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A Dynamic Collusion Analysis Framework Considering Generation and Transmission Systems Maintenance Constraints

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Abstract— **Capacity withholding of generation companies is an important issue in market monitoring procedures. The capacity withholding can be intensified in the transmission and generation constrained system. The strategic maintenance of market participants can impose multiple constraints on the system and changes the wholesale electricity market prices. The strategic maintenance of transmission and generation facilities is known as dynamic capacity withholding (DCW) and all of the market-monitoring units need algorithms to detect and reduce DCW. In this paper, a new dynamic capacity withholding index is presented. The method is analyzed on the IEEE 30, 57-bus test system. The numerical results show the effectiveness of the proposed index.**

Index Terms--**Dynamic capacity withholding, Maintenance planning, Electricity market, Transmission system, Strategic Behavior.**

I. INTRODUCTION

The wholesale electricity markets are mainly Oligopoly markets that the competitiveness of the market may be reduced by multiple transmission and generation systems constraints. Transmission and generation companies can change the electricity price and reduce social welfare. Further, the collusive behavior of transmission and generation companies in maintenance scheduling can intensify the market power of market participants that may be led to more inefficiency of the market [1, 2]. The capacity withholding (CW) is a major problem that reduces the competitiveness of the market and it depends on multiple technical and economic parameters [3]. The market monitoring units (MMU) of different wholesale electricity markets utilize multiple algorithms, indices and procedure to detect, prevent and penalize the capacity withholders [4, 5]. Over the years, multiple papers have been presented the indices and algorithms for capacity withholding analysis. In [6], the pricing strategies of generation companies (GenCos) in the California electricity market is analyzed and a game-theory approach for analyzing of CW is presented. The strategic maintenance of generation units is proposed in [7].

In [8], the Herfindahl-Hirschman Index (HHI) is implemented for dynamic capacity withholding (DCW) analysis. In [9], two structures are presented for considering the effect of transmission capacity on the market power. In [10], a market with a double price cap is modelled to determine the CW for the different operational condition.

The market power indices can be divided into structural and behavioral indices [11]. In [12], must-run ratio (MRR) index is proposed to consider the constraint of the capacity of transmission lines and this index consider transmission system congestion. In [13], expected nodal must-run share (ENMRS), must-run share (MRS) and nodal must-run share (NMRS) are proposed and the constraints of the transmission system in different load and generation patterns are considered. A supply function equilibrium (SFE) model that considers the transmission system is modelled in [14].

The Cournot-Nash equilibrium model is presented in [15] that considers various scenarios of network constraints and GenCos parameters. The nodal withholding-supply ratio (NWSR) is proposed to model integrated generation and transmission maintenance scheduling impacts on the capacity withholding. Based on the literature review, the dynamic capacity-withholding problem needs more analyzing tools.

An integrated model that considers the dynamic capacity withholding of GenCos and formulates the generation and transmission maintenance strategies to present a DCW index is less frequent in the literature and is not presented in the available literature before, to the best of the authors′ knowledge.

In brief, the main novelty of paper can be listed as:

- The DCW index (DCWI) in the transmission constrained system is proposed;
- The formation of collusive groups of GenCos is considered in the DCWI and reduced;
- The strategic maintenance of transmission and generation companies is analysed.

This paper is organized as follows: Section II provides the problem formulation and the model of the wholesale electricity market in wholesale electricity markets. Section III presents a case study for different IEEE. Finally, the conclusion of the paper is presented in Section IV.

II. PROBLEM MODELING AND FORMULATION

A three-level optimization method is presented as shown in Fig. 1. At the first level, GenCos optimize their long-term generation strategies and maintenance schedule. GenCos are optimizing their long-term profits by choosing generation and maintenance strategies as well as their estimated maintenance intervals. At the second level, the GenCos optimize the short-term generation and maintenance schedule. At the third level, the independent system operator system (ISO) maximizes the social welfare of the system considering its constraints. In this case, the strategies of the GenCos may change due to security constraints. The planning horizon is considered as planning horizon for long-term maintenance. GenCos should specify their maintenance plans for several weeks, considering their system and ISO constraints. A generation unit can withhold capacity and it may maintain its facilities in a specified period to gain more profit. Further, it can dynamically withhold its capacity and form collusive groups with other GenCos to increase the market price.

At the third level, the strategies of the GenCos may change the network security. The short-term GenCos and transmission system constraints are for 24 hours horizon.

It is assumed that the generation cost of i^{th} unit at t^{th} time of a generation unit can be presented as:

$$C_{i,t}^{Genco} = a.P^2 + b.P + c \tag{1}$$

The fixed parameters of generation costs are *a, b, c* and *P* is the generated power of GenCos. Further, the electricity price at j^{th} bus can be formulated as [15]:

$$\gamma_{j,t} = -\nu.y + \zeta \tag{2}$$

where, ν and ζ are the inverse of the slope of the demand and the width of the inverse function of the demand, respectively. Further, *y* is the load of the bus.

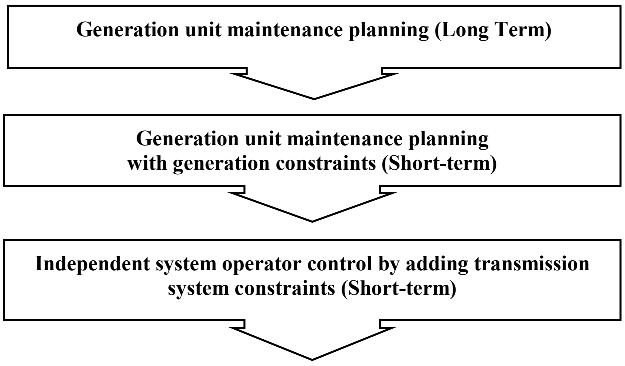

Figure 1. Proposed framework for DCW analysis

The first level optimization problem can be presented as:

$$Max\ \mathfrak{M} = \sum_{t=1}^{NLT}\sum_{i=1}^{NG}(\gamma.P - I.C_{i,t}^{Genco}) \tag{3}$$

Subject to:

$$P^{\min}(1-I) \le P \le P^{\max}(1-I) \tag{4}$$

$$\sum_{t=1}^{NLT} I = K \tag{5}$$

where, *I* is the binary variable for GenCos long-term maintenance scheduling; when *I=1*, the unit is in maintenance mode, otherwise, the unit is on generation mode, *K* is the number of required time periods for maintenance, *NG* is the total number of generation units of GenCos, and $P^{\max}$, $P^{\min}$ are the minimum and maximum power generation, respectively. *NLT* is the long-term maintenance planning of GenCos.

The continuity of maintenance constraint is also considered and for the sack of simplicity is not presented [15]. Equations (4) and (5) present the generation of power in maintenance time and the total required time for maintenance constraints, respectively.

The second level of the problem is a short term optimization of the first level and all of the described equations can be presented for this level. Thus, the second level optimization problem can be presented as:

$$Max\ \mathfrak{A} = \sum_{t=1}^{NST}(\gamma.P - I'.C_{i,t}^{Genco}) \tag{6}$$

Subject to:

$$P^{\min}(1-I') \le P \le P^{\max}(1-I') \tag{7}$$

$$\sum_{t=1}^{NST} I' = K' \tag{8}$$

where, *I'* is the binary variable for GenCos short-term maintenance scheduling. K' is the number of required time for maintenance, *NST* is the short-term maintenance planning of GenCos.

Further, *NST* is the number of the short-term interval of simulation. The crew, continuity of transmission system maintenance and time window of maintenance constraints must be considered in Eq. (8).

Finally, at the third level optimization problem, the ISO maximizes short-term social welfare and it considers the transmission system optimal operation and maintenance scheduling as the third term of the following formulation:

$$\begin{aligned} Max\ \mathbb{S} = &\sum_{t=1}^{NST}\sum_{j=1}^{NLB}(-\frac{1}{2}\upsilon.y^2 + \zeta.y) \\ &-\sum_{t=1}^{NST}\sum_{i=1}^{NG}(\frac{1}{2}a.P^2 + b.P - I.C_{i,t}^{Genco}) \\ &-\sum_{t=1}^{NST}\sum_{j=1}^{NL}(\chi(1-I'')) \end{aligned} \tag{9}$$

Subject to:

$$\sum_{i=1}^{NG} P = \sum_{j=1}^{NLB} y \qquad (10)$$

χ and *I"* are maintenance cost of the line and binary variable of line maintenance, respectively. When *I"=1*, the line is in the repair mode. The power flow upper and lower bounds and load flow of system constraints must be considered. The third term of Eq. (9) minimizes the maintenance costs of transmission system owners.

The capacity withholding of power generation ΔP^{CW}, capacity distortion of power generation ΔP^{CD} and price distortion $\Delta\gamma^{CD}$ parameters can be presented as:

$$\Delta P^{CW} = P^{FCMMP} - P^{MPC} \qquad (11)$$

$$\Delta\gamma^{CD} = \gamma^{FCM} - \gamma^{MPC} \qquad (12)$$

$$\Delta P^{CD} = P^{FCM} - P^{MPC} \qquad (13)$$

where, P^{FCMMP} represents the power generation of the unit in the full competition market multi-polar (FCMMP) and P^{MPC} is the power generation of the unit for the multi-polar competition (MPC) market, respectively. Further, P^{FCM} and P^{PMC} are the generated electricity for the specified unit for the full competition market (FCM) and MPC conditions, respectively. γ^{FCM} and γ^{PMC} are the price of electricity for the specified bus for the full competition market (FCM) and MPC conditions, respectively.

The DCWI presents the ability of groups of GenCos for collusive behavior in the market as follows:

$$DCWI = \sum_{t=1}^{24} \sum_{i=1}^{NG} \frac{\Delta P^{CD}}{\Delta P^{CW}} \qquad (14)$$

The ISO can analysis the collusive behavior of GenCos by calculating *DWCI.*

III. CASE STUDY

In the following, the DCW priority lists of GenCos for the 30, and 57-bus IEEE test systems are evaluated and the DCWI is calculated. The characteristics of GenCos of test systems are given in [15, 16]. Further, the minimum up and down times are 8, 4 hours, respectively. Table I shows the maintenance cost of test systems. Two scenarios of case studies are presented. The first scenario does not consider the maintenance scheduling of transmission system. However, the second scenario considers the maintenance of the transmission system. The GenCo and the most collusive groups that have the highest impact on the DCWI values are highlighted in blue and red, respectively.

A. Numerical studies for IEEE 30-bus test system without the maintenance scheduling of transmission system

At first, the GenCos optimizes their long-term maintenance scheduling and then, the problem is optimized for three 8-hour horizon. Table II depicts the output results of the algorithm and according to the results, the DCWI for the three participants in the collusive group is higher than other groups according to the DCW priority list.

B. Numerical studies for IEEE 57 -bus test system without the maintenance scheduling of transmission system

The maintenance planning for the IEEE 57-bus test system is analyzed, and the results are shown in Table III. As the number of generation units in the group increases, the DCWI is rapidly changed.

C. Numerical studies for IEEE 30-bus test system considering the maintenance scheduling of transmission system

In this scenario, the previous case study is performed considering the maintenance scheduling of transmission system.

TABLE I. MAINTENANCE COSTS OF IEEE TEST SYSTEMS FOR GENERATION UNITS

$C_{i,t}^{Genco}$ [\$/h]	Test system IEEE	Generation Units							
	30-bus	1	2	5	8	11	13		Total generation units=5
		5500	2520	2062	1240	1600	1600		
	57-bus	1	2	3	6	8	9	12	Total generation units=6
		5713	2238	1825	1290	1217	1290	1436	

TABLE II. DCWI PRIORITY GROUPS FOR GENCOS IN IEEE 30-BUS TEST SYSTEM

Number of Members in Groups	**GenCos In Dynamic Capacity Withholding Group**						***DCWI***	***Long-term Maintenance Scheduling (Week)***
	13	**11**	**8**	**5**	**2**	**1**		
2		✓				✓	1.9	12
3		✓			✓	✓	2.265	16
4		✓		✓	✓	✓	-0.592	23
5		✓	✓	✓	✓	✓	0.051	19
6	✓	✓	✓	✓	✓	✓	-3.849	29

TABLE III. DCWI PRIORITY GROUPS FOR GENCOS IN IEEE 57-BUS TEST SYSTEM

Number of Members in Groups	**GenCos In Dynamic Capacity Withholding Group**							***DCWI***	***Long-term Maintenance Scheduling (Week)***
	12	**9**	**8**	**6**	**3**	**2**	**1**		
2			✓				✓	2.36	7
3			✓			✓	✓	2.704	19
4	✓		✓			✓	✓	-0.108	27
5	✓		✓	✓		✓	✓	0.409	32
6	✓	✓	✓	✓		✓	✓	-3.5	39
7	✓	✓	✓	✓	✓	✓	✓	-3.97	46

TABLE IV. MAINTENANCE COSTS OF TEST SYSTEMS FOR TRANSMISSION CONSTRAINED SYSTEM

Maintenance costs (h/$)	Test system IEEE	Candidate lines					
	30-bus	8	9	17	18	31	41
		1500	1500	1500	1500	1500	1500
	57-bus	1	2	10	11	24	34
		5713	2238	1825	1290	1217	1290

TABLE V. DCW PRIORITY LIST OF 30-BUS SYSTEM

Number of Members in Groups	GenCos In Dynamic Capacity Withholding Group						*DCWI*
	13	11	8	5	2	1	
2	✓					✓	164.937
3	✓				✓	✓	165.362
4	✓			✓	✓	✓	163.862
5	✓		✓	✓	✓	✓	161.394
6	✓	✓	✓	✓	✓	✓	159.72

TABLE VI. DCW PRIORITY LIST FOR 57-BUS SYSTEM

Number of Members in Groups	GenCos In Dynamic Capacity Withholding Group							*DCWI*
	12	9	8	6	3	2	1	
2	✓						✓	168.75
3	✓					✓	✓	170.125
4	✓			✓		✓	✓	167.4
5	✓	✓		✓		✓	✓	165.865
6	✓	✓	✓	✓		✓	✓	163.1
7	✓	✓	✓	✓	✓	✓	✓	173.37

Table IV displays the costs of the candidate line of the transmission system. The maintenance cost of GenCos is same as Table I.

The DCW priority list for the IEEE 30-bus system, considering the simultaneous maintenance planning of generation and transmission systems is shown in Table V. The DCWI pattern and values have changed based on the fact that the restrictions on the commitment of generation units and transmission system maintenance planning constraints. The market power of some GenCos has increased Fig. 2 shows the DCW of groups formed in the wholesale electricity market for the 8 hours of the day.

It should be noted that the groups with two members have more collusive behavior than groups with five members, and therefore, ISO should prevent the occurrence of predicted collisions according to the final priority list.

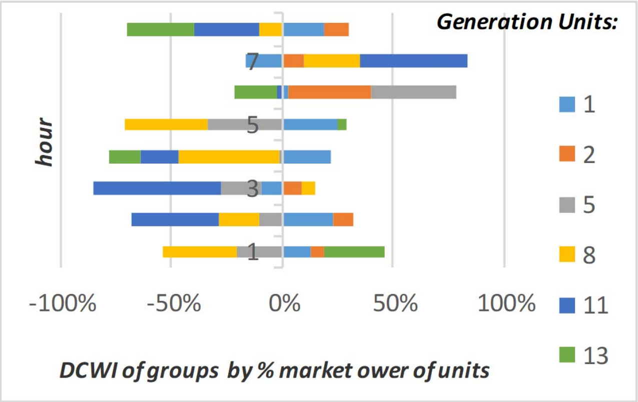

Figure 2. The greatest power of DCW of groups formed in the wholesale electricity market for 8 hours of day for the IEEE 30-bus test

D. Numerical studies for IEEE 57-bus test system considering the maintenance scheduling of transmission system

The DCW priority list for the IEEE 57-bus system, considering the simultaneous maintenance planning of generation and transmission systems is shown in Table VI. The value and pattern of collusive groups are changed concerning the first scenario.

IV. CONCLUSION

Dynamic capacity withholding assessment is one of the most important issues in market monitoring procedures. The capacity withholding may change wholesale market power price and reduce the total social welfare. In this paper, a new dynamic capacity withholding index is proposed and a three-level optimization algorithm is introduced. The optimization algorithm considers the long and short term maintenance scheduling and the third level of optimization considers the transmission system impacts on the procedures. The dynamic capacity withholding index was calculated for two scenarios that consisted of relaxed transmission system constraint problem and transmission constrained problem. Two scenarios were assessed for IEEE 30, and 57-bus test systems. The results showed that the formation of collusive groups in transmission constrained system increased the values of dynamic capacity withholding index. Further, as the number of collusive groups increased, the amount of collusion between generation units decreases. Transmission system maintenance planning can increase the collusive behavior of generation companies and the ISO must detect these collusive groups and penalize them.

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