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A METHOD OF INCLUSION OF SECURITY CONSTRAINTS WITH DISTRIBUTED OPTIMAL POWER FLOW

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Abstract

In this paper, we propose that the SCOPF be solved in a decentralized framework, consisting of regions, using a price-based mechanism. We first solve the distributed OPF problem to determine the maximum secure simultaneous transfer capability of each tie-line between adjacent regions by taking only the security constraints imposed on the tie-lines into account. And then, the regional SCOPF is performed using the conventional LP approach. A description on the inclusion of security constraints with distributed OPF algorithm will be given, followed by a case study for 3-region IEEE 24-Bus reliability test system.

Keywords : distributed OPF, security-constrained OPF

I. INTRODUCTION

Recent forces such as advances in generation technology, increasing competition, interests in deregulation, and the advent of new advanced planning strategy have put pressure on electric utilities to become more efficient. Consequently, the role of OPF is changing and the importance for real-time computation, communication, and data control is greatly increasing. And, it is becoming necessary to incorporate security constraints into the OPF formulation, and more rapid updates of telemetered data and faster solution times are also becoming necessary to better track changes in the system.

However, the inclusion of security constraints with OPF greatly increases the computational difficulties in solving the OPF problem, and moreover, the computational requirements for OPF problem are at the limit of current centralized implementations [1]. Thus, the requirement for faster and more frequent solutions has encouraged the recent development of a number of new OPF technologies, and resulted in the consideration of parallel implementations using decentralized processors.

We described, in our previous work [2,3], a method that enables distributed implementation of parallel OPF. In the present paper, we newly propose a method of inclusion of security constraints with previously presented distributed OPF scheme [2]. We propose that this security constrained OPF (SCOPF) also be solved in a decentralized framework, consisting of regions, using a price-based mechanism that models each region as an economic unit, as we did in non-security constrained OPF [2,3].

We first solve the distributed OPF problem to determine the maximum secure simultaneous transfer capability of each tie-line between adjacent regions by taking only the security constraints imposed on the tie-lines into account. Once the secure transfer capability of each tie-line, consequently the transfer capability between adjacent regions, is determined, the regional SCOPF is performed using the conventional LP approach. In this procedure, it is assumed that each regional SCOPF can be solved, that is each region has enough generation units to correct any overloads on transmission lines. Our paper concentrates on the issue of coordinating the regional SCOPFs.

The SCOPFs solved in each region can be implemented with the fastest available algorithms. Moreover, it is also possible for each utility to have a different SCOPF implementation for its area.

In this paper, we will first briefly present how OPF problems can be decomposed regionally using the mathematical decomposition techniques. Then a description on the inclusion of security constraints with distributed OPF algorithm will be given, followed by a case study for 3-region IEEE 24-Bus reliability test system.

II. DISTRIBUTED OPF

The distributed implementation of OPF has been described previously in [2,3]. The basic idea is to divide a whole power system and corresponding overall OPF problem into regions, and is based on the auxiliary problem principle [4,5]. We proposed that individual utility solves a modified OPF that includes its own area and borders it shares with other utilities, and this approach could be used by utilities to optimize economy interchange without disclosing details of their operating costs to competitors. For example, for a system consisting of two regions, *a* and *b*, with a single tie-line joining them, the decomposition scheme takes the following form to implement distributed computation [2]:

$$(x^{k+1}, y_a^{k+1}) = \underset{(x, y_a) \in A}{\arg\min} \left\{ C_a(x) + \beta/2 \cdot \left\| y_a - y_a^k \right\|^2 + y_a^T \left[\gamma \left(y_a^k - y_b^k \right) - \lambda_k \right] \right\}, \quad (1)$$

$$(y_b^{k+1}, z^{k+1}) = \underset{(y_a, z) \in A}{\arg\min} \left\{ C_b(x) + \beta/2 \cdot \left\| y_b - y_b^k \right\|^2 + y_b^T \left[\gamma \left(y_b^k - y_a^k \right) - \lambda_k \right] \right\}, \quad (2)$$

$$\lambda^{k+1} = \lambda^k + \alpha \left(y_a^{k+1} - y_b^{k+1} \right) \quad (3)$$

, where the subscript k is the iteration index and α and β are positive constants, and λ is the vector of Lagrange multipliers.

Any transmission lines that cross between two adjacent regions are conceptually divided into two lines by duplicating the bus at the overlap region or adding a dummy bus. The overall algorithm involves alternating solution of individual OPFs and updates of multipliers on the constraints. The multipliers could be used to set prices for exchange of real and reactive power. In our distributed scheme, the regions buy and sell electricity from adjacent regions at prices that are coordinated by negotiations between adjacent regions. The price-setting itself can be performed without a centralized processors. The advantage of such decentralization is that only synchronization information needs to be exchanged globally, improving reliability in the event of communication failure. To minimize the coupling between the regions and therefore maximize the solution speed, it is best to divide the overall system in a way that minimizes the number of transmission lines in the cutsets of lines defining the regions. The objective function for each regional optimization problem is similar to the objective function of a standard OPF. The cost of each generator within the region is represented in the objective. However, in addition to these costs, there are dummy generator terms which represent the rest of the system.

With increasing competition, utilities will be less inclined to pool knowledge about their systems or to telemeter measured system and cost data to a common pool operator. Furthermore, from an implementation perspective, pooling data from several utilities would require conversion of each individual utility's data format into a common format and transmitting system and cost data over relatively long distances to a pool center. However this is a difficult and complex task. Nevertheless, as the gains from trade such as economy interchange are important, competition forces systems to be operated in a systematic and efficient manner [6]. This was the driving force behind our development of an approach to OPF that is capable of optimizing many-thousands of bus systems without having to pool all data in one place.

We have presented an effective parallel algorithm that can achieve significant speed-up over serial implementations. In a distributed environment there are overheads that may reduce the possible speed-up. Nevertheless, there would still be powerful incentives to explore a distributed implementation. First, communication bottlenecks at a central control center may prove a major obstacle for centralized multi-utility OPF. A distributed implementation using our approach will be much more attractive than a central implementation, in particular, for real-time application. Second, most traditional approaches to parallelizing OPF are unlikely to be practical for on-line applications, because they involve a master process assigning tasks to slave processes, making communication overhead heavy for distributed implementation. As our parallel approach is based not on the master/slave processor(s) but on the independent regional distributed processor, heavy communication overheads problem in a master processor does not happen. Moreover, communication failure between regions can also be handled more gracefully by a group of decentralized processors.

III. INCLUSION OF SECURITY CONSTRAINTS

One of the major objectives of a modern electric utility company is to produce and deliver electrical energy safely and reliably to the end users at the lowest costs. Before the introduction of security concepts to power system operation, the OPF problems are usually focused on economics rather than security or safety, though some generators in a system were constrained-on for security reasons. As the use of networks close to their limits led to a fear of line overloading, incorporation of several security constraints into the context of OPF, so-called security-constrained optimal power flow is becoming an important tool to determine the system state under considerations of load and operating constraints. The objective of SCOPF is to determine a minimum cost operation point where the system is kept in a normal state after a major disturbance such as transmission line and/or generator outage.

In SCOPF, the system operating constraints under various configurations are added to the normal OPF problem to impose additional limits on line flows and bus voltages for the post-disturbance configurations resulting from a given set of contingencies. That is, for each contingency considered, the post-contingency variables and power flow and operating constraints are appended to the basic pre-contingency OPF formulation to represent the contingency condition. This greatly increase the size and computational complexity of the problem formulation. In general, the appended constraints depend on both the pre- and post-contingency variables; however, an approach based on linearization of a pre-contingency base-case can simplify the representation of the constraints.

To incorporate security constraints, we will use an LP approach that iterates between solution of a base-case and calculation of post-contingency states [7-10]. In each iteration, a pre-contingency base-case OPF is first solved. For each contingency, the post-contingency state is determined based on the solution to base-case. The post-contingency constraints are then linearized in terms of the solution to the base-case. The linearized contingency constraints are appended to the base-case OPF. In each subsequent iteration, the base-case OPF incorporate the linearized contingency constraints from the previous iteration.

In the distributed OPF scheme, contingency constraints are not easily expressed in terms of the core and border variables for each region, and because of regional decomposition and λ updates at the border, the conventional LP approach may not be applied directly. Therefore, we propose an approach to solving the SCOPF problem.

IV. DISTRIBUTED SCOPF

The secure operation of tie-line is of prime importance in a large inter-connected system. Our approach mainly concentrates on tie-line security. We propose to solve an SCOPF problem in a sequential manner as follows. We first solve the distributed OPF problem to determine the maximum secure simultaneous transfer capability of each tie-line between adjacent regions by taking only the security constraints imposed on the tie-lines into account. In this case, a tie-line outage is treated as a generator outage, and the Generalized Generation Distribution Factor (GGDF) [11,12] and Line Outage Distribution Factors (LODF) calculated at the current state are used to formulate the appended constraints. Once the secure transfer capability of each tie-line, consequently the transfer capability between adjacent regions, is determined, the regional SCOPF is performed using the conventional LP approach. When performing LP, all the generations from the dummy generators are held fixed. Figure 1 summarizes the procedure in implementing a distributed SCOPF.

In the procedure, it is assumed that each regional SCOPF can be solved, that is, each region has enough generation units to correct any overloads on transmission lines. The infeasible case is not considered in the present paper [13,14,15].

V. CASE STUDY FOR SCOPF

This section presents a case study implementation of the proposed approach for solving an SCOPF problem. The primal purpose of solving SCOPF is to maintain the system in steady-state after a contingency on transmission lines or generators has occurred. In this study, we are focusing only on determining the secure tie-line flows for the tie-lines joining the regions. That is, we first determine the secure tie-line flows by performing the non-security constrained regional OPFs in parallel. Then the regional SCOPFs are performed with the determined tie-line flows as fixed power exports or imports.

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Solve the distributed non-security constrained OPF.
Determine the secure tie-line flow limits over all the tie-lines.
Repeat until the solutions converge to within tolerance.

        Increment k.
        Perform a power flow for the entire inter - connected system.
        Calculate the network sensitivity factors GGDF and LODF.
        Solve the regional OPF with revised set of tie-flow constraints, in parallel.
        Exchange information between regional processors.
        Update using (4)

Perform regional SCOPF with the determined tie-flows fixed;
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Fig. 1. Distributed implementation of parallel SCOPF

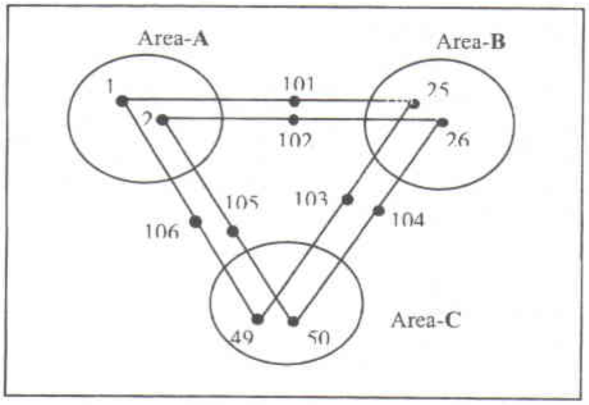

Fig. 2. Case study system

A. *Case study system and Test-run*

For the case study, the 3-region IEEE 24-Bus Reliability Test System (RTS) [16] was adopted, where 2 tie-lines are joining each pair of adjacent regions, and a single - contingency on tie-line was assumed to all 6 tie-lines. The features of the case study system are given in Table 1.

The first column of Table 1 shows that the total number of buses in the case study system is 78.

Table 1. Case study system data

Buses	Regions	Core Buses	Tie Lines	Lines
78	3	24, 24, 24	2, 2, 2	126

Table 2. Tie-line data of the case study system

Tie-line No.	From Bus	To Bus	Line capacity for case 1(pu)	Line capacity for case 2(pu)
1*a*	1	101	3.25	2.50
1*b*	101	25	3.25	2.50
2*a*	2	102	3.25	2.50
2*b*	102	26	3.25	2.50
3*b*	103	25	3.25	1.50
3*c*	49	103	3.25	1.50
4*b*	104	26	3.25	1.50
4*c*	50	104	3.25	1.50
5*a*	1	105	3.25	1.50
5*c*	105	49	3.25	1.50
6*a*	106	2	3.25	1.50
6*c*	50	106	3.25	1.50

The second and third columns show that the number of regions is 3 and the number of core buses in three each regions is 24, where a core bus is a bus not included in border region but in each original region. The fourth column shows that the number of tie-lines that interconnect the regions is 2, while the fifth column shows that the total number of lines in overall system is 126.

The total production cost for real and reactive power for the overall system is considered as an objective function to be minimized. The parameter α, β, and γ were tuned for the system to improve the convergence property. The optimal selection of parameter α, β, and γ to improve the convergence is now under study.

A state-of-art interior point OPF code (INTOPF) was applied to perform the test runs [17,18]. We chose the maximum mismatch between the border variables as the stopping criterion: 1.E-03 pu mismatch for the real and reactive powers, and 1.E-02 for the phase angle and voltage magnitude. In order to see how this algorithm responds to small changes in system status, the two different cases are simulated.

Table 2 summarizes tie-line data for the system, and shows the two different cases. The first column shows the duplicated tie-line number. In practice, for example, 1*a* and 1*b* are same single tie-line which connect the bus 2 in region *a* and the bus 37 in region *b*. But, with the introduction of dummy bus 101, the two tie-lines which represent the same single tie-line behave as if they were distinct. However, our distributed algorithm was designed to enforce the variables of the two tie-lines to be the same value.

B. *Case study results*

The key results are presented in Table 3. Non-security constrained OPF case was also solved for the system to compare the performance with the results of SCOPF case. Both the non-security constrained OPF and SCOPF are solved on multiple processors using decomposition scheme.

One can see that the SCOPF yields smaller tie-line flows in overall than does the ordinary OPF. This is mainly due to the post-contingency system security constraints imposed on the SCOPF problems as described[19]. Performance comparisons are based on the tie-line flow, iteration number, cpu time, and production cost, respectively. Table 3 summarizes the main results of case studies. Figure 3 shows the real power flow on each tie-line of both OPF and SCOPF implementation incase 1, and Figure 4 shows the case 2.

Table 3. Case Study Results: Tie-line Flows (in pu)

Tie-line No.	From Bus	To Bus	Real power flow : case 1		Real power flow : case 2	
			OPF	SCOPF	OPF	SCOPF
1*a*	1	101	2.374	2.073	2.226	1.667
1*b*	101	25	2.358	2.061	2.223	1.659
2*a*	2	102	3.250	2.214	2.500	1.667
2*b*	102	26	3.220	2.119	2.481	1.657
3*b*	103	25	0.880	0.556	0.765	0.598
3*c*	49	103	0.883	0.557	0.767	0.600
4*b*	104	26	1.804	1.359	1.493	0.897
4*c*	50	104	1.813	1.365	1.500	0.900
5*a*	1	105	1.509	1.532	1.486	1.083
5*c*	105	49	1.502	1.525	1.479	1.080
6*a*	106	2	1.430	0.840	0.990	0.756
6*c*	50	106	1.424	0.838	0.987	0.754
Cpu(sec)			3.3	4.7	3.3	4.6
Cost(k$)			1,779	1,787	1,784	1,801

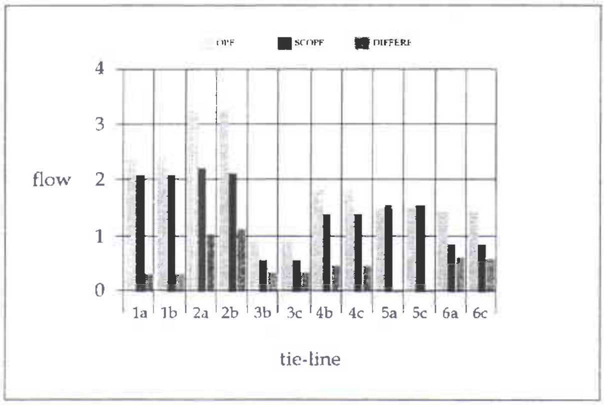

Fig. 3. Tie-line flow (case 1)

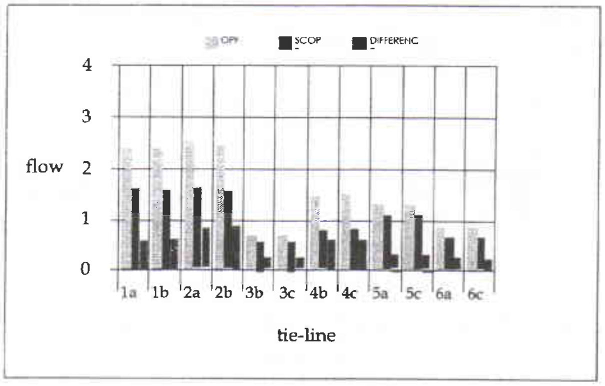

Fig.4. Tie-line flow (case 2)

VI. CONCLUSION

We have presented an approach to implementation of parallel OPF with inclusion of security constraints. We believe that our method is suitable for distributed implementation and is applicable to very large inter-connected power systems.

To solve the distributed SCOPF, we proposed an LP-based approach. In this approach, we are focusing on the secure operation of tie-lines first, and then solve the regional SCOPF using the conventional LP techniques without considering the infeasible case of regional SCOPF. The results of our case studies show a potential applicability of the proposed approach.

The proposed SCOPF approach may not be amenable to the infeasible cases in solving regional SCOPF. So, the incorporation of security constraints will be further studied, and we will investigate ways to better represent security constraints and to solve the SCOPF more efficiently and reliably.

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