PWP-035

Contract Paths, Phase-Shifters, and Efficient Electricity Trade

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for the California Energy Commission
Interagency Agreement 700-93-003

October, 1995

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ABSTRACT

Phase-shifting transformers offer the opportunity to partially control the flows in an electricity network. In the US electricity industry, these devices currently operate under decentralized private ownership. This pattern, coupled with a commercial trading regime based on the contract path concept, creates potential inefficiencies. There is currently litigation at FERC over proposals to coordinate phase-shifter operation in the WSCC. This paper summarizes that litigation and illustrates the basic interactions in a simple four node model based broadly on conditions in the WSCC region. In addition to the potential inefficiencies of decentralized phase-shifter operation, we also show how they can enhance the overall utilization of the network. We compare regulatory approaches to managing these issues with more extensive structural reform of electricity trade.

1. Introduction

Phase-shifting transformers are one of the principal control devices used in modern power systems to help direct electricity flows in local parts of the transmission network. These control devices operate in the US, and the Western System Coordinating Council (WSCC) region in particular, under decentralized ownership. Utilities in the WSCC have negotiated for ten years regarding the coordinated operation of these control devices. They have been unable to reach consensus, but a large majority has filed a plan with the Federal Energy Regulatory Commission (FERC) to share cost and responsibility for the use of these devices. This plan has been contested by a small group of utilities in the Pacific Northwest. The FERC litigation over this issue illustrates the coordination difficulties that arise under decentralized ownership. As competitive forces in the electricity industry increase, these coordination problems are likely to be exacerbated.

In this paper, we summarize the FERC litigation and attempt to draw out the basic implications of the issues that it raises. Because the WSCC is large and complicated, it is difficult to understand conceptually the problem posed by control devices in such a setting. Therefore, we abstract from the actual WSCC configuration and address the basic issues in a simplified and stylized model. We examine a simple four bus system with three generation sources, a load, and one or more phase-

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shifting transformers. We use the system to understand the interplay of contract transmission paths, the operation of phase-shifters, and the utilization of transmission capacity. Our model involves a major regional demand center initially supplied by contract purchases from each of the generation sources. We then examine the incremental supply opportunities when demand increases at the demand center by varying amounts. We observe that with the initial set of endowments and contract rights, incremental trade in the system may not be efficient, because individual competitors will have market power. We discuss the implications for conduct regulation of increasing electricity trade in the presence of this market power and also discuss potential structural re-organization of the market.

The style of analysis adopted here is to represent complex institutional arrangements with simple networks that facilitate analysis of the basic economic and regulatory problems arising in electricity markets (Baldick and Kahn, 1993). Using a four node system to describe a complex network like the WSCC necessarily exaggerates the problems described. Clearly, we can at best only represent "major" loop flow around the whole of the WSCC and not "minor" loop flows in smaller regional loops (IEEE, 1991). While this procedure is analytically useful, it should not be taken to describe closely any particular condition in the WSCC.

Our basic theme is that contract paths are incompatible with an efficient pattern of electricity trade. This point has been made by economists previously. Hogan (1992), for example, argues that property rights on the electricity network should be guaranteed by financial performance, not the specific or physical performance standard that underlies the contract path notion. The problems with contract paths have also been raised by utilities (IEEE, 1991; Garfield, 1994). Nonetheless, the practice of specific performance still dominates commercial activity and we start our analysis by considering this reality of industry structure.

Our contribution is to examine how the use of phase-shifters to enforce existing property rights can increase trade inefficiencies. This point has been made qualitatively by Tenenbaum, Lock and Barker (1992). In our examples we show how this occurs, but we also illustrate the opposite, namely that phase-shifters can offer the opportunity to control network flows to expand trade possibilities. Sensible regulation of electricity trade needs to develop rules that will capture the benefits of control devices and limit their potential abuse.

The discussion is organized as follows. Section 2 summarizes the FERC litigation. Section 3 describes our model system and potential responses to increased demand. Section 4 illustrates how, in the case of our simple network, phase-shifters can be used by their owners to foreclose trade possibilities of other agents. Section 5 addresses the potential responses of participants affected by the use of phase-shifters to foreclose trade. We examine the opportunities to counter one party's control device with another. In Section 6 we examine the potential use of phase-shifters to expand access by making better use of the existing network capacity. Section 7 compares some possible regulatory approaches to the problems and opportunities previously discussed with some possible structural changes in the organization of electricity trade. Conclusions are offered in Section 8.

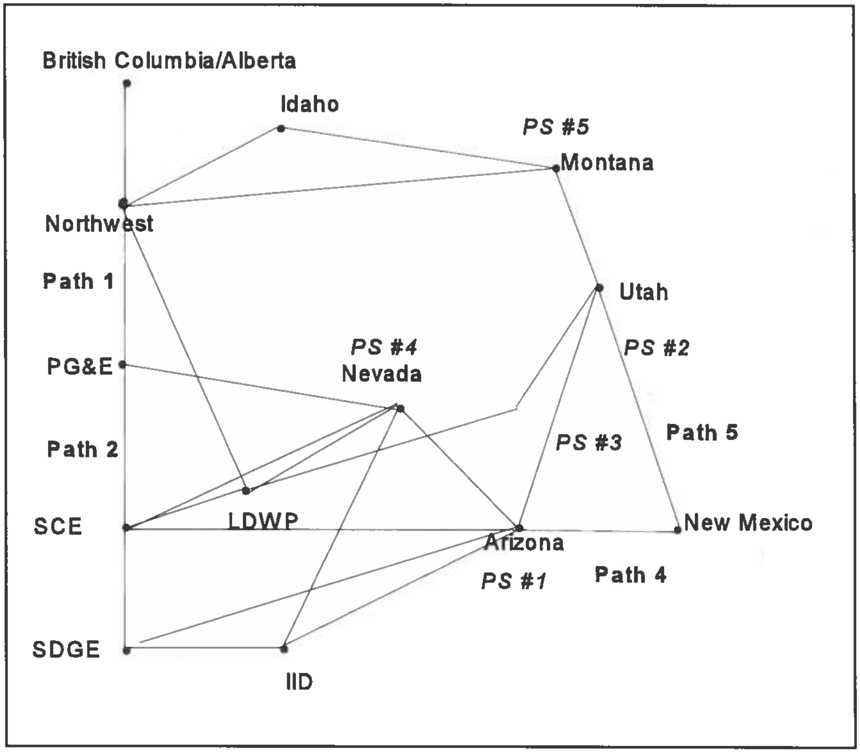
2. The FERC Litigation

In November, 1994 the WSCC filed its Unscheduled Flow Mitigation Plan with the FERC (WSCC, 1994). This plan presents an operating agreement and financial compensation proposal for "controllable devices" that is intended to reduced unscheduled flow throughout the region. The plan allows for a variety of possible controllable devices, defined only by minimum qualifications for controlling flow on certain important paths in the system; however, the only devices qualified to date are phase-shifting transformers.

A number of utilities in the Pacific Northwest intervened at FERC, objecting to the plan on several grounds including their claim that they did not contribute to the unscheduled flow, and objecting to the rate proposal which would require that they contribute to the approximately $13 million annual revenue requirement (Puget, 1994). FERC set formal hearings to address the dispute.

The principal argument put forward by the WSCC majority group in response to the objections of the Pacific Northwest intervenors was that, despite the intervenors' claims to the contrary, all participants in WSCC electricity trade contribute to unscheduled flow (Delawder, 1995). This argument is made qualitatively by use of a simple 4 node model of the WSCC region. We generalize from this model in our subsequent conceptual discussion. The question of causation, however, turns out to be rather ambiguous. On the one hand, the proponents of the agreement acknowledge that causal responsibility for unscheduled flow is difficult to assign. This difficulty has frustrated all previous attempt to negotiate agreement concerning mitigation. Yet the rate proposal presented to FERC relies essentially on the same incremental calculation procedures that have been recognized as inadequate to establish cost responsibility.

Figure 1. WSCC Schematic



The rate proposal seeks to recover a certain portion of the revenue requirements associated with particular phase-shifters that have been deemed "qualified" to control flows on certain "qualified paths" in the WSCC. The qualified paths and qualified phase-shifters are listed in Table 1. The locations of most of the qualified paths and qualified phase-shifters are illustrated schematically in Figure 1. The exceptions are the East of the River (Path 3), which consists of the lines from Nevada and Arizona to SCE and SDG&E, and Tot

1A (Path 6), which is an east side path going north from New Mexico to the Rocky Mountain region. The only qualified phase shifter omitted from Figure 1 is Cal Sub (#6), which is located within Northern California.

Table 1 summarizes the results of studies used to argue for the proposed cost allocation. This table, reproduced from WSCC (1994), shows for each of the six qualified paths and the six qualified phase-shifters (or sets of phase-shifters) a percentage "path effectiveness" assigned to each pair. The "path effectiveness" concept measures that fraction of the maximum flow on each path which a given phase-shifter can control. For each phase-shifter these percentages are averaged over all paths (see last column of Table 1), and that average determines the fraction of costs that can be recovered in the proposed rate. The table shows, for example, that the WAPA phase-shifters (#1) can control about 40% of the path flows. This fraction of their costs is then to be recovered in the proposed rate.[1]

A major problem with this procedure is that each of these path effectiveness percentages is computed from incremental simulations of some "base-case" that may or may not represent the reality of the system. The problem of arbitrariness in incremental calculations using an assumed base-case has been analyzed previously by Kahn, Outhred and Bushnell (1995) in the context of establishing line ratings for new transmission facilities. The essential difficulty is that any base-case is most likely to represent a negotiated compromise of the views of industry participants, and does not represent a necessarily robust view of future conditions.

Despite the potential arbitrariness of the calculations underlying Table 1, there are interesting and important facts that emerge from this analysis. First, the WSCC claims that about 400 MW of control will be feasible on average from the qualified devices. As applied to the loop flow duration curves presented in Delawder (1995), this would control most of the energy associated with the phenomenon. Second, the ability to control appears much greater on the weak (or low capacity) paths on the east side of the WSCC (Four Corners 345/500 and Tot 1A), at least in percentage terms, than on the stronger (or high capacity) paths. This fact will be used in our conceptual analysis below. Third, the ability of individual phase-shifters to control flows that are not in their immediate geographical vicinity is considerable. Notice, for example, that the WAPA phase-shifters in Arizona and New Mexico have significant impacts in California, for example, on the Malin-Round Mountain path and the Midway-Vincent path. This shows the extent of geographic externalities in the WSCC.

Whatever the outcome of this particular litigation, it illustrates concretely the nature of the coordination problem. Competitive tensions may or may not underlie the present cost allocation conflict. In the future, however, these tensions will increase. In our abstraction of the phase-shifter problem indicated by this case, we emphasize competitive issues.

Table 1. WSCC Phase-Shifter Compensation Proposal (% Path Effectiveness)

	Qualified Paths						
Path	Malin-Round Mountain	Midway-Vincent	East of the River	Four Corners-West	Four Corners-345/500	Tot 1A	Average
Path Number	1	2	3	4	5	6	
Path Rating	4,800	3,500	5,700	2,200	840	550	
Phase Shifter	% Path Effectiveness						
#1 WAPA (Shiprock/ San Juan)	14.6	21.5	16.5	35.6	53.8	100	40.4
#2 Pinto	12.5	18.9	16.5	42.1	60	84.4	39.1
#3 Sigurd	6	9.3	8.6	9.8	5	33.5	12
#4 Harry Allen	9.4	14.2	11.2	17.7	28.8	41.8	20.5
#5 Billings/ Crossover	10.5	13.7	7.2	12.8	20	48.4	18.8
#6 Cal Sub	15.6	8.1	3.7	6.1	9.6	13.1	9.4
Total MW Control	495	450	545	410	223	349	412

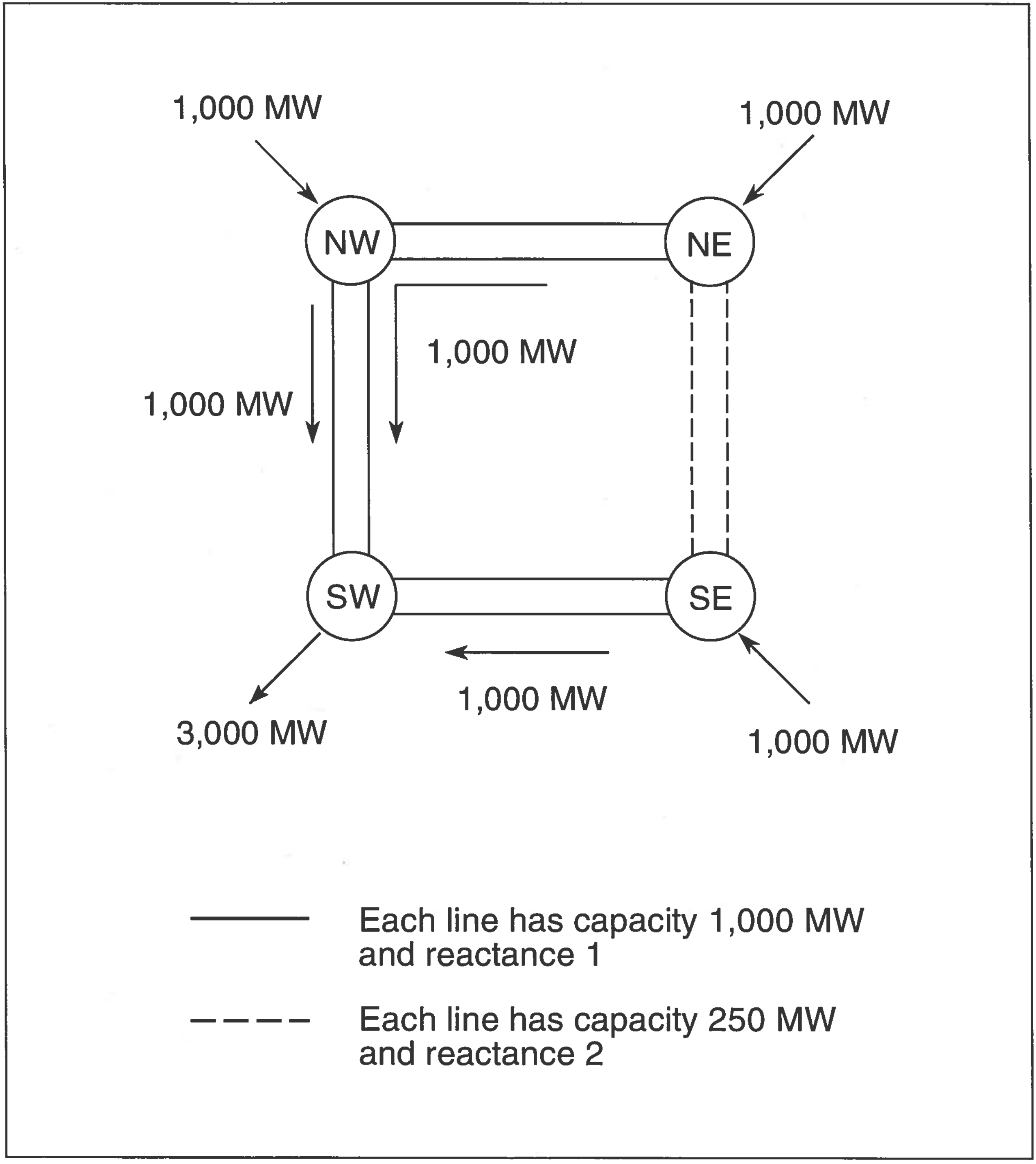
3. Model of System and Demand

The model we adopt is a stylized characterization of the WSCC. We selectively model certain features of the WSCC to illustrate conflicts between the commercial motives of participants and the economically efficient pattern of trade. Some of the issues that we model have arisen explicitly in the FERC litigation, while others have not.

3.1 Initial Conditions

Consider the four bus system shown in Figure 2. There is a load in the South-West corner (SW), and three generators in the other three corners (NW, NE, and SE). Between NE and NW, between NW and SW, and between SW and SE there are transmission corridors with rating 2000 MW consisting of pairs of individual identical lines of rating 1000 MW and reactance 1 unit (in a suitable base.)[2] These lines are shown solid in the figure. Between NE and SE there is a pair of lines each with rating of 250 MW and reactance 2 units. These lines are shown dashed. The total corridor capacities are therefore 2000 MW for the NW to SW, NE to NW, and SE to SW corridors and 500 MW for the NE to SE corridor.

Figure 2. Contract Flows in Initial System



We deliberately incorporate a low rating on the NE to SE corridor since that is an important feature of the WSCC, as indicated from the data on path ratings in Table 1. Weak paths are a common source of externalities in electric power networks (Baldick and Kahn, 1993) and typically arise where there are parallel paths from generation to demand centers with lines operated at different voltages.

We assume that the lines are lossless and that they are fully reactively compensated so that we can concentrate on real power flows only. We use the DC power flow approximation and initially assume that there are no phase-shifting transformers in-service. Our analysis therefore neglects important issues involving reactive power. (See, for example, Kahn and Baldick, (1994) for an analysis of some of these issues in a similar setting.)

The supply and demand scenario is as follows. Each of the generators has a long-term contract to supply 1000 MW of power to SW, which has a total load of 3000 MW. Furthermore, the generators have obtained transmission services along the contract paths between the generators and load from the owners of these transmission lines. In the case of NW, it has obtained 1000 MW of service on the path from NW to SW. NE has obtained 1000 MW of service on the path from NE via NW to SW. SE has 1000 MW of service from SE to SW. Note that the transmission service is described in terms of the *contract* paths, which are also shown in Figure 2. In terms of contract service, the NW to SW corridor is at capacity, while the other corridors are below contract capacity. Initially, we will not specify the ownership of the remaining transmission capacity, but will discuss alternative scenarios below.

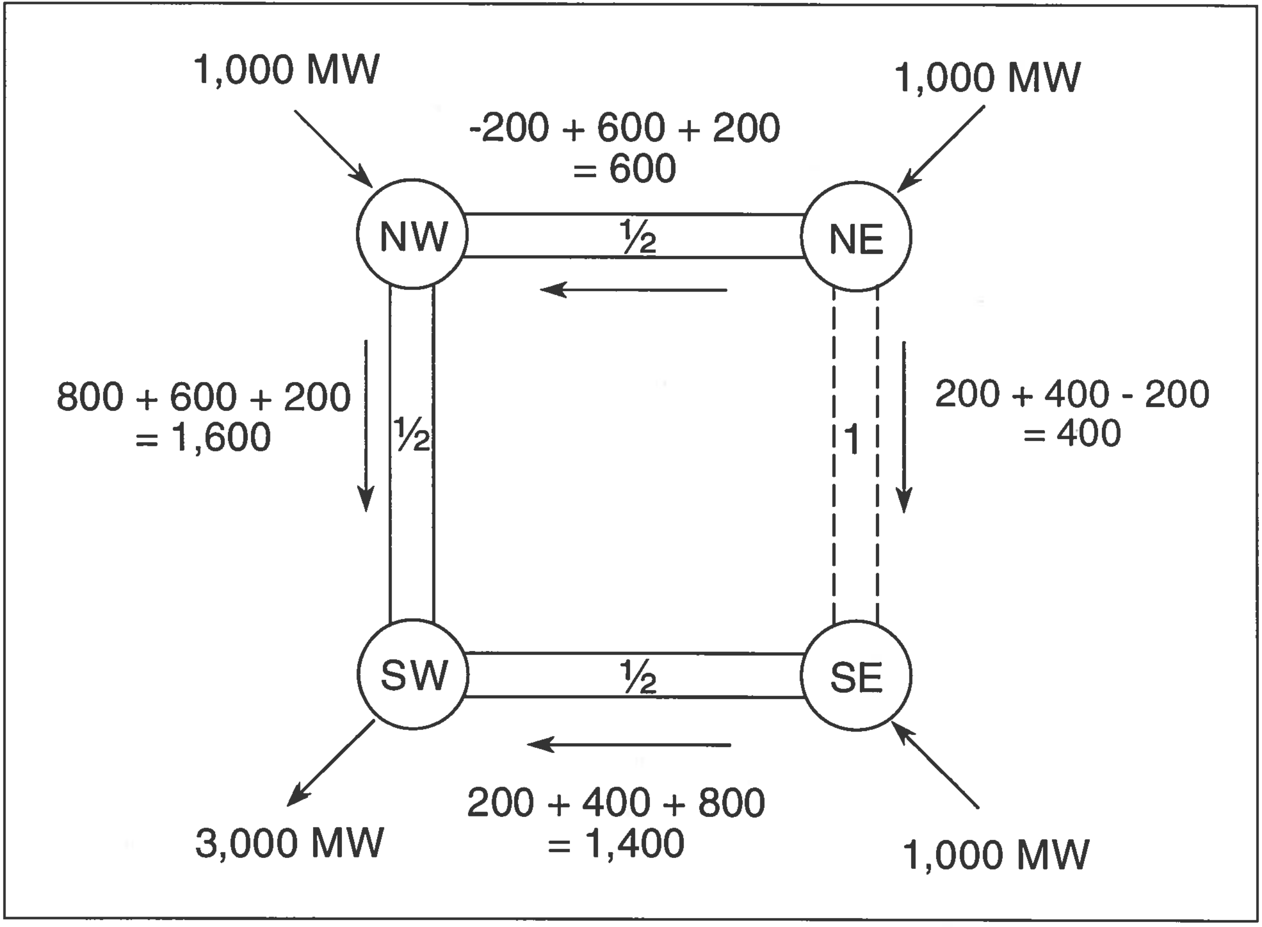
The contract flows differ from the actual flow of electricity due to Kirchhoff's laws. For the simple network we can approximate the actual flows with relative ease using superposition. These flows are shown in Figure 3. (Calculation of the flows is discussed in the Appendix.) The figure shows the net flow on each line expressed as the sum of the flows due to each generator, NW, NE, and SE, alone. (The DC loadflow approximation allows us to superpose these flows). Flow due to a given generator is either in one direction along a line or the other. For convenience, for each line, we have chosen the direction of the net flow of power to define positive flow. Contributions to this net flow can be either positive, indicating that generation at a particular generator serves to increase net flow, or they can be negative, indicating that increased generation decreases net flow.

For example, in Figure 3 the net flow along the NE to NW line is from NE to NW. For convenience we define flow in this direction to be positive. The generation at NW contributes 200 MW of flow from NW to NE, which is -200 MW using the convention for the sign of the flow. The contributions from NE and SE are 600 MW and 200 MW, respectively. To show the contribution from each generator, we express the net flow of 600 MW as the sum of the -200 MW from NW, the 600 MW from NE, and the 200 MW from SE. Similarly, the net flows on the other lines are expressed as the sums of the contributions from NW, NE, and SE, respectively.

Notice that in Figure 3 despite the contractual arrangements, there is non-zero flow on the NE to SE corridor, while the NW to SW flow is lower than the sum of the contract path flows along it. This is, of course, normal and simply due to the circuit equations. The flow along non-contract paths is usually called loop flow. More generally loop flow is defined as the difference between scheduled contract flow and actual flow.

Loop flows of the order of half the scheduled flows have been reported in the WSCC (USOTA, 1989, Box 4-D, p114) and in the Eastern Interconnection (IEEE, 1991). Conversely, some individual lines in the WSCC experience unscheduled flows of up to 50-75% of their scheduled capacity

Figure 3. Actual Flows in Initial System (No P-S).



(Bladow and Montoya, 1991). Our example is therefore not unrealistic in the proportion of loop flow.

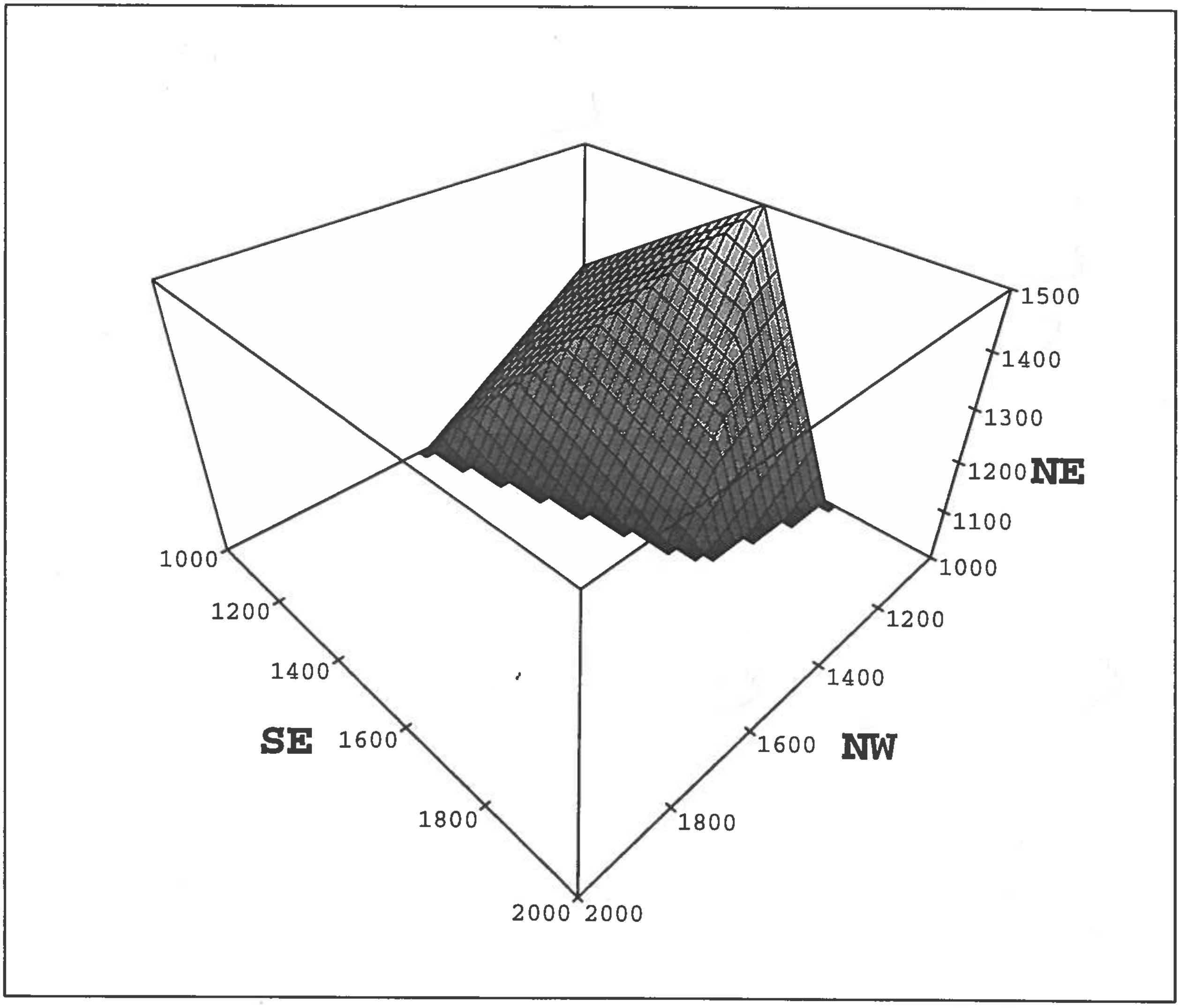
3.2 Incremental Demand

We now consider the case that the demand at SW is increasing by various amounts and analyze how this incremental demand can be met by increased generation at some combination of NW, NE, and SE. We use the DC power flow equations to express actual line flows in terms of generations. Letting *NW, NE,* and *SE* stand for the NW, NE, and SE generations, respectively, we can then write the constraints on actual power flow in the NW to SW, NE to NW, NE to SE, and SE to SW corridors in terms of these generations as follows:

$$0.8NW+0.6NE+0.2SE\leq 2000,$$
$$-0.2NW+0.6NE+0.2SE\leq 2000,$$
$$0.2NW+0.4NE-0.2SE\leq 500,$$
$$0.2NW+0.4NE+0.8SE\leq 2000.$$

These inequalities define a surface in *NW*, *NE*, *SE* space illustrated in Figure 4. The boundary of the feasible surface is defined by the binding constraints. The surface has three facets, corresponding to, respectively, the first, third, and fourth constraints. The second constraint is never binding for the generations we are considering.

Figure 4. Feasible Generations at NW, NE, and SE without Phase-Shifter Operation



To understand Figure 4 more concretely, we illustrate the extreme cases where demand is met by only one of NW, NE, or SE. We see by how much the demand can increase at SW without the actual line flows violating the transmission constraints. Figure 5 shows the case of incremental generation at NW. NW generation can increase to 1500 MW and SW demand increase to 3500 MW before actual flows equal the line flow limits. Notice that both the NW to SW corridor and the NE to SE corridor are at their limits when generation increases to 1500 MW at NW. This operating point corresponds to the vertex on the left side of the surface in Figure 4.

Figure 5. Actual Flows, NW Increase to 1,500 MW, SW Increase to 3,500 (No P-S)

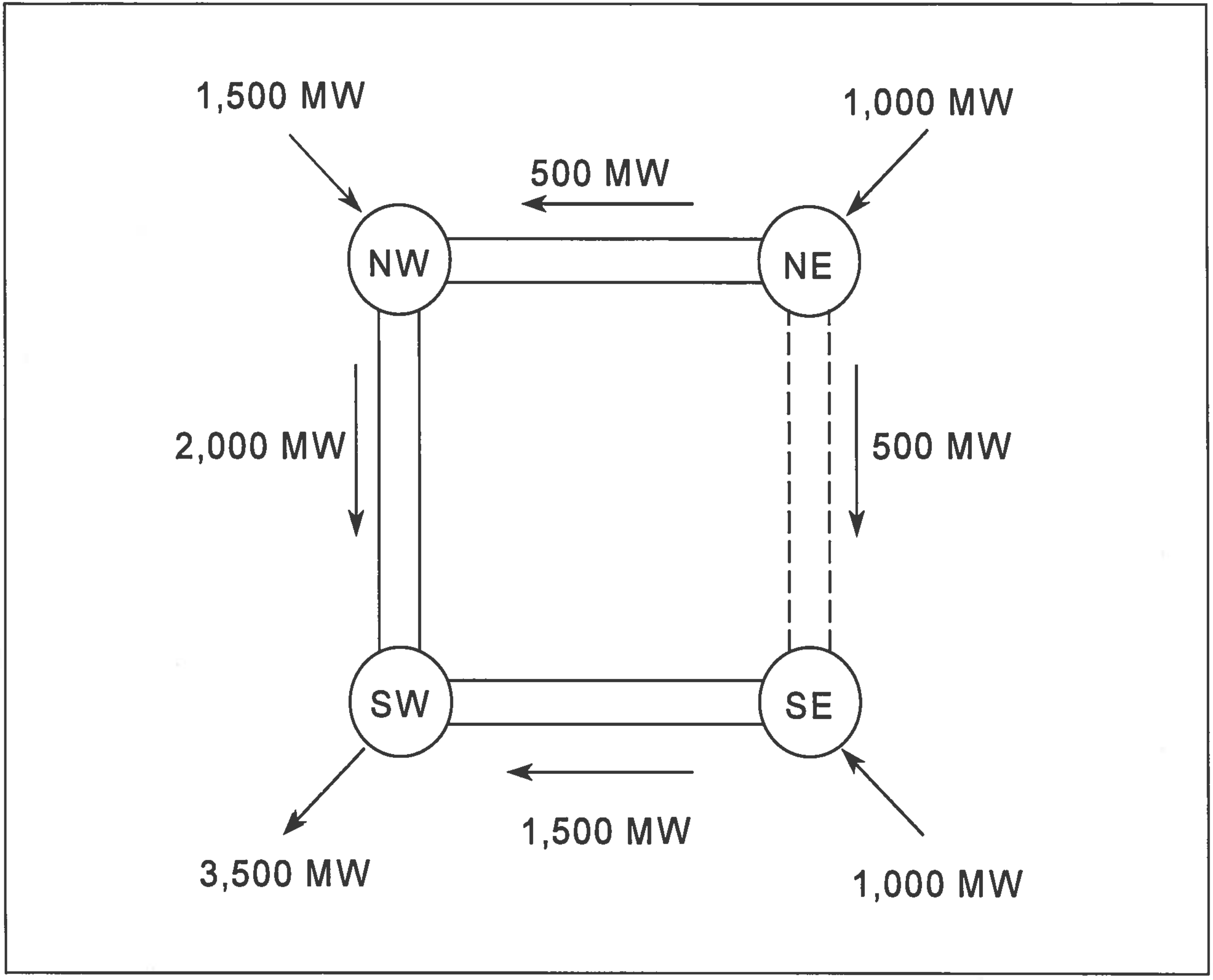
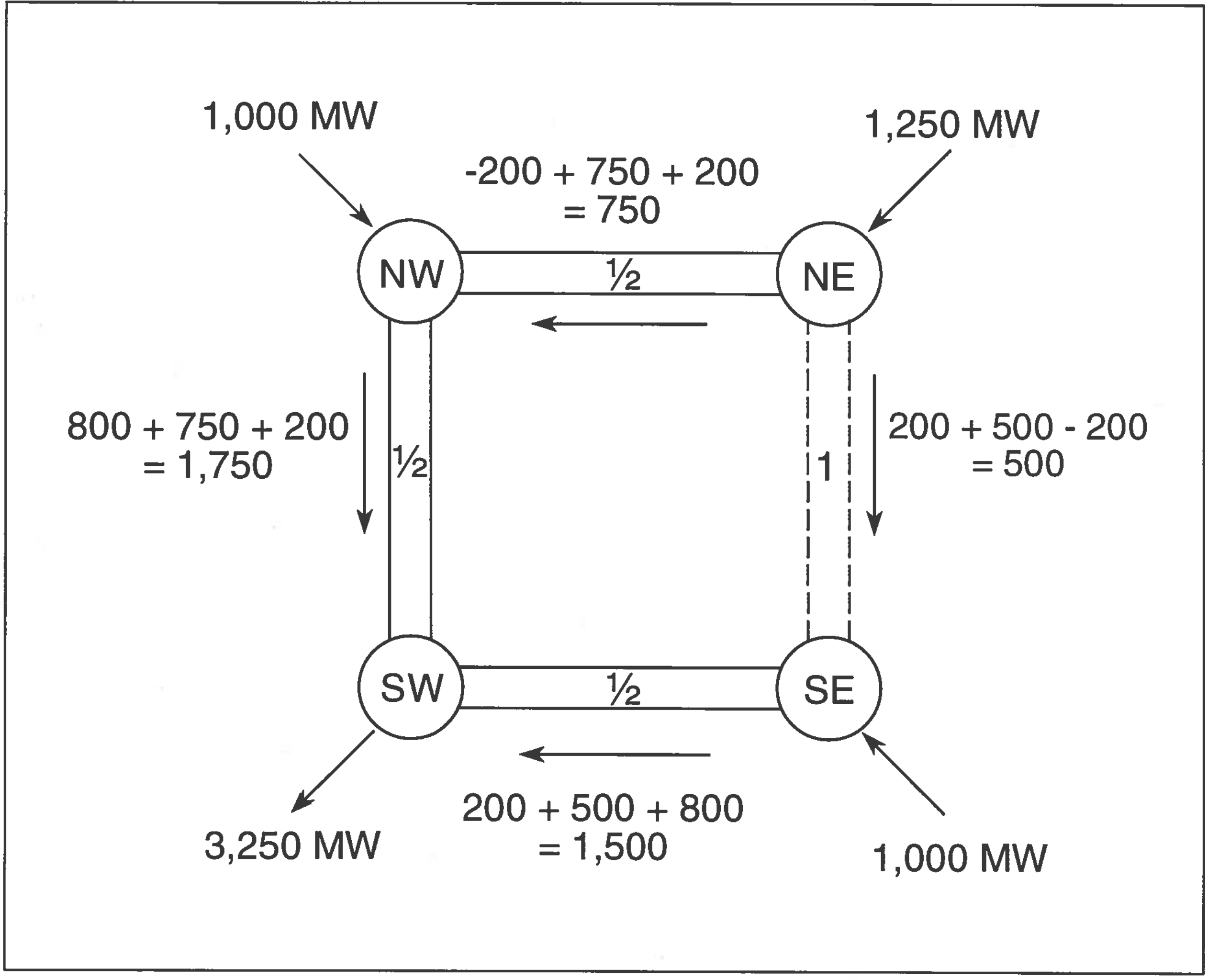


Figure 6 shows the case of incremental generation at NE. NE generation can increase to 1250 MW and SW demand increase to 3250 MW before the actual flow on the NE to SE corridor equals the limit. Note that in Figure 6, the NE to SE corridor has the smallest flow in the system, but is at its capacity. The other corridors are operating well below their capacities. This operating point corresponds to the vertex at the top left of the surface in Figure 4.

The combination of one line at its limit while the others are not binding, as shown in Figure 6, is often referred to as the weak line externality. The capacity of the weak line limits the allowed flows in the other corridors and hence limits the increase in generation at NE. This situation has been identified previously in the WSCC as occasionally limiting potential trades (Stalon, 1990).

Figure 7 shows the case of incremental generation at SE. SE generation can increase to 1750 MW and SW demand increase to 3750 MW before the actual flow on the SE to SW corridor equals the limit. The other corridors are operating below capacity. This operating point corresponds to the vertex at the bottom right in Figure 4.

Figure 6. Actual Flows, NE Increase to 1,250 MW, SW Increase to 3,250 (No P-S)

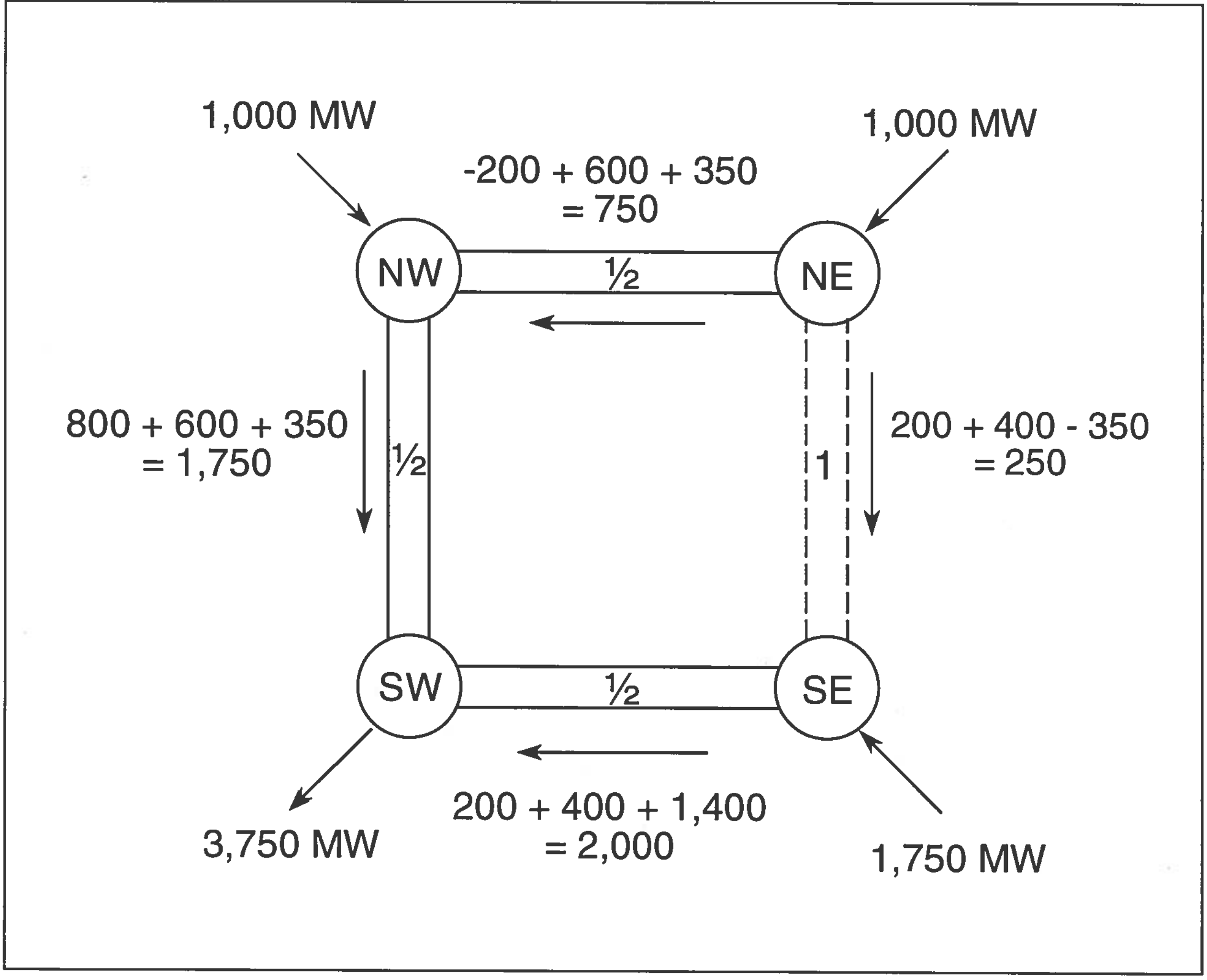


We now consider the optimal incremental dispatch case for 250 MW of incremental demand. That is, we start with the initial generations from Figure 2 as given minima at each bus and ask what increases would supply the incremental demand at least cost while still satisfying transmission constraints based on actual flows. (In general, this solution could differ from the optimal solution obtained if the initial demand was also supplied optimally from the available generation.) We use this case as a point of departure to analyze the effects of transmission contracts and phase-shifters.

From Figures 5, 6, and 7, the incremental demand can be supplied from any of the generators without violating line limit constraints. (In fact, because of the convexity of the linearized line constraints and as illustrated in Figure 4, the incremental demand can also be supplied by any combination of the generators without overloading lines.) Therefore, optimal incremental dispatch involves using the cheapest incremental generation. Notice that we did not consider costs of transmission services because in a loss-less system they are simply transfer payments and are not relevant to minimizing production costs. (For the analysis in Section 4 we will, however, consider the effect of such charges on distorting trade opportunities.)

In the initial system, the contract flows along the corridor from NW to SW shown in Figure 2 indicate no additional capacity on this corridor. However, there is in fact additional capability in the system to schedule incremental generation from the north to the demand at SW. If NW were the least cost alternative to serve incremental demand, for example, it would be efficient for the NW to SW transaction to occur. Under a transmission open-access regime, and given that no overloads occur, it would be efficient to make that capacity available to allow NW to export to SW. Whether that would actually happen under current institutional arrangements is the next question that we examine.

Figure 7. Actual Flows, SE Increase to 1,750 MW, SW Increase to 3,750 (No P-S)



4. Phase-Shifters: The Foreclosure Strategy

We have indicated that there is loop flow in the system. In particular, there is loop flow on the corridor from NE to SE, despite there being zero contract flow on this corridor. In response to such unscheduled flows, many utilities have installed phase-shifters to control the flow. This is common in the WSCC, for example. In general, the phase-shifter could be operated either to increase or decrease the flow along the NE to SE corridor; however, our example will concentrate on the case of using the phase-shifter to decrease the flow along that corridor. We will consider two alternatives for ownership of the phase-shifters: by NE and by the owner of the NE to SE transmission corridor.

4.1 Phase-Shifter Owned by NE

Let us suppose that NE has installed a phase-shifter on its interconnection with the NE to SE corridor. It could legitimately argue that the ownership and use of the phase-shifter is necessary to enforce its property right to the contract path it has purchased from NE via NW to SW or, alternatively, to enforce any rights it has separately purchased on the NE to SE corridor. By adjusting the phase shift, the flow in the system can be controlled so that the full 2000 MW of contract flow does in fact actually flow along the NW to SW corridor in the initial system. That is, by operating a phase-shifter, the actual flows in the initial system can be made to coincide with the contract flows shown in Figure 2.

By controlling the flow to adhere to the contract path, the actual flow on the NW to SW corridor is at capacity. As we suggested in the previous section, the most inefficient case occurs if NW has the lowest cost incremental generation cost, so that it is the optimal supplier of incremental demand at SW. Unfortunately, NW is unable to obtain service on the NW to SW corridor for incremental generation. The alternative route, from a contract path perspective, is from NW via NE and SE. This alternative route could be expected to incur greater transmission charges than the more direct route. Under a MW-mile pricing scheme, for example, where measured flows are the basis for pricing (Kovacs and Leverett, 1994), the charges could be three times as great assuming that the distance was three times greater.[3]

Even with incremental generation at NW significantly cheaper than at NE, the additional transmission charge could therefore make SW averse to a contract with NW involving a long transmission route compared to a contract with NE involving a shorter transmission path. With typical differences between fuel costs in the WSCC currently of the same order of magnitude as transmission charges, the cost of the longer route might even eliminate all of the potential gains from trade. Furthermore, negotiation of the longer route may be much more difficult or impossible.

Operation of the phase-shifter in conjunction with contract path rights to transmission can be used to foreclose the opportunity for NW to sell incremental generation to SW. Presuming that NE has a commercial interest in selling its own incremental generation to SW, then it will be motivated to restrict supply by so operating the phase-shifter. If NE's cost of incremental generation is lower than SE and assuming that NE can negotiate transmission service from NE via SE to SW at a suitable price, then NE will be able to supply the incremental generation at SW. In fact, as illustrated in Figure 8, if NE can negotiate 500 MW of contract transmission capacity on the path from the NE via SE to SW, then it can supply as much as 500 MW of incremental demand at SW, while foreclosing trade from NW.

If, on the other hand, SE generation is cheaper than at NE and furthermore, if SE can negotiate transmission service from SE to SW, then SE will be able to supply the incremental demand at SW. Contractual rights to firm transmission service are typically negotiated over long terms. Rights to transmission capacity therefore often reflect historical circumstance rather than optimal allocation of capacity through time. For example, SE may actually own the rights to all 2000 MW of the SE to SW capacity. In this case, it is likely that SE will be able to provide the incremental demand to SW to the exclusion of NW and NE even if its costs are higher than both of them. (We point out that the phase-shifter cannot be used simultaneously in this network to foreclose both sales from NW *and* SE.)[4]

In summary, if the phase-shifter is used to establish actual flows equal to contract, then NW may not be able to supply incremental generation even if it is the cheapest supplier. In this case, incremental generation will presumably be supplied by either NE or SE. The problematic issue is that the price of NW incremental generation does not enter into the analysis, since its transmission access to SW has been foreclosed by the phase-shifter operation.

4.2 Phase-Shifter Owned by NE to SE Corridor Owner

Now consider the case where the phase-shifter is owned by the owner of the NE to SE corridor. In this case, the phase-shifter will not be operated to advance NE's position directly. However, there is still motivation to use the phase-shifter in a way that will foreclose the possibility of incremental generation at NW. Notice that due to loop flow, the NE to SE corridor has uncompensated flow along it. This uncompensated flow limits the capacity of the corridor and incurs losses (IEEE, 1991). If, for example, the NE to SE line were owned by SE, then operating the phase-shifter to limit loop flow on the line would foreclose NW and facilitate the commercial interest of SE in selling to SW. It is not uncommon for utilities in the WSCC to own transmission lines and phase-shifters located outside of their immediate franchise area.

The transmission line owner may find that the phase-shifter is necessary to enforce its ownership rights in the corridor and to limit the losses it incurs due to unscheduled flow. The use of the phase-shifters to limit losses may not be so clear cut, however, since operation of the phase-shifter itself incurs losses and requires maintenance as we discuss below.

4.3 Results of Phase-Shifter Operation

Whether the phase-shifter is owned by NE or the NE to SE corridor owner, the outcome of operating a phase-shifter to eliminate unscheduled flow on the NE to SE corridor will sometimes be sub-optimal from the perspective of minimizing total regional production costs. In particular, NW is not able to supply incremental demand at SW, so if NW in fact has the cheapest incremental cost then the outcome will be sub-optimal. Interestingly, it is the combination of the contract path fiction *and* the ability to limit and reduce loop flow with a phase-shifter that prevents the cost minimizing outcome. If NE owns the phase-shifter, then by controlling the flows, and presuming that NE can negotiate a transmission contract on the path via SE to SW, it can supply the incremental demand at SW. Similarly, SE can advance its commercial interests if it is the owner of the phase-shifter on the NE to SE line and operates it to limit loop flow on that corridor. These actions would preclude the optimal dispatch. In contrast, we will see below in Section 5 a case where operation of a phase-shifting transformer *is* necessary for supplying optimal incremental demand.

The main technical limit to this behavior is that the operation of phase-shifting transformers incurs maintenance costs and also incurs losses in two ways:

1) the transformer itself has losses, and
2) redistributing flows in the way we have described will usually increase the total losses in real systems by as much as 10% of the flow that is shifted (IEEE, 1991), although some lines will experience reduced and some will experience increased losses.[5]

The transformers can be switched out of service when no phase-shift is required, while in-service losses in the transformer will be on the order of a percent.

The technical limits mitigate behavior in different ways depending on ownership. First, consider the case where the phase-shifting transformer is owned by NE. Use of the phase-shifting transformer by NE to keep market share will only be profitable if the margin on sales exceeds the maintenance costs and losses that must be incurred to operate the phase-shifting transformer. (We are assuming here that the losses incurred by the phase-shifter are actually paid for by NE.)

Second, consider the case that the phase-shifting transformer is owned by the NE to SE corridor owner. In this case, there is a trade-off for the corridor owner between decreased losses in the corridor and the maintenance costs and losses in the transformer. It may not be advantageous for the corridor owner to completely limit unscheduled flow; however, the owner may still operate the phase shifter in a way that helps to foreclose opportunities for NW to sell to SW.

5. Dueling Phase-Shifters

The main market limit on the foreclosure strategy is that other participants besides NE or the NE to SE line owner can install and operate phase-shifting transformers at various points in the system. In the discussion so far, NE or SE (as owner of the NE to SE line) have gained market share by the operation of a single phase-shifter in the system. However, either NW or SE (as a generator) or the other line owners may also consider installing phase-shifters and we consider these possibilities in detail in the following paragraphs. Of course, additional phase-shifters will impose significant capital costs that will make the overall system more expensive than otherwise.

While NW may install a phase-shifter, its ability to utilize one to its advantage may be constrained by the existing contract paths. For example, NE can argue that NW should not adjust the flow *deliberately* to make the flows differ from the contract flows, even if this would increase capacity from NW to SW, particularly since doing so would require unscheduled flow on the NE to SE and SE to SW lines.

On the other hand, if the phase-shifter can be used to increase the transfer capacity of the system reliably, then from a normative perspective this extra contract capacity should be assigned to the owner of the phase-shifter. Walton (1993), for example, argues this case for a single path. Walton's examples, however, do not involve multiple paths. Uprating of the system transfer capacity over multiple paths would typically require complex negotiations with all interested parties. NE may not cooperate in this negotiation if it serves to limit its own market power.

SE may be less restricted from obtaining increased transfer capacities by utilizing phase-shifters since the contract flows do not fill all the capacity on the lines to which it is connected. SE and NE are in competition to supply the incremental demand to SW. While it is in both their interests to preclude NW supply to SW, the division of the incremental generation between SE and NE depends on being able to negotiate transmission contracts to the point of demand at SW. If SE also installs a phase-shifter it may be able to alter the flows in the system to limit NE's ability to schedule to SW. However, in a complicated system such as the WSCC, the ability of any given phase-shifter to unilaterally control transmission capacity will be more limited than in the one-loop system we have described.

Phase-shifter investment could affect the economics of particular transactions. The examples in Section 3 presumed that the costs of the phase-shifter were sunk. If the phase-shifters must be installed to facilitate the transactions, then their costs might be sufficiently large to affect the least cost choice of incremental transactions.

6. Phase-shifters: Facilitating Transmission Access

In Figures 5, 6, and 7, which all illustrate flows with no phase-shifting transformers in-service, the actual flows in at least one of the corridors equals its rating. At the same time, other lines in the network have unused capacity. Under certain conditions, adjustments can be made in the entire system that will have a net positive benefit when summed across all parties. This situation has been addressed, for example, by Hogan (1992) and Wu and Variaya (1995) who have identified changes of dispatch as necessary for better utilization of the network.

If long-term specific performance contracts exist for supply and transmission services, however, reduction of generation at one node to improve efficiency may not be a viable option. In these circumstances, for the cases illustrated in Figures 5 and 7, *further* incremental demand at SW can only be supported with transmission line upgrades or the use of phase-shifters. In Figure 6, some extra generation is possible at SE and NE without violating constraints. Nevertheless above a limit, further incremental demand is again impossible without either transmission upgrades or phase-shifters.

Even if specific performance contracts are not problematic, phase-shifters still have a role in facilitating trade if they can be operated to allow better utilization of capacity. In the following subsections, we investigate whether a phase-shifting transformer in the system can be used to control flows to utilize the capacity more completely.

6.1 Phase-Shifters Not Effective

Let us first observe where phase-shifters *cannot* help with serving incremental demand. The situation in Figure 5 illustrates the case where phase-shifters cannot offer any increase in transmission capability from the north (that is, either NW or NE) to the SW. This is because all the lines in the *cutset* obtained by dividing the system from north to south are at full capacity. Phase-shifters can only alter the balance between flows along paths, they cannot reduce the total flow across a cutset. (In practice, because of losses, operation of phase-shifters will typically slightly increase the total flow across a cutset.) Therefore, if additional NW generation is desired, either new transmission or reduction in generation at NE is necessary. Similarly additional NE generation requires new transmission or reduction in generation at NW.

6.2 Phase-Shifters Effective

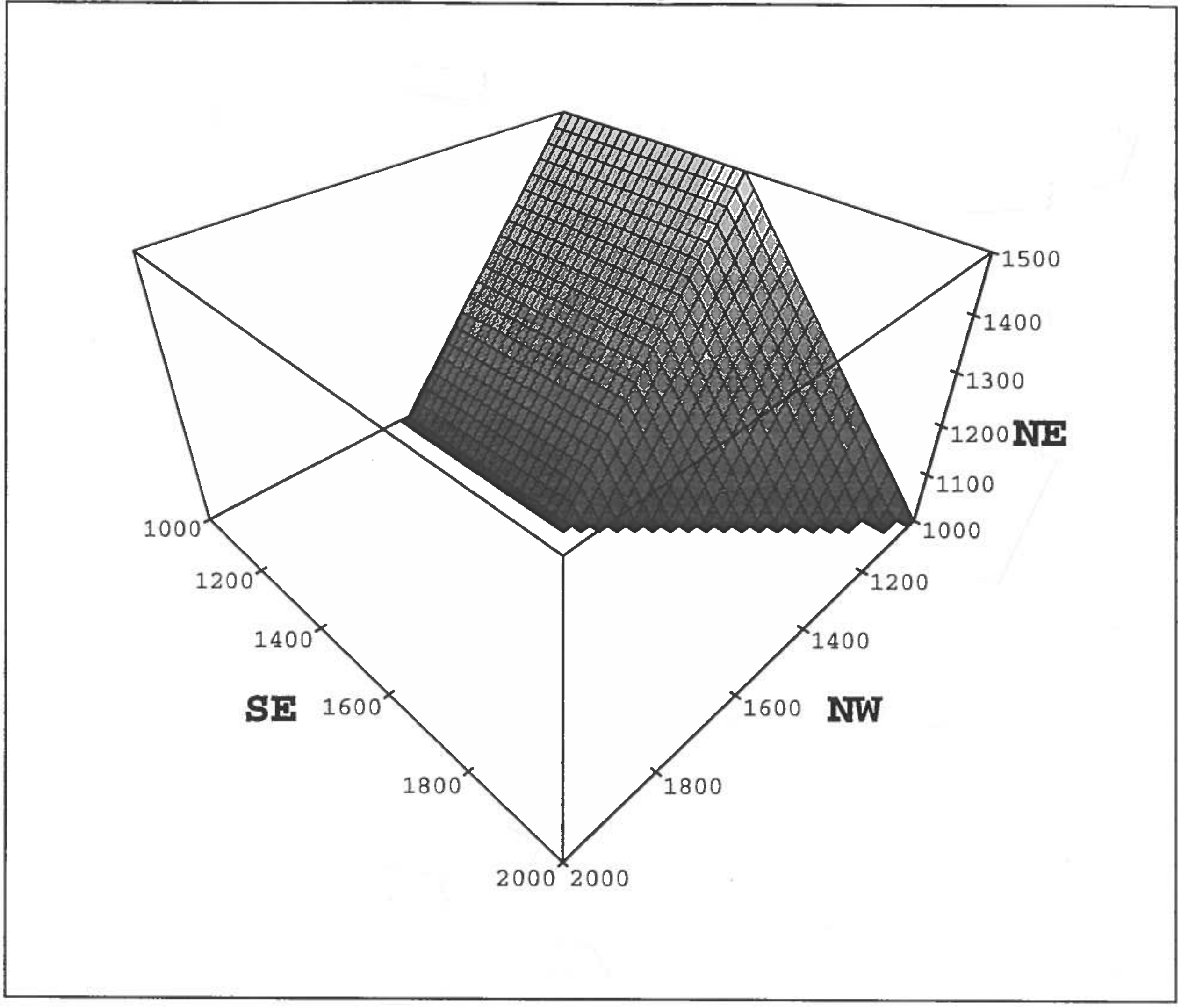
We now consider the case where phase-shifters *can* provide additional transmission capability by assuming that demand at SW increases above that illustrated in Figures 5, 6, and 7. In the example in Section 4 of the demand increasing from 3000 MW to 3250 MW, phase-shifters could be used to *restrict* supply. In contrast, in the case of demand increasing further, we will see that phase-shifters can be instrumental in *allowing* supply. If the phase-shifter were controlled with the goal of helping potential market participants to support incremental flows, then transmission capacity utilization can be increased.

In the case of phase-shifters, our equations change to:

$$\begin{gathered}0.8NW+0.6NE+0.2SE+S\leq 2000,\\ -0.2NW+0.6NE+0.2SE+S\leq 2000,\\ 0.2NW+0.4NE-0.2SE-S\leq 500,\\ 0.2NW+0.4NE+0.8SE-S\leq 2000,\end{gathered}$$

where S is the change in flow produced by the phase-shifter.[6] Figure 8 shows the surface defined by these constraints assuming that the phase-shifter is controlled to maximize the utilization of the transmission system. Notice that the feasible region shown in Figure 8 is considerably larger than the feasible region in Figure 4, indicating that the phase-shifter has increased the trade possibilities considerably. There are two facets in the feasible region. One is defined by the 4000 MW limit on total imports into SW, while the other is defined by the 2500 MW limit on total exports from the NW and NE. These are constraints on cut-set capacities. Notice that the phase-shifter allows operation up to the capacity of the transmission cut-sets. The other transmission cut-set constraints do not bind for the generations we consider.

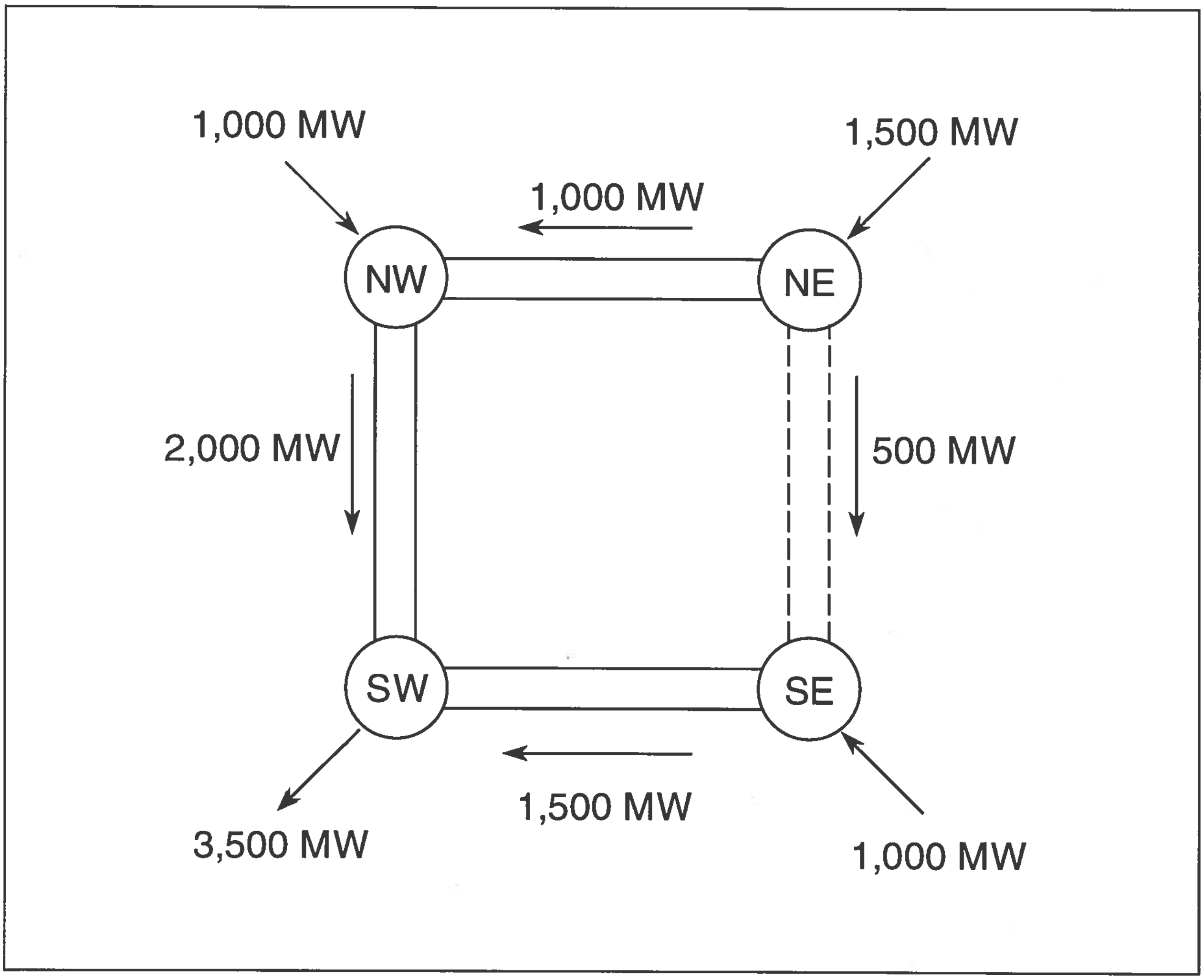
Figure 8. Feasible Generations at NW, NE, and SE Using Phase-Shifter



Again, we illustrate the increase in trade possibilities by considering some extreme cases. Consider Figure 9, which shows NE generation increased to 1500 MW and demand at SW increased to 3500 MW. In this case, the phase-shifter has been controlled to keep the NE to SE corridor flow to the limit of 500 MW. Again, the cutset formed by dividing north to south is at capacity and therefore no more transmission capability is available from phase-shifters to increase generation at NE. Nevertheless, 250 MW of additional transmission capability has been obtained compared to Figure 6. This operating point corresponds to the vertex at the top left of the surface in Figure 8. Further generation at SE can also be accommodated.

Consider Figure 10, which shows SE generation increased to 2000 MW and demand at SW increased to 4000 MW. In this case, the phase-shifter has been controlled to keep the NE to SE corridor flow to zero. Notice that the cutset formed by dividing the SW from the rest of the system is at capacity so that there is no more transmission capability to increase generation at SE. (In fact, there is no

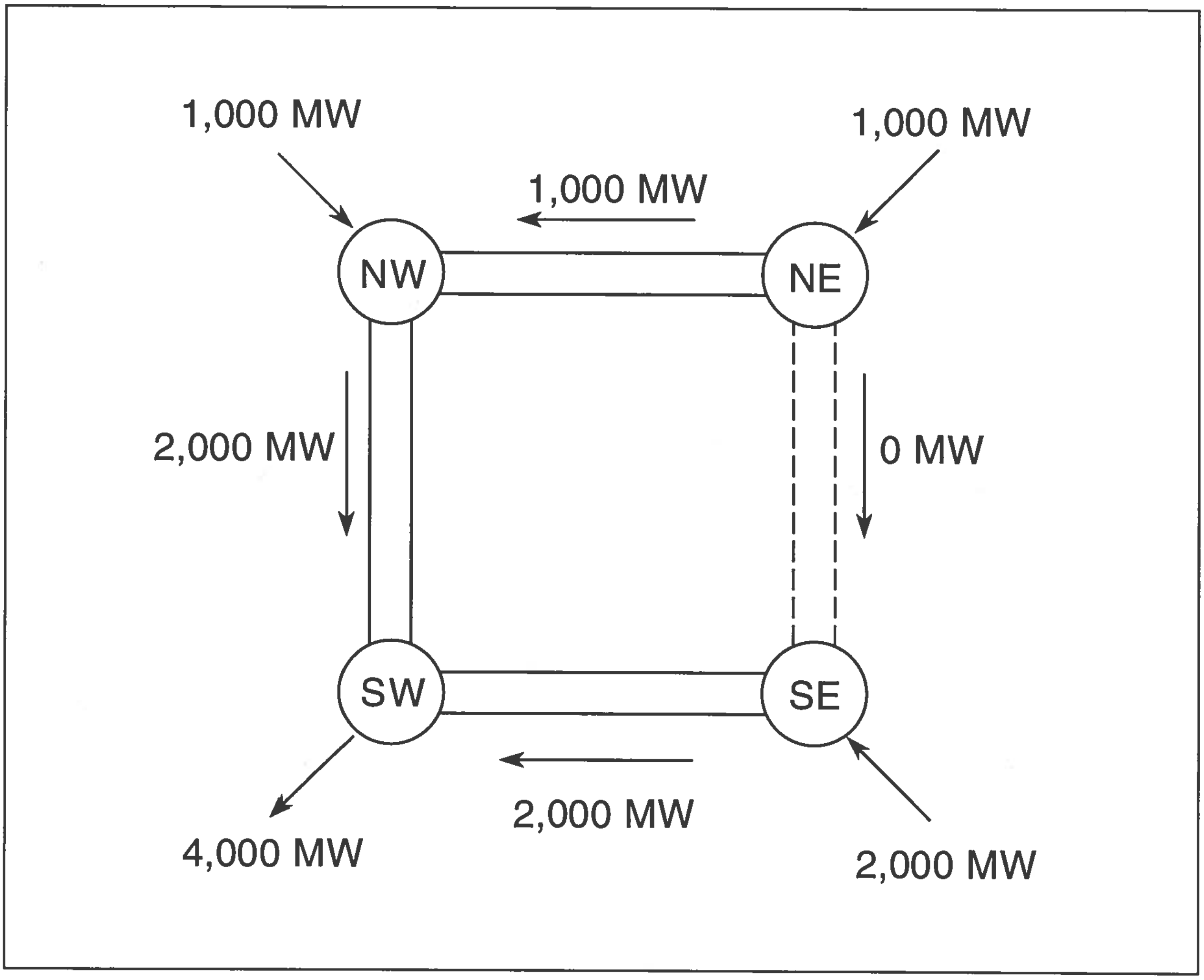
Figure 9. Actual Flows, NE Increase to 1,500 MW, SW to 3,500 MW, Phase-Shifter Adjusted to Limit NE to SE to 500 MW



capability to increase demand at SW through increasing generation at any of NW, NE, or SE because all transmission corridors into SW are fully loaded.) The same result could have been obtained in this case by opening the corridor between NE and SE; however, this may reduce the ability of the system to survive contingencies. This operating point corresponds to the vertex at the bottom right of the surface in Figure 8.

These examples show that phase-shifters clearly have strong potential for maximizing the utilization of the system, even when options for re-dispatching generation are not available. This poses a difficult problem for regulation of phase-shifting transformers because, on the one hand, it is important to harness competition to uncover potential increases in transmission utilization, but on the other hand, strong regulation of the control of phase-shifting transformers may be necessary to limit market power. In the next section, we discuss two different approaches to achieving efficient operation of phase-shifters.

Figure 10. Actual Flows, SE Increase to 2,000 MW, SW Increase to 4,000 MW, Phase-Shifter Adjusted to Reduce NE to SE to Zero



7. Encouraging Efficient Utilization of Phase-Shifters

Our examples illustrate the regulatory problem posed by decentralized implemention of control devices such as phase-shifters. Using phase-shifters to enforce property rights can be inefficient. Their potential use to expand trade may not be consistent with private motives. There are two potential remedies to this situation, either:

1) the conduct of phase-shifter owners could be subject to regulatory oversight, or,
2) structural changes in the organization of electricity trade could be introduced.

7.1 Regulatory Intervention

The regulatory alternative would inevitably rely substantially on information gathered by industry participants affected by foreclosure. The regulator always operates at a substantial information disadvantage compared to industry participants. Therefore, regulating the conduct of bulk power markets requires some method to reduce the information problem. Since transmission is necessary to electricity sales, it is in the interests of all participants to be aware of options for improving transmission utilization. Deliberate control by NE of its phase-shifter effectively to limit competition may be observed by competitors. Remedy may be sought either on a voluntary basis from an industry association or from the industry regulator.

Nevertheless, observation of phase-shifter operation to limit competition depends on there being sufficient technical expertise available to competitors. Therefore, it is to be expected that smaller utilities, which typically have smaller and perhaps less sophisticated technical staffs, will possess less capability to detect such behavior. In a large and complicated system such as the WSCC where there are a large number of phase-shifters, deliberate action to limit scheduling capacity may be more difficult to detect than in our simple system. However, as remarked above, the presence of a complex meshed network in this system also makes it more difficult for a single phase-shifter to have a large influence.

In addition to the observation problems inherent in the regulatory approach, it is probably better adapted to restraining abuses than to implementing positive solutions. The regulation of conduct is fundamentally reactive. Even if it succeeds in limiting market power, there is no reason to believe that it will foster the kinds of efficiencies discussed in Section 6.

7.2 Structural Change

Alternatively, the competitive problems illustrated by these examples are precisely the kinds of cases that underlie proposals for structural changes to the organization of electricity trade. Most of these proposals have in common an independent system operator (ISO) that would manage technical constraints in the network in an unbiased fashion to facilitate trade (Wu and Varaiya, 1995; Stalon and Woychik, 1995). The ISO concept has been implemented in a number of countries, usually in the setting of centrally managed pooling institutions. The discussions in the US of the ISO concept are still exploratory, and have not converged on a market model that is generally accepted. Moreover, these discussions have not yet addressed the role of either initial endowments of property rights or the operation of control devices in the management of electricity competition. The general line of argument in these proposals, however, would support the centralized operation of phase-shifters by an ISO under almost any market model, because of the potential for decentralized control of phase shifters to affect the terms of trade to the benefit of individual agents.

Structural reform of electricity trade based on an ISO would require redefining the roles of existing industry institutions, principally voluntary industry associations, such as the reliability councils and regional transmission groups (RTGs), which currently perform, or propose to perform, related functions. The reliability councils have traditionally been closely involved with operational issues, which would argue for coordinating an ISO function with that activity. The reliability councils, however, have historically been reluctant to engage in coordinating economic functions. RTGs are emerging institutions, and their role is less clearly defined (Kahn, 1994). Their principal orientation is more toward long term planning issues, which is less compatible with the trade issues discussed here. On the other hand, RTGs are more clearly chartered to address economic issues than the reliability councils. The economic orientation would argue for amalgamating an ISO function with an RTG.

The operational requirements for unbiased management of electricity trade through an ISO would necessitate an asset transfer to shift financial responsibility for phase-shifter costs from their current owners. Instead of the current decentralized financial responsibility for phase-shifter costs, ISO operation would require some grid tariff mechanism that would compensate the ISO for its costs and share them among market participants. Economic realignment of this kind can be difficult to negotiate. Previous experience with interstate cost sharing mechanisms for transmission has been contentious, since some parties' positions will improve, while others will be harmed compared to prior arrangements. Maliszewski (1995), for example, gives an account of these difficulties in the case of a multi-state holding company. The WSCC agreement itself is a good example of the difficulties that arise in negotiating multi-state agreements.

The transactions costs of establishing an ISO are much greater than relying upon regulatory intervention. The prospects for satisfactory regulation, however, may not be promising, particularly with regard to complex coordination schemes to enhance total utilization of the network.

8. Conclusion

Increasing competition in bulk power markets raises the prospects of inefficient use of control devices such as phase-shifters for the commercial advantage of individual agents. The legal fiction of contract paths could easily facilitate such problems. We have illustrated both the potential inefficiencies as well as opportunities for better utilization of the network.

The regulatory problem posed by these technical possibilities requires further examination. Although the transactions costs associated with establishing an ISO are significant, it may be necessary in the long run. There are a number of questions that will need resolution for successful management of an electricity trading regime. These include both short run and long run issues.

In the short run, a reasonable role for the ISO is to facilitate trade by ensuring that transmission capability is matched to the availability of generation resources. As our examples show, phase-shifters can facilitate this goal; however, the coordination of multiple transactions requires considerable knowledge about the generation costs and transmission system (Wu and Varaiya, 1995). It may be possible, nevertheless, to facilitate most of the potential trades by making use of simple operational rules. For example, one simple rule that *may* yield reasonable outcomes and encourage beneficial trades is to always operate the phase-shifters to even out the excess capability on transmission paths as much as possible. Whether such rules do indeed yield favorable outcomes is the topic for further research.

In the long run, new investment in transmission capacity will be required. In the evolving institutional framework of electricity it is increasingly unclear how the decision will be made to expand the network. RTGs are the most likely candidate for the planning analysis. In the planning process, phase-shifters are one candidate to relieve congestion that is associated with loop flow. To facilitate evaluation of this alternative there must be some consensus on the operation of such control devices.

Therefore something equivalent to an ISO rule for operating phase-shifters needs to be established for planning as well as operating purposes.

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Appendix: Calculation of Line Flows

The DC loadflow assumption means that flows on paths will be proportional to susceptance, which is the inverse of the path reactance. For example, for generation at NW and load at SW, the two paths from generation to load are the direct NW to SW line and the longer path from NW via NE and SE to SW. The reactance of the direct path is 1 unit in parallel with 1 unit, which is 0.5 unit, yielding susceptance of 2 units. The longer path has reactance 0.5 unit in series with 1 unit in series with 0.5 unit, which is 2 units, yielding susceptance of 0.5 units. Therefore, generation at NW splits in the ratio 2 to 0.5 between the direct and longer paths, respectively.

Generation from NE splits in the ratio 1 to 2/3 between the scheduled path via NW and the alternative path via SE. Generation from SE splits in the ratio 2 to 0.5 between the direct and indirect paths. Total flows can be calculated by adding together the flows due to each generator.

These approximations are often well satisfied in typical networks although under conditions of heavy flows the losses and reactive power flows can have a significant effect. Even under heavy loading, however, the DC loadflow equations are usually a good representation of the qualitative real power flows. Further details concerning the DC loadflow approximation can be found in Wood and Wollenberg (1984).

Acknowledgment

This research was funded by the California Energy Commission under Interagency Agreement No. 700-93-003 with the University of California Energy Institute. The first author was supported in part by the National Science Foundation under Grant ECS-9457133.

Endnotes

1. Besides the choice of base case, there are two other normative flaws in this allocation. First, averaging the percentage effectiveness combines quantities inappropriately. A better measure of effectiveness, for example, would be to sum the MW flows that a given phase shifter can control and divide by the sum of the path capacities. Second, the allocation assumes that 100% control corresponds to 100% cost recovery. However, 100% is an arbitrary datum that is not necessarily related to the design and cost of the phase shifter.

2. Recall that the complex impedance is the sum of resistance and the square root of negative one times the reactance. For our lossless lines and with no shunt elements modeled, resistance is zero, while the reactance is positive. Complex admittance is the sum of the conductance and the square root of negative one times the susceptance. For our lossless lines, the admittance of the line has zero conductance and negative susceptance. For convenience in the text, we will use susceptance to refer to the absolute value of the susceptance.

3. There are various ways that MW-mile pricing can be implemented. In our example the contract path from NW via NE and SE to SW would result in "counterflow" along the NW to NE line. If that resulted in a pricing credit, then this long path would be charged a lower rate than if all three line segments were charged.

4. If the prices paid by SW to its suppliers are based on a split savings rule, for example, then it is still in NE's interest to limit sales to SW from cheap sources, even if NE does not supply the incremental demand itself.

5. In an actual lossy system, the reduction in flow along the NE to SE and the SE to SW corridors will decrease losses, while the increase in flow along the NE to NW and the NW to SW corridors will increase losses.

6. Phase-shifting transformers insert a variable phase-shift in the line. We can convert from the phase-shift to a shift in the line flow, and vice versa, assuming that the phase angle capacity of the phase-shifter is not exceeded.