IMPACT OF NETWORK TOPOLOGY ON STEADY STATE CONTROL INTERACTIONS AMONG SERIES FACTS DEVICES

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Abstract

One of the attractive control objectives for series connected FACTS devices is regulation of active power or current flow through the device. Such regulation can improve the "natural" flow within a network, permitting more even loading of the various network components, enhancing security margins, and reducing system losses. Series devices include TCSC, UPFC and TCPS, as well as power electronic enhancements to traditional devices such as phase shifting transformers. This paper examines the impact of network topology on the siting of flow control devices, exploring implications for control when interacting series devices are attempting simultaneous flow regulation. An efficient graph theoretic algorithm is presented to quantify the potential steady state control interactions among series devices, based exclusively on the topology of the network. It is shown that a set of devices spanning a "cutset" cannot all be used to regulate either power or current flows without undesirable consequences. An "interaction index" to quantify the degree of interaction among series devices and line flows is defined. Finally, in cases for which interactions can occur, simple modifications are proposed for the controllers to mitigate undesirable consequences of series device interactions.

1 Introduction

Series FACTS devices and other series components intended for use in a power system have been advocated as useful tools for modifying the "natural" flow of electric power on the network, permitting the more even loading of the various network components, increasing security margins, and reducing system losses [1], [2]. The placement of

FACTS devices has appeared as an important topic in current literature in the field [3]. Power system engineers must be concerned about not only with the placement of these devices, but also with potential interactions among them [4]. In this paper, steady state control interactions among series devices are analyzed. The proposed idea is to assign "interaction indices" to each branch that is relevant to the placement of a series FACTS device. Series devices include TCSC, UPFC and TCPS as well as slower reacting devices such as phase shifting transformers [5], [6] and [7].

These proposed "interaction indices" will help an engineer make better choices when placing series FACTS devices and/or selecting the proper control modes for the device. Some series devices (such as TCSC) can be used to regulate the effective series impedance of a line. However, in many proposed applications, it will prove useful to operate a series devices to regulate either the power or the current through a given line. Clearly, perfect control of flows is not universally feasible. For example, in a steady state power flow model, the flow in a radial line cannot be controlled because the power going to the remote bus may be determined by a constant active power draw at the load. More generally, any combination of devices that partitions the network creates a possibility for flow control setpoints that can be incompatible with the power flow constraints on a network. Physical proximity of these devices is not necessary for such adverse interactions. Any combination of devices that renders one or more links critical for connectivity indirectly controls the flows through these links. The "interaction index" would automatically show these without the engineer having to look for radial lines, critical connections or splits in the network. An interaction index is proposed to establish which control combinations are impossible. The theory that leads to "interaction indices" is explained in the following two sections. This is followed by the description of a suggested algorithm to compute these indices for arbitrary networks and by several illustrative examples.

Start with the notion of a power system describable as a simple directed graph in which every physical bus forms a node. Every physical system branch (transformer or line) connecting a bus (node) i to a bus (node) j is represented as by two directed edges in the graph, one directed from i to j, and a second directed from j to i. All shunt devices may be ignored for the topological analysis to be performed here. This includes shunt susceptances of line models, loads, generators, shunt capacitors and in general any other shunt device.

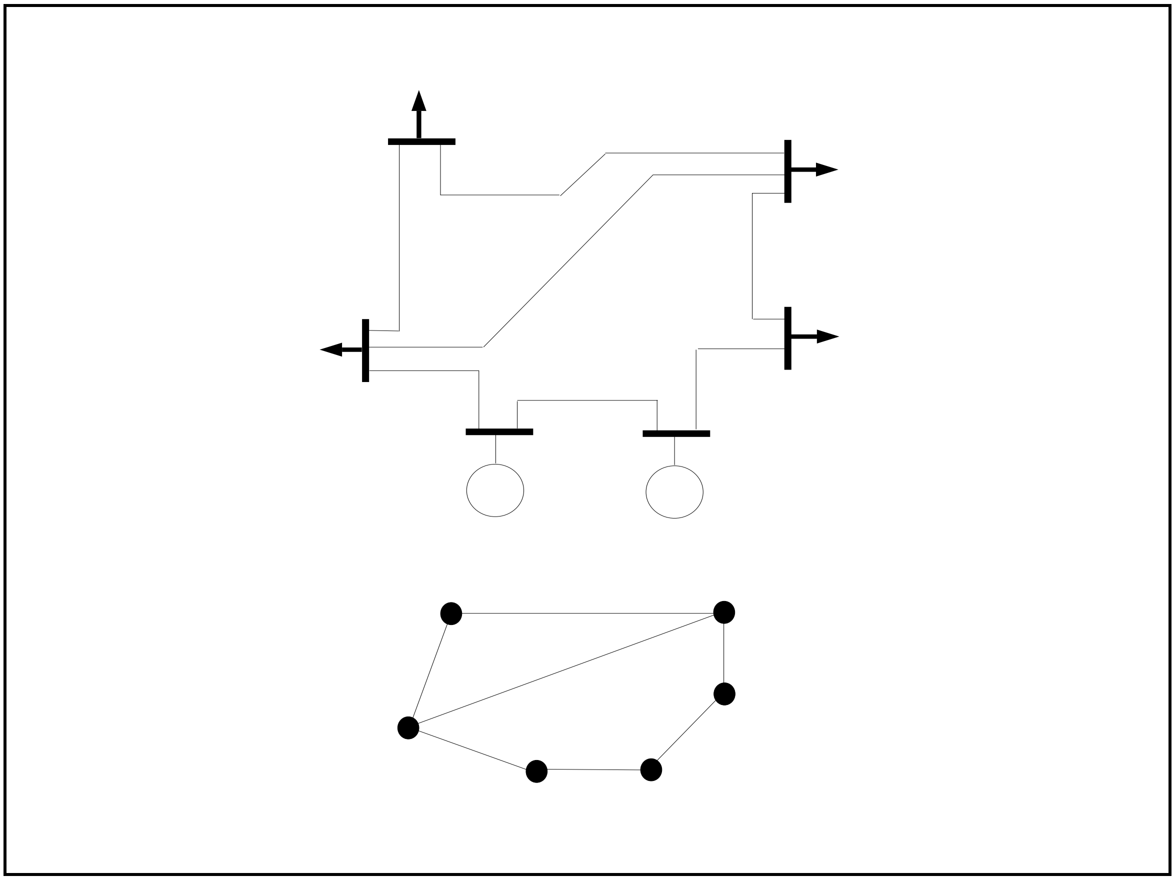

Figure 1: One line diagram and its corresponding graph

Figure 1 illustrates a one line diagram for a system and its corresponding graph. A *cutset* of a graph is a set of branches that partition the graph into disconnected subgraphs [8]. Figure 2 illustrates a cutset. There are many cutsets possible. Also, every branch belongs to one or more cutsets. The *cardinality* of the cutset is the number of branches in the cutset. A branch can be associated with cutsets of different cardinalities. It is of interest to consider the minimum and maximum cardinality of the cutsets associated with a given branch.

There are some cases for which the computation of the cardinality of a branch is trivial. For a tree, both the minimum and maximum cardinalities of any branch are exactly one: any branch removal splits the network. For a completely dense graph with *n* nodes, the cardinality is *n*-1. In general, the minimum and maximum cardinalities are not the same. The minimum cardinality is of greatest interest, and will be termed simply the cardinality of a branch.

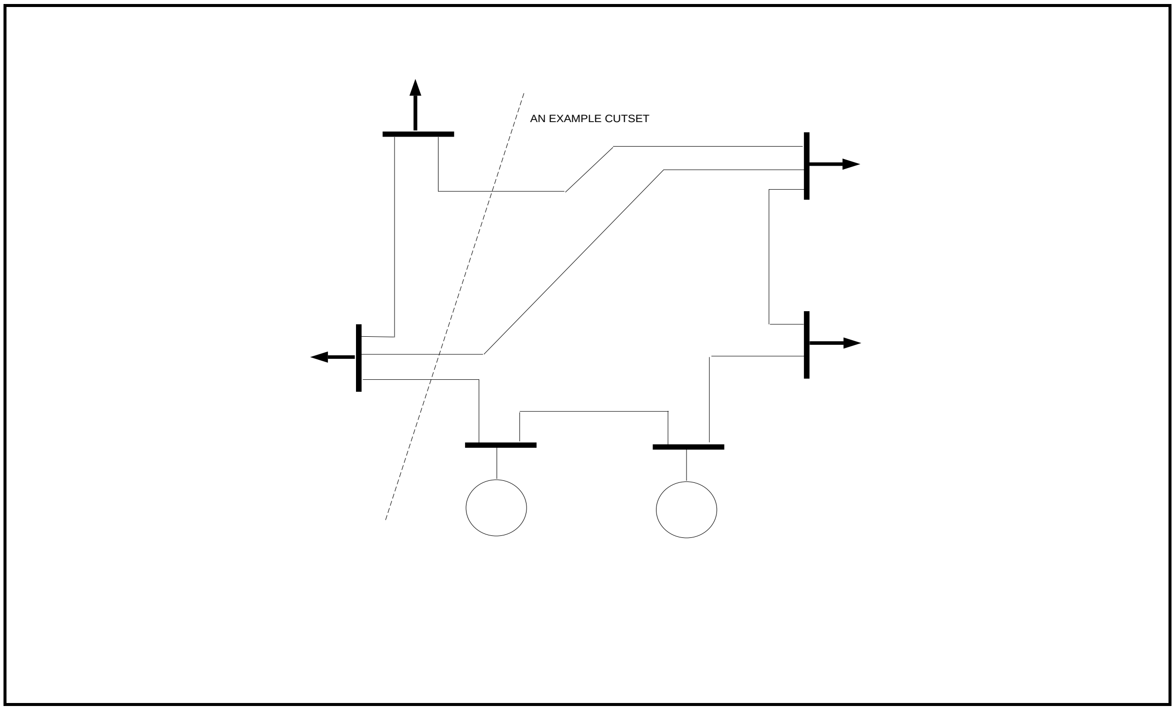

Figure 2: Example of a cutset that isolates two buses from the rest of the system

To find the cardinality of the branch between nodes i and j, we must partition the set of nodes S into two sets S_1 and S_2, with

- $S_1 \cap S_2 = \varnothing$
- $S_1 \cup S_2 = S$
- $i \in S_1, j \in S_2$
- The number of connections between S_1 and S_2 is minimized.

The features of this problem allow its solution by very efficient algorithms for general graph theoretic problems. Most critical is the fact that, by selecting a branch of interest in which the flow control device lies, we are also specifying the two nodes (buses), i and j, that must lie at opposite sides of the cutset. This indicates that the problem is an instance of the well-know "Max-Flow, Min-Cut Problem," examined in the classic work of Ford and Fulkerson [9]. Since that original work, tremendous advances have been made in algorithms for efficiently solving these problems, with particular attention to network sparsity. Algorithms for the maximum flow problem have been developing rapidly in recent times. Currently, solutions of $O(EV\log(\frac{V^2}{E}))$ are available, where V is the number of nodes (buses) and E is the number of edges (branches). For a highly accessible overview of these problems, the reader is referred to Chapter 3 of [10]. The essence of the preferred solution algorithm is paraphrased below:

Consider the edges of the network to correspond to pipes with given fluid carrying capacities, and the nodes to be pipe junctions. Each node has an outflow pipe to a reservoir that can accumulate fluid. Additionally consider each node and its reservoir to be on a platform whose "height" increases as the algorithm progresses. The source height is fixed at *V*, and the sink height fixed at zero. All other nodes are initialized to a height of zero.

The algorithm proceeds by pushing fluid "downhill." Initially all routes from the source are filled to capacity, which accumulates in the neighbor nodes reservoirs. This excess is eventually pushed downhill. When all the pipes that leave an overflowing node *u* which are not filled to capacity connect only to nodes on the same level or are higher than *u*, the height of *u* is increased to one unit more than the height of the lowest neighbor to which an under-capacity pipe connects.

Eventually the amount of flow arriving at the sink is maximized. The algorithm then gets rid of the overflows by sending the excess back to the source by lifting the overflowing nodes above the source. Once all the overflows are eliminated, the flow is a maximal flow. The cardinality of the minimal cut is the value of this flow if all edge capacities are equal to one.

2 The Interaction Index

Topological cardinality indicates simple feasibility of locating FACTS devices, but says nothing about the impact of these devices on other branches. That is, if the cutset contains 5 branches and FACTS devices are placed at four of the locations, then the 5th branch can not be controlled, otherwise some part of the network will be isolated. Certain controls could be seen to be impossible right away. For example, any branch that has an index of one would split the network and should not be controlled. Radial lines are good examples to this argument, any radial line would have an index of one and this would automatically show in the interaction index.

An interaction index quantifies the degree of freedom of locations. As the FACTS devices are placed in the system the indices need to be updated. So when another device needs to be placed, it is clear where not to place it. An example of this is illustrated in Figure 3, where the index of each line is shown before and after a device is placed on one of the branches.

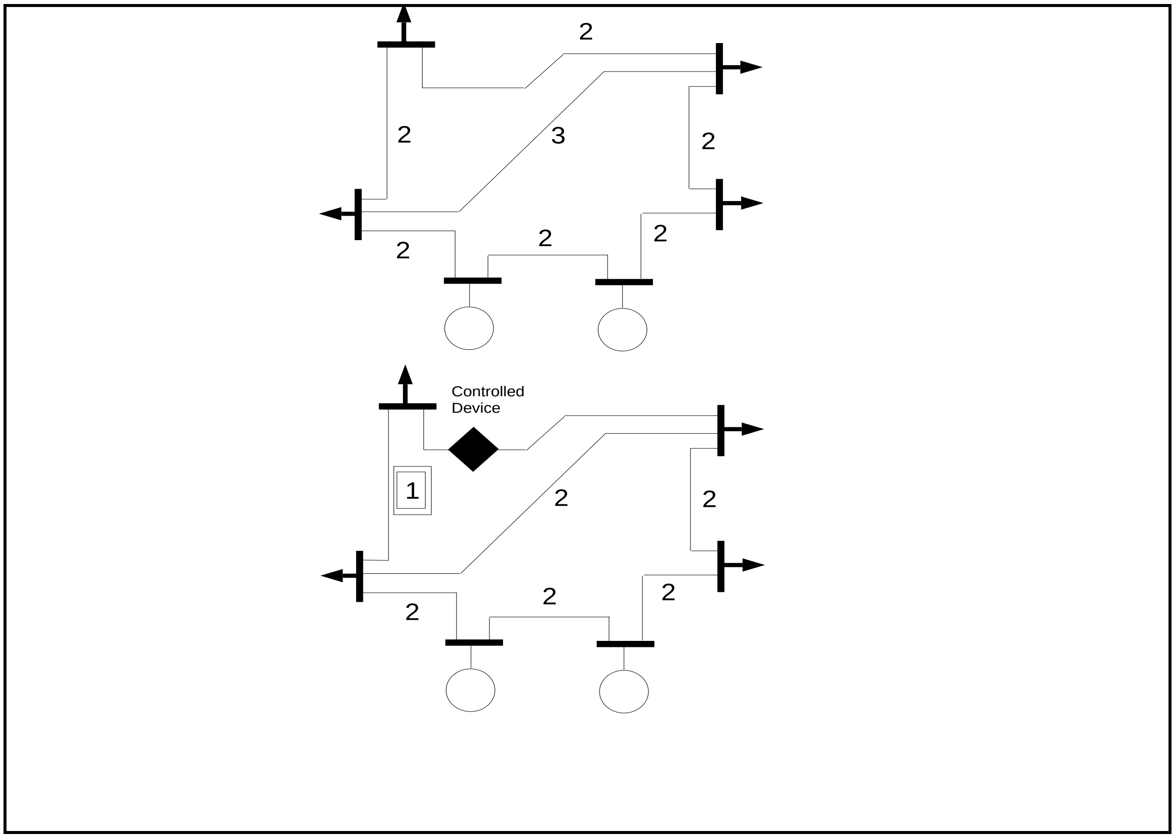

Figure 3: Interaction indices before and after placing a FACTS device

Two devices interact if controlling P in one determines P in the other. Thus the second device may not also control P. It is important to know when the degree of freedom of another branch changes, especially when it becomes one. Therefore *change* in degrees of freedom is used to identify interaction between locations. If the final degree of freedom is one, coordination is essential. If the final degree of freedom has changed but is greater than one, coordination is recommended. As can be seen from Figure 3 after a device has been placed on one of the lines and the indices are updated, one of the lines gets an index of one. Any line with an index of one is an improper place for an additional series device attempting to regulate a flow. This small system example is used to show how the interaction index idea works. The algorithm explained in the previous section would enable one to do the updates of interaction indices after each device placement helping the engineers in their placement choices.

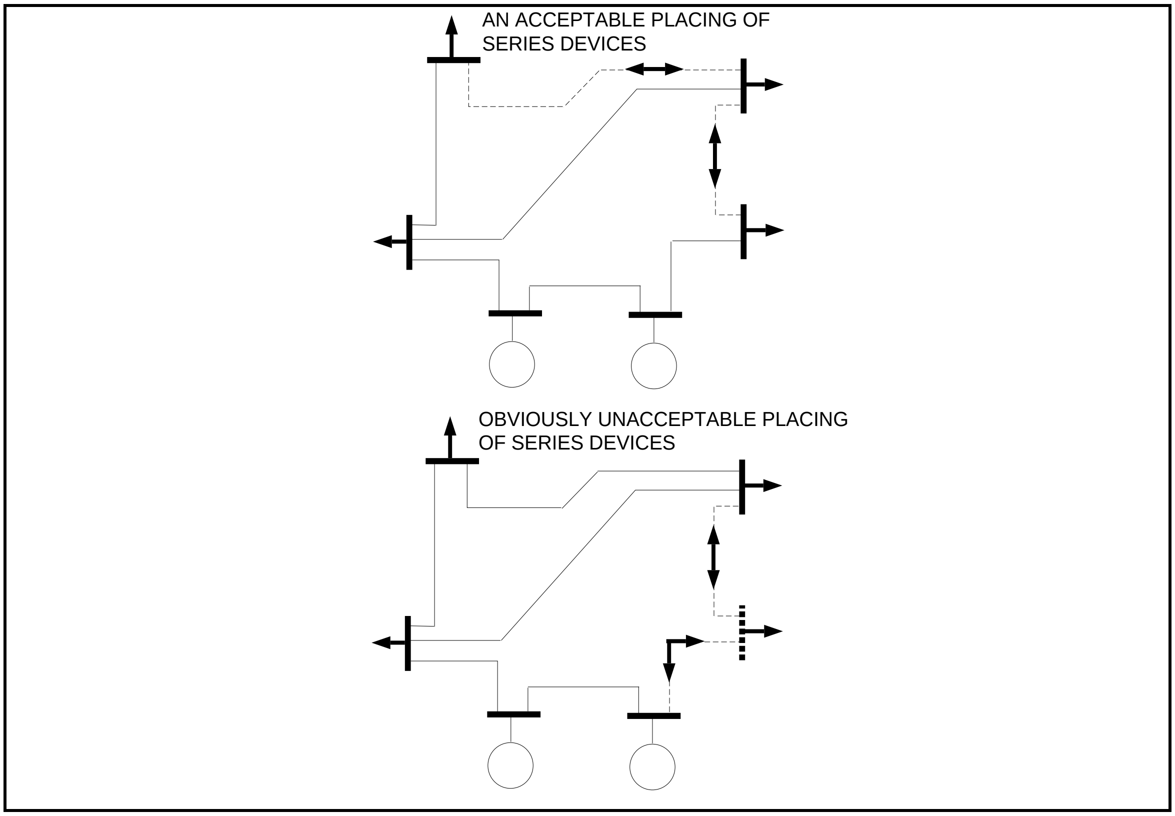

Figure 4: Acceptable and unacceptable placement of devices

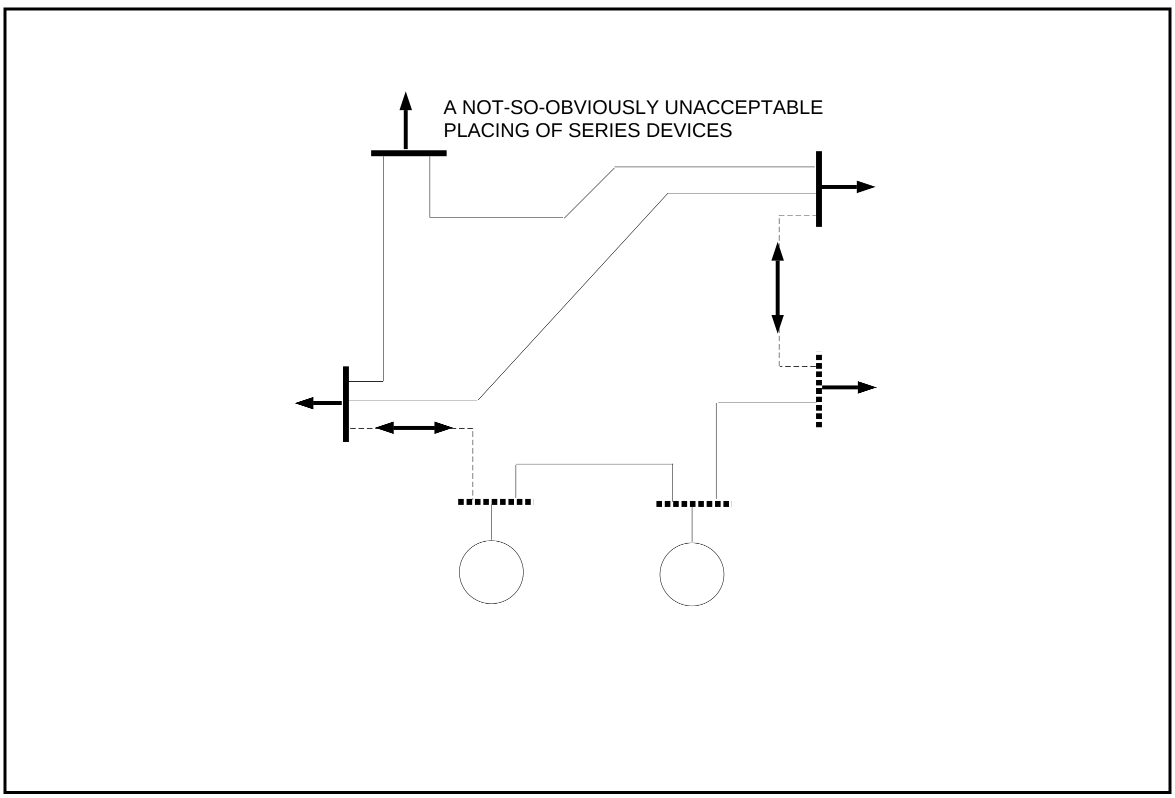

Figure 5: More subtle control conflict situation

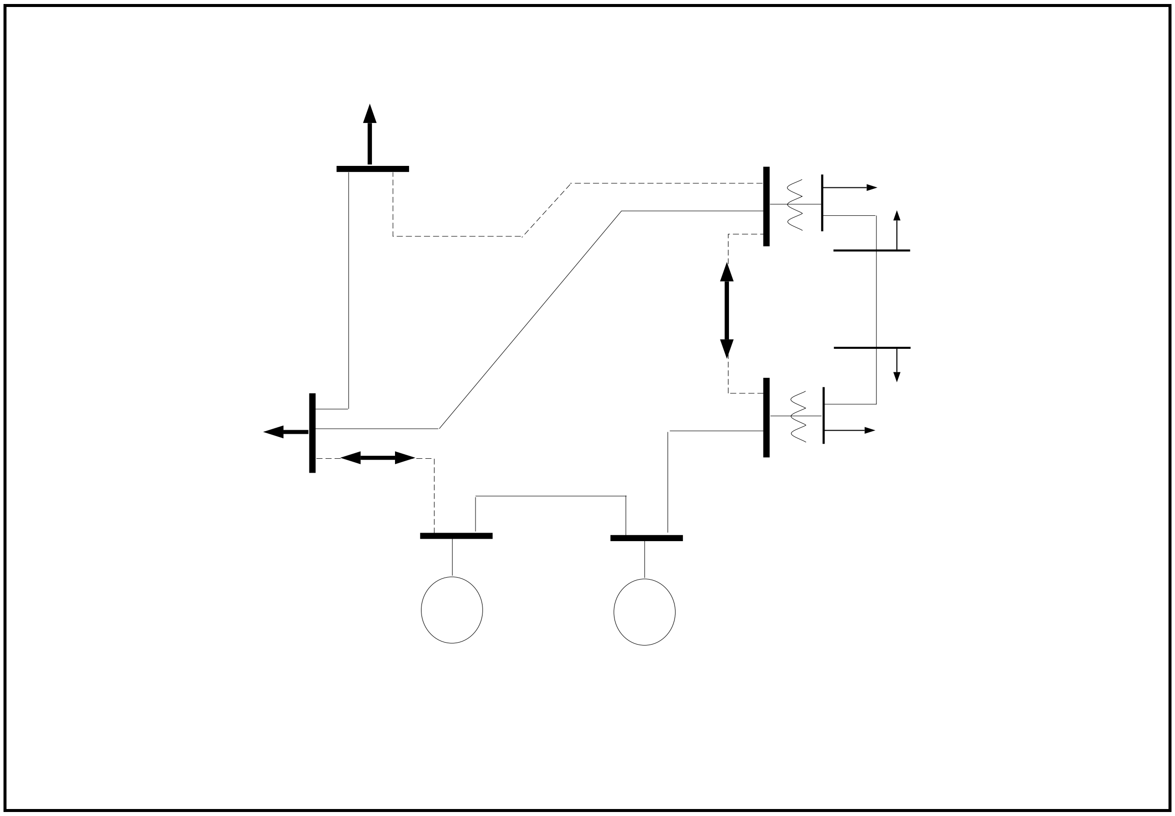

Figure 6: Potential overloading of low voltage circuits by control of high voltage flows

3 Voltage Level Issues

In some cases, controlling a FACTS device on a high voltage line may overload lower voltage lines. It is necessary to take into consideration the voltage class in assessing the controllability of flows. If the power flow connection of a certain number of nodes to the main network is controlled that part of the network becomes isolated. It would be possible to see this from the interaction index, however if the high voltage connections are controlled and the low voltage connections still exist this would overload the low voltage lines. In Figure 4 an acceptable placing of series devices is shown, along with an obviously unacceptable placing. Figure 5 shows a not-so-obvious unacceptable placement of devices.

In reality, it is unlikely that the network would be truly disconnected as a result of the two devices. More than likely, there would be some lower voltage connection between the two seemingly disconnected portions of the network. This is shown in Figure 6. While theoretically feasible, such a configuration would imply that adjustments to the controls of the high voltage FACTS devices would have to be absorbed by the lower voltage portion of the network. This would probably not be acceptable. Thus, topological controllability should be restricted to network graphs formed from either a single voltage class or at most from two adjoining voltage classes.

4 Adaptive Admittance Limits for Interacting Flow Controllers

As noted above, in a power flow formulation treating load and generation active power injections as given, interacting devices across a cutset can not regulate (current or active power) flow independently. This section describes what would happen in an actual system if interacting steady state control orders were to be issued, and proposes an adaptive methodology for coordinating controls under these circumstances.

If one considers in more detail the possible outcomes of such interaction where devices are attempting simultaneous flow control across a cutset, (at least) three possibilities present themselves. For illustration, consider a representative TCSC device with PI control on line current, as illustrated in Figure 7 below. The three possibilities of interest may be summarized as follows.

- First, one or more of the controllers might encounter its limit on achievable admittance, as represented by Y_{max} and Y_{min} in the K_g element of the block diagram in Figure 7. Once saturated, the device no longer controls flow, and, by our strict definition, is no longer interacting with other flow control devices.

- The second possibility is clear in the case of the radial line example discussed earlier. The TCSC can succeed in controlling current or active power flow only if the load has a voltage dependent component (though this component may or may not be represented in a power flow model). The result would be potentially significant deviations in load voltage, in response to the device's attempt to regulate flow. For the discussion to follow, we will focus on the problem of low voltage at the receiving point, though the technique to be proposed is amenable to handling either under or over voltage.

- A final potential problem associated with interacting controllers is obvious: active power imbalance can be created on either side of the cutset. This would typically create instantaneous frequency errors due to governor droop, on a time scale comparable to the first stage of generator governor response. On a longer time scale, automatic generation control (AGC) would act to correct this imbalance, but at this will have undesirable side effects. For simplicity in the presentation to follow, we will focus on the potential problem of frequency dropping at the sending end of the series FACTS device.

Faced with these three potential outcomes in the case of interacting flow controllers, a wide range of possible corrective steps are possible in the control loop. However, the first of the three possibilities discussed above suggests a natural solution. Once a controller has saturated, its behavior returns to a constant admittance, and it is no longer interacting.

In considering limits on a device, it is clear that any FACTS device will have limits on its achievable flow control dictated by inherent firing angle limits. In the illustrative case of a TCSC device, these limits will also include the protective action to limit maximum voltage across the series capacitor element. However, these types of inherent admittance limits imposed by firing angle constraints may not be tight enough to avoid the potential problems of voltage or frequency drop. We propose to "rein-in" the control by making these limits on achievable admittance depend on external signals. In particular, for the problems discussed above, the upper limit on allowable admittance is reduced when significant frequency drop is observed on the sending end. Conversely, the lower limit on allowable admittance is increased when significant voltage drop is observed at the receiving end.

The key selections in designing the adaptive saturating. These adaptive limits are attained by replacing the fixed limits Y_{min} and Y_{max} in Figure 7 with functions denoted as $sat_{high}(\Delta\omega)$ and $sat_{low}(\Delta V)$. Here $\Delta\omega = \omega_{send} - \omega_o$ and $\Delta V = V_o - V_{receive}$, where ω_o and V_o are nominal frequency and voltage magnitude. An important objective is that the controller relax its flow control when its role in a set of interacting controllers is the likely cause of frequency or voltage problems, but not to over-compensate for problems that may have other sources. In our context, this suggests that the variable upper limit should not drop below the nominal admittance of the device that corresponds to the "center" of its control range. Similarly, the variable lower limits shouldn't rise above a selected "center" point for achievable admittance. Representative $sat_{high}(\Delta\omega)$ and $sat_{low}(\Delta V)$ plots can be based on offset arctan functions, as pictured in Figure 8. Y_o denotes a selected admittance center point.

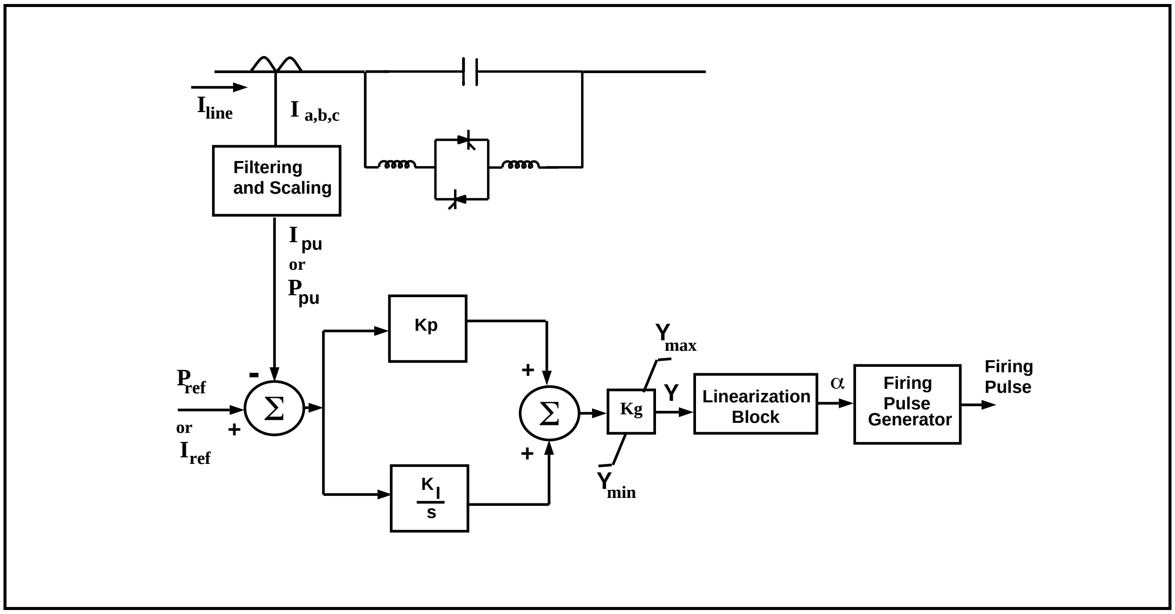

Figure 7: Block diagram of adaptive interactive flow controller

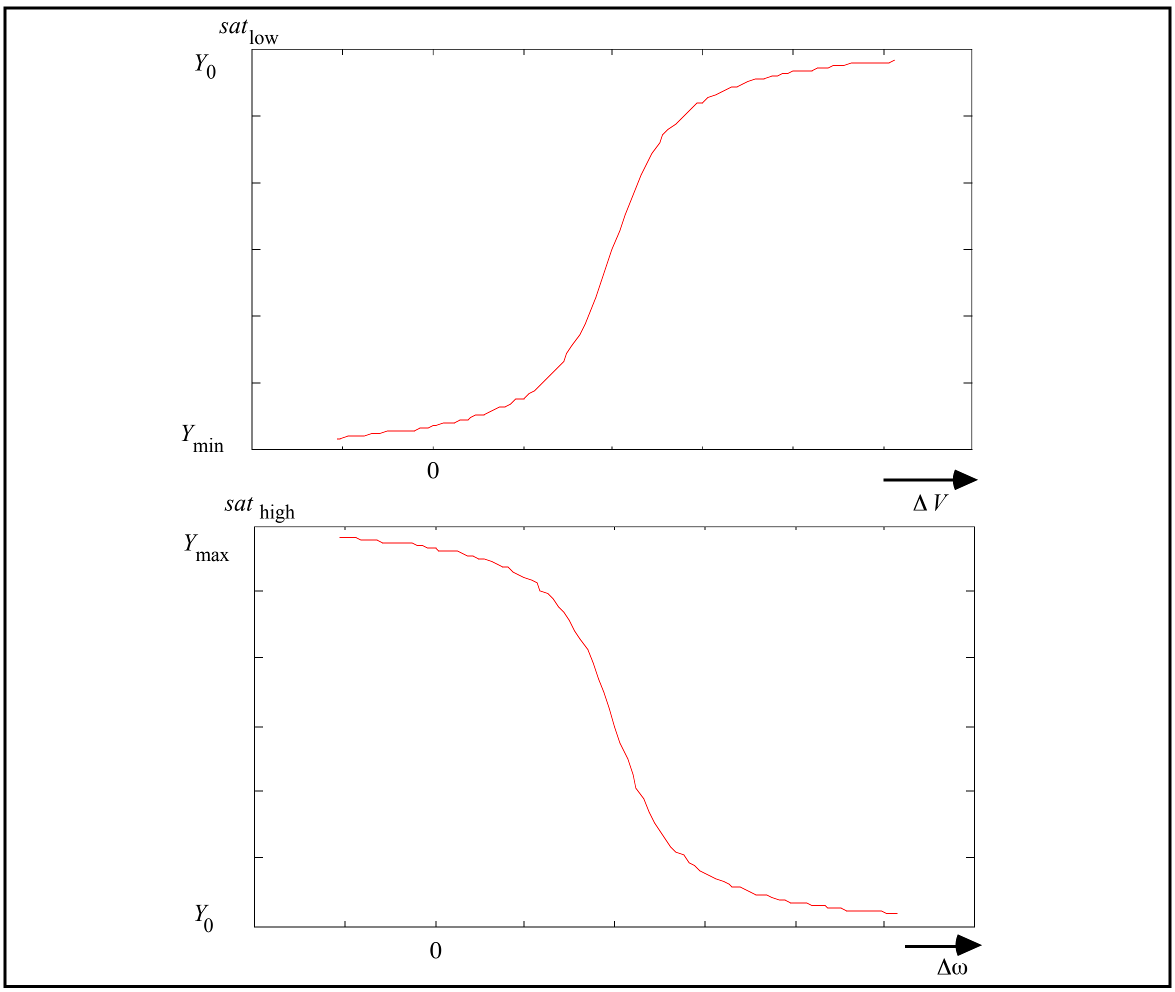

Figure 8: Representative Low and High Limit Saturation Functions

The voltage dependent admittance limit proposed above is reminiscent of the voltage dependent current order limit (VDCOL) often employed in control of HVDC transmission. HVDC links are often employed as connections between asynchronous systems, and in that case form a cutset of a single branch. For this special case, the VDCOL action would constitute an instance of the voltage based control limits being proposed here.

5 Numerical and Topological Results

In addition to the several small examples in the previous sections, we have performed experiments on larger systems. The system illustrated in Figure 9 was used to study device interaction problems. The system contains 131 buses (plus several trivial "buses" associated with series compensation devices). It has a total of 259 branches, plus 2 dc lines. If it is assumed that the dc lines are normally used in a mode where either the power flow or the current is regulated, these lines can be simply *removed from consideration* for topological analysis. Several experiments were performed. The results of one experiment are illustrated: if the flow on the line shown is regulated by a FACTS device, the lines that are highlighted become critical and FACTS devices at these locations have a potential for conflict with the first device. In addition, several other lines do not become critical, but the cardinality of their minimum cutset is reduced, indicating an interaction.

The algorithm used to determine the effect of one device on others involves the repeated use of the cutset algorithm. First, the minimum cardinality cutset for every location is determined. Then, a device is placed at a given location (in effect, the corresponding line is *removed* from the diagram) and a new minimum cardinality analysis is performed. Next, any branches where the minimum cardinality has decreased are identified. In the example at hand, there are 54 branches with reduced cardinality, six of them now critical. Those lines that have become critical are highlighted in the Figure. These lines are locations in direct conflict with the devices already in place.

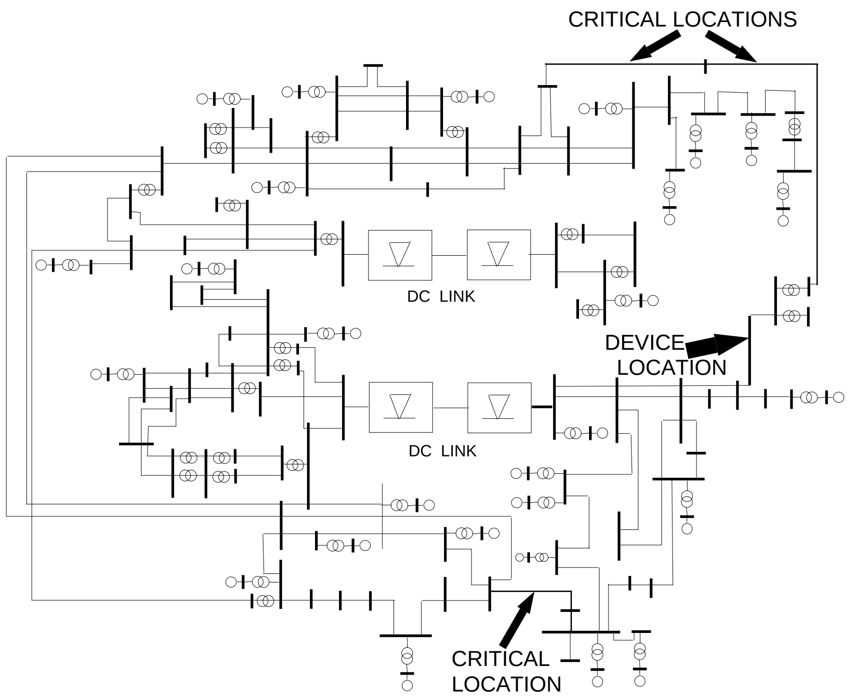

Figure 9: Test system illustrating the new critical locations as a result of placing a series FACTS device at the location indicated

When the system was run until voltage collapse conditions were attained, the lines that became overloaded at this point were detected. The most overloaded lines were located at the "north" part of the test system right along one of the tie lines. When a FACTS device is used to limit the power flow at this location, the only "other" tie line available for the power to flow gets overloaded. When this line is fixed by means of another FACTS device at a given constant maximum power, separation eventually occurs precisely along the lines predicted by the topological analysis as critical locations. These results confirm that the cutset found by the algorithm mentioned above is in fact important. System separation occurs exactly across the same lines that got overloaded as was shown by the algorithm.

6 Conclusions

Series FACTS devices can have far reaching effects within a networked system. This paper has presented a simple means for quantifying and understanding interactions among series FACTS devices using purely topological considerations. The notion of minimum cardinality cutsets, and in particular, the notion of *changes* in the value of these minimum cardinality cutsets can be used to identify conflicts among devices. It is expected that this type of analysis will lead to better methods for siting devices. Furthermore, the on-line use of these ideas can detect and prevent operational conflicts in systems when line outages or other discontinuous changes in the system take place. As a minimum, the foregoing is expected to contribute to the understanding of interaction phenomena.

Acknowledgments

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