stresses to the system components or a complete blackout goes well beyond the cost of the reactive support resources. Nowadays, the interest towards the use of dynamic resources is also emerging because of the presence of new sources of fluctuating power injected in the transmission systems, for instance from wind parks.

The value of the reactive power resource available at a generation bus depends on its capability to ensure a secure operation under disturbances caused by load variations or line and generator outages. Under a specific contingency, the value of the possible actions also depends on the path of return to the feasible solution, since some correcting actions could prove to be ineffective [7]. Among the possible solutions that satisfy security considerations, the IGO may further reduce as much as possible the transmission losses by adequate dispatch of the reactive resources.

Under emergency conditions, there is a need for distinguishing among "slow" and "fast" reactive support. For fast-operating dynamic resources (e.g., SVCs, FACTS and D-VAr) the prevailing activity could occur in transient conditions. Hence, the capacity of these resources is often sized according to dynamic considerations, leading to the need of adopting very expensive resources. However, fast-acting dynamic resources are high-valued due to their essential role during emergencies. As such, suitable criteria have to be formulated for providing incentives to their procurement and use. In particular, the use of *mobile sources* could lead to beneficial effects in improving the system security. Other sources such as capacitors and reactors provide slower dynamic performance, so that their value is lower with respect to those of fast-acting dynamic devices.

The dynamic resources cannot generally count on significant rewards in normal operating conditions. As such, their procurement cannot be subject to a competitive market with the participation of all the sources. It could be reasonable to envision separate long-term markets dedicated to reactive resources with faster and slower operation, each market based on bids associated to the resource capacity. Further incentives to the adoption of such technologies could depend on the introduction of dedicated mechanisms such as forward contracts for risk hedging. In the real-time, a significantly lower additional reward could be obtained, depending on the effective amount of reactive support provided.

The value of the reactive power support can be determined by measuring the importance of the reactive power sources, without a direct relationship to the costs, defining an equivalent reactive security, for instance from the value curves defined in [21]. The value of the reactive power support can be incorporated into a general framework to calculate the value of voltage security, in addition to other terms representing the value of lost load and the costs of possible corrective actions (generation rescheduling, variations of the voltage control set points and possible load shedding) required in case of violations of the operating limits [31]. Extended analysis techniques must be formulated in order to obtain a unified view of the behavior of static and dynamic reactive power sources. In this respect, relevant references come from the specific results obtained in over two decades of voltage stability studies [32]. The information provided by various types of voltage stability indicators should be properly associated to economic indicators, in order to provide useful information to the procedures used for acquiring the reactive power and voltage support from generators and potentially from other local sources.

IV. CONCLUDING REMARKS

The specific features of the reactive power and voltage support ancillary service raise several challenges to the procurement of the corresponding resources in a market-orientated framework. Even though there is a widespread trend towards introducing market mechanisms where possible, reactive power cannot be considered as a commodity of the same nature of active power or active energy. At present, the most effective solutions for allowing the IGO to acquire the needed reactive power support refer to the formulation of contract or auction mechanisms in the long term, namely, with annual or multi-year time horizons.

In the short term, it is important to consider the interactions between energy markets, reserve markets, congestion management and ancillary service provision. The reactive support side has to be taken into proper account for what concerns reliability and security aspects. The mechanisms used for procuring the reactive power support must be widely accepted and able to provide the correct technical and economic signals. In case of use of optimal procedures, such as the ones formulated for jointly optimizing day-ahead market outcomes and reactive power and voltage support, the objective function must be based on economic concepts, including the opportunity costs and an appropriate valuation of the system security. The use of a specific reactive *OPF* tool with an objective function formulated to optimize the reactive power support could be in contrast with the scopes of the *OPF* and congestion management procedures run for clearing the energy market. Multi-objective *OPF* formulations could be ineffective as well, because of the compromise introduced among the individual objectives. The suggested solution is to specify the reactive power aspects as local constraints within a single *OPF* run under the IGO responsibility. The capability limits of the generating units must be explicitly modeled and specified among the constraints. The outcomes of the procedures used by the IGO should specify all the voltage control settings, avoiding the possible manipulation of those settings by other entities.

Among the future perspectives, the reactive power and voltage support provided by equipment other than generators in the transmission networks could be taken into account in the formulation of suitable pricing mechanisms and possible incentives to their operation. Another issue to be fully discussed is the appropriate treatment of the reactive power loads. In addition, the dynamic performance of the systems has to be associated to the value of reactive support by carrying out specific analyses, for instance based on the results of voltage stability and security studies. The formulation of effective mechanisms of incentive for encouraging the use of dynamic resources is advisable as one of the most promising ways for procuring a sufficient amount of these resources.

V. References

[1] H. Singh and A. Papalexopoulos, "Competitive Procurement of Ancillary Services by an Independent System Operator," *IEEE Trans. on Power. Systems*, Vol. 14, No. 2, May 1999, pp. 498–504.

[2] Federal Energy Regulatory Commission of the United States of America, Promoting Wholesale Competition Through Open Access Nondiscriminatory Transmission Services by Public Utilities, *FERC Docket no. RM95-8-00, Order no. 888*, April 1996.

[3] S. Hao and A. Papalexopoulos, "Reactive Power Pricing and Management", IEEE Trans. on Power Systems, Vol. 12, No. 1, February 1997, pp. 95-104.

[4] J. Barquín Gil, T.G. San Román, J.J.A. Rios and P.S. Martin, "Reactive Power Pricing: A Conceptual Framework for Remuneration and Charging Procedures", *IEEE Trans. on Power Systems,* Vol. 15, No. 2, May 2000, pp. 483-489.

[5] J. Zhong and K. Bhattacharya, "Reactive Power Management in Deregulated Electricity Markets – A Review", *Proc. IEEE/PES Winter Meeting 2002*, pp. 1287-1292.

[6] Federal Energy Regulatory Commission Staff Report on Principles for Efficient and Reliable Reactive Power Supply and Consumption, *FERC Docket No. AD05-1-000*, February 4, 2005.

[7] G. Gross, S. Tao, E. Bompard and G. Chicco, "Unbundled Reactive Support Service: Key Characteristics and Dominant Cost Component", *IEEE Trans. on Power Systems* 17, 2, April 2002, pp. 283-289.

[8] P. Kundur, *Power system stability and control*, EPRI Power Systems Engineering Series, McGraw Hill, New York, 1994.

[9] E. Hirst and B. Kirby, "Electric Power Ancillary Services", Oak Ridge National Laboratory, Tech. Rep., Oak Ridge, TN, 1997.

[10] L.L. Garver, P.R. Van Horne and K.A. Wirgau, "Load Supplying Capability of Generation-Transmission Networks", *IEEE Trans. on Power Apparatus and Systems*, Vol. PAS-98, May/June 1979, pp. 957-962.

[11] E. Chiodo, A. Losi, R. Mongelluzzo and F. Rossi, "Capability Chart for Electrical Power Systems", *IEE Proc. C*, Vol. 139, No. 1, January 1992, pp. 71-75.

[12] M.M. Adibi and D.P. Milanicz, "Reactive Capability Limitation of Synchronous Machines", *IEEE Trans. on Power Systems*, Vol. 9, No. 1, February 1994, pp. 29-40.

[13] J.W. Lamont and J .Fu, "Cost Analysis of Reactive Power Support", *IEEE Trans. on Power Systems*, Vol. 14, No.3, June 1999, pp. 890-898.

[14] T. Orfanogianni and G. Gross, "A General Formulation for LMP Evaluation", *IEEE Trans. on Power Systems*, Vol. 22, No. 3, August 2007, pp. 1163-1173.

[15] D. Gan and E. Litvinov, "Energy and Reserve Market Designs With Explicit Consideration to Lost Opportunity Costs"**,** *IEEE Trans. on Power Systems*, Vol. 18, No. 1, February 2003, pp. 53-59.

[16] Federal Energy Regulatory Commission of the United States of America, Standardization of Generator Interconnection Agreements and Procedures, *FERC Docket No. RM02-1-000; Order No. 2003*, July 24, 2003.

[17] G. Chicco, G. Gross and S. Tao, "Allocation of the Reactive Power Support Requirements in Multitransaction Networks", *IEEE Trans. on Power Systems*, Vol. 17, No. 4, Nov. 2002, pp. 1283-1289.

[18] A.D. Papalexopoulos and G.A. Angelidis, "Reactive Power Management and Pricing in the California Market", *Proc. 13th IEEE Melecon Conference*, Benalmádena, Malaga, Spain, May 16-19, 2006, Vol. 2, pp. 902-905.

[19] W. Rosehart, C. Canizares and V. Quintana, "Costs of Voltage Security in Electricity Markets", *Proc. IEEE/PES General Meeting 2000*, 16-20 July 2000, Vol. 4.

[20] S.Hao, "A Reactive Power Management Proposal for Transmission Operators", IEEE Trans. on Power Systems, Vol. 18, No. 4, November 2003, pp. 1374-1381.

[21] W. Xu, Y. Zhang, L.C.P. da Silva, P. Kundur and A.A. Warrack, "Valuation of Dynamic Reactive Power Support Services for Transmission Access", *IEEE Trans. on Power Systems*, Vol. 16, No. 4. August 2001, pp. 719-728.

[22] K. Bhattacharya and J. Zhong, "Reactive Power as an Ancillary Service", *IEEE Trans. on Power Systems,* Vol. 16, No. 2, April 2001, pp. 294-300.

[23] Y. Wang and W. Xu, "An Investigation on the Reactive Power Support Service Needs of Power Producers", *IEEE Trans. on Power Systems*, Vol. 19, No. 1, Feb. 2004, pp. 586-593.

[24] P. Marannino, F. Stefanelli, F. Zanellini, M. Delfanti and M. Merlo, "Impact of Real Losses and Operational Constraints on the Reactive Support Value in Presence of a Hierarchical Voltage Control", *Proc. IEEE PowerTech 2003*, Bologna, Italy, June 2003.

[25] G. Chicco, "A New Method for Reactive Market Power Assessment in Competitive Electricity Markets", *Proc. 12th IEEE Melecon Conference*, 12-15 May 2004, pp. 1061-1064.

[26] G. Gross, P. Marannino and G. Chicco, "Reactive Support and Voltage Control Service: Key Issues and Challenges", *Proc. 13th IEEE Melecon Conference*, Benalmádena, Malaga, Spain, May 16-19, 2006, Vol. 2, pp. 897-901.

[27] A.C. Zambroni de Souza, F. Alvarado and M. Glavic, "The Effect of Loading on Reactive Market Power", *Proc. 34th Hawaii Int. Conf. on System Sciences*, 2001, pp. 1-5

[28] J. Zhong and K .Bhattacharya, "Toward a Competitive Market for Reactive Power", *IEEE Trans. on Power Systems*, Vol. 17, No. 4, November 2002, pp. 1206-1215.

[29] J. Zhong, E. Nobile, A. Bose and K. Bhattacharya, "Localized Reactive Power Markets Using the Concept of Voltage Control Areas", *IEEE Trans. on Power Systems*, Vol. 19, No. 3, August 2004, pp. 1555-1561.

[30] L. de Mello Honório, A.C. Zambroni de Souza, J.W.M. de Lima, G.L. Torres and F. Alvarado, "Exercising Reactive Market Power Through Sensitivity Studies and HHI", *Proc. IEEE/PES Winter Meeting 2002*, pp. 345-351.

[31] D.S. Kirschen, K.R.W. Bell, D.P. Nedic, D. Jayaweera and R.N. Allan, "Computing the Value of Security", *IEE Proc. Gener. Transm. Distrib.*, Vol. 150, No. 6, November 2003, pp. 673-678.

[32] T. Van Cutsem and C. Vournas, *Voltage Stability of Electric Power Systems*, Kluwer, Boston, MA, 1988.