Multi-Area ATC Evaluation Based on Kron Reduction

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***Abstract*— In a deregulated power system, the need to perform fast multi-area available transfer capability (ATC) evaluation emerges. This paper introduces a multi-area ATC evaluation method based on system decomposition and Kron reduction. The new method is a four-step procedure including system decomposition, area equivalencing, data exchange and topology checking. The implementation of the new method requires only limited information exchanges between different control areas and the central coordinator. Due to the distributed nature of the new method, the massive calculation of multi-area ATC is broken down and parallel computed in each control area in a distributed way. An enhanced DC-ATC model is adopted to boost speed with reasonable accuracy. The method is validated through both an IEEE 118-BUS test case and a real case in East China.**

***Index Terms*-- Available Transfer Capability (ATC); Sensitivity Analysis; Kron Reduction; Multi-Area System; parallel computation**

I. INTRODUCTION

Congestion management is one of the major obstacles for the development of an increasingly deregulated power system. Available transfer capability (ATC) is a measure of the transfer capability remaining in the physical transmission network for further commercial activity over and above already committed uses [1]. In a fully developed electric market, consumers have the freedom to purchase electric energy from remote areas. And with the prevalence of large scale renewable energy, the remote locations of those renewable energy resources such as wind farms, will also lead to an increase in multi-area transfers. This paper proposes an effective, distributed method to evaluate multi-area ATC.

Since the concept of ATC was introduced, various evaluation approaches have been proposed for its determination. Continuation power flow (CPF) method [2], [3] searches the transfer limit by increasing power transfer continuously until the system stability is challenged. Optimal power flow (OPF) method [4], [5] could further increase ATC by optimizing system controls such as generator outputs and transformer taps. Unfortunately, these methods are not suitable for online ATC calculation due to the slow calculation speed. Instead of using AC model, sensitivity analysis method based on DC model can determine ATC values very fast with a reasonable accuracy. On one hand, power transfer distribution factors (PTDF) are widely adopted to achieve fast ATC online evaluation [6] [7]. On the other hand, due to ignoring the impact of reactive power, DC model usually leads to an over optimistic result, which is illustrated in [8]. To reduce the error caused by ignoring reactive power, [9], [10] suggest fixing the original transmission line capacity for DC models.

However, multi-area ATC evaluation still faces various challenges[11] when using traditional ATC evaluation methods and frameworks:

a) The basic data for multi-area ATC evaluation is difficult to acquire. Most traditional ATC evaluation methods require full access to the model and the real-time operating data of a system being studied, such as system topology, parameters, and real-time transmission line and transformer loading. In multi-area ATC evaluation, these real-time operation data must be collected from multiple control areas, and the challenge of processing such massive amounts of data is prohibitive. Given the limitation of current communication infrastructure capability and the highly competitive market environment, the information necessary for online multi-area ATC evaluation is cumbersome to acquire.

b) The computation burden of multi-area ATC evaluation is prohibitively large. An inter-connected power system may consist of tens of independent control areas and tens of thousands of nodes. The scale of such large calculation is beyond the capacity of any single control area.

c) Because multi-area power transfers may have a negative impact on the reliability of the system as a whole, contingency analysis is necessary. As the system scale grows, the N–1 contingency list of multi-area ATC is much larger than that of a single area ATC. Moreover, when multiple transactions occur simultaneously, those transactions need be ranked and considered one by one, according to their available transfer margins (ATM). All these factors make multi-area ATC evaluation much more complex than ATC for a single control area.

d) Finally, as stated by NERC, an ATC evaluation result has specified time duration. In a fully developed market, sellers and buyers need to get access to the latest ATC evaluation results in time. As a result, a fast and reliable way for online multi-area ATC evaluation is quite important.

This paper proposes a novel ATC calculation method based on multi-area system decomposition and Kron reduction. The new multi-area ATC calculation uses system decomposition and Kron reduction in order to break the entire power system into control areas. Multi-area power transfer distribution factors (MAPTDF) are introduced to depict the correlation among different independent control areas. With the help of MAPTDF, the multi-area ATC calculation is broke down into regional ATC calculation and performed within each control area in a distributed way. Given the consideration of speed and accuracy, a DC model is chosen to meet the requirement of online ATC. The effects of reactive power are considered by using the improved linear ATC method described in [9].

The remainder of this paper is structured as follows: In Section 2, the ATC sensitivity analysis and Kron reduction method are presented. In Section 3 and Section 4, the structure of the proposed multi-area ATC calculation method is discussed in detail. In Section 5, two test cases are presented to validate the proposed method.

II. SENSITIVITY ANALYSIS AND KRON REDUCTION

A. Sensitivity Analysis

Sensitivity analysis is a common tool for power system analysis. A linear DC model is adopted based on the considerations of computational speed. Moreover, from the practitioners' point of view [12], it is widely accepted that the linear model is sufficient for sensitivity analysis.

In the linear ATC model, the changes of real power for transmission lines in the system are linearly related to the changes of power transfer scale. The elements of PTDFs represent the changes of real power flow of the specific lines when a unit of power transfer takes place, see (2).

$$PTDF_{km,T} = \left[\frac{\partial p_{km}}{\partial p}\right] \tag{2}$$

where, $PTDF_{km,T}$ stands for the changes of real power on line km under unit power transfer in the direction T, where T is a balanced vector of bus injection participation factors.

The ATC of line km can be calculated by (3).

$$ATC_{km} = \begin{cases} \dfrac{\bar{L}_{km} - L_{km}}{PTDF_{km}} & PTDF_{km} > 0 \\ \dfrac{-\bar{L}_{km} - L_{km}}{PTDF_{km}} & PTDF_{km} < 0 \end{cases} \tag{3}$$

where, $\bar{L}_{km}$ stands for the capacity of line km; L_{km} is the current real power flow on line km. $PTDF_{km}$ stands for the PTDF of the line km for the transfer direction T.

Finally, $ATC_{Multi-Area} = \min\left(ATC_{line}\right)$ is chosen as the final ATC value under the current operating condition.

To further improve the ATC evaluation accuracy, an enhanced linear ATC calculation method is proposed in [9].

Traditionally, the maximum real power flow $P_{\max}$ allowed through each line is assumed to be the line capacity $S_{\max}$ by ignoring the reactive power flow Q. However, this assumption would be optimistic ATC value. In [9], the concepts of operating circle and limiting circle are introduced. The active and reactive power flow on a transmission line should be confined on the operating circle and in the limiting circle if the voltages are considered to be constant at their based case values during the transfer, a softer assumption compared to the DC assumption that all the bus voltage magnitudes be equal to exactly 1 p.u. The original line capacity $S_{\max}$ is replaced by $P_{\max} \in \left\{P_{\max}^1, P_{\max}^2\right\}$ by considering the constraints of the active and reactive power relationship.

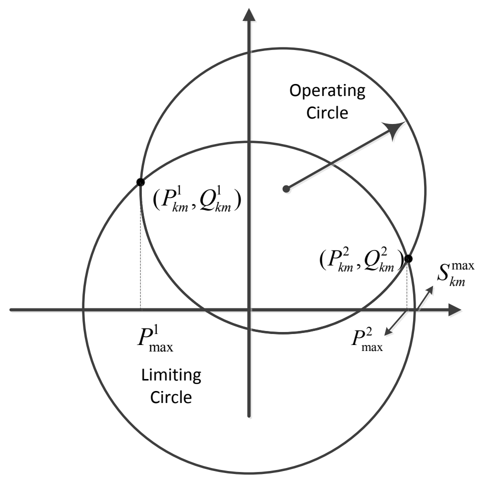

Figure 1. Operating Circle and Limiting Circle

B. Kron Reduction

Kron reduction is widely used as a simplification method for linear and nonlinear power system [13], [14]. This paper adopts Kron reduction to simplify the original topology of each control area into a simplified model. Since Kron reduction is performed within each control area, the real power flow on the tie lines remains the same. The Kron reduction procedure is explained as follows:

1. For each control area, all nodes are classified into two types of nodes: nodes that need to be retained in the model and nodes that need to be eliminated.

2. Assume that the currents injected at the eliminated nodes are zero. The relation between node voltage and node current injection is

$$\begin{bmatrix} 0 \\ I_m \end{bmatrix} = \begin{bmatrix} Y_{nn} & Y_{nm} \\ Y_{nm}^t & Y_{mm} \end{bmatrix} \begin{bmatrix} V_n \\ V_m \end{bmatrix} \tag{6}$$

3. Eliminate V_n as (7).

$$
\begin{aligned}
I_m &= [Y_{mm} - Y_{nm}^t Y_{nn}^{-1} Y_{nm}]V_m \\
&= Y_{bus} V_m
\end{aligned} \tag{7}
$$

where, $Y_{bus} = Y_{mm} - Y_{nm}^t Y_{nn}^{-1} Y_{nm}$ is the Ybus of the new system.

III. Multi-area ATC Calculation

The new multi-area ATC calculation method is especially effective in dealing with problems in large interconnected systems. The new method requires only limited information exchanges among different control areas. A thin, central coordinator is introduced to facilitate the process. Multi-area ATC calculation consists of four steps: system decomposition, area equivalence, data exchange and topology checking.

A. System Decomposition

An interconnected system consists of several independent control areas. The procedure of system decomposition decomposes a multi-area system into several independent control areas. Each control area contains internal buses and transmission lines, and is connected to other control areas by tie lines. Figure 2. shows a 10-node system, which is divided into 3 control areas: A, B and C.

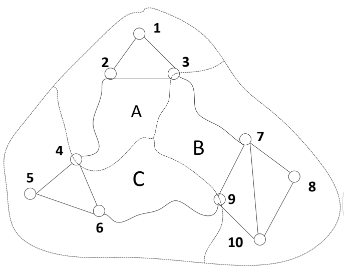

Figure 2. 10-node system

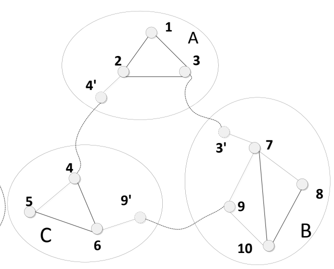

Figure 3. System decomposition

A pseudo bus and a corresponding pseudo tie line are introduced to assign ownership of a tie line as seen in Figure 4. A pseudo tie line is a transmission line with zero impedance and infinite capacity. As a result, all control areas are connected with pseudo tie lines. The original 10-node example system is then decomposed as shown in Figure 3, where 3', 4' and 9' are pseudo buses.

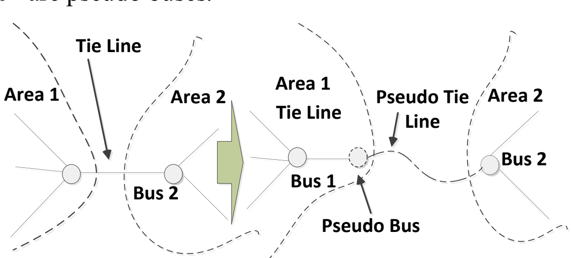

Figure 4. Pseudo Tie Line and Pseudo Bus

B. Area Equivalencing

An equivalent model for each control area is obtained by performing Kron reduction. This process is conducted within each control area independently. After system decomposition, the buses of control area are classified into 4 categories: (1) boundary buses; (2) inner buses; (3) selling buses; (4) buying buses. In the previous example, in order to calculate the ATC from bus 1 to bus 10, the bus categorization results are shown in TABLE I.

TABLE I. Bus Classification

BUS TYPE	**Control Area**		
	A	***B***	***C***
Boundary buses	3, 4'	3', 9	4, 9'
Inner buses	2	7, 8	5, 6
Selling buses	1	--	--
Buying buses	--	10	--

During Kron reduction, all the inner buses of control areas are eliminated. In the previous example, all equivalent area networks are shown in Figure 5.

Take control area C as an example and assume the impedances of all lines are Z . After Kron reduction, bus 5 and bus 6 are eliminated and the entire area C is replaced by a single line 3'-9' with an equivalent impedance (reactance). From the system's point of view, the impedance of area C remains the same after the equivalencing process. As a result, the real power flow on tie lines remains unchanged.

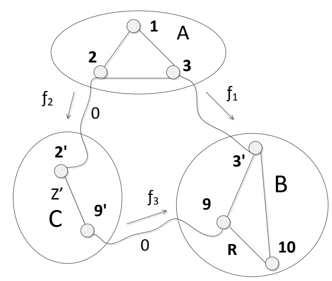

Figure 5. 10-node system after Kron Reduction

C. Data Exchange

After Kron reduction, the multi-area ATC calculation is performed within each control area independently, and limited information is exchanged among the central coordinator and control areas. The detailed process is as follows:

Step 1: The central coordinator gathers all the equivalent models from each control area and pieces them together to form a simplified interconnected system, see Figure 5.

Step 2: Calculate the PTDFs of all the tie lines, according to a specific power transfer direction *T*. In the previous example, all three tie lines have three corresponding PTDFs: f_1 , f_2 and f_3 , see Figure 5. And we define these PTDFs corresponding to tie lines as multi-area PTDFs (MAPTDFs):

$$
MAPTDF = \begin{bmatrix} f_1 & f_2 & \ldots & f_n \end{bmatrix} \tag{8}
$$

Step 3: A new within area power transfer T_{area} is formed according to MATPDF for each control area. And a within area ATC calculation is performed. In the previous example, three within area ATC values are calculated.

Step 4: The central coordinator collects all the ATC_{area} and picks the minimum ATC_{area} as the final multi-area ATC value.

D. Topology Checking

Because the equivalent system achieved by Kron reduction is based on the current system topology, the equivalent system is subject to topology changes. If topology checking is ignored, MAPTDFs can no longer precisely represent the real power changes on tie lines.

As an example, consider the 10-node system. If the topology of area C changes as line 4-5 being out of service, a new equivalent area will be generated as shown in Figure 6. A new line with resistance of $Z'' = 2Z$ must be generated to replace the old one in Figure 5.

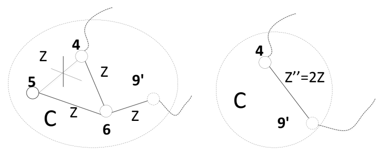

Figure 6. Topology checking

As a result, whenever a control area changes its topology, a new equivalent model must be obtained and communicated. The MAPTDFs should be updated accordingly.

IV. ADDITIONAL CONSIDERATIONS

A. Implementation

The new multi-area ATC calculation method introduces a new structure for power system distributed control strategy in multi-area systems. Figure 7. shows both the flow chart of the new ATC calculation method and the data flows among different control areas and the central coordinator.

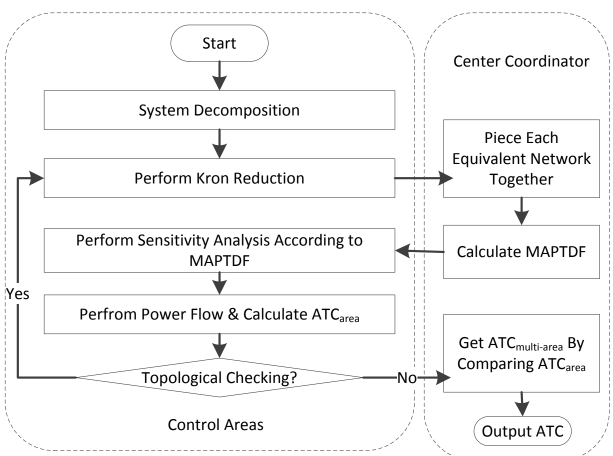

Figure 7. Multi-Area ATC Calculation Flow Chart

B. Kron Reduction

In Kron reduction, all eliminated buses are assumed to have zero current injection. In fact, the Kron reduction process including this assumption will not introduce any new error compared with the original DC ATC model.

In the new method, Kron reduction serves to a quick estimation of MAPTDFs. Since multi-area ATC is calculated within each control area according to MAPTDFs, we only have to prove that the elements in MAPTDF vector remain unchanged during the Kron reduction process.

According to the DC assumption, the changes of the system real power flow depend only on the impedance of each transmission line. In fact, the physical meaning of Kron reduction is to eliminate unwanted buses through a series of Y-△ and △-Y transformation, which will not change the real power flow distribution on the tie lines across different control areas.

Moreover, various enhanced linear ATC methods [9] can also be applied to acquire higher accuracy, as long as those methods are based on the same linearity assumption.

C. Discussion

Because the computation burden for DC ATC increases linearly with the scale of the power system, the proposed method breaks the PTDF matrices calculation of the multi-area ATC calculation without extraordinary decrease in total computational time. However, the proposed method enables multi-area ATC to be evaluated in a distributed way and each control area could run independently, sharing limited information.

Another limitation of this new method is that the new ATC calculation still needs a central coordinator to coordinate the behaviors of the independent control areas. Compared with the fully centralized method, the new method is much more flexible and better meets the requirement of a distributed system control strategy. For example, each control area could use different ways to calculate ATC_{area}, such as enhanced linear ATC method or OPF method. Moreover, the calculation performed by the central coordinator under the proposed method is very limited (calculate MAPTDFs), which greatly relieves the calculation burden of the traditional central coordinator.

V. NUMERICAL RESULTS

In this section, the proposed multi-area ATC calculation method is applied to two different cases: an IEEE 118-bus test case and a real case in East China. The new method is compared with the traditional DC-ATC model.

A. IEEE 118 Test Case

The IEEE test case consists of 118 buses and 186 transmission lines. The system is partitioned into three control areas as seen Figure 8. and TABLE II. Because the original test case did not contain transmission line capacity, those were added as in TABLE III. The proposed multi-area ATC model is compared with the traditional DC-ATC model in TABLE IV. The resulting equivalent system for the first transfer in TABLE IV. is shown in Figure 8. -2.

The simulation results indicate that the new method does not introduce any error compared to the traditional DC model.

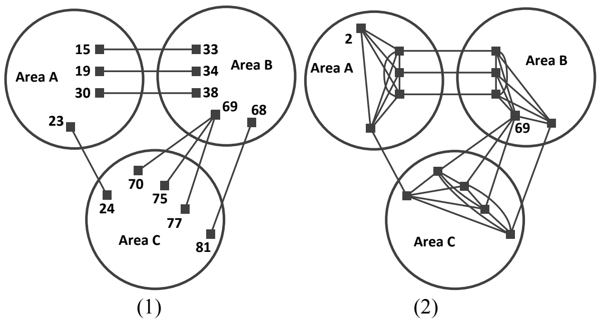

Figure 8. Partitioned IEEE 118-Bus System

TABLE II. IEEE 118-BUS SYSTEM DECOMPOSITION

Transmission Lines			Buses		
Area A	**Area B**	**Area C**	**Area A**	**Area B**	**Area C**
1~45	46~53	108~177	1~23	33~69	24
54	55~107	185~186	25~32	116	70~112
178~182	183	--	113~115	--	118
184	--	--	117	--	--

a. Tie lines are included in the decomposition process.

TABLE III. IEEE 118-BUS SYSTEM LINE CAPACITY

Transmission Lines	Capacity
1~6,10~12,14~20,22~30,34,35,37,39~49,52,53,55~59,91, 92,100, 101,103~106,109,111~115,117~122,125,126, 128~133,135,136,140, 143~162,164~182,184~186	150MW
7,9,13,21,31,33,38,50,90,94,96~99,108,110,116,123,124, 137~139,141,142,163,183	800MW
8,32,36,51,54,93,95,102,107,127,134	1000MW

TABLE IV. MULTI-AREA ATC CALCULATION RESULTS

Trans ID	Selling Bus	Buying Bus	ATC¹	ATC²	ERR‰
1	69	2	360.610	360.562	0.13315
2	69	101	257.837	257.856	0.07164
3	100	7	161.860	161.863	0.02156
4	113	50	129.825	129.821	0.02984
5	6	110	117.786	117.809	0.19641

a. ATC[1]: traditional DC ATC model without system decomposition.

b. ATC[2]: proposed new multi-area ATC model with system decomposition.

B. A Real System in East China

The second case is a real system in East China. The system covers five provinces: Shanghai, Jiangsu, Anhui, Zhejiang and Fujian. As a result, the system is decomposed into 5 different control areas, see Figure 9. The real system is also modified so that we only consider transmission lines that are on 500kV level or above. The system consists of 231 buses and 284 transmission lines.

The results of traditional DC-ATC model and the new model are compared in TABLE V. The proposed method results in the correct values. The new multi-area model could avoid the large scale exchange of system model and real-time operating information, while evaluating the ATC value in a distributed way.

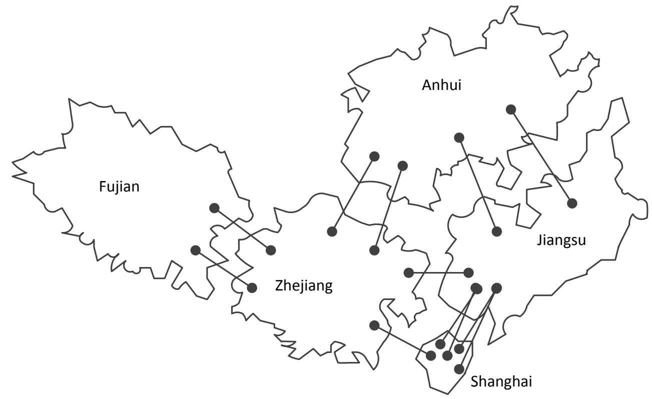

Figure 9. East China Power System with Tie Lines

TABLE V. MULTI-AREA ATC CALCULATION RESULTS

Selling Bus		Buying Bus		Results (MW)		
Name	**Area**	**Name**	**Area**	**ATC¹**	**ATC²**	**ERR‰**
Suyangzhou	Jiangsu	Huminhang	Shanghai	178.8369	178.8365	0.0025
Wanluohe	Anhui	Suwujiang	Jiangsu	248.0575	248.0569	0.0024
Zheyuhuan	Zhejiang	Sunanjing	Jiangsu	91.6749	91.6747	0.0024
Wantong	Anhui	Zhetianyi	Zhejiang	269.0908	269.0906	0.0007
Minhoushi	Fujian	Zhelanting	Zhejiang	281.5981	281.5980	0.0003

a. ATC[1]: traditional DC ATC model without system decomposition.

b. ATC[2]: proposed new multi-area ATC model with system decomposition.

VI. CONCLUSION

In this paper, a new multi-area ATC calculation method is proposed. In this method, multi-area ATC calculation is divided into computations for each control area, and the ATC is determined with the use of a thin coordinator. The correlation among different control areas is represented by MAPTDFs, which are derived from a simplified system obtained using Kron reduction. The numeric results indicate that the new method does not introduce any additional error compared with traditional linear ATC model.

Because the proposed method is based on a linear model and a central thin coordinator is needed, further work will explore the possibility of using AC ATC model and building a calculation structure using a fully de-centralized approach.

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