Unbundled Reactive Support Service: Key Characteristics and Dominant Cost Component

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***Abstract*—In this paper, we present a systematic exposition of generator-provided reactive support as an unbundled ancillary service under open access transmission. We discuss the nature and salient physical characteristics of reactive support and analyze their implications in acquiring VAr support as one of the ancillary services. The paper provides an analysis of the dominant component in the cost structure of this service. This component is determined from the opportunity costs, which are evaluated from the foregone profits of a generator in making sales in real power markets by providing reactive support instead of real power. We illustrate the combined effects of the voltage set points of the generators and of the generator capability constraints on the transactions in competitive electricity markets, both under normal and contingency operating conditions. We discuss the key role of the grid operator in the provision of the reactive support, and the key considerations in the acquisition and pricing of the reactive support service.**

***Index Terms*—Ancillary services, electricity markets, opportunity costs, reactive support, transmission services, unbundling.**

I. Introduction

A BASIC requirement in the supply of electricity is to ensure the voltage magnitude is within a specified range at each bus. Consequently, voltage control is an inherent part of power system operations. Due to the tight coupling between reactive power and voltage magnitude, reactive support is the means used to maintain the desired voltage profile, i.e., to ensure that the voltage magnitude is within the specified range for each bus of the network, under normal and contingency conditions. Since the reactive support supplied at the various buses directly affects the voltages throughout the system, such support has a profound impact on the operation and security of the power system and plays a critical role in facilitating power transactions. This role, then, is very important in competitive electricity markets. With the entry of a large number of new players and the proliferation of power transactions, the transmission system is increasingly being used in the *common carrier* mode. The more intensive use of the transmission network results in the more frequent hitting of the voltage constraint limits specified in the desired voltage profile, thereby leading to congestion more often. To avoid violation of the desired voltage profile, the system requires reactive support, which can compensate the reactive power losses in the transmission network. Reactive support may be provided by a variety of devices including generators, shunt capacitors/reactors, synchronous condensers and static VAr compensators. Since it is very ineffective to *transport* reactive support from one location to another, these sources must be distributed geographically throughout the system.

In the vertically integrated utility structure, where generation, transmission, and distribution were typically owned and controlled by a single entity, the provision of reactive power and voltage support was *bundled* with other services in supplying electricity to the end users. There was no need for separate costing/pricing of reactive support since the utility was virtually assured that it could recover the costs of this service through the rates charged for the bundled electricity. Under open access, however, *reactive support and voltage control from generation sources* becomes one of the six ancillary services specified in the FERC Order No. 888 [1]. Under the newly emerging structure with an independent system operator or regional transmission organization in the U.S. and a transmission system operator in other jurisdictions, this central entity is responsible for operating the transmission system to facilitate transactions and ensure its reliability/security. We use the generic term independent grid operator or IGO for such an entity. The IGO functions include the acquisitions of all unbundled ancillary services [2] from generation sources. Since generators providing the services are independent of the IGO, it is important to understand the relevant aspects of each such service. This is particularly true in the area of reactive support where the physical characteristics and operations aspects are not well understood by many of the market participants. Moreover, the cost structure is particularly important since FERC regulation requires cost-based pricing for this service.

The focus of this paper is on the provision of the reactive support service from generator sources. The paper addresses the fundamental issues of how reactive support is provided as an *unbundled* service and what costs are incurred by the generator in providing this service. We assume throughout that all the reactive support is provided by generators. Such support uses the voltage setting point at each generator as the control variable to determine the amount of VArs absorbed/produced by the generator taking into account the constraints of the network interconnecting the various generators. This paper's objectives are to provide:

- a tutorial review of the nature and the physical characteristics of the reactive support service;

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- an analysis of the dominant component of the cost structure of the service;
- the key considerations in acquiring and pricing the service in the open access environment.

We make detailed use of numerical examples to meet these objectives. Since we primarily focus on the reactive support required under the normal operating conditions, several important aspects of reactive support including voltage stability margins and the dynamic response capability of reactive support [3] are outside the scope of the paper. In many cases, the connection of generators to the grid is subject to technical constraints requiring the power factor of the generated power to lie within a specified range. This constraint is not considered in this paper.

In Section II, we illustrate the salient features of reactive support service and evaluate the impacts of the physical characteristics of this service. Section III presents an analysis of the explicit evaluation of the dominant component of the reactive support cost structure. This component is derived from the opportunity costs of providing reactive support [4]. In Section IV, we provide a number of key considerations in acquiring and pricing reactive support as an unbundled ancillary service under the open access structure. The concluding section provides specific directions for future work.

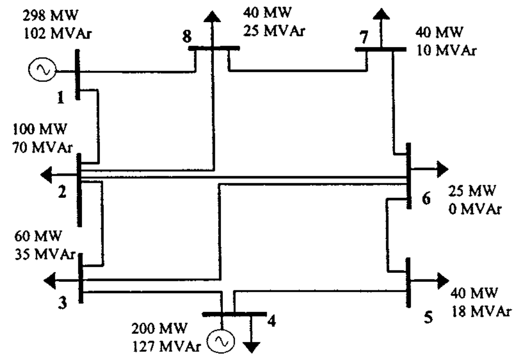

Fig. 1. Eight-bus test system one-line diagram.

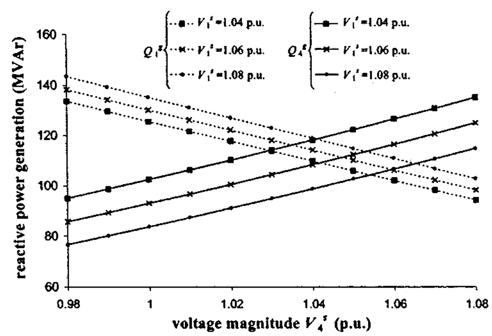

Fig. 2. Plots of generator voltage support requirements as a function of V_1^s.

II. Characteristics of the Reactive Support Services

Since electricity must be supplied within the specified range of voltage magnitudes, voltage control is an inherent part of the power system operation. Reactive support is the means used to meet the objective of maintaining the specified voltage profile. The transmission system parameters and the voltage settings at the generator buses influence directly the reactive support requirements.

We illustrate various aspects of the reactive support service on the 8-bus test system of Fig. 1. We denote by V_i^s and Q_i^g the voltage setting and reactive power output, respectively, of the generator at bus i. Bus 1 is the slack node. We first consider the system without any transactions. The maintenance of a specified voltage profile requires reactive support to compensate the reactive losses on the transmission lines. The line charging capacitance provides part of the intrinsic reactive support of the transmission system, but additional support may be required from the generators. The generator reactive support from a generator may consist of absorption/generation of VArs to compensate for the presence of both inductive/capacitive components in the system. For the 8-bus test system with $V_1^s = 1.04$ p.u. and $V_4^s = 1.06$ p.u., the line charging capacitance more than compensates for the effect of the series reactance; in fact, the generator reactive support requires $Q_1^g = -28.3$ MVAr and $Q_4^g = -5.5$ MVAr so that the two generators are required to absorb reactive power.

In the presence of transactions on the system, the amount of reactive support depends on the transaction magnitudes and is needed to compensate the reactive power losses in the transmission system, even in the absence of reactive loads. The presence of reactive loads imposes an added burden on the system for reactive support.

We consider the *base case* to be the system with the transactions undertaken to supply the active power loads. The voltage profile constraint requires maintaining the voltage at each load bus within the range [0.93, 1.04]. With $V_1^s = 1.04$ p.u. and $V_4^s = 1.06$ p.u., the power flow in the base case results in the reactive power generations of $Q_1^g = 102$ MVAr and $Q_4^g = 127$ MVAr.

A. Voltage Setting Impacts

The generator voltage setting is a key control variable in maintaining a specified voltage profile. We study the variation in generator reactive support as a function of the voltage setting keeping the transaction amounts fixed at their base case values. For example, as V_4^s increases, Q_1^g decreases while Q_4^g increases as shown in Fig. 2. A generator may avoid providing its share of the reactive power support and *lean on* other generators, by lowering its voltage setting point and thereby withholding some of its reactive power output. For the test system with $V_1^s = 1.04$ p.u., the specification of $V_4^s = 0.9935$ p.u. results in $Q_4^g = 100$ MVAr, corresponding to a reduction of 27 MVAr from the base case. While all the voltage magnitudes are maintained within the specified range, the generator at bus 4, by withholding its reactive output, *leans* on the system for reactive support. Consequently, the reactive output Q_1^g has to increase to 128 MVAr from the 102 MVAr value in the base case.

B. Local Nature of Reactive Support

A salient characteristic of reactive support, which distinguishes it from real power, is its local nature. Due to the unavoidable reactive losses on the transmission network, it is neither desirable nor many times feasible to provide reactive support using remote sources. We illustrate this concept with an example. We change the voltage setting of each generator bus

TABLE I
REACTIVE SUPPORT FOR THE BASE CASE AND FOR TWO DIFFERENT ADDITIONAL TRANSACTIONS

case	*description*	voltage magnitude (p.u.)				MVAr generation	
		V_1^s	V_4^s	V_3	V_6	Q_1^g	Q_4^g
a	base case	1.040	1.060	0.934	0.958	102	127
b	100 MW additional transaction from bus 4 to bus 6	1.040	1.060	0.914	0.926	119	128
		1.040	1.098	0.930	0.952	103	144
c	100 MW additional transaction from bus 1 to bus 6	1.040	1.060	0.856	0.871	184	203
		1.115	1.060	0.938	0.930	175	148

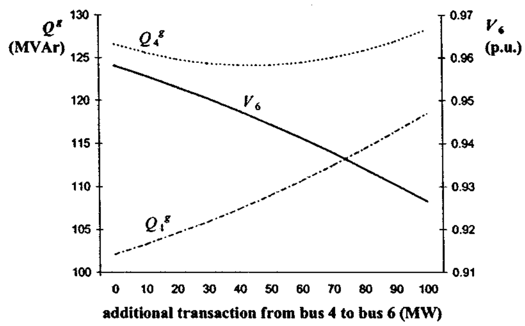

Fig. 3. Reactive support requirements from the generators for the transaction from bus 4 to bus 6 as a function of the amount of the transaction.

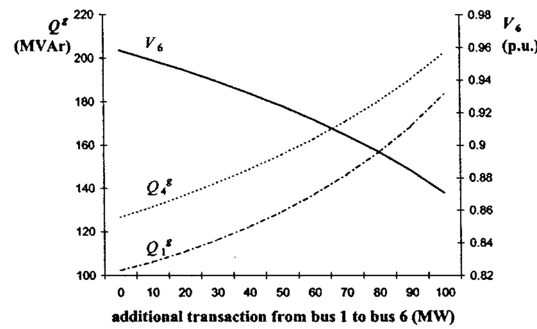

Fig. 4. Reactive support requirements from the generators for the transaction from bus 1 to bus 6 as a function of the amount of the transaction.

in order to raise the voltage V_8 at bus 8 from the base case value (0.957 p.u.) to 0.980 p.u., and we monitor the total reactive losses in the system. This change requires the generator at bus 1 to raise V_1^s to 1.0638 p.u. to provide the needed reactive support. The total VAr losses are 38.7 MVAr. On the other hand, to maintain the specified voltage V_8 using the generator at bus 4 would require that it raise V_4^s to the unreasonably high value of 1.180 p.u. The total reactive losses would then be 56.1 MVAr. Not only do the reactive losses increase markedly, but the provision of reactive support results in an unacceptably high voltage at the supply bus. This example then shows that reactive support from distant buses is ineffective.

C. Impacts of Transaction Amounts

We consider the introduction of a transaction from the bus 4 generator to the bus 6 load. We plot the reactive generation at buses 1 and 4 and the bus 6 voltage magnitude as a function of the transaction amount in Fig. 3. Even though the generator at bus 1 is not participating to the transaction, it is *required* to provide reactive support above that in the base case due to the loop flows in the network. Only a portion of the new transaction from bus 4 to bus 6 flows on the direct path from bus 4 to bus 6 along the lines 4,5 and 5,6 with the rest reaching bus 6 through the paths involving other network lines. While the additional 100 MW transaction requires Q_1^g to increase to 119 MVAr, Q_4^g is required to increase very slightly to 128 MVAr. Note that, due to the loop flow impacts, the support provided by the generator Q_4^g changes in a nonlinear manner. In addition, as the transaction amount increases, V_6 and V_7 drop below the lower limit of the specified voltage profile. To maintain all the voltages in the specified range, the bus 4 generator needs to raise V_4^s, an action that entails providing more reactive support. For example, if the transaction amount is 100 MW, raising V_4^s to 1.098 p.u. restores the voltage profile with V_7 raised to 0.930 p.u. and V_6 to 0.952 p.u.; in addition, Q_1^g is reduced to 103 MVAr and Q_4^g is increased to 144 MVAr. This situation corresponds to ***case b*** in Table I.

Consider next the introduction into the base case of a transaction of 100 MW from bus 1 to bus 6. This situation corresponds to ***case c*** in Table I and the voltage and reactive support results are different. The behavior of V_6 and the reactive generation at the two generator buses as a function of the transaction amount are plotted in Fig. 3. It is instructive to assess the different impacts of two equal transactions by comparing the plots in Figs. 3 and 4. These two cases illustrate that, due to loop flows, a generator not participating in a transaction may nevertheless be required by the system to provide reactive power service to support that transaction.

D. Reactive Support Capability of the Generator

A key physical constraint in the provision of the reactive support by a generator is its generation capability constraint [5]. It represents the hard physical limitation of a generator's capability for the simultaneous production of real and reactive power. Since this constraint results in a strong coupling between a generator's capability for real power generation and that for reactive power generation/absorption, meeting the system requirement for reactive support may directly limit a generator's real power output. A typical *generation capability curve* is shown in Fig. 5. The boundary of the feasible operating region of the generator is formed by the intersection of four physical limiting relationships: the minimum loading, the field current, the armature current and the under excitation of the generator. We define two functions $Q_{\max}^g(\cdot)$ and $Q_{\min}^g(\cdot)$ mapping the real power output $P \in [P_{\min}, P_{\max}]$ into reactive power with $Q_{\max}^g(P) \in [0, Q_{\max}^g(P_{\min})]$ and $Q_{\min}^g(P) \in [Q_{\min}^g(P_{\min}), 0]$ to describe the boundary curve in the region of interest. In this way, a generator's reactive support capability is viewed as a function of its real power production: at a given level P^0 of real power output, the reactive power Q^g

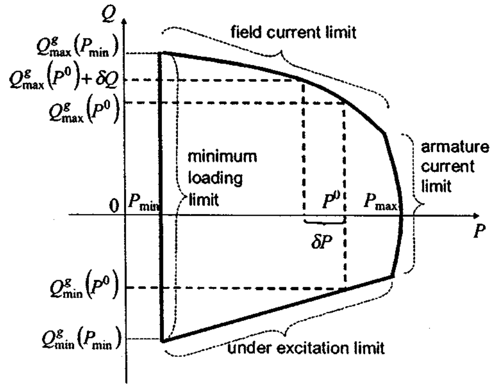

Fig. 5. Generation capability constraint.

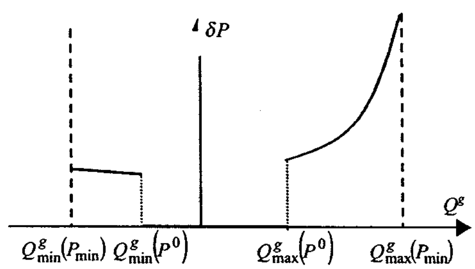

Fig. 6. Marginal output reduction δP in MW as a function of the reactive support requirement Q^g for a given real output P^0.

must lie in $[Q^g_{\min}(P^0), Q^g_{\max}(P^0)]$. Consider the case when a generator operates at the boundary point $(P^0, Q^g_{\max}(P^0))$. Then, if the system requires additional δQ MVAr generation, the generator has no choice but to reduce its real power output by some amount δP MW to meet this requirement. In concept, the positive quantity δP is determined using the value(s) of $[\partial Q^g_{\max}(P)/\partial P]^{-1}$ at one or more points. Similarly, if the generator operates at the boundary point $(P^0, Q^g_{\min}(P^0))$ and the system requires additional δQ MVAr absorption from the unit, it has to reduce its real power output by δP MW; δP is computed using the value(s) of $[\partial Q^g_{\min}(P)/\partial P]^{-1}$. For a given P^0, Fig. 6 plots δP as Q^g is varied.

For the test system of Fig. 1, we consider the generator at bus 4 to be operating close to its field current limit in the base case—point A in Fig. 7. We study the effects of undertaking an additional transaction ΔP_{1-6} from bus 1 generator to bus 6 load. While bus 4 is not a party to this transaction, as the amount of the transaction increases the reactive generation Q^g_4 must increase to provide reactive support. For $\Delta P_{1-6} = 24.3$ MW the Q^g_4 reaches its maximum reactive power production limit corresponding to its scheduled real power generation of 200 MW—point B in Fig. 7. A further increase of ΔP_{1-6} decreases V_4 from $V^s_4 = 1.06$ p.u. For $\Delta P_{1-6} = 39.5$ MW is $V_4 = 1.045$ p.u. The only way to restore V_4 to V^s_4 is to curtail one or more transactions. For example, the curtailment of the transaction from bus 4 to bus 3 by 9 MW enables the generator at bus 4 to provide the required reactive support of 143.2 MVAr and to hold V^s_4 at 1.06 p.u.—point C in Fig. 7. This example, then, clearly illustrates that the following occurs.

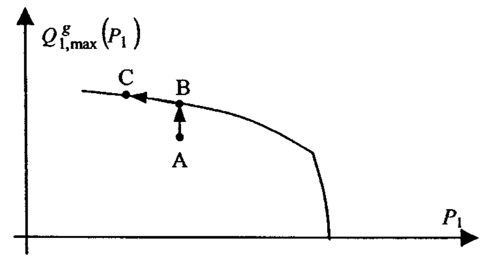

Fig. 7. Field current limit imposes a hard constraint.

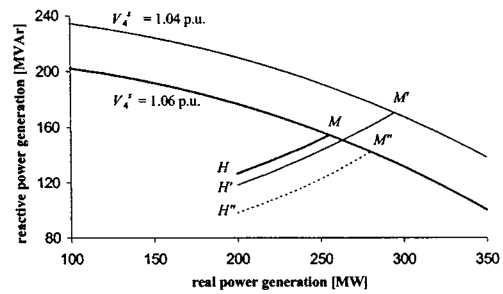

Fig. 8. Maximum increase of the transaction from bus 4 to bus 5 depends on the generator voltage settings.

1) The generation capability constraint imposes a hard physical limit in the provision of reactive support.
2) The only feasible way to meet the reactive support requirement to maintain a specified generator voltage setting is to decrease the real power generation and hence to curtail the transaction.

E. Effects of Voltage Settings and Field Current Limits on the Transactions

We analyze the combined effect of field current limits and generator voltage settings on the transactions. We plot in Fig. 8 the field current limits of the generator at bus 4 for $V^s_4 = 1.06$ p.u. and $V^s_4 = 1.04$ p.u. We introduce into the base case an additional transaction ΔP_{4-5} from bus 4 to bus 5. As ΔP_{4-5} increases, the operating point of the generator moves from the base case—the point H of Fig. 8—to the point M for $\Delta P_{4-5} = 60$ MW. The further increase of ΔP_{4-5} is possible without violating the field current limits by either

1) reducing the voltage set point V^s_4: in this case, there are two desirable effects—the change in the generator field current limits and the lower reactive power requirements from the generator; for example, the transaction can be increased to 95 MW (from point H' to point M') by setting $V^s_4 = 1.04$ p.u.;
2) raising V^s_1 of the generator at bus 1 (not a party in the transaction) and keeping V^s_4 constant: the field current limits of the generator remain the same, but the system requires less reactive power from generator 4; e.g., an increase of ΔP_{4-5} to 80 MW is possible by setting $V^s_1 = 1.08$ p.u. (from point H'' to point M''). Note that the increase of ΔP_{4-5} is limited by the maximum voltage V^s_1 allowed in the specified voltage profile. Any further increase of ΔP_{4-5} is only possible by using the approach in 1).

III. Reactive Support Cost Dominant Component

Under open access, the generator-based reactive support is one of the ancillary services whose acquisition is within the scope of responsibilities of the IGO. Since the feasibility of a competitive market in this ancillary service is severely limited and the current regulatory framework requires cost-based rates, the determination of the cost structure of this service is necessary. The focus of this section is on the dominant component of this cost structure.

The two classes of costs in the provision of reactive support are the fixed costs and the variable costs. The fixed costs are the investment costs for the equipment and do not depend on the quantity produced. Our interest focuses on the variable costs involved in VAr production/absorption by a generator. Since a generator may simultaneously produce two "commodities"—real and reactive power—there exists a need to determine the variable costs for reactive power generation/absorption. Some of the aspects related to these costs are reported in [6]–[9]. As long as a generator operates within the limits of its generation capability curve, the variable costs for reactive power production/absorption are negligibly small compared with those for real power generation. However, once the generation capability limit of the generator is reached, this is no longer true. There are costs incurred in meeting VAr support requirements [10]. These arise primarily because the only way to satisfy such requirements is to curtail real power generation. In other words, due to the generation capability constraint, the fulfillment of the VAr support requirement leaves the generator with no other choice than to forego some of its participation in the real power market. In such case, there may be profits that a generator would forego. We refer to these foregone profits as the opportunity costs. The latter represent the value of the opportunity the generator gives up in order to provide the system-required VAr support. Although these opportunity costs come into being only when the generator reaches its generation capability limit, the magnitude of these costs is of the same order of magnitude as the profits of a generator. Consequently, we deem these opportunity costs to be the *dominant component* of the cost structure. The market design in certain jurisdictions explicitly includes compensation of opportunity costs to generators [11], [12].

We use a system based on the IEEE 118-bus network to illustrate the notion of the opportunity costs incurred in providing reactive support services. We consider the system to operate under the *bilateral transactions model* structure with the generators negotiating directly with the loads. We consider the IGO imposes, for security reasons, the requirement that the generator capability constraint under any contingency cannot be violated. In the base case, the generator at bus 12 is operating at the point O in Fig. 9, which is near its field current limits. At O, $V_{12}^{s} = 0.99$ p.u. and $Q_{12}^{g} = 94.4$ MVAr. We assume the loads at buses 12, 20, and 117 purchase power by undertaking transactions with the generator at bus 12 at the uniform price of \$10/MWh. We next consider a contingency case in which the line from bus 3 to bus 5 is lost. Under this contingency, the operating point[1] would shift to point P of Fig. 9, which is outside the capability boundary of the generator at bus 12. To avoid this physically impossible move, there are three distinct alternatives. These include the following.

[1]We assume the dynamics related to the contingency allow reaching the operating point P without causing any stability problems.

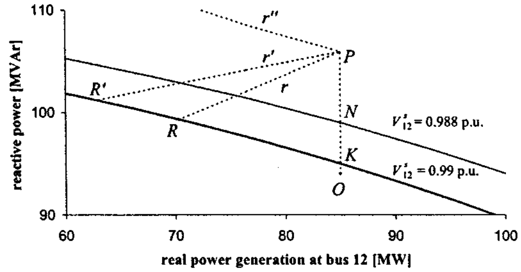

Fig. 9. Provision of VAr support under a contingency for the 118-bus system.

1) The IGO modifies V_{12}^{s} for the generator at bus 12 and consequently, both Q_{12}^{g} and the capability curve of the generator at bus 12 change; setting $V_{12}^{s} = 0.988$ p.u. satisfies the capability constraints resulting in operation at point N in Fig. 9.
2) The IGO modifies the voltage set points of the generators at one or more other buses; for example, increasing V_{4}^{s} from 0.998 p.u. to 1.006 p.u. with all the other voltage set points remaining unchanged would shift Q_{12}^{g} back to its capability boundary, leading to operation at point K of Fig. 9.
3) The IGO maintains the voltage set points unchanged at all the generators, leaving the generator at bus 12 no choice but to curtail its real power generation by reducing one or more transactions; the choice of the curtailed transactions has a major impact on the reactive support provided by the generator at bus 12.

We next discuss alternative 3) in greater detail. For example, a possible curtailment is the reduction of the transaction between buses 12 and 117. The curve r through point P in Fig. 9 shows the locus of operating points corresponding to a cut in the transaction between buses 12 and 117. The intersection point R with the capability curve corresponds to the operating point for a 17 MW reduction. On the other hand, the curtailment of the transaction between the generator and load at bus 12 corresponds to the locus r' in Fig. 9. The operating point R' at the intersection of this locus and the capability curve corresponds to 22 MW curtailment. Note also that the curtailment of the transaction between buses 12 and 20 results in the locus of curve r'' in Fig. 9. Such a curtailment is unable to move the generator at bus 12 toward its constraining capability limit.

Of these three alternatives, curtailment of the transaction between buses 12 and 117 involves the smallest amount. Since the generator at bus 12 gives up a valuable opportunity in the real power market by curtailing its transaction to meet the reactive support requirements, its opportunity costs of the profits foregone on the \$170 of sales of the 17 MW cut need to be compensated. Such compensation is necessary so as to make the generator indifferent whether it produces active or reactive power.

It follows from this example that the IGO has considerable discretion in terms of the alternative selected to ensure that the reactive power requirements are adequately satisfied. When the selected option is the curtailment of transactions, the discretion of the IGO is rather broad. For large systems, with several contingencies considered, the "$N-1$" security criterion can be met but may entail the compensation of the opportunity costs. This example has clearly illustrated that the opportunity cost compensation is dependent on the discretion of the IGO.

We summarize the dominant cost component characteristics of the reactive support as follows.

- As long as the generator operates within the limits of the capability constraint curve, the operating costs for reactive power outputs are negligibly small compared to those for real power production; once the generator hits a generation capability limit and its voltage set point is not varied, the system requirements for VAr support can be met only by curtailing its real power production; such curtailment forces the generator to forego profit-making opportunities in the real power markets and these profits constitute the opportunity costs of providing reactive support services.
- The opportunity costs are not only dependent on the generator's physical characteristics, but also highly dependent on the electricity market structures, its rules, and the discretion of the IGO.
- To ensure the required reactive support is provided, the IGO may need to provide incentives to a generator by compensating the opportunity costs so as to render it indifferent whether it generates real or reactive power.

IV. Reactive Support Acquisition Considerations

The physical characteristics of reactive support illustrated in the various examples in Section III make the acquisition and pricing of this ancillary service very different from those for the MW/MWh-based ancillary services [13], [14]. While reactive support is a system-wide requirement that needs a certain level of central coordination to ensure that it is effectively met, the local nature of VArs virtually foreclose the setting up of a network-wide competitive market in reactive power. Even if VArs were available in some geographically small region, it is unlikely that there would be sufficient number of sources to enable the existence of competition in VArs. Under such conditions, individual generators would be able to manipulate and strategically game the situation and without the appropriate *rules of the road*, some exorbitant prices could result. Hence, the IGO faces a considerable challenge in discharging his responsibility for the acquisition of reactive support service. The fact that markets in VArs are not in place brings about the necessity to develop other mechanisms for this service. One possible means is to base the acquisition of this service on long-term contracts negotiated between the IGO and VAr providing generators. Such a scheme has been adopted by the California ISO. The pricing of reactive support service is likely to remain cost-based, as is the case today. However, the price signals need to be appropriately specified to provide incentives to generators to generate reactive support, both for normal and contingency operating conditions. The prices of such contracts need to be designed to ensure that all costs, including any foregone profits—the opportunity costs associated with the provision of this service by the generator—are compensated. In this way, a generator is indifferent whether it generates MW for a profit or provides the reactive support the IGO needs. Under this structure, generators receive fair compensation for their VAr generation and the IGO ensures adequate supplies of reactive support for system operations. In addition, the long-term nature of the structure allows the IGO to develop alternative schemes to protect against gaming by generators located at critical buses of the network.

V. Concluding Remarks

Reactive support for voltage control is an integral and critical part of power system operations. While the specification of transactions is made purely in terms of real power, the role of reactive support is essential for enabling the undertaking of the transactions. The important role and the physical characteristics of the reactive support service, with and without considering contingencies, have been illustrated through a number of examples. The dominant component of the reactive support cost structure has been determined from the opportunity costs that arise when a generator has to forego profits it could otherwise collect in the real power markets to provide this service.

There remains considerable additional work on several aspects of the unbundled VAr support service. The allocation of the reactive support service among the transactions needs to explicitly address the reactive power pricing issues [15]. Other relevant topics associated with competitive electricity markets are the role of reactive support in the evaluation of available transfer capability (ATC), the voltage stability/collapse considerations in the ATC evaluation, the possible exercise of market power through the specification of voltage set points, and the reactive support associated to the provision of dynamic reserves. There are several areas that are promising avenues of research. One topic is the development of appropriate economic signals for the improvement/expansion of the transmission network emanating from reactive support service requirement considerations. Another area of future research is the implementation of schemes for the effective coordination of competing generators, by taking into account both operation and reserves for real and reactive power, and including the possible limitation in the provision of the reserve support due to bottlenecks in the transmission system. Results on these topics will be reported in future papers.

References

[1] 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.
[2] E. Hirst and B. Kirby, "Electric power ancillary services," Oak Ridge National Lab., Tech. Rep., Oak Ridge, TN, 1997.
[3] S. Hao and A. Papalexopoulos, "Reactive power pricing and management," *IEEE Trans. Power Syst.*, vol. 12, pp. 95–104, Feb. 1997.
[4] H. R. Varian, *Intermediate Microeconomics: A Modern Approach*. New York: W. W. Norton, 1999.
[5] A. R. Bergen, *Power System Analysis*. Englewood Cliffs, NJ: Prentice-Hall, 1986.
[6] R. A. Wakefiled *et al.*, "Transmission services costing framework," EPRI, Palo Alto, CA, EPRI Rep. TR-105 121-V1/V2, Apr. 1995.
[7] D. Curtice, "Costs of providing ancillary services from power plants," EPRI, Palo Alto, CA, EPRI Rep. TR-107 270-V1, Mar. 1997.
[8] P. J. Turner and R. J. Nicholls, "Cost of providing ancillary services from power plants: Reactive supply and voltage control," EPRI, Palo Alto, CA, EPRI Rep. TR-107 270-V3, June 1997.

[9] J. Barquín *et al.*, "On the cost of the reactive power generation and voltage support service," in *Proc. Bulk Power Syst. Dynamics Contr.—IV: Restructuring*, Santorini, Greece, Aug. 24–28, 1998.
[10] J. Lamont and J. Fu, "Cost analysis of reactive power support," *IEEE Trans. Power Syst.*, vol. 14, pp. 890–898, Aug. 1999.
[11] New York Independent System Operator, "NYISO ancillary services manual," NYISO, July 1999.
[12] National Electricity Market Management Company, "Operating procedure: Ancillary services," National Electricity Market Management Company, Doc. SO_OP3708, July 2000.
[13] L. D. Kirsch and H. Singh, "Pricing ancillary electric power services," *Electr. J.*, vol. 8, pp. 28–36, Oct. 1995.
[14] H. Singh and A. Papalexopoulos, "Competitive procurement of ancillary services by an independent system operator," *IEEE Trans. Power. Syst.*, vol. 14, pp. 498–504, May 1999.
[15] G. Chicco, G. Gross, and S. Tao, "Allocation of the reactive power support requirements in multi-transaction networks," *IEEE Trans. Power Syst.*, to be published.

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