Unbundled Reactive Support Service: Key Characteristics and Dominant Cost Component

George Gross Shu Tao
Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign
Urbana, IL 61801

Ettore Bompard Gianfranco Chicco
Dipartimento di Ingegneria Elettrica Industriale
Politecnico di Torino
Torino, Italy

Abstract: In this paper we provide a systematic review of generator-provided reactive support as an unbundled ancillary service under open access transmission. Through a number of illustrative examples, we discuss the nature and salient physical characteristics of reactive support. Also, we analyze their implications in acquiring VAr support as one of the ancillary services. The paper presents the 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 the real power markets in providing reactive support instead of real power. In addition, we discuss the key considerations in the acquisition and the pricing of the reactive support service.

1. 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 becomes particularly critical 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 to 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 (VIU) 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 what we term an independent grid operator (IGO), the IGO is responsible for operating the transmission system to facilitate transactions and ensure its reliability/security. The IGO functions include the acquisitions of all unbundled ancillary services 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 the costs to the generator are 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; the network interconnecting the various generators provides additional constraints that must be satisfied. This paper's objectives are to provide

(1) a systematic review of the nature and the physical characteristics of the reactive support service;

(2) an analysis of the dominant component of the cost structure of the service; and,

(3) the key considerations in acquiring and pricing the service in the open access environment.

Since we primarily focus on the reactive support required under the normal operating conditions, several important aspects of reactive support including reactive power reserves and the dynamic response capability of reactive support [2] 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 2, we use a number of examples to illustrate various aspects of reactive support service and assess the implications of the physical characteristics of this service. Section 3 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 [3]. In Section 4, we provide a number of key considerations in acquiring and pricing reactive support as an unbundled ancillary service under the open access structure. The paper's concluding section provides some directions for future research.

2. REACTIVE SUPPORT SERVICES CHARACTERISTICS

We first focus on the nature and some salient characteristics of reactive support service that we illustrate with a number of examples using small power systems

<u>Reactive support is an inherent physical system requirement</u>

Since electricity must be supplied within a specified range of voltage magnitudes, voltage control is an inherent part of power system operations. Due to the tight coupling between reactive power and voltage magnitudes, reactive support is the means used to meet the objective of maintaining the specified voltage profile.

Example 1: We start our discussion with a simple two-bus network with a generator at bus 1 and a load at bus 2. We assume that the generator at bus 1 is the single source of reactive support. Using the simple π-model of the line connecting the two buses, we assume losslessness and the line reactance is j0.2 p.u. with charging capacitor admittances of –j0.005 p.u. at each end of the line. The voltage profile constraint is to require maintaining the voltage at each bus within the range [0.93, 1.05] p.u. The excitation system of the generator at bus 1 is the control used to maintain a specified voltage magnitude at bus 1. This is called the voltage setting point and is denoted by V_1^s. The ability to maintain the specified voltage setting V_1^s depends on the physical characteristics of the generator and its integration into the network. The reactive power Q_1^g output of the generator is used to maintain the bus voltages within the specified range. The results of the power flow for the various cases considered in this example are summarized in Table 1.

Case a -- the transactionless system. We consider the system without any transactions. The specified voltage setting point is $V_1^s = 1.0$ p.u. Consequently, there is no real power flowing on the line between the two buses. Due to the representation of line charging capacitance at each end of the line, there is an injection of MVArs at each bus. The injection at bus 2 results in V_2 rising to a value of 1.001 p.u., which is slightly higher than V_1^s. The injection at bus 1, on the other hand, is absorbed by the generator so as to maintain the voltage at V_1^s. The situation in this case illustrates the reactive support of the generator: this support consists of absorbing rather than generating reactive power.

Case b -- a single transaction. We consider a 100 MW transaction from the generator at bus 1 to the load at bus 2. V_1^s is set to 1.0 p.u. Even without any reactive demand at bus 2, the transaction gives rise to a current, which, in turn, results in reactive power losses on the line. These losses must be compensated so as not to violate the voltage profile constraint. The generator MVAr output is $Q_1^g = 20$ MVAr but V_2 drops to 0.98 p.u. The reactive power generated at bus 1 acts to maintain the voltage at bus 2 within the specified limits.

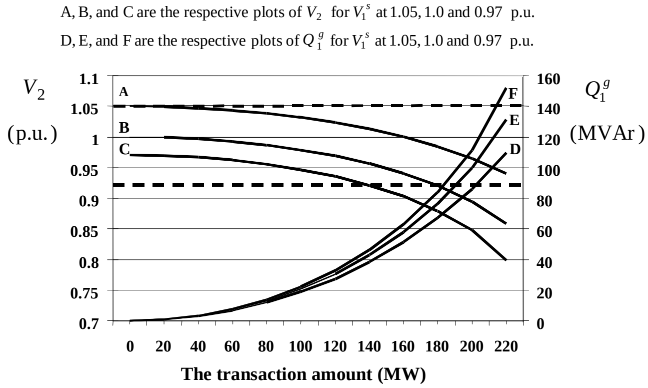

Figure 1. Voltage at bus 2 and reactive support by the generator

Next, we study the impacts when the transaction amount is varied. Figure 1 presents the plots of V_2 and Q_1^g corresponding to three different values of V_1^s as the amount of transaction is varied from 0 to 220 MW. Of course, for a fixed transaction quantity as V_1^s increases, V_2 increases. The reactive power output of the generator must change appropriately to take into account the interaction with the network. For a fixed transaction quantity, Q_1^g decreases as V_1^s increases. Figure 1 also shows that for a fixed V_1^s, Q_1^g increases as the transaction amount increases.

Case c -- reactive load impacts. Next, consider the case of non-unity power factor for the load at bus 2. In particular, we assume the power factor is 0.9 for the load 100 MW+ j 50 MVAr. In this case, as shown as Table 1, V_2 is lowered to the unacceptably low value of 0.86 p.u., and the generator reactive power output is increased to 83 MVAr. Thus, the non-unity power factor load imposes an added burden on the system for reactive support. The load at bus 2 may, of course, alleviate this additional burden on the system by installing local devices such as shunt capacitors to correct for the impact of non-zero reactive load.

Table 1. The results on the two-bus system

Case	V_1^s (p.u.)	Line impedance (p.u.)	Power factor of the load at bus 2	V_2 (p.u.)	Q_1^g (MVAr)
a	1.0	0.02	--	1.001	-1
b	1.0	0.02	1.0	0.98	20
c	1.0	0.02	0.9	0.86	83
d	1.0	0.04	1.0	0.90	49

Case d -- line reactance impacts. We explore the impact of the line reactance for the single transaction case. For example, consider the doubling of the line reactance. For the 100 MW transaction V_2 decreases from 0.98 to 0.90 p.u. and Q_1^g increases from 20 to 49 MVAr as the reactance is doubled. Figure 3 plots the variation of V_2 and Q_1^g as the line reactance is varied from 0.05 to 0.4 p.u. It is straightforward to verify that the larger the line reactance is, the lower the load voltage becomes and the larger the amount of reactive support that is required from the generator.

We summarize the nature and characteristics of reactive support illustrated by the various cases of this example:

(1) reactive support from a generator may consist of either absorption or output of VArs.
(2) due to reactive losses on transmission lines, the maintenance of a specified voltage profile requires reactive support to compensate these reactive losses.
(3) the maintenance of a specified voltage profile imposes a requirement for reactive support even absent reactive loads; the amount of support is, however, a function of the transaction magnitude.
(4) the voltage setting selected by the generator is a key control variable in maintaining a specified voltage profile.
(5) the transmission system parameters influence directly the reactive support requirements.

Reactive support must be provided on a system-wide basis

Due to the transmission network characteristics, voltage magnitudes at buses throughout the system are tightly coupled. The action of raising a low voltage at one bus may result in an unacceptably high voltage at one or more other buses. As such, it would not be possible to support the voltage magnitudes required by the profile constraint at one or a small number of locations. In effect, to meet the voltage profile constraint, reactive support is required from sources throughout the system.

Example 2: We use the 4-bus system of Figure 2 to illustrate this physical requirement. For this system each bus voltage $V_i, i = 1,...,4$ must be kept within the range of [0.95, 1.07] p.u. V_1^s and V_2^s are clearly set to be within this range. The reactive power outputs of the two generators are denoted by Q_1^g and Q_2^g. The power flow results of cases of **Example 2** are tabulated in Table 2.

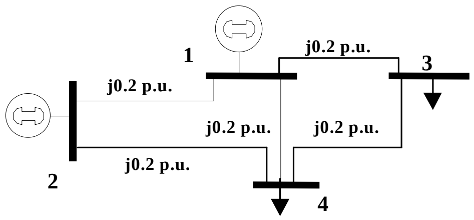

Figure 2. The 4-bus system

Case a -- the transactionless system. First, we assume that there is no transaction in the system. With V_1^s = 1.0 p.u. and V_2^s = 1.03 p.u., the voltage difference gives rise to currents flowing on the lines which, in turn, result in reactive losses. Since, in general, reactive power flows from a bus at a higher voltage to one at a lower voltage, then, in this case reactive power flows from bus 2 to bus 1. There is no other outlet for reactive power since there is no load on the system. Thus, the generator at bus 2 generates reactive power Q_2^g = 24.7 MVAr; the generator at bus 1 absorbs reactive power Q_1^g = -24 MVAr. Note that a portion of the generated VArs is lost on the line. This simple case illustrates that even when no transaction is present in the network, the reactive losses of the transmission network create the need for reactive support to maintain the specified voltage profile.

Table 2. The results of the cases studied on the 4-bus system of Figure 2

Case	V_1^s (p.u.)	V_2^s (p.u.)	V_3 (p.u.)	V_4 (p.u.)	Q_1^g (MVAr)	Q_2^g (MVAr)
a	1.00	1.03	1.01	1.01	-24.0	24.7
b	1.00	1.03	0.96	0.94	70.7	151.5
	0.87	1.03	0.85	0.84	0.0	282.8
c	1.05	1.07	1.04	1.03	28.0	78.0
	1.00	1.07	1.01	1.00	0.0	112.0
d	1.05	1.03	0.98	0.95	159.5	121.3

Case b -- the loop flow effects. Next, we consider the undertaking of a single 400 MW transaction from the generator at bus 2 to the load at bus 4. Due to this transaction, V_4 drops to 0.94 p.u., which violates the voltage profile constraint, and both Q_1^g and Q_2^g increase. To raise V_4 to an acceptable level, the generator at bus 2 needs to raise V_2^s to provide more reactive support since it is the seller in the transaction. However, due to the network structure, the generator at bus 1, which is not participating in the transaction, is required to provide reactive support and Q_1^g = 70.7 MVAr. This is because though the transaction is from bus 2 to bus 4, only a part of the transacted 400 MW flows on the direct path from bus 2 to bus 4, while the rest reaches bus 4 through the network loops through the path of buses 2, 1 and 4 and the path of buses 2, 1, 3, and 4. These are the loop flows due to the transaction and they require the generator at bus 1 to provide reactive support. If the generator at bus 1 generates no reactive support, then the transaction would cause V_4 to reach the unacceptably low value of 0.84 p.u. In addition, the voltage at bus 1 can no longer be held at the value of 1.0 p.u. and drops to 0.87 p.u.

Case c -- reactive support leaning. Now we consider a 300 MW transaction from the generator at bus 2 to the load at bus 4. V_1^s and V_2^s are set at 1.05 p.u. and 1.07 p.u., respectively. Then, both V_3 and V_4 are at acceptable levels. The generator at bus 1 produces Q_1^g = 28 MVAr although it is not participating in the transaction. Next, consider the generator at bus 1. By taking advantage of the fact that the reactive power flows from a bus at a higher voltage to one at a lower voltage at bus 1, it decides to lower its voltage setting V_1^s so as to produce less reactive power, thereby lessening its share of VAr support. As shown in Table 2, the generator at bus 1 by setting V_1^s at 1.0 p.u. generates no reactive support. Meanwhile, V_3 and V_4 are still kept within the acceptable range. However, since the generator at bus 1 withholds its reactive output and *leans* on the system for reactive support, the generator at bus 2 becomes the only source of VArs for the entire system. Its reactive output Q_2^g has to increase from 78 to 112 MVAr. Moreover, since bus 2 is electrically more remote from bus 3 than bus 1, the reactive losses are increased measurably. Since the voltage constraints are "soft" constraints, different combinations of voltage setting of generators may achieve equally acceptable voltage profiles. Hence, a generator may take advantage by lowering its voltage setting and *leaning* on others for reactive support.

Case d -- two transactions. We add a second 150MW transaction from the generator at bus 1 to the load at bus 3 to that of ***case b***. Not only is V_3 decreased, but V_4 is also lowered to an unacceptably low level. The generator at bus 1 has to raise V_1^s to 1.05 p.u. to hold V_3 and V_4 within the specified voltage profile limits. Compared to ***case a***, Q_1^g and Q_2^g increase by 184 MVAr and 97 MVAr respectively. These increases in reactive power outputs of the generators may be considered to illustrate the reactive support service provided for the two transactions. However, we have no information to determine how many MVArs each generator provides to each individual transaction.

We may draw a number of conclusions from this example:

(1) even in the absence of transactions on the system, different voltage levels cause reactive losses in the transmission system which, in turn, give rise to the need for reactive support to maintain the specified voltage profile.

(2) the maintenance of a specified voltage profile requires that reactive support be provided on a system-wide basis; in particular, a generator, which is not participating in a transaction, may be required by the system to provide reactive power service to support that transaction.

(3) a generator may avoid providing its share of the reactive support and *lean* on other generators; it can do so by lowering its voltage setting point and thereby withholding some of its reactive power output.

(4) in a network with multiple transactions, it is difficult to determine the reactive support service provided by each generator to each individual transaction.

The 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 sometimes feasible to provide reactive support using remote sources.

Example 3: We use the 7-bus system of Figure 3 to illustrate the local nature of reactive support. In this example, we assume that all load bus voltages must be kept within [0.93, 1.1] p.u. The power flow results for this system indicate that the voltage V_3 is 0.90 p.u. and is in violation of the voltage profile constraint. Additional reactive support needs to be provided to raise V_3 . We consider the situation in which the local reactive support at bus 3 is unavailable and we have to depend on support provided by the generators to meet this objective. We use the generators at buses 1, 6 and 7, having different electrical distance with respect to bus 3. For each selected location, with the voltage setting points of all other generators remaining fixed, we raise the voltage setting point of the generator until V_3 is increased to 0.93 p.u. Consequently, not only the reactive power output of the generator at the selected location is changed, but the reactive power outputs of all other generators are also impacted. The comparison results in Table 3 show that as reactive support is provided from an electrically more distant location, the control of the reactive support over V_3 becomes less effective since the reactive power losses increase as the electrical distance increases. This is indicated by the ratio of the relative voltage changes at bus 3 to that of the selected bus[1]. Δl_q is the change in the total reactive losses. Note since the ratio is 1 at bus 3, the reactive support at bus 3, if available, is most effective. As the electrical distance increases, this ratio drops markedly. Furthermore, the supply of reactive support at a more remote location to improve V_3 might not even be feasible. For example, the generator at bus 6 has to increase its voltage setting value to 1.15 p.u., which violates the voltage profile constraints and would need to inject 246 MVAr additional reactive power to increase V_3 to 0.93 p.u.. The MVA line flow from bus 7 to bus 5 would then be

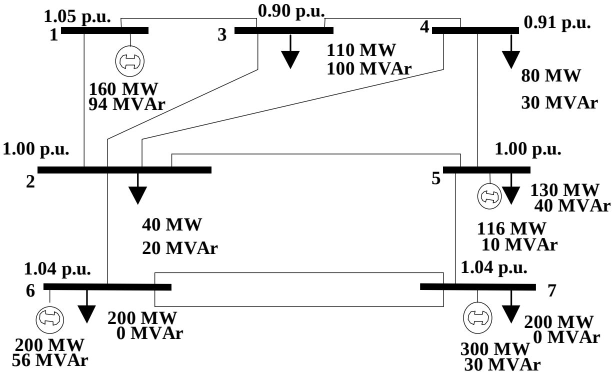

Figure 3. The 7-bus system with a voltage magnitude violation at bus 3

---

[1] The relative voltage change is the ratio of the change in the voltage magnitude to the voltage magnitude at the bus.

increased from 38 to 180 MVA. This may hit a line limit. For an even more acute case, the reactive support provided by the generator at bus 7, which is the most electrically distant from bus 3, has practically no effect on V_3. The implications of this fact are that it would be very difficult to develop a competitive market in VArs due to the need of providing them in the vicinity of the required location. The location of multiple generators at the same bus is not that likely so that a single generator may, in effect, have a monopoly in the supply of reactive support.

Example 3 illustrates that effective supply of reactive support for voltage control must be *local* due to the inescapable line losses.

Table 3. Comparison of the reactive support required from the generator buses to raise the voltage at bus 3 from 0.9 p.u. to 0.93 p.u.

reactive support bus	V_i^s (p.u.)	ΔV_i^s (p.u.)	$\frac{\Delta V_3}{V_3} \Big/ \frac{\Delta V_i^s}{V_i^s}$	ΔQ_i^g (MVAr)	Δl_q (MVAr)
1	1.05	0.05	0.7	67	0.48
6	1.04	0.11	0.3	246	23.80
7	1.04	0.11	0.0	321	36.45

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 [4]. 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 *loading diagram*, or *generation capability curve*, is shown in Figure 4. The diagram specifies the boundary of the feasible operation region of the generator. This boundary is formed by the intersection of four physical limits -- 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 the capabilities of reactive power generation and absorption 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: for real power output of P^0, the reactive power output Q^g must be within the range $[Q_{\min}^g(P^0), Q_{\max}^g(P^0)]$. Consider the case when a generator operates at the boundary point $(P^0, Q_{\max}^g(P^0))$. 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 evaluation of the positive quantity δP is simple using the value(s) of $\left[\partial Q_{\max}^g(P)/\partial P\right]^{-1}$ evaluated at one or more points. Similarly, if the generator operates at the boundary point $(P^0, Q_{\min}^g(P^0))$ 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 $\left[\partial Q_{\min}^g(P)/\partial P\right]^{-1}$. For a given P^0, Figure 5 plots δP as Q^g is varied.

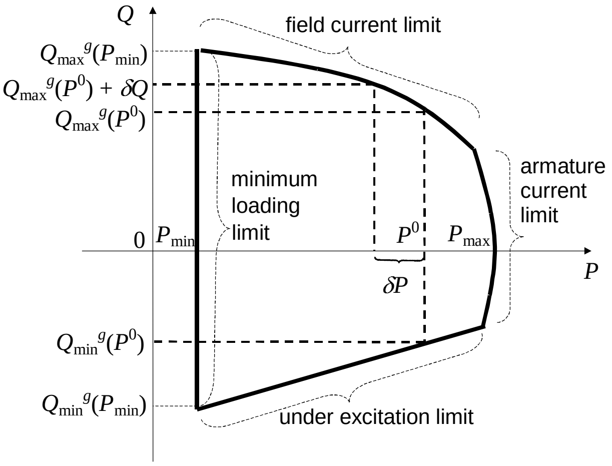

Figure 4. The generation capability constraint (the loading diagram)

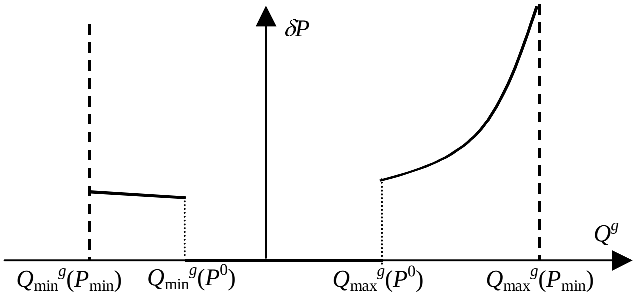

Figure 5. The marginal reduction δP in MW output as a function of the reactive support requirement Q^g corresponding to the real output P^0 in Figure 4

Example 4: For the simple two-bus system of ***case b*** in **Example 1,** we consider a 200 MW transaction between buses 1 and 2 and assume all bus voltages must be held within [0.96, 1.06] p.u.. Figure 6 gives the plot of a segment of the generation capability curve of the generator for the MW range of interest together with the reactive support requirement curve, which is identical to curve A in Figure 1. V_1^s at the generator bus needs to be set to 1.05 p.u. to maintain V_2 at 0.96 p.u. Consequently, as indicated by the point $(\overline{P}_1, \overline{Q}_1^g)$ in Figure 6, the generator needs to produce 86 MVAr to support this transaction. This reactive generation is larger than its reactive power production capability $Q_{1,\max}^g(\overline{P}_1) = 40$ MVAr. Consequently, for the real power output $\overline{P}_1$, the generator can operate only at the point $(\overline{P}_1, Q_{1,\max}^g(\overline{P}_1))$. The generator is at its maximum reactive power production limit. Moreover, since at this VAr output, V_1^s cannot be held at the value of 1.05 p.u. and is lowered, the plots in Figure 1 indicate that V_2 will also be lowered leading to a voltage magnitude below the specified voltage profile. This leaves no choice but to curtail the transaction. At the point $(\hat{P}_1, Q_{1,\max}{}^g(\hat{P}_1))$ where the two curves intersect, the unit is able to provide the required reactive support of 63 MVAr and hold V_1^s at 1.05 p.u. The transaction has to be cut down to 175 MW and V_2 is within the specified voltage profile.

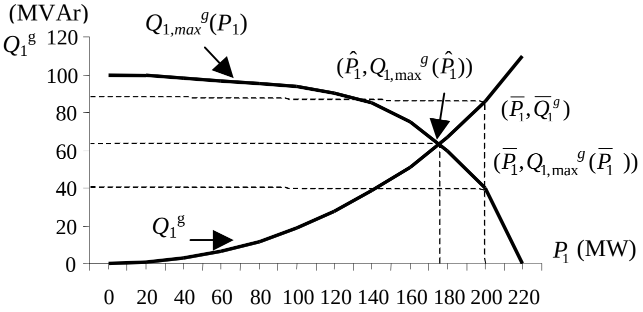

Figure 6. The generation capability imposes a hard constraint

In summary, **Example 4** clearly illustrates that:

(1) the generation capability constraint imposes a hard physical limit in the provision of reactive support.

(2) since a generator's reactive support capability is a function of its real power production, the only feasible way to meet the VAr support requirement is to decrease the real power generation and hence to curtail the transaction.

3. DOMINANT COMPONENT OF THE REACTIVE SUPPORT COST

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 investment costs and such costs do not come into consideration when actual costs of VAr production/ absorption by a generator are considered. 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 references [5]-[8]. 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. 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, i.e., these 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.

We use a simple three-bus system to illustrate the notion of the opportunity costs incurred in providing reactive support services.

Example 5: Consider a three-bus system with generators at buses 1 and 2 with capacities of 500 and 800 MW, respectively and a 700 MW load at bus 3. Each line is lossless, with a reactance of 0.1 p.u.. We assume that the generator at bus 1 is subject to the generation capability constraint shown in Figure 7, while the generator at bus 2 has sufficient capacity for both real and reactive production so that its generation capability limit is not an issue. The voltage profile constraints require each bus voltage magnitude to be kept in the range of [0.96, 1.05] p.u. We illustrate the opportunity costs of reactive support under the *Pool* and the *Bilateral Transactions* model structures.

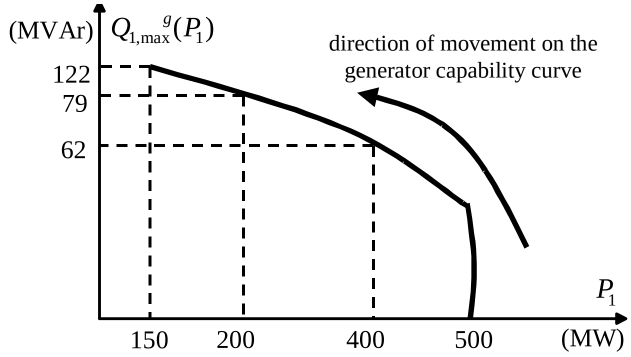

Figure 7. The generation capability constraint of the generator at bus 1

Case a -- Pool model. In this case, the 3-bus system is operated in a pool model. The generators at buses 1 and 2 submit bids consisting of the price function of MW output and available capacity. The unit at bus 1 bids \$20/MWh for its entire capacity of 500 MW, and the unit at 2 bids \$30/MWh for its entire capacity of 800 MW. Based on received bids, the least cost dispatch to meet the demand and the resultant system marginal price are determined without taking the transmission constraints into consideration. All successful generators are paid uniformly at the market clearing price. Therefore, the generator at bus 1 is dispatched with $P_1^* = 500$ MW and the generator at bus 2 serves the remaining 200 MW with $P_2^* = 200$ MW. The market clearing price is \$30/MWh and the unit at bus 1 makes a profit[2] of \$10 per MW it produces. Its total profits

---

[2] The profits are determined based on the bids submitted by the units. Since a bidder may not necessarily reveal his actual costs, the profits evaluated need not be the true benefits of the unit.

are \$5,000. However, if this unconstrained schedule were actually dispatched, both buses 1 and 3 violate the voltage profile constraints, as shown in Table 4. This is because once the unit at bus 1 is at its full MW capacity, it is able to produce 0 MVAr. Note V_2^s is set to 1.05 p.u, which is at a limit of the specified voltage profile. The unit at bus 2 then cannot provide any additional VAr support without violating the voltage profile constraint. This leaves the unit at bus 1 as the only possible source of reactive support to relieve the voltage constraints. The unit at bus 1 needs to provide 81 MVAr to maintain V_1^s at 1.0 p.u. so as to raise V_3 to be within the specified limits. However, this amount of reactive support may only be obtained from the unit at bus 1 by curtailing its real power generation. Since the load remains fixed, the unit 2 replaces the reduced production at bus 1. Then, the dispatcher has to shift real power production from the cheaper unit at bus 1 to the more expensive unit at bus 2 so that the former can increase its reactive power capacity to meet the specified voltage profile constraint. The unit at bus 1 would move on the boundary curve so as to minimize the reduction in its real power generation. The power flow result in Table 4 indicates that 100 MW production has to be shifted from bus 1 to bus 2 so that the unit at bus 1 can produce 62 MVAr to hold its voltage at 1.0 p.u. and V_3 is raised to 0.96 p.u. The deviation in the actual dispatch from the unconstrained dispatch reduces the profits of the generator at bus 1 by \$1,000. The opportunity costs incurred in the provision of 62 MVAr are \$1,000.

Case b -- Bilateral Transactions model. Under the structure of the Bilateral Transactions model, generators at buses 1 and 2 negotiate with the load at bus 3 directly. We assume the load purchases power by undertaking a 500 MW transaction from the generator at bus 1, and a 200 MW transaction from the generator at bus 2. The power flows due to these two transactions are identical to those of ***case a*** shown in row A of Table 4. These two proposed transactions result in congestion since V_3 violates the voltage profile constraint. The IGO relieves the congestion by curtailing the first transaction by 100 MW. The situation is identical to that of ***case a*** and is summarized in row B of Table 4. Suppose that the negotiated price of the first transaction gives the unit at bus 1 a profit of \$5/MWh. Consequently, it foregoes \$500 in providing the system required reactive support in this case. In other words, the opportunity costs incurred in providing the required 62 MVAr are \$500.

Table 4. Power flow results for Example 5
(A: unconstrained schedule, B: actual schedule)

Sched	bus 1			bus 2			V_3 (p.u.)
	P_1^* (MW)	$Q_{1,\max}^g(P_1^*)$ (MVAr)	V_1^s (p.u.)	P_2^* (MW)	Q_2^g (MVAr)	V_2^s (p.u.)	
A	500	0	0.93	200	339	1.05	0.91
B	400	62	1.00	300	208	1.05	0.96

In both cases, the generator at bus 1 gives up a valuable opportunity in the real power market to meet the reactive support requirements. Since, the reactive support has to be acquired from this unit, the compensation of these opportunity costs may be necessary so as to give incentives to the unit to provide this service to the system. For instance in ***case a***, while the unit at bus 1 is paid at the system marginal price of \$30/MWh for the 400 MW it actually produces, the pool dispatcher might also have to compensate the lost profits of \$1000 for the 100 MW that was scheduled but not produced. Similarly in ***case b***, the IGO may have to cover the opportunity costs of the system required reactive support. Then, the generator at bus 1 would be indifferent to producing either 500 MW and 0 MVAr or 400 MW and 62 MVAr, as the total profits from the two commodities are identical.

We note that, for a larger system, there may exist multiple ways of redispatching the system to relieve the transmission constraints. Since the opportunity costs of reactive support of a generator depend directly on the way in which the system is redispatched, the opportunity costs are heavily influenced by the discretion of the IGO. Moreover, *a priori* quantification of the opportunity costs is difficult due to the many uncertainties. The opportunity costs can be determined, in effect, only *ex post*.

We summarize the dominant cost component characteristics of the reactive support illustrated by **Example 5** as follows:

(1) 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, 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

(2) 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

(3) to ensure the required reactive support is provided, the IGO may have to give incentives to the generator by compensating the opportunity costs so as to make them indifferent whether they provide real or reactive power.

4. REACTIVE SUPPORT SERVICE ACQUISITION

The physical characteristics of reactive support illustrated in the various examples above make the acquisition and pricing of this ancillary service very different from those for the MW/MWh-based ancillary services [9],[10]. 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 forecloses 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 absent the setting up of 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. 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 *strategically* located generators.

5. CONCLUDING REMARKS

Reactive support for voltage control is an integral and critical part of power system operations. The important role and the physical characteristics of the reactive support service 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. An important extension is the characterization and quantification of the role of reactive reserves that are essential for maintaining appropriate margins for the specified voltage stability limits and for ensuring the voltage security of the system in withstanding possible contingencies.

Further work is sorely needed in establishing the relationship between transactions on the system and reactive support. 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 allocation of the reactive support service and the costs involved among the transactions on the system are topics of current research. Another topic associated with competitive electricity markets is the role of reactive support in the evaluation of available transfer capability (ATC). We are planning to report shortly our investigations of voltage stability/collapse considerations in the ATC evaluation. A further topic under investigation is the study of the possible exercise of market power through the specification of voltage setpoints. The results will be reported in a future paper.

6. REFERENCES

[1] Federal Energy Regulatory Commission of the United States of America, Order No. 888, “Promoting Wholesale Competition Through Open Access Non-discriminatory Transmission Services By Public Utilities,” Docket No. RM95-8-00, April 1996.

[2] S. Hao and A. Papalexopoulos, “Reactive Power Pricing and Management,” *IEEE Trans. Pow. Syst.*, Vol. 12, pp. 95-104, February 1997

[3] J. Lamont and J. Fu, “Cost Analysis of Reactive Power Support,” *IEEE Trans. Pow. Syst.*, Vol .14, No. 3, pp. 890-898, August 1999.

[4] J. J. Grainger and W. D. Stevenson, Jr., Power System Analysis, McGraw-Hill, Inc., 1994, pp. 110-114.

[5] R. A. Wakefiled et al., “Transmission Services Costing Framework,” EPRI Reports TR-105121-V1/V2, Palo Alto, CA, April 1995.

[6] D. Curtice, “Costs of Providing Ancillary Services from Power Plants,” EPRI Report TR-107270-V1, Palo Alto, CA, March 1997.

[7] P. J. Turner and R. J. Nicholls, “Cost of Providing Ancillary Services from Power Plants: Reactive Supply and Voltage Control,” EPRI Report TR-107270-V3, Palo Alto, CA, June 1997.

[8] J. Barquín et al., “On the Cost of the Reactive Power Generation and Voltage Support Service”, *Proc.* Bulk Power Systems Dynamics and Control IV - Restructuring, Santorini, Greece, August 24-28, 1998.

[9] L. D. Kirsch and H. Singh, “Pricing Ancillary Electric Power Services,” *Electricity Journal*, Vol. 8, pp. 28-36, October 1995.

[10] H. Singh and A. Papalexopoulos, “Competitive Procurement of Ancillary Services by an Independent System Operator,” *IEEE Trans. Pow. Syst.*, Vol .14, No. 2, pp. 498-504, May 1999.

ACKNOWLEDGMENTS

The research of the UIUC authors was sponsored by the Power System Engineering Research Center. The financial support of the Italian Ministry of University and Scientific and Technology Research is acknowledged for the research of the Politecnico di Torino authors.

BIOGRAPHIES

George Gross (F’ 88) is Professor of Electrical and Computer Engineering and Professor, Institute of Government and Public Affairs, at the University of Illinois at Urbana-Champaign. His current research and teaching activities are in the areas of power system analysis, planning, economics and operations and utility regulatory policy and industry restructuring. His undergraduate work was completed at McGill University, and he earned his graduate degrees from the University of California, Berkeley. He was previously employed by Pacific Gas and Electric Company in various technical, policy and management positions.

Shu Tao (M’ 99) received his B.S. and M.S. degrees in Electrical Engineering from Tsinghua University, China, in 1992 and 1995, respectively. Since August, 1995, he has been a graduate student at the University of Illinois at Urbana-Champaign. His research interests focus on power system operations, control, optimization and economics.

Ettore Bompard (M'99) received his Ph.D. degree in Electrotechnical Engineering in Italy in 1994. In May 1997 he joined the Politecnico di Torino, Italy, as Assistant Professor. His research activities include power systems, distribution systems, electricity markets and power quality.

Gianfranco Chicco (M'98) received his Ph.D. degree in Electrotechnical Engineering in Italy in 1992. In November 1995 he joined the Politecnico di Torino, Italy, as Assistant Professor. His research activities include power systems, distribution systems, electricity markets and power quality.