

Market-Based Power Flow Control With Reduced Wide-Area Impact

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Abstract

Applications of network control devices such as phase shifting transformers and flexible AC transmission system (FACTS) devices in power systems include congestion management and parallel flow reduction. In a market environment, it is common for these devices to be primarily operated for local congestion relief. However, this single objective control may not utilize the controller to its maximum extent. It may be possible for the device to both manage congestion and reduce parallel flow. This paper develops a two-level hierarchical multiobjective optimization method that determines the operating points of an area's network control devices for local congestion management and inter-area parallel flow reduction, as measured by a novel wide-area impact index. This index is comprised of the weighted sum of the changes in line flow over a large number of transmission lines caused by the operation of an adjacent area. The method and index are validated through an application to a 30-bus test system.

Keywords

Multiobjective Optimization – Congestion Management – Parallel Flow – Phase Shifting Transformer – FACTS.

1. Introduction

In the years following deregulation, investments in transmission have been outpaced by growth in generation and demand. A consequence of this can be increased congestion within an area and on tie lines. Congestion occurs when a system's generation schedule is constrained by the

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operational limits of line flow. The impact of these constraints can be a decrease in market efficiency.

Congestion can be caused by line flow originating both within an area as well as from surrounding areas. In a 2002 UCTE report, several European countries claimed to have remarkable levels of unscheduled line flow in their system [1]. This unscheduled flow is called parallel flow, and may congest a system or exacerbate an already congested system [2].

In order to reduce parallel flow, several system operators (SOs) have installed network control devices such as phase shifting transformers (PSTs) on tie lines [2]. Furthermore, series flexible AC transmission system (FACTS) devices have been shown to have utility in parallel flow prevention and limitation [3]. PSTs and series FACTS devices, collectively known as network control devices, can readily be used to manage congestion in a local area. However, the operation of these devices have wide-area implications as well.

In this paper, it is shown that network control devices installed for the specific purpose of local congestion management can be dually employed to reduce the amount of parallel flow between areas. These objectives are hierarchically structured, as local congestion relief is the first priority of network control device use. This is due to the assumption that an SO is likely to consider the needs of its area before it is concerned with adjacent areas. The optimal operation of the devices and the generation dispatch schedule are determined through a newly developed two-level hierarchical multiobjective optimization (HMO). In addition, a new metric, the wide-area impact index, is introduced. This index accurately measures the effects of parallel flow on a given area.

In the next section, the optimization problem is explicitly stated, with details on the congestion management and wide-area impact index objectives. Section 3 introduces the system, device and constraint models used in the optimization. Using these representations as a framework, the two-level HMO method is developed in Section 4. The method is applied to a modified IEEE 30-bus system in Section 5, followed by conclusions in Section 6.

2. Problem Formulation

It is assumed that the SO operates the network control devices within its area based on two objectives: maximize economic efficiency through congestion management and minimize parallel flow as measured by the wide-area impact index. Furthermore, it is assumed that these devices are operated such that the congestion management is the first priority and any attempt to reduce the wide-area impact is performed only if it does not increase local congestion. By operating in this manner, the local market participants garner the maximum benefit of the devices in their area.

2.1 Congestion Management

Congestion management can be defined as the steps an SO takes in order to alleviate binding transmission constraints. Techniques to manage congestion include redispatching generation, curtailing transactions, or changing the settings of network control devices [4]. The first two options can be costly to the market participants and should be avoided. The network control devices are then the preferred tools for congestion management.

The operation of network control devices to manage congestion can be implicitly accomplished through an optimization whose objective is to minimize the price of generation as defined by generation offers. The objective for an area with m generators is expressed as

$$f = \sum_{i=1}^m C_i(P_{G,i}) \quad (1)$$

where C_i is the offer function of generator i as a function of real power output, $P_{G,i}$. The nature of C is dependent on the market rules; in this paper it is assumed to be quadratic. The objective in (1) will increase from a minimum value as the system becomes more congested. Therefore, the value of f when compared to a base case can be used as a metric to evaluate the congestion of a system.

2.2 Wide Area Impact

The use of parallel flow as a metric to account for the effect that an area's transactions have on an adjacent area can be misleading. Parallel flow is usually measured as the deviation of actual line flow from scheduled line flow between two systems as measured at the interface lines. However, the effects of parallel flow are not limited to interface lines alone. Lines within the adjacent area may be affected as well. This leads to the main distinction between the wide-area impact index and parallel flow. The wide-area impact index accounts for all lines into or inside the adjacent area while parallel flow only looks at tie lines.

The wide area impact index is a weighted linear combination of the change in line flow in the adjacent area as a result of another area's operation. This is expressed as

$$f = \|\mathbf{W}\mathbf{F}\|^2 \quad (2)$$

where \mathbf{F} is a vector of the change in line flow in the adjacent area and \mathbf{W} is a diagonal weighting matrix defined as

$$\mathbf{W} = \begin{bmatrix} \alpha_1 & & \mathbf{0} \\ & \ddots & \\ \mathbf{0} & & \alpha_l \end{bmatrix} \quad (3)$$

where α_k is the weight of line k . The weighting allows the adjacent SO to rate each line in its area by criticality. The weighting factor is applied as follows: for most lines, a nominal value of $\alpha = 1$ is applied, tie or lightly loaded lines are given a low or zero weighting and critical lines are given higher values such as $\alpha = 2$. Critical lines are lines that are heavily loaded, sensitive for voltage or stability reasons, or whose capacity is important for scheduled transactions. Tie lines containing the network control devices used in the optimization are given weights of zero as it is the intent of these devices to alter the power flow through them. The specifics of how the change in line flow is computed depends upon the system models used, as presented in the next section.

3. System Representation

3.1 Network Model

It has been shown that a linear network model with DC assumptions can approximate the flow of real power through a system with sufficient accuracy for some market applications [5]. Indeed,

this model is utilized by most markets to determine the unit commitment in the day-ahead market [6]. An important feature of the linear network model is that it allows superposition to be applied. It is because of superposition that the wide-area impact index can be formulated independently of the actual operating point of the other area. This greatly reduces the required data and complexity of the network model.

3.2 Network Controller Model

There have been many papers devoted to the representation of network control devices in power flows and optimizations [7]. The model used in this paper is the power injection model [8]. In this representation, each network control device is modelled by a power injection at each terminus bus. These injections are of equal and opposite magnitudes. The operating point of the device determines their magnitude. Modelled as such, each network control device is effectively represented as two generators with equal and opposite injections.

3.3 Constraints

The system, generation and device constraints of an n -bus system with m generators and r network control devices in a linear model with DC assumptions are expressed as

$$\sum_{i=1}^m P_{G,i} - \sum_{i=1}^n D_i = 0 \quad (4)$$

$$P_G^{\min} \leq P_G \leq P_G^{\max} \quad (5)$$

$$P_I^{\min} \leq P_I \leq P_I^{\max} \quad (6)$$

$$H\theta \leq F^{\max} \quad (7)$$

$$-H\theta \leq F^{\max} \quad (8)$$

where P_G is an m -dimensional vector of generator real power injections, D is an n -dimensional vector of loads at each bus, and P_I is an r -dimensional vector of equivalent power injections of the network control devices, and θ is a vector of bus angles. This angle vector is a linear function of generation, loads, as well as network control device set points as represented by positive and negative net power injections. Finally, H is a matrix of line flow thermal and/or stability constraint coefficients whose values are determined by the bus impedance matrix and the location of the network control devices. The power balance equation expressed in (4) ensures that generation matches load and that the network control device injections are equal and opposite. Generation and device limits are represented in (5) and (6), respectively. The line flow constraints for each direction are represented in (7) and (8).

4. Two-Level Hierarchical Multiobjective Optimization

The congestion management and wide-area impact objectives are now combined in a two-level hierarchical multiobjective optimization. Most multiobjective optimization methods work to find a set of Pareto optimal points known as a Pareto-front [9]. The preferences or hierarchy of the objectives are used to select the appropriate solution from the Pareto-front.

In the case considered, the two objectives are hierarchically structured. The congestion management objective dominates the wide-area impact index minimization. There is only one Pareto optimal point that minimizes the congestion over the entire feasible space; therefore, a Pareto front is not needed. This single point can be found efficiently by using a two-level hierarchical multiobjective optimization.

Hierarchical multiobjective optimization is similar to reduced feasible region or e-constraint methods [9]. However, those techniques are often iterative while the two-level HMO is performed in a single run. Assume the objectives are ordered such that f_1 is the objective in (1) and f_2 is the objective in (2). Also, let \mathbf{x} be a vector of generator output and network control device set points in the unconstrained space, X . The optimization begins at the upper level by solving

$$\min\{f_1(\mathbf{x})\} \quad (9)$$

subject to

$$\mathbf{x} \in X_1 \quad (10)$$

where X_1 is defined by the constraints in (4) – (8). Let the solution to this problem be \mathbf{x}_1 with corresponding optimal solution $f_1(\mathbf{x}_1)$. In a system with multiple network control devices and under DC assumptions, the solution to (12) may not be unique, in which case the solutions comprise a set, X_2 . All points in X_2 have the property

$$X_2 = (X_1 : \mathbf{x} \in X, f_1(\mathbf{x}) = f_1(\mathbf{x}_1)) \quad (11)$$

In other words, all points within X_2 satisfy the network, generation and device constraints and achieve the lowest price of generation through congestion management. Working within this space, the optimization proceeds to the lower level. Here it solves

$$\min\{f_2(\mathbf{x})\} \quad (12)$$

subject to

$$\mathbf{x} \in X_2 \quad (13)$$

The solution, \mathbf{x}_2 , corresponding to a wide-area impact index value of $f_2(\mathbf{x}_2)$ is the output of the algorithm and is Pareto optimal. By sequentially optimizing the objectives, in reduced spaces, the hierarchy of objectives is strictly observed. In general, the spaces created have the relationship: $\mathbf{x}_2 \in X_2 \subset X_1 \subset X$, as seen in Fig. 1. It should be noted that if the solution to the upper level optimization is unique then there is no need to perform the lower level optimization as all the network control devices will be at their limits of operation.

5. Validation

The two-level HMO is now applied to a modified IEEE 30-bus test system. The price of generation and wide-area impact index at the HMO's solution are compared with the values at the solution of a local congestion management optimization. In addition, the wide-area impact index optimization is compared to a parallel flow-based optimization to illustrate the use of line weighting and the index's overall accuracy at measuring the impacts of an area's operation.

The original system has been modified so that the various features of the optimization can be highlighted. The system, shown in Fig. 2 has been divided into two areas: Area A and Area B. In Area A, the inexpensive generation lies to the north, while major load centers exist in the south. This load pattern causes a parallel flow through Area B. There are no scheduled

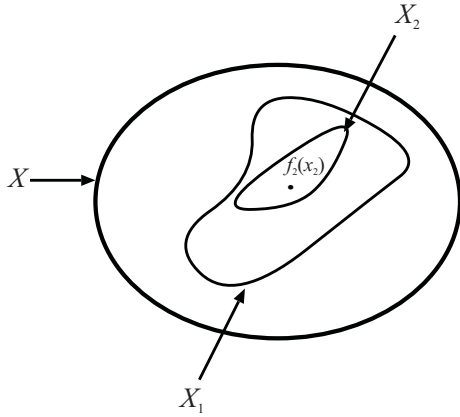


Fig. 1. Illustration of the two-level HMO

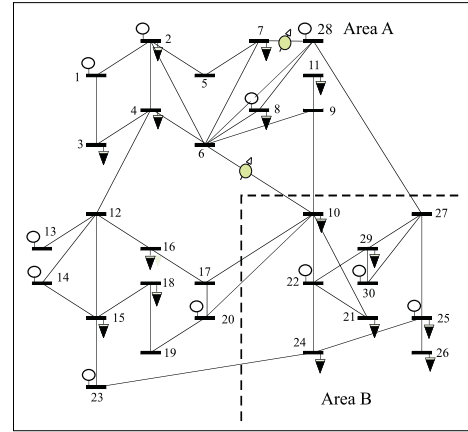


Fig. 2. Modified IEEE 30-bus system

Table I
Network Control Device Parameters

Device Terminus Buses	Min Setting	Max Setting
7 – 28	-20°	5°
6 – 10	-10°	15°

transactions between the areas; therefore any line flow on the tie lines can be considered parallel flow. A binding thermal constraint of 40 MW exists on line 28 – 6. Area A utilizes the HMO to determine the optimal set points of the PSTs on lines 6 – 10 and 7 – 28. The objectives of the HMO are to manage local congestion and to limit its impact of operation on Area B. The parameters of the PSTs are given in Table I. The operating conditions of Area B are not needed, as the system model is linear.

The advantages of the HMO over a local congestion management optimization when applied to this system are now shown. The first and second rows of Table II display the total price paid for generation and the wide-area impact index associated with the optimal solutions of these optimizations. The line weightings used in all the wide-area impact index calculations hereafter are given in Table III. From this, it is seen that the tie lines without a PST are weighted as 0.125 and that line 27 – 29 has been deemed critical by Area B. From Table II, it is seen that the two-level HMO is able to both effectively manage the congestion in Area A and decrease the wide-area impact index when compared with the local congestion management single objective optimization.

The wide-area impact index as a metric of measuring the impact of an area's operation is now

Table II
Optimization Results

Objective	Gen. Cost	Imp. Index	PST (7 – 28)	PST (6 – 10)
Two-Level HMO	\$30,998	2,195	-20°	15°
Local Congest. Management Only	\$30,998	3,531	-7.15°	-6.39°
Impact Index Only	\$46,737	1,836	-5.79°	15°
Parallel Flow Only	\$46,737	3081	-3.79°	-10°

Table III
Area B Line Flow

To Bus	From Bus	α	Impact Obj Line Flow (MW)	Parallel Obj. Line Flow (MW)
6	10	0	152.35	68.19
9	10	0.125	-10.22	31.19
10	20	0.125	43.03	36.69
10	17	0.125	84.25	69.97
10	21	1	8.96	-4.40
10	22	1	5.89	-2.89
21	22	1	8.96	-4.40
22	24	1	25.30	16.00
23	24	0.125	-40.66	-36.83
24	25	1	-15.37	-20.83
25	26	1	0.00	0.00
25	27	1	-15.37	-20.83
28	27	0.125	25.81	44.12
27	29	2	7.49	16.72
27	30	1	2.95	6.57
29	30	1	-2.95	-6.57
29	22	1	10.44	23.29
Total Parallel Flow (MW)			356.33	286.98
Impact Index			1836.26	3081.67
Total Flow Within Area B (MW)			103.68	122.50

compared with a parallel flow-based metric. The fourth and fifth columns of Table III show the line flow in Area B when Area A's operating point has been optimized to minimize the wide-area impact index and to minimize the total parallel flow on the tie lines, respectively. For completeness, the solution to these objectives are given in Table II. The last row in Table III shows the total amount of line flow through Area B's lines as a result of the operation of Area A. This is the amount of capacity that Area B cannot use for its own transactions and is the true measure of the impact of Area A's operation. It is seen that this value is lowest when the wide-area impact index is minimized. From this comparison, it is shown that the wide-area impact index is a better measure of Area B's loss of transmission capacity than a parallel flow-based measure.

The sensitivity of the line flow on the critical line with respect to weighting is shown in Fig. 3. From this figure, it is seen that as the weighting is increased, the real power flow decreases. This decreases continues until $\alpha = 1.4$. At this point, the PST on line 6 – 10 reaches its limit and further decrease in line flow is no longer possible. Therefore, by selecting a higher weight for a critical line, the line flow caused by Area A is likely to decrease. This comparison has demonstrated that the wide-area impact index is responsive to the line weighting of Area B.

6. Conclusions

It has been shown that the two-level HMO is capable of determining device set points for congestion management and reduced wide-area impact. Unlike most multiobjective optimizations,

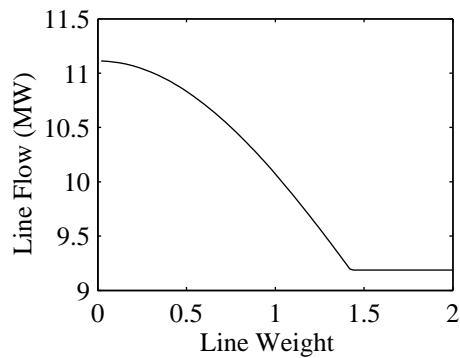


Fig. 3. Effect of weighting on the power flow of line 27 – 29

this method does not require a Pareto-front to find a Pareto optimal solution. The linear problem formulation allows the optimization to be independent of the actual operating point of the adjacent areas. Topological and line weighting data are the only information needed from adjacent areas. These features allow an SO to make full use of an already installed device, thereby increasing its utility and value.

The proposed wide-area impact index has been shown to accurately measure the reduction in line capacity caused by the parallel flow, not just the parallel flow amount. This index utilizes topological information from adjacent areas that are normally not included in parallel flow calculations and can be seen as an extension of the parallel flow metric. The index has been shown to be superior in limiting the total unscheduled flow on lines over a wide area. In addition, the optimization is sensitive to line weighting and is therefore more adaptive than traditional methods.

References

- [1] Union for the Co-ordination of Transmission of Electricity UCTE. UCTE system adequacy retrospect 2002: http://www.ucte.org/publications/library/e_default_2003.
- [2] D. Hayward et al. Operating problems with parallel flows. *IEEE Transactions on Power Systems*, 6(3):1024–1034, August 1991.
- [3] N. G. Hingorani and L. Gyugyi. *Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems*. IEEE Press, Piscataway, USA, 1999.
- [4] R. D. Christie, B. F. Wollenberg, and I. Wangensteen. Transmission management in the deregulated environment. *Proceedings of the IEEE*, 88(2):170–195, February 2000.
- [5] J. Grainger and W. Stevenson. *Power System Analysis*. McGraw-Hill, Inc., New York, USA, 1994.
- [6] A. L. Ott. Experience with PJM market operation, system design, and implementation. *IEEE Transactions on Power Systems*, 18(2):582–534, May 2003.
- [7] D. J. Gotham and G. T. Heydt. Power flow control and power flow studies for systems with FACTS devices. *IEEE Transactions on Power Systems*, 13(1):60–65, February 1998.
- [8] X. Wang, Y. H. Song, Q. Lu, and Y. Z. Sun. Series FACTS devices in financial transmission rights auction for congestion management. *IEEE Power Engineering Review*, 21(11):41–44, November 2001.
- [9] R. Steuer. *Multiple Criteria Optimization*. John Wiley & Sons, New York, NY, 1986.