A Deterministic Approach to Locating Series Flow-Controllers Within Transmission Systems to Alleviate Congestion

Paul Cuffe^a, Andrew Keane^b

^aSchool of Electrical & Electronic Engineering, University College Dublin, Ireland and Visiting Scholar, University of Melbourne ^bSchool of Electrical & Electronic Engineering, University College Dublin, Ireland

Abstract

This paper proposes a new technique to intelligently split busbars within a meshed power system, to facilitate the insertion of series active power flow-controllers into the high voltage transmission systems. Such flow-controllers have historically been placed at system and national boundaries to modulate cross-border flows for regulatory, commercial and security purposes. The present work proposes a new concept for power system control, and embeds series flow-controllers *within* meshed transmission networks to gauge the extent to which their dispatchable flows can be used to alleviate thermal congestion. To articulate the value that such flexibility might provide, a new simplified unit commitment and dispatch formulation is presented, which integrally uses series flow-controllers to manage congestion and thus reduce operating costs. While both the siting and operation methodologies are shown to be practical, the achieved cost savings are modest at best, even on systems which are weakened to have significant levels of thermal congestion.

1. Introduction

Congestion in high voltage transmission systems is costly and undesirable [1, 2]. The thermal limits of certain lines can prohibit the utilisation of the most cost-effective generators, meaning more expensive generation elsewhere must be brought online instead, which increases the cost of serving the demand in the system. As noted by [3] "the physical laws that govern power flows have traditionally presented a range of challenges both in the operation and the market design of electricity systems. These challenges can be mitigated to a certain extent by an array of transmission control technologies."

Taking its cue from this, the present paper proposes a novel method of managing congestion in a meshed power system, by inserting series active power *flow-controllers* at carefully selected locations within the network. The traditional use for active power control flowcontrollers, historically implemented as a phase-shifting transformer, was at national and system boundaries, where they were used to regulate cross-border flows for commercial or security purposes [4]. For instance, quadrature boosters have been used at area boundaries in the UK to regulate market flows [5]. Modern power electronic devices (the review in [6] discusses several) offer new ways to use smart flow-controllers to unlock flexibilities *within* power networks [7, 8]. However, published approaches to siting such power electronic devices have typically considered direct series or shunt connections to existing lines or buses. To extend the search space of potential installation locations, the present work describes a novel technique for *exhaustively sectionalising* buses and evaluating the flow-controlling coverage offered by straddling each split. This represents the first research question addressed by the present work: how much additional flexibility is realised by expanding the search space for flow-controller insertions in this way?

The methodology described is largely technology-agnostic: for instance, such a flowcontroller could be realised as a pair of back-to-back HVDC converters [9], or perhaps as an interline power flow-controller [10]. The ability to dispatchably withdraw active power at one terminal, and inject it at the other, is the functional characterisation of the flow-controller that will be embraced in this work (this *power-injection model* follows [11]). Cheaper generator dispatch schedules should be possible when such a flow-controlling flexible resource is both strategically located and fully integrated with the unit commitment and dispatch procedure. The present paper treats both topics, to gauge the incremental cost savings that may be attainable by installing these flow-controller to straddle carefully chosen splits in existing bus-bars.

There is a substantial extant literature on locating power electronics devices to improve power system operation (partial reviews can be found in [12, 13, 14, 15]). Such devices can be located in power systems using diverse strategies and in pursuit of various objectives. There are three general approaches to placement: analytic and sensitivity methods [16], formal optimization techniques [17], and computational approaches using metaheuristics [18]. Alleviation of congestion is a common theme [19, 20, 21, 22, 23, 24].

A substantial shortcoming of prior work on locating series devices is that they generally consider extant branches as candidate installation locations. By contrast, the present work enumerates *all* possible ways of *splitting* the existing buses in a system, to find many more candidate divisions for the flow-controller to bridge, and to articulate what additional value this approach offers.

Optimal transmission switching is another way to add flexibility to the generator scheduling formulation so that it may intelligently avoid congestion [25, 26]. The optimal transmission switching approach exploits the counter-intuitive phenomenon whereby weakening a transmission system, by selectively removing certain branches from service, can ameliorate congestion and facilitate cheaper generation schedules.

Optimal transmission switching schemes can achieve substantial generation cost savings. One influential work [27] introduced a basic optimal transmission switching model and found generator cost savings up to 25%, though this was only on one particular test system under notional conditions (given the high, ongoing costs of operating power systems, savings of even a fraction of percent are meaningful, and figures such as the foregoing only point out the potential here) The biggest limitation to optimal transmission switching schemes is that they become computationally intractable on systems of realistic scale [28, 29]. This is because each branch in the network must be associated with a binary status decision variable, which can cause a combinatorial explosion of complexity on large systems.

By contrast, the present scheme here only proposes to add a small number of flowcontrollers to a system, which does not substantially increase the number of decision variables. Additionally, the flow through the controller is a continuous, bounded variable, and so can be optimally fine-tuned to suit the prevailing circumstances. The binary nature of the optimal transmission switching decision does not enjoy such finesse. Conversely, the ability to switch every single line inherently offers system-wide flexibility, whereas a finite number of flow controllers can only offer flow flexibility on a certain subset of branches.

Novel contributions of the present work include an original technique for appraising the suitability of a split in a power system for hosting a series flow-controller and a unit commitment and dispatch formulation that directly exploits the flexibility such controllers afford.

Methodologies for both siting and operating the flow-controllers are presented in Section 2. The placement technique is applied to two test systems in Section 3, and is trialled operationally in Section 4 to determine the value of such novel flexibility. A simple sensitivity analysis is conducted in Section 5. Conclusions are drawn in Section 6.

2. Methodology

The proposed methodology seeks to add flow-controllers to a power system so their dispatchable cross-flow has the maximum possible influence on branches throughout the network. Each flow-controller is placed by enumerating every available way to split busbars in the system, and then analysing the effect a controllable cross-split flow would have at that location. This technique can be applied sequentially until the desired number of controllers have been added to the system. The selected locations depend only on the system's basic connective structure: this siting methodology is not specific to any particular generation dispatch schedule.

2.1. Siting flow-controllers

2.1.1. Flow-controller model

Conceptually, a series power flow-controller can be thought of as two coupled generators, constrained so that one injects active power into the network, and the other withdraws an equal quantity. This framework models, for instance, two HVDC controllers placed back-to-back in a network. The present work rejects the common implicit assumption that such flow-controller can *only* be placed in direct series with an existing branch in the network. Rather, this work assumes that these flow controllers can be physically located at any existing substation in the network, for instance bridging a split created by strategically sectionalising a bus bar there. This exhaustive technique considers both the conventional case of *direct series* connection, where the flow-controller is connected with just a single line at one terminal, as well as the novel *bus split* insertion, where the bus bar is bisected and multiple lines are rewired to either side of the controller (see figure 1). The direct series arrangement must necessarily prevail when a bus has just two or three incident branches:



(a) The initial bus under examination



Figure 1: The two broad types of bus sectionalisation considered in this work. The]=[symbol represents the flow-controller

the potential for strategic rewiring of branches only emerges when four or more lines are present.

Two questions naturally arise under this paradigm: which substation should be chosen to host such a flow-controller, and how should its incident branches be rewired after it is split into two electrically distinct buses?

2.1.2. Flow sensitivity analysis

The idea of *Power Transfer Distribution Factors* [30] is essential to the siting methodology. For each proposed split of the system, a shift factors sensitivity analysis is undertaken, which measures the incremental flows on *all* branches in the system for an active power injection at one side of the split, and corresponding withdrawal at the other. This analysis characterises the system-wide effect of the flow-controller's dispatchable cross-flow. This analysis can be rapidly performed as it exploits the linearizing DC power flow assumptions [31]. As superposition prevails in DC power flow, this work assumes and proposes that the controllable flow sensitivities can be used to optimally offset generator-induced line flows that would otherwise exceed thermal limits. As [11] notes, *"line-flow control of FACTS devices can be understood as an additional controllable power flow through the line, which is superimposed on the 'nature' power flow."* Building from this, the present work investigates the hypothesis that the most desirable location for a flow-controller is the split which offers the widest coverage over as much of the system as possible (the authors in [32] take a similar approach)

Note however that this hypothesis assumes that flow-controllers are placed myopically, solely to maximise the flow coverage they achieve over the whole network. In practice, operator experience, informed by historic dispatch schedules, might readily identify those lines most prone to congestion, whose coverage by flexible controllable flows would logically be a priority. For the sake of the generality and clarity, the present work proceeds without assuming prior knowledge on branches' prospensity to experience congestion. Additionally, it should be noted that the DC power flow assumptions are only an approximation of how power flows in a meshed network. However, as the same linearizations underpin conventional approaches to unit commitment and dispatch, in which context these flow-controllers will be utilised, they seem a legitimate basis for the siting methodology also.

2.1.3. Combinatorial sectionalisation

For each bus bar, all the ways that it can be bisected into two distinct buses must be exhaustively enumerated. To be explicit: for each split, some of the incident branches will connect to one side, and the remainder to the other. Load and generator connections remain constant in this analysis, as they do not affect the flow sensitivity analysis from one side of the split to the other.

How many ways can such a bisection be achieved? The Stirling number of the second kind, S(n,k), gives the number of ways that a set of n distinct objects can be partitioned into k nonempty subsets [33]. The Stirling number of the second kind is evaluated as:

$$S(n,k) = \frac{1}{k!} \sum_{j=0}^{k} (-1)^{k-j} \binom{k}{j} j^n \tag{1}$$

In the present analysis, k = 2 and n equals the number of branches incident at a particular substation i.e the node degree d. Note that the number of potential splits demonstrates a combinatorial explosion with respect to the number of incident branches, as shown in Fig. 2, noting the vertical log axis. However, this explosion is actually desirable: *ceteris parabus*, having more splits to enumerate means that the siting methodology has more opportunity to find a favourable location.

Some splits of the system will be invalid and will be discarded from the analysis. This situation arises when a split divides the network into two separate connected-components, with only the flow-controller connecting them as an *isthmus*. These configurations are invalid as there is no available path for the controlled flow to back-propagate through the system, from one side of the split to the other. Relatedly, under DC assumptions, siting a flow-controller in direct series connection with either end of a particular branch is functionally equivalent, so such cases are only counted once.

In summary, every legal split of every bus is tested. Sequentially, each bus is converted into two separate buses, with the incident branches connected, in turn, to these two buses in every conceivable combination. For each such combination, a flow-sensitivity analysis is conducted, which imposes an active power cross-flow, equal to the capacity of the flow controller, P_f^+ , from one bus to the other. This analysis gives a vector of the incremental flows, ΔF that this controllable transaction will invoke on lines (index: l, cardinality: l^+) elsewhere in the system. This analysis exploits the principle of superposition which holds under the linear power flow assumptions, though admittedly this only approximates the flow of active power in the AC system model.



Figure 2: Combinatorial explosion of the number of possible splits versus the number of incident branches at a substation

The quality, Q of a particular split, s, is gauged as the summation of the absolute value of the corresponding partial flows, expressed as a fraction of each branch's thermal limits, F_l^+ :

$$Q_s = \sum_{l=1}^{l^+} \frac{|\Delta F_l|}{F_l^+} \tag{2}$$

This figure of merit records the total change in branch loadings that occurs when the controller's cross-flow is modulated from zero to its maximum capacity, in either direction. Once all legal splits have been evaluated, the best available split, s^* , is selected where Q_s takes its maximum value, Q^* , with resulting controllable flows, ΔF_l^* .

2.1.4. Recursion

If more than one controller is to be added to the system, the siting technique is applied recursively, so that each flow-controller has its own distinct pale of lines within its influence. The procedure is as before, modified to prevent double accounting of controllable branch flows. This is achieved by including a vector, R_l , which records the controllable flows already achieved in each branch *before* iteration n.

Accordingly, when adding the n^{th} flow controller to the system, the quality for each split is calculated as:

$$Q_s^n = \sum_{l=1}^{l^+} \frac{|\Delta F_l^n| - R_l^n}{F_l^+}$$
(3)

When a controller is added to the system in iteration n, the R record is updated as follows:

$$R_l^{n+1} = R_l^n + |\Delta F_l^{n,*}| \tag{4}$$

Here, $|\Delta F_l^{n,*}|$ records the incremental flows associated with the most recently inserted controller, so they are added to the running tally, R_l , so that the next controller insertion takes account of the pre-existing flow controllability on these branches.

2.2. Exploiting the flow controllers

To permit the flow-controllers to alleviate congestion in an optimal way, their flexibility must be exploited within the unit commitment and dispatch procedures that create the generation schedules. The flow-controllers are included in this formulation by inserting coupled fictitious generators at each of their terminals.

2.2.1. Unit commitment and dispatch rudiments

The exemplary unit commitment and dispatch optimization formulation described here is conventional. To maintain a clear exposition and a tractable formulation, various subtleties of the problem are omitted:

- Generator inter-temporal constraints are not modelled, nor are startup/shutdown costs, and so this formulation optimizes a snapshot of the system state in isolation.
- Security requirements, such as (N-1) branch constraints, are not included (note though that thermal congestion in the (N-1) sense can be significant, so this assumption may tend to underestimate the value of flow-controllers)
- Generators are dispatched solely to meet the demand; no dynamic reserves are carried
- The formulation is entirely deterministic

Such simplifications are in line with e.g [27]. The quadratic cost function to be minimized is given by:

$$\min\sum_{g}^{g^{+}} c_{g,1} P_{g}^{2} + c_{g,2} P_{g} + c_{g,3}$$
(5)

Where P is a decision variable giving the power output for each generator (index: g cardinality: g^+) The c parameters describe the heat rate costs for each generating unit.

A binary decision variable, S, determines the status of each unit. It is incorporated alongside the minimum and maximum output power for each unit:

$$S_g P_g^- \le P_g \le S_g P_g^+ \tag{6}$$

Kirchoff's laws are enforced at every bus (index b):

$$P_{net,b} = P_{g,b} + P_{d,b} \tag{7}$$

The parameter $P_{d,b}$ is a vector describing the fixed power demands at each bus, while $P_{g,b}$ identifies the generator connecting at bus b. The vector of branch power flow variables, F_l , also contributes to the power balance at each bus:

$$P_{net,b} = F_l^T A_{l,b} \tag{8}$$

The matrix $A_{l,b}$ is the system's incidence matrix.

For a branch connecting bus *i* to bus *j*, with reactance X_l , the power flow is determined by the voltage angle ϕ difference:

$$F_l^{i,j} = \frac{\phi_i - \phi_j}{X_l} \tag{9}$$

The vital thermal limits are imposed by:

$$-F_l^+ \le F_l \le F_l^+ \tag{10}$$

2.2.2. Flow-controller model

The flow-controllers are directly included within the formulation of the unit commitment and optimal dispatch problem. Crucially, their presence does not substantially alter the composition of the problem.

For a flow controller (k index) straddling buses i and j, new notional generators are placed at both of these buses. Their output is constrained by:

$$P_{g,i} = P_{f,k} = -P_{g,j}$$
(11)

Where $P_{f,k}$ is a control variable denoting the flow through the flow controller. Each flow controller also has a binary status variable, S_k , denoting its operational mode. With $S_k = 1$, the flow controller is operational and freely controllable, subject only to its capacity constraint, given by the parameter $P_{f,k}^+$:

$$-P_{f,k}^{+} \le P_{f,k} \le P_{f,k}^{+} \tag{12}$$

With $S_k = 0$, the flow controller is taken off line and a parallel breaker is closed, to short together the split buses and return them to their original, connected status. This operational flexibility ensures that the flow controller's capacity limits, $P_{f,k}^+$, do not impede power flows that would otherwise be desirable. In this case the cross-flow is given by the voltage angle difference at buses *i* and *j*, accounting also for the negligible reactance of the breaker, X_k :

$$P_{f,k} = \frac{\phi_i - \phi_j}{X_k} \tag{13}$$

Note that optimally setting $P_{f,k} = 0$ imposes the open-circuit condition, so the optimization formulation enjoys the flexibility of shorting the buses together, isolating them entirely, or precisely modulating the flow of power from one to the other.

3. Test platform

3.1. Software

The siting methodology was implemented in MATLAB [34] using MATPOWER [35] and the combinatorics functions of [36]. The optimal operational methodology was implemented using the YALMIP toolbox [37].

3.2. Test systems

The nesta_case73_ieee_rts and nesta_case118_ieee systems, both from [38], were chosen to demonstrate the siting and operational methodologies for the flow-controllers. The nesta_case73_ieee_rts system is a version of the case presented in [39]. The existing DC link in this system has been removed.

In common with previous works on congestion alleviation (e.g [40]), for the present validation these test system were artificially weakened to induce congestion (as most common test power systems are generously specified, branch thermal limits do not tend to constrain generator schedules, except perhaps in the (N-1) sense) Firstly, branch thermal limits were reduced to 50% of their rated values. Then, to allow the two systems to be compared in an even-handed way, their loadings were normalized, by running an optimal power flow whose sole objective was maximising their total demands by uniformly scaling all loads in the system (as in [41]). By creating substantial congestion costs, it is easier to appraise the ability of flow-controllers to improve the optimality of generation schedules. Some characteristics of the normalized systems are given in table 1.

To gauge the efficacy of the flow controllers over the full gamut of operational situations that may arise on each system, a scenario creation approach from [41] was adapted. This technique was used to produce 100 representative snapshots of potential generator dispatch profiles on each system. To create these, the generator cost curve parameters were randomly *shuffled* between generators from scenario to scenario. Likewise, the total load was randomly scaled between 75% and 100% for each snapshot. Then, a cost-minimising dispatch was performed to produce a generation schedule for each operating scenario, with each therefore having a different disposition of potential thermal congestion issues. This cost-shuffling approach reflects the increasing diversity of line loadings in modern smart power grids, due to stochastic renewable resources and volatile fuel prices. The nesta_case118_ieee system is parameterized in [38] with many units with zero generation cost, so it can be seen to represent a modern, highly renewable power system.

System	Total Load	Total Generation	No. Buses	No. Branches
nesta_case73_ieee_rts	$8.93~\mathrm{GW}$	$10.22 \ \mathrm{GW}$	73	120
nesta_case118_ieee	$3.29~\mathrm{GW}$	$7.13 \mathrm{GW}$	118	186

Table 1: Normalized Test System Characteristics

4. Results: siting methodology

Three flow-controllers were recursively added to each test system, with a maximum capacity of $P_{f,k}^+ = 300MW$. While arbitrary, placing three 300MW controllers was selected as a reasonable test case for these medium-sized systems, given their modest capacities of installed generation.

System	N.	Computational Time (s)
nesta_case73_ieee_rts	1	0.98
	2	1.01
	3	1.08
nesta_case118_ieee	1	45.69
	2	44.27
	3	44.61

Table 2: Computational Time for Siting Methodology

Table 3: Counts of Each Available Split Type							
System	ystem Direct Series Insertion Sites Bus Split Insertion Site						
nesta_case73_ieee_rts	105	199					
nesta_case118_ieee	136	2788					

The raw data underpinning the siting, operational and sensitivity analyses is available at [42]. Calculation times for the siting methodology are shown in table 2, as performed on a standard desktop PC (HP EliteDesk Core i7)

4.1. Split types analysed

Recall that the siting algorithm implicitly evaluates two connection paradigms: the more traditional *direct series*, where the flow-controller has a sole branch at one of its terminals, and the more novel *bus split*, where buses are bisected and multiple branches rewired to connect in combinations to both terminals of the flow-controller. The counts of each of these types of split locations are enumerated in table 3. Notably, the nesta_case73_ieee_rts system has just about twice as many bus split sites as direct series, whereas nesta_case118_ieee has about twenty times more. This is due to the combinatorial nature of these calculations: just a few high degree nodes in nesta_case118_ieee could greatly expand the search space for potential splits.

4.2. Selected insertion locations

The results tabulated in table 4 show how the flow-controllers were inserted in each system. It is clear that the flow-controllers inserted in the nesta_case118_ieee offer about twice the level of controllability as their counterparts in nesta_case73_ieee_rts. This is consistent with table 3, which shows the much larger search space that the former system enjoys.

System	Ν.	At Bus	Туре	Branches <i>i</i>	Branches <i>j</i>	Q_s
nesta_case73_ieee_rts	1	223	Direct series	(62,63,67,68)	(119)	27.02
	2	107	Direct series	(11)	(12)	23.79
	3	101	Direct series	(1, 3)	(2)	19.63
nesta_case118_ieee	1	23	Direct series	(29, 31, 41)	(30)	48.74
	2	34	Direct series	(45, 49, 50)	(60)	40.23
	3	85	Bus split	(133, 135, 136)	(131, 132)	39.43

Table 4: Recursive Splitting Details

4.3. nesta_case73_ieee_rts

The panel of diagrams in figure 3 show where the flow-controllers were inserted into this system, and also illustrate the set of branches that each controller can influence. The first insertion, at bus 223, is seen to have far-reaching influence throughout the network, by controlling the flows on the inter-area tie linking bus 325 to 121. The second and third insertions, at buses 107 and 101, respectively, have a more local effect, principally affecting flows in area number 1, to the left of the figure.

4.3.1. nesta_case118_ieee

The diagrams in figure 4 illustrate where the flow-controllers were inserted into this system, and the set of branches that each controller can influence. The first insertion, at bus 23 takes a commanding position, controlling flows on the central branches in the network. The controller at bus 34 also takes a central position, with the last controller, at bus 85, taking a more peripheral role in a less-integrally connected portion of the network to the bottom right.

4.4. Efficacy distribution of potential insertion sites

Remarkably, five of the six insertions were of the direct series type, even though there are far less potential sites for this connection type. Does this reflect a structural reality, where the direct series sites consistently achieve better flow coverage? Figures 5 and 6 show the ranked distribution of Q_s achieved for *every* split considered, for all three iterations of the methodology on each test system. The two categories of split types are denoted using green for direct series splits, and red for bus splits. It is clear that the bus split type is more common, and that the figures of merit for the direct series type are distributed fairly evenly over the available range. However, in figure 6 there is some evidence that the efficacy of the direct series type is clustered at both the middle and the extreme right of the range, which may help to explain why so many of these sites were selected for the flow-controller insertions.

It is also apparent that nesta_case73_ieee_rts has a fairly linear progression of split efficacy, starting from near zero and proceeding to around 25, whereas nesta_case118_ieee

shows a pronounced exponential uptick to the right of the distribution. While both distributions are diminished somewhat from iteration to iteration, this diminution doesn't suggest a major site exhaustion effect.

5. Results: operational methodology

Using the unit commitment and dispatch formulation previously described, the test systems were optimally dispatched for each of the 100 representative operating scenarios. The computational times required for these optimizations are shown in table 6: it is notable that including the flow-controllers does not substantially affect the computational tractability of the dispatch problem.

System	Case	Total Cost	Congestion	Saving
nesta_case73_ieee_rts	No thermal limits	\$21,438,762	\$0	-
	With thermal limits	\$22,747,384	\$1,308,623	-
	Control at 223	22,741,987	\$1,303,225	0.41%
	Control at 223 & 107 $$	22,580,076	\$1,141,314	12.79%
	Control at 223, 107 & 101	22,556,693	$$1,\!117,\!931$	14.57%
nesta_case118_ieee	No thermal limits	\$1,515	\$0	-
	With thermal limits	\$43,886	\$42,370	-
	Control at 28	\$41,676	\$40,161	5.21%
	Control at 28 & 34 $$	\$40,643	\$39,128	7.65%
	Control at 28, 34 & 85	\$37,338	\$35,823	15.45%

Table 5: Usefulness of Flow-Controllers Across 100 Operational Scenarios

5.1. Efficacy of flow-controllers

The total generation costs for each system and case are shown in table 5. As previously noted, nesta_case118_ieee is specified with many zero marginal cost units, so its cheaper generation schedules are not surprising. Indeed, the nesta_case118_ieee without thermal limits imposed can nearly serve the load at zero cost. However, both systems are alike in the extent to which the flow-controllers can alleviate the congestion costs, at a reduction of around 15% with all three operating. Given how heavily, and artificially, congested these systems are, this suggests that the present methodology for siting and operating flow-controllers is no more than moderately effective in practice. Recall though that the unweighted Q_s metric used in this work was chosen for its simplicity and transparent interpretation: in practice, operator knowledge of which lines experience congestion could inform weighting approaches which may give more effective performance here.

System	Case	Total Optimization Time (s)
nesta_case73_ieee_rts	No thermal limits	475.23
	With thermal limits	390.60
	Control at 223	390.71
	Control at 223 & 107	394.88
	Control at 223, 107 & 101	394.79
nesta_case118_ieee	No thermal limits	424.29
	With thermal limits	428.93
	Control at 28	424.29
	Control at 28 & 34 $$	428.71
	Control at 28, 34 & 85 $$	430.40

Table 6: Computational Time for Operational Methodology

5.1.1. Flow-controller usage profile

To investigate how the flow-controllers were optimally utilised over the 100 representative operating scenarios, histograms of their cross-flows are shown in figures 7 and 8. These histograms are taken from the simulation case where all three controllers are operating. Firstly, it is noticeable that five of the six histograms exhibit an operational profile entirely within the controllable envelope of $\pm 300MW$. Only the controller at bus 28 of nesta_case118_ieee shows persistent uncontrollable crossflows outside of this range. This indicates that the controller at bus 28 only delivers marginal benefit to the system. However, from the other cases it appears that the 'natural' cross-bus flows that are being interrupted by the sectionalisation procedure are of a comparable magnitude to the flow-controller's capacity.

It is also interesting to note the consistent use pattern of certain controllers such as those at buses 107 and 34 in the respective systems. Each of these is used primarily to manage flow between 0 MW and 100 MW in just one direction: this might suggest that the generous flexibility offered by a back-to-back flow-controller may be excessive, and that simpler control solutions may achieve comparable cost savings. On the other hand, the flow-controllers at buses 223, 101 and 85 on their respective system are seen to control flows in both directions and over a range of magnitudes, showing how the full available flexibility is being used in an optimal fashion.





(a) A single line diagram for ${\tt nesta_case73_ieee_rts}$

(b) First split, at bus 223, with controllable flows, $F_l^{1,\ast},$ in blue



(c) Second split, at bus 107, with controllable flows, $F_l^{2,\ast},$ in green

(d) Third split, at bus 101, with controllable flows, $F_l^{3,\ast},$ in violet

Figure 3: Pales of influence for each incremental flow-controller inserted into nesta_case73_ieee_rts. The symbol]=[represents the inserted flow-controller.



(c) Second split, at bus 34, with controllable flows, $F_l^{2,\ast},$ in green

(d) Third split, at bus 85, with controllable flows, $F_l^{3,\ast}$, in violet (the single line diagram somewhat obscures the actual connectivity)

Figure 4: Pales of influence for each incremental flow-controller inserted into **nesta_case118_ieee**.



System: nesta_case73_ieee_rts Categories: Bus split Direct series

Figure 5: The distribution of summed line flow controllability, Q_s , for a 300 MW flow-controller, for each examined split, with each pane showing a recursive application of the siting methodology on the nesta_case73_ieee_rts system



Figure 6: The distribution of summed line flow controllability, Q_s , for a 300 MW flow-controller, for each examined split, with each pane showing a recursive application of the siting methodology on the nesta_case118_ieee system



Figure 7: Histograms showing the distribution of flows through each controller on the nesta_case73_ieee_rts system. Flows in the leftmost and rightmost bins correspond to operating scenarios in which the breaker was closed and uncontrolled crossflows were permitted.



Figure 8: Histograms showing the distribution of flows through each controller on the **nesta_case118_ieee** system.

6. Results: split type sensitivity analysis

A key research goal of the present work was to articulate the incremental value of including exhaustive bus sectionalisations in the search space for new flow-controller insertion locations. However, as table 4 shows, five of the six sites chosen were of the traditional direct series style, even though there are many more potential bus split sites, per table 3. This is surprising, and perhaps largely coincidental, as figures 5 and 6 show no overt advantage to either style of insertion. To provide further insights on the relative merits of the two insertions styles, this section performs a simple *sensitivity analysis*. Here, the siting methodology is revisited, but first restricting it to only consider bus split sites, and likewise again for direct series locations. The operational methodology, using the same data as previously, is run again for the resulting sensitivity cases, so that their relative performance can be compared.

6.1. Selection of restricted insertion locations

Table 7: Recursive Splitting Details, Restricted To Bus Split Sites						
System	N.	At Bus	Type	Branches i	Branches j	Q_s
nesta_case73_ieee_rts	1	203	Bus split	(43, 47)	(12, 48)	20.85
	2	216	Bus split	(65, 69)	(64, 70)	26.11
	3	110	Bus split	(14, 17, 18)	(9, 10)	19.02
nesta_case118_ieee	1	70	Bus split	(108, 114, 115)	(109, 110)	48.74
	2	85	Bus split	(133, 135, 136)	(131, 132)	39.45
	3	37	Bus split	(47, 48, 50, 51)	(52, 53)	36.13

Table 8: Recursive Splitting Details, Restricted To Direct Series Sites

System	N.	At Bus	Type	Branches i	Branches j	Q_s
nesta_case73_ieee_rts	1	223	Direct series	(62,63,77,78)	(119)	27.02
	2	107	Direct series	(11)	(12)	23.79
	3	101	Direct series	(1, 3)	(2)	19.63
nesta_case118_ieee	1	23	Direct series	(29, 31, 41)	(30)	48.74
	2	34	Direct series	(45, 49, 50)	(60)	40.23
	3	82	Direct series	(128, 149)	(129)	39.43

The sites chosen for the two restrictive cases are shown in table 7 and 8. As may be anticipated, table 8 is equivalent to the original sitings in table 4 aside from the third

insertion on the nesta_case118_ieee system. Generally, the achieved Q_s values are not hugely different from those given in table 4, suggesting that the operational performance of these controllers might be comparable to the unrestricted case.

Notably, table 7 shows that the Q_s value *increases* from the first to the second iteration on the **nesta_case73_ieee_rts** system. While this may seem counter-intuitive, recall that the first recursive splitting can have profound effects on the system's global connectivity, which here apparently permits a second splitting which has yet wider coverage.

6.2. Operational performance with restricted insertion locations

Table 9: Congestion Cost Savings Under Different Insertion Regimes						
System	Case	Unrestricted	Direct series	Bus split		
nesta_case73_ieee_rts	1 flow-controller	0.41%	0.41%	7.55%		
	2 flow-controllers	12.79%	12.79%	14.64%		
	3 flow-controllers	14.57%	14.57%	16.64%		
nesta_case118_ieee	1 flow-controller	5.21%	5.21%	5.22%		
	2 flow-controllers	7.65%	7.65%	13.06%		
	3 flow-controllers	15.45%	15.47%	18.96%		

The results in table 9 show the percentage cost savings achieved over the 100 operational scenarios, using the various flow-controllers as inserted under the restricted siting analysis (this table duplicates some of the results in table 5 for clarity) It is immediately clear that the regime restricted to direct series insertions effectively duplicates the performance achieved in the original analysis. This is unsurprising, as the unrestricted regime chose direct series insertion locations in five out of six cases.

More interestingly, though, this table shows superior performance achieved by the bus split insertions. On both test systems, even one flow controller inserted in this way can make a meaningful contribution to alleviating the cost of congestion. These gains are also maintained as subsequent flow-controllers are added. One the one hand, these results seem to demonstrate the value of including exhaustive bus sectionalisation in the search space for flow controller insertion locations. Conversely, the presented insertion methodology, which simply maximises Q_s , did not identify these locations, which indicates the shortcomings of such a myopic approach.

7. Conclusions

This work has articulated a new paradigm for the use of flow-controlling technologies within high voltage transmission systems. By siting flow-controlling devices internally within the power system, new controllability over the bulk transmission of electrical power becomes possible. This paper has critically examined the extent to which this flexibility can improve the optimality of generation schedules.

Several conclusions stem from the presented research:

- The presented methodology only achieved modest cost savings, even on test systems which were artificially weakened to experience substantial congestion problems
- A combinatoric approach to find the many ways that buses in a system can be bisected offers many more locations to install series flow-controllers than are typically considered
- Using the power-injection model, flexible devices such as flow-controllers can be readily integrated into a unit commitment and dispatch formulation.
- A recursive, exhaustive approach to locating series devices was shown to be feasible. However, it is arguable that the unspectacular performance observed could be improved by siting a flow-controller to take account of operator experience, such as placing it to cover lines known to experience congestion.
- Several of the inserted controllers only modulated flows within a narrow range, suggesting that simpler, cheaper devices may achieve similar cost savings.

The unit commitment and dispatch formulation used in the present work was selected to preserve simplicity. Future work may consider how flow-controllers interact and operate under (N-1) security constraints, reserve requirements, and stochastic power injections.

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